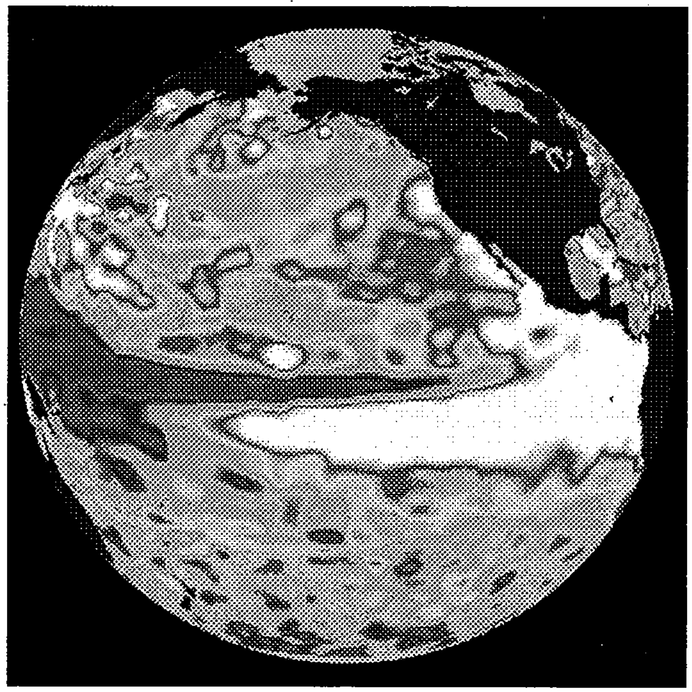
Science for Solutions

NOAA COASTAL OCEAN PROGRAM
Decision Analysis Series No. 11

CHANGE IN PACIFIC NORTHWEST COASTAL ECOSYSTEMS

Edited by
Gregory R. McMurray
and
Robert J. Bailey

April 1998



U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
Coastal Ocean Office

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Cover photo: *This image of the Pacific Ocean was produced using sea surface height measurements taken by the U.S./French TOPEX/POSEIDON satellite. The image shows sea surface height relative to normal ocean conditions on November 10, 1997. The white areas indicate unusual patterns of heat storage; the sea surface is between 14 and 32 centimeters (6 to 13 inches) above normal. The surface area covered by the warm water mass is about one and one-half times the size of the continental United States. (Source: NASA Jet Propulsion Laboratory World Wide Web home page at www.jpl.nasa.gov.)*

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Pacific Northwest Coastal Ecosystems Regional Study (PNCERS)

Edited by Gregory R. McMurray
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PNCERS

April 1998

U.S. DEPARTMENT OF COMMERCE
William M. Daley, Secretary
National Oceanic and Atmospheric Administration
D. James Baker, Under Secretary
Coastal Ocean Office
Donald Scavia, Director

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Note to Readers

Change in Pacific Northwest Coastal Ecosystems is a product of the Pacific Northwest Coastal Ecosystems Regional Study (PNCERS), a NOAA Coastal Ocean Program study begun in 1996. This document presents the results of a workshop conducted during August, 1996, to better define a research agenda to study the combined effects of natural variability and anthropogenic change in Pacific Northwest coastal ecosystems. It contains five complementary syntheses written for the workshop on the topics of human intervention in coastal ecosystems (Chapter 2), the socioeconomic causes and consequences of coastal ecosystems change (Chapter 3), variability and stability of climatic/oceanic regimes (Chapter 4), variability of marine ecosystems (Chapter 5), and variability of riverine and estuarine ecosystems (Chapter 6). It also contains the critical responses and research ideas of the peers who attended the workshop (Chapter 7).

The Coastal Ocean Program (COP) provides a focal point through which NOAA, together with other organizations with responsibilities for the coastal environment and its resources, can make significant strides toward finding solutions to critical problems. By working together toward these solutions, we can ensure the sustainability of these coastal resources and allow for compatible economic development that will enhance the well-being of the Nation now and in future generations. The goals of the program parallel those of the NOAA Strategic Plan.

A specific objective of the COP is to provide the highest quality scientific information to coastal managers in time for critical decision making and in formats useful for these decisions. To help achieve this, the COP inaugurated a program of developing documents that would synthesize information on issues that were of high priority to coastal managers. As a contribution to the Decision Analysis Series, this report provides a critical synthesis and foundation for new research and assessment in the Pacific Northwest. A list of available documents in the Decision Analyses Series can be found on the inside back cover.

As with all of its products, the COP is very interested in ascertaining the utility of the Decision Analysis Series, particularly in regard to its application to the management decision process. Therefore, we encourage you to write, fax, call, or E-mail us with your comments. Please be assured that we will appreciate these comments, either positive or negative, and that they will help us direct our future efforts. Our address and telephone and fax numbers are on the inside front cover. My Internet address is DON.SCAVIA@NOAA.GOV.

Donald Scavia
Director
NOAA Coastal Ocean Program

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The Pacific Northwest Coastal Ecosystems Regional Study workshop was scoped by the PNCERS Program Management Team of Robert Bailey (Oregon Department of Land Conservation and Development), Andrea Copping (Washington Sea Grant Program), and John Stein (National Marine Fisheries Service). Robert Malouf and Jan Auyong of the Oregon Sea Grant Program, and James Good and Patrick Corcoran of Oregon State University also helped to scope the workshop. Credit is due Daniel Bottom, David Greenland, Daniel Huppert, Charles Simenstad, Ronald Thom and Robert Wissmar for chairing the workshop sessions and reacting positively to criticism and constructive comments on the draft synthesis papers. The success of the workshop was also due in great part to the facilitating skills of Patrick Corcoran, Michael Eng, James Good, Steven Harbell and Paul Klarin. The many ideas discussed at the workshop were effectively captured by the recorders recruited from the Oregon State University Marine Resource Management Program: Katie Busse, Larissa Lubomudrov, Kris McElwee, Chuck Schonder and John Weber.

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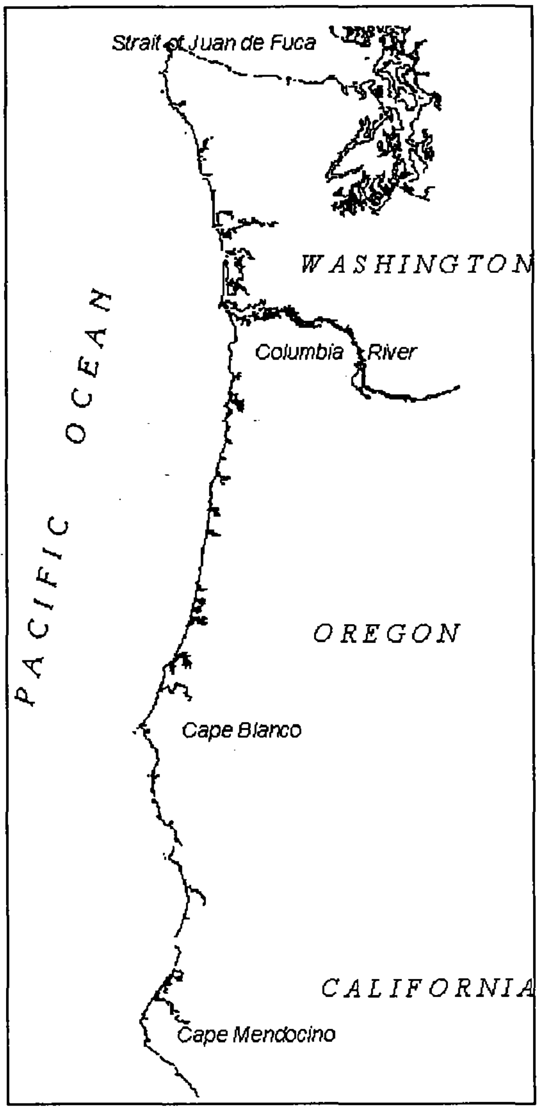
Finally, thanks are due to all of the participants of the Pacific Northwest Coastal Ecosystems Regional Study workshop, who gave freely of their time and wisdom. Their names and affiliations are contained in Appendix A.

EXECUTIVE SUMMARY

BACKGROUND

Over the past one hundred and fifty years, the landscape and ecosystems of the Pacific Northwest coastal region, already subject to many variable natural forces, have been profoundly affected by human activities. In virtually every coastal watershed from the Strait of Juan de Fuca to Cape Mendocino, settlement, exploitation and development of resources have altered natural ecosystems. Vast, complex forests that once covered the region have been largely replaced by tree plantations or converted to non-forest conditions. Narrow coastal valleys, once filled with wetlands and braided streams that tempered storm runoff and provided salmon habitat, were drained, filled, or have otherwise been altered to create land for agriculture and other uses. Tideflats and saltmarshes in both large and small estuaries were filled for industrial, commercial, and other urban uses. Many estuaries, including that of the Columbia River, have been channeled, deepened, and jettied to provide for safe, reliable navigation. The prodigious rainfall in the region, once buffered by dense vegetation and complex river and stream habitat, now surges down simplified stream channels laden with increased burdens of sediment and debris. Although these and many other changes have occurred incrementally over time and in widely separated areas, their sum can now be seen to have significantly affected the natural productivity of the region and, as a consequence, changed the economic structure of its human communities.

This activity has taken place in a region already shaped by many interacting and dynamic natural forces. Large-scale ocean circulation patterns, which vary over long time periods, determine the strength and location of currents along the coast, and thus affect conditions in the nearshore ocean and estuaries throughout the region. Periodic seasonal differences in the weather and ocean act on shorter time scales; winters are typically wet with storms from the southwest while summers tend to be dry with winds from the northwest. Some phenomena are episodic, such as El Niño events, which alter weather, marine habitats, and the distribution and survival of marine organisms. Other oceanic and atmospheric changes operate more slowly; over time scales of decades, centuries, and longer. Episodic geologic events also punctuate the region, such as volcanic eruptions that discharge widespread blankets of ash, frequent minor earthquakes, and major subduction zone earthquakes each 300 to 500 years that release accumulated tectonic strain, dropping stretches of ocean shoreline, inundating estuaries and coastal valleys, and triggering landslides that reshape stream profiles. While these many natural processes have altered, sometimes dramatically, the Pacific Northwest coastal region, these same processes have formed productive marine and coastal ecosystems, and many of the species in these systems have adapted to the variable environmental conditions of the region to ensure their long-term survival.



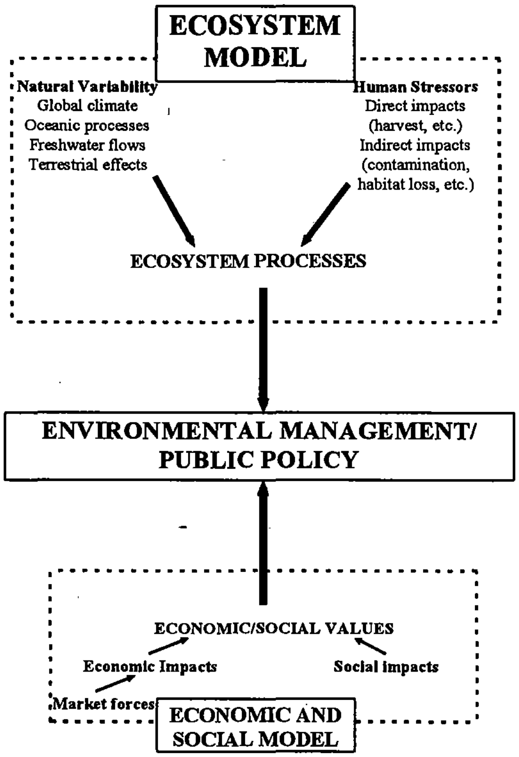
The combination of these many natural processes has resulted in highly productive marine and coastal ecosystems that are adapted to the widely variable conditions of the region.

The economy and culture of the Pacific Northwest coastal region continue to depend to a large degree upon natural resources. As the landscape and coastal resources continue to be developed and, in some cases, depleted, the economic and social systems that depend on a stable, predictable set of environmental conditions to provide goods and services are increasingly vulnerable to environmental change, whether natural, human-caused, or both. Changes in environmental conditions and consequent disruptions of ecosystem functions trigger reactions in political, social, and economic systems that can consume immense amounts of social, political, and economic capital. The decline of coastal salmon stocks, for instance, has resulted in a significant effort by the Oregon and Washington state governors and agencies, Federal agencies, and local communities to find "the cause", and "restore" these stocks in coastal streams. Developing and carrying out resource management programs that are ecosystem-sensitive and have public support requires that scientists and managers work together to significantly improve understanding of the function and variability of coastal ecosystems, the effects of management practices, and the economic and social, as well as ecological, consequences of change.

PNCERS PROGRAM AND CONTENTS OF THIS REPORT

The Pacific Northwest Coastal Ecosystems Regional Study (PNCERS) is a multiyear, regional initiative of the Oregon Coastal Management Program, Washington Sea Grant Program, and National Marine Fisheries Service Northwest Fisheries Science Center. It is supported by the NOAA Coastal Ocean Program. The goals of PNCERS are: 1) to improve the understanding of the relative impacts of natural variability and anthropogenic stressors on coastal ecosystems that support Pacific salmon; and 2) to translate that understanding into improved management of resources and activities that affect coastal ecosystems.

The scope of the PNCERS program is broad, as shown by the conceptual model below. The program recognizes that because Pacific salmon stocks use all parts of the coastal ecosystem at some point in their lives, they appear to be susceptible to a combination of natural and human-caused ecosystem change. While the goals of this program are broadly conceived, PNCERS considers salmon to be an integrator and indicator of coastal ecosystem health. In understanding the relationship between ecosystem change and salmon survival, PNCERS also intends to provide a better understanding of how ecosystem change affects many other resources of social, economic, and ecological importance to the Pacific Northwest. Additionally, PNCERS seeks to understand how information on natural variability, human stressors, and broad-scale indicators of change and/or ecosystem integrity can best be integrated and effectively translated for use by managers and policy makers. Ultimately, PNCERS intends that this new understanding will provide a basis for more appropriate and effective management of human activities for the sustainable use of coastal resources.



This report contains seven chapters, each with a list of references, and a glossary of terms. Five of the chapters (Chaps. 2-6) were originally developed as "theme" papers for a 1996 workshop sponsored by PNCERS to summarize present scientific understanding and identify key research issues as a prelude to developing a multiyear research plan. Chapter 1 is an introduction. Chapters 2 and 3 describe the effects of human intervention in the coastal environment and the resulting socioeconomic changes. Chapters 4, 5, and 6 provide a conceptual framework for describing, assessing and synthesizing the present understanding of the physical and biological parts of Pacific Northwest coastal ecosystems and, in particular, how salmon populations relate to these various parts. Chapter 7 is a summary of the 1996 workshop.

HUMAN INTERVENTION IN PACIFIC NORTHWEST COASTAL ECOSYSTEMS

Chapter 2 highlights major issues related to the effects of human habitation of the landscape and ecosystems of the Pacific Northwest coastal region, with emphasis on the factors that affect salmon use. The major intervention activities have been fishery harvest and enhancement (hatcheries), forest resource harvest and associated activities, agricultural land conversion and practices, the construction and operation of dams, and urban development. Cumulatively, human intervention has resulted in significant physical, hydrological, chemical, and biological modifications of the coastal environment, including the estuarine and riverine ecosystems that support salmon.

Physical modifications include the outright loss of habitat in forests, streamside riparian areas, freshwater wetlands, and estuaries, as a result of forest practices and by dredging, filling and diking for agriculture and urban growth. They also include subtle physical modifications such as the filling of deep pools with sediment or the scouring of stream beds, which reduce the composition and diversity of in-stream habitat or structure. Among other effects of these physical changes are degraded or insufficient in-stream habitat, removal of riverine and estuarine habitat from the ecosystem, and changes in sediment transport and deposition in coastal streams. The hydrologic regimes (streamflow patterns) of many watersheds have been modified by human activities. Logging of forests and conversion of lands to agriculture, residential and other uses has reduced or eliminated water-retentive vegetation throughout many watersheds. Urbanization, has reduced the number of absorbent wetlands and has increased hard-surfaced areas. Dams and water diversion structures have reduced flow, dampened streamflow cycles, blocked fish passage, and have caused indirect impacts, such as increased temperatures and nitrogen supersaturation.

Chemical modification of coastal waters has resulted principally from watershed activities that have increased the drainage of non-point and point-source pollutants into coastal freshwater, estuarine, and marine systems. The pollutants reaching coastal water bodies are largely pesticides, herbicides, and nutrients from fertilizers, animal wastes and failing septic systems, with varying amounts of other toxic industrial compounds, heavy metals, other synthetic chemicals and petroleum and its byproducts. These inputs of chemical contaminants have affected both water and sediment quality and have been shown to adversely affect aquatic organisms. Impacts on biota are primarily found in regions of urban development or industrialization. In the case of salmon, direct effects from chemical contaminants are difficult to assess; however, recent evidence suggests that growth and survival of juvenile salmon can be decreased by exposure to toxic chemicals. Contaminants are only one source of stress to aquatic species, and it is important to note that they can act in concert with one another or interact with other stressors, such as parasites, to increase the level of stress, and thereby increase the likelihood of toxicity.

Biological modifications of coastal ecosystems have been both direct and indirect. Fish harvest has directly modified fish abundance and distribution. Other actions, such as removal or destruction of habitat, introduction of exotic or non-native species, and changes in predator or prey species, have affected populations indirectly. The introduction of artificially propagated salmon from hatcheries has had significant effects on the genetic diversity and survival of wild fish stocks, and the harvest and removal of returning fish have changed nutrient cycling in coastal streams. The combination of direct and indirect biological modifications has impaired the capacity of aquatic ecosystems to support salmon and other species, and has resulted in the loss of particular salmon stocks and their associated genetic traits, thereby reducing genetic diversity among salmon populations.

Two broad questions about human intervention require research before they can be adequately addressed: 1) how has human intervention affected coastal ecosystems that support salmon (and other aquatic resources) in relation to natural large-scale variability?; and 2) how can the effects of human activities on aquatic resources be mitigated in order to restore salmon populations? Currently, scientists have little understanding of how to separate and assess the effects of individual factors from the cumulative effects of many human-caused stressors that affect coastal ecosystems, especially in the context of natural large-scale variability. A variety of stressors have clearly had major effects on salmon, but many questions remain as to the effects of specific stressors in any particular watershed. The highly variable nature of ecosystem conditions over different time scales and in different areas has caused ecosystem managers and restoration scientists in the region to seek flexible, appropriate management measures and feasible, useful restoration activities. Adaptive management is a valuable approach because it uses the accumulation of credible information gained through monitoring of management actions to support ongoing management decisions, including restoration projects.

SOCIOECONOMIC CAUSES AND CONSEQUENCES OF COASTAL ECOSYSTEMS CHANGE

Chapter 3 examines the social and economic aspects of ecosystem change in the Pacific Northwest coastal region. The social and economic systems of the region, with local variations, have been shaped by two major sets of factors. One is the set of local natural resources (i.e., ecosystem goods, services, and amenities) that have been exploited to provide economic value to individuals and, collectively, communities. The ecosystems that produce these resources are subject to variability due to natural forces. The other set of factors includes external, large-scale economic and social changes, such as world trade flows and rates of immigration/emigration, which are themselves also subject to a variety of other external forces.

Within the socioeconomic systems of communities, people acquire and transform ecosystem resources, usually characteristic of the region (e.g., trees), with labor, energy, and technology to produce goods (e.g., lumber) and services (e.g., construction). People also take advantage of coastal ecosystem amenities for recreation and aesthetic enjoyment, and they utilize ecosystem services for waste disposal, clean air and water, etc. The process of using these resources, transforming materials, and distributing them is subject to the constraints of economics (markets, competition, etc.) and government (regulations, rules, commitments, etc.). When these activities affect the basic production or availability of resources from these coastal ecosystems (depletion, change in size or content) and feedback from the systems affects society (scarcity or inferior quality of materials, etc.), changes in human well-being are perceived and reflected in a variety of quantitative and qualitative ways, collectively called socioeconomic consequences. These consequences push the social system to adapt (for example, to the lack of availability of salmon).

There are three basic approaches to studying the process of socioeconomic response and change: 1) a legal/institutional approach; 2) a sociological approach; and 3) an economics approach. While the issues and phenomena studied by these three overlap considerably, each focuses on particular aspects of the social system, uses specific assumptions and models, and addresses unique dimensions of experience. Hence, each approach results in measures for different variables and emphasizes different issues and problems. Common property resources management and natural resource accounting are two integrative approaches.

The legal/institutional approach focuses on the processes and the hierarchy of laws and authorities that influence coastal resource policy. Such techniques as "institutional mapping" provide a means of identifying and assessing existing laws, governmental organizations, authorities, and their geographic extent in relation to managing a particular ecosystem. Then, duplication, conflicts and gaps may be identified, as has recently been done with watershed planning in Puget Sound. Political science models are used to describe and understand the dynamic process of organizational change and collective learning. Of particular interest is the "advocacy coalition framework" that characterizes the various beliefs held by organized policy coalitions. Recent legal/institutional changes affecting coastal ecosystems include changes in private property and Native American treaty rights, and the emergence of collaborative models such as the National Estuary Program, watershed planning and ecosystem management (e.g., the President's Ecosystem Management Task Force).

Sociological research relevant to the interactions between natural processes and human activities has found that: 1) social and biogeochemical systems are seen as two parts of one larger system; 2) either the human system or the natural system can be taken as the dependent variable; and 3) there is an extensive body of knowledge regarding social consequences of interactions with natural systems. Social Impact Assessment (SIA) is often employed to determine impacts on *individuals* (health and safety, attitudes, economic prosperity), on *organizations* (profitability, membership levels, conflicts), or on *communities* (structure and capacity to provide services, economic impacts). The Forest Ecosystem Management Assessment Team (FEMAT) recently undertook a major SIA in the region that included work on the California, Oregon and Washington coasts.

Economic studies typically examine the material side of human activities, using theories of market equilibrium, "externality", and government regulation to explain and predict the economic consequences of resource scarcity. Pertinent economic study models include structural descriptions of coastal economies (e.g., economic impact or market equilibrium models) and economic evaluations of ecosystem services and functions (e.g., recreational demand models, contingent valuation of existence values for public goods). For specific economic changes triggered by policy initiatives or by exogenous shifts in climate, benefit-cost studies can help to assess net benefits. Because measurable economic variables are frequently limited, a quantitative cost-benefit analysis is often supplemented by descriptive accounts of environmental effects and other social effects. Some recent progress has been made in estimating the recreational resource value and the existence value of salmon in the Pacific Northwest.

VARIABILITY AND STABILITY OF CLIMATIC AND OCEANIC REGIMES IN THE PACIFIC NORTHWEST

In Chapter 4, the complex interactions of the atmospheric and oceanic systems that affect the Pacific Northwest coastal region are examined. An analysis of scales is used to separate the actions and relationships of phenomena that operate over differing lengths of time and areas of various sizes, to identify the causes and effects unique to particular scales, and also to identify appropriate space and time scales as they relate to management activities. The principal time (temporal) scales for considering the dynamics of the atmospheric and oceanic systems are: the *millennial* (thousands of years; including Ice Age/Holocene warming, deep ocean basin mixing, etc.); *century* (hundreds of years; including sea level rise, Little Ice Age events, major tectonic events, etc.); *decadal* (tens of years; including apparent shifts in ocean background state, etc.); *quasi-quintennial* (3 to 7 years; including El Niño events, etc.); *interannual* (year-to-year; including variations in air temperature, spring transition timing, etc.); and *annual* (seasonal and shorter events; including tides, upwelling, summer/winter changes, etc.).

The major climatic/oceanic signal on the quasi-quintennial-scale is the ENSO (El Niño-Southern Oscillation) phenomenon, which has apparently occurred for at least 5.5 million years. In the atmosphere, El Niño is characterized by a change in the organization of high and low air-pressure cells across the equatorial Pacific that drive the Westerly Winds. These winds push tropical waters westward, creating a large pool of warm water with an elevated sea surface. When the arrangement of atmospheric cells shifts, winds relax, warm waters flow eastward along the equator to the Americas, and then flow north and south along the coasts. An opposite phase, dubbed La Niña, results in the colder than normal conditions along the coasts of the Americas. During an El Niño, teleconnections in the atmosphere shift the location and intensity of the storm-generating Aleutian Low, which changes the track of the jet stream, thereby altering the landfall of storm tracks over the West Coast. Retrospective studies have shown that typical El Niño conditions result in warmer and drier weather than usual during Pacific Northwest winters, though the strong 1982-83 El Niño did not follow this pattern. In the Pacific Northwest ocean, an El Niño is typified by high sea surface temperatures due to a change in normal wind patterns that normally generate a supply of cold, upwelled water, as well as due to the arrival of the warm water from the tropics. It is not clear at this time whether the El Niño phase is becoming more frequent and/or more intense, but the La Niña phase has occurred less frequently than usual for the past 20 years.

A major climatic/oceanic signal on the decadal scale, termed appropriately, the Pacific Decadal Oscillation (PDO), has also been identified. The background state of the Pacific Ocean appears to oscillate between two atmospheric flow-regimes that relate to the strength and location of the Aleutian Low. A so-called West Coast flow-regime results from a deeper and east-shifted Aleutian Low that shifts storm tracks northward and results in cooler and wetter weather in the Pacific Northwest. A so-called Alaskan flow-regime, generated by a westward shift and weakening of the Aleutian Low, results in a shift of storm tracks southward, and warmer and drier weather in the Pacific Northwest. In the ocean, the PDO is characterized by a shift in the bifurcation point of the Sub-arctic Current as it approaches the continent. The point moves northwards, as do storm tracks, during the West Coast flow- regime and southwards, as do storm tracks, during an Alaskan flow-regime. This point of bifurcation strongly influences oceanographic habitat characteristics of the ocean off the Pacific Northwest. The last clear PDO shift was to an Alaska flow-regime coincident with a 1976-77 El Niño event.

By contrast, variability on the millennial scale, century scale (particularly with respect to the past 1000 years), and on the daily scale have received less research attention. Significant research needs abound, from the potentially long-lasting effects of severe storm events on a daily-scale to the possibility of human-influenced global climate warming on the century scale. There are also many questions about linkages between the atmosphere and ocean both within the regions affecting the Pacific Northwest, especially about the relationships between basin-wide functions, effects on coastal upwelling, and enhancement of El Niño effects in the coastal ocean by later atmospheric effects.

VARIABILITY OF PACIFIC NORTHWEST MARINE ECOSYSTEMS AND RELATION TO SALMON PRODUCTION

Chapter 5 evaluates the influence of variability on the capacity of ocean habitat to support Pacific salmon. Two sets of factors are proposed to measure the capacity of the ocean to produce salmon. The first set involves the ocean environment and the influence of such variations as the primary biological productivity of coastal waters (which is determined by many interacting environmental conditions), the distribution and abundance of marine species (including predators and prey), and physical processes such as ocean currents and upwelling that may directly influence salmon mortality in the ocean. The second set involves the timing and distribution patterns of life-histories in various salmon populations. Salmon have developed life-history strategies that respond to the unique mix of environmental characteristic and variability of different geographic locales. For salmon to survive in the ocean, they must first survive the riverine and estuarine environment. Selective forces in rivers and estuaries determine the range of sizes, physiological condition, and time of ocean entry of the population of migrants leaving each river system (see Chapter 6).

Several important geographically-related oceanic conditions influence salmon populations, including north-south gradients in the strength of coastal upwelling, the availability of protected inlet or estuarine habitat, the relative influence of the Columbia River plume, and the patterns of distribution for northern and southern species. Certain geographic "discontinuities" in the physical environment may have an important influence on salmon production and life-histories and the distribution of other shallow water marine organisms. Such discontinuities include differences in regional precipitation and streamflow patterns, as well as variations in winds, upwelling intensity, and currents, between areas to the north of and areas to the south of Cape Blanco on the southern Oregon coast. The ocean migration patterns of coastal chinook salmon do, in fact, show a discontinuity at Cape Blanco: stocks north of Elk River (on the south flank of the cape) appear to rear in waters to the north while stocks from streams to the south generally rear to the south.

The physical processes that influence salmon production may be conceptualized as a nested hierarchy. Localized, seasonal upwelling events (including effects of the Columbia River Plume) and advective processes (California Current) along the entire regional coast are embedded within a larger global system that regulates winds and currents over various time and spatial scales (see Chapter 4). Although survival of juvenile salmon has been correlated with wind-driven upwelling, the correlation has shifted from positive to negative, apparently in concert with the present Alaskan flow-phase of the Pacific Decadal Oscillation. Research has recently shown that interannual variations in the productivity of the California Current system are 1) correlated with variations in the strength of the current and flow of nutrients from the Sub-Arctic Current, 2) may be a controlling factor in pelagic production, and 3) may influence the size and distribution of prey species important to salmon. El Niño events, which connect the upwelling systems, thermal structure, and biotic assemblages of the California Current to the equatorial Pacific Ocean, directly affect the mortality of salmon in the Pacific Northwest. Fluctuations among chinook and coho stocks from the Pacific Northwest appear to be out of phase with cycles of abundance among stocks of pink, sockeye, and chum salmon in the Gulf of Alaska. These patterns illustrate that the Pacific Ocean and atmosphere are not in a steady-state condition but continuously respond to changes in the global heat budget and thus continually shift the conditions that affect biological increase and decline around the Pacific Ocean Basin ecosystem.

Because ocean conditions vary from year to year or decade to decade (e.g., timing of the spring transition, onset of upwelling, presence of predators or prey, etc.), slightly different migration times in various locations along the coast may be advantageous or disadvantageous to salmon stocks and thus affect ocean survival. The total productive capacity of salmon in the ocean environment is therefore influenced by the diverse array of populations and life-histories within species that allows them to adapt to changing conditions throughout the entire system. A "member/vagrant" hypothesis proposed by Sinclair, 1988, explains abundance, variability, geographic structure, and richness of populations. In this hypothesis, the role of "spatial" processes (i.e., physical processes such as ocean currents) in the recruitment of marine species is fundamental, particularly during the earliest and most vulnerable stages of the life-history when the direct physical or temporal displacement of individuals from a critical sequence of habitats can result in mortality. A second major factor in the recruitment or loss of individuals is the role of "energetics" related to predation, competition, or disease. The role of mortality due to spatial displacement during the marine life-history of salmon has received little research, but may be particularly relevant in the physically-controlled California Current System.

VARIABILITY OF ESTUARINE AND RIVERINE ECOSYSTEM PRODUCTIVITY FOR SUPPORTING PACIFIC SALMON

Chapter 6 discusses the variability of the estuarine and riverine components of coastal ecosystems in response to variable natural conditions and to human-induced changes. An overarching hypothesis is that Pacific salmon species have evolved diverse life-histories to take advantage of the varying environmental conditions resulting from conditions in the atmosphere and ocean and that vary over numerous temporal and spatial scales (see also Chapters 4 and 5). The life-history patterns of five species of Pacific salmon can be characterized in eight "stanzas": 1) incubation and emergence; 2) freshwater residence; 3) downstream migration; 4) freshwater-estuary transition; 5) estuarine residence; 6) estuary-ocean transitions; 7) ocean residence; and 8) return migration to spawn. Within each stanza there is considerable potential for variability and thus complexity among different stocks.

A large number of factors influences Pacific Northwest estuaries. Regional estuaries exhibit a wide variety of structural characteristics and sizes, including fjords, drowned river valleys, and bar-built lagoons. Fluvial drainages vary from only 10 to 100 km^2 for many coastal estuaries of Oregon, up to 100,000 to 1,000,000 km^2 for Puget Sound and the Columbia River. Circulation patterns in estuaries vary extensively as a function of river flow volume and seasonal cycles, tidal range, and the depth and shape of the estuarine basin. Typically, more than 40% of total estuarine surface area is intertidal; intertidal habitats are usually colonized by emergent marsh vegetation along the brackish salinity regimes and tidal shrub-scrub swamps and forest in tidal/freshwater reaches. Estuarine production in the Pacific Northwest is extremely pulsed, depending on the season and the flow of energy within the system. Estuarine food webs are based predominately on detritus, and the composition of organic matter contributing to the estuarine detritus pool may vary significantly depending upon regional location, extent and type of watershed, climate, geology, oceanic energy regimes, and human effects. The quality, rather than quantity, of organic matter reaching estuaries appears to be important, implying that particular sources of organic matter are important. The differential pulses of organic matter and distribution of the material across estuarine habitats may account for differences in trophic support of salmon and other secondary consumers.

The hydrologic regime and vegetation patterns of river drainages in the Pacific Northwest result from two major factors: 1) geologic and geomorphic conditions, including topographic features, such as mountain ranges, elevation, topographic relief, stream gradient and length, and soils; and 2) marine influences, which drive seasonal precipitation loads and moderate temperatures. Flow patterns in coastal rivers reflect major seasonal differences in the regional climate. During fall and winter high precipitation is delivered by numerous storm fronts; during summer, there is low precipitation and few storms. Different river drainages can be affected by different flood-producing mechanisms, including rainfall-induced, rain-on-snow runoff, snowmelt-induced, or combinations of the three. Nutrient cycling dynamics of freshwater ecosystems can be important in salmonid production. The availability of nitrogen (N) and phosphorus (P) limits the biological productivity of most rivers and streams in the Pacific Northwest coastal region. Historically, the timing of the supply of nutrients in riverine systems could have been closely coupled to the return and decay of spawned-out carcasses of salmon, transported upstream and then releasing significant amounts of nutrients into the riverine ecosystem.

Most estuarine and riverine ecosystems in the Pacific Northwest have experienced major changes over the past 150 years (see Chapter 2). Excessive sedimentation, channel erosion, removal of large woody debris, and lower streamflows have reduced the complexity of channels, eliminated pools and habitat for refuge, and altered temperature regimes. Many of these human-caused changes have occurred at frequencies and magnitudes that transcend natural disturbances. Degraded salmon habitat in many stream systems, coupled with high rates of exploitation, has contributed to the depletion or extinction of a number of Pacific salmon populations in the region. Salmon have adapted to a wide range of low-frequency, large-magnitude, and large spatial-scale natural phenomena and possess traits that enable individual fish to respond rapidly to environmental conditions. Present day extinctions of many salmon populations may be attributable to short-term temporal and spatial variations in environmental conditions that are outside the ranges of conditions that have promoted optimum traits for survival.

PNCERS WORKSHOP

Chapter 7 reports the results of the PNCERS workshop held on August 13 and 14, 1996, with 85 participants (see Appendix A), in Troutdale, Oregon. The goals of the workshop were to bring together and synthesize available information for the PNCERS Program Management Team to further define the conceptual model and develop a research program. The workshop was supported by five theme papers prepared in advance that summarized available information and understanding of the theme topics, refined the PNCERS model where possible, and identified areas or topics of needed research (i.e., Chapters 2-6 of this report). These papers were circulated to participants in advance. A dozen peers were identified and invited in each theme group to discuss and review the theme papers, add to the theme-specific research questions and, in cross-cutting focus groups, discuss linkages between the theme areas. Additional research questions and interdisciplinary issues identified at the workshop are reported in the chapter.

CHAPTER 1

INTRODUCTION

BACKGROUND

Pacific Northwest coastal ecosystems are part of a dynamic natural system that is widely variable across a range of time and spatial scales. Numerous atmospheric, oceanic, hydrologic, and ecological processes intersect in the region at the eastern edge of the Pacific Ocean basin where the eastward-flowing Sub-Arctic Current encounters the North American continent and bifurcates to form two components, the northward-flowing Alaska Current and the southward-flowing California Current. The California Current System, an eastern boundary current, is a complex transition zone between water masses in the larger Pacific Ocean basin and freshwater discharged from coastal watersheds. The Pacific Northwest Coastal Ecosystems Regional Study (PNCERS) area (Figure 1.1), generally between Vancouver Island and Cape Mendocino, is a zoogeographic transition between the Aleutian biological province to the north and the Californian to the south.

Several important factors that influence productivity within this region are north-south gradients in the strength of coastal upwelling, the relative influence of the Columbia River Plume, the availability of estuarine habitat, and patterns of distribution of northern and southern species. Other factors include the north-south location of the point of bifurcation of the Alaska and California currents, which varies over several time scales, and distinct seasonal differences between winter and summer current regimes. Characterization of the ocean surface reveals rich, highly dynamic flow structures along the coast such as eddies, jets, and filaments superimposed on the generally slow, southward flow of the California Current. Conditions and processes are occasionally transformed by events of high impact such as El Niño-Southern Oscillation (ENSO) events and apparent regime shifts linked to basin-wide and global processes.

Habitat conditions and ecosystem relationships are many and complex throughout the region. The interaction of highly variable atmospheric, oceanic, and biologic processes results in continually shifting water-column habitat nearshore and over the shelf. Differences in shoreline geomorphology create a variety of habitat conditions. Rocky shores and associated reefs occur along the Olympic Peninsula, southern Oregon, and northern California coasts. Numerous small estuaries south of the large Columbia River estuary contrast with two large estuaries to the north

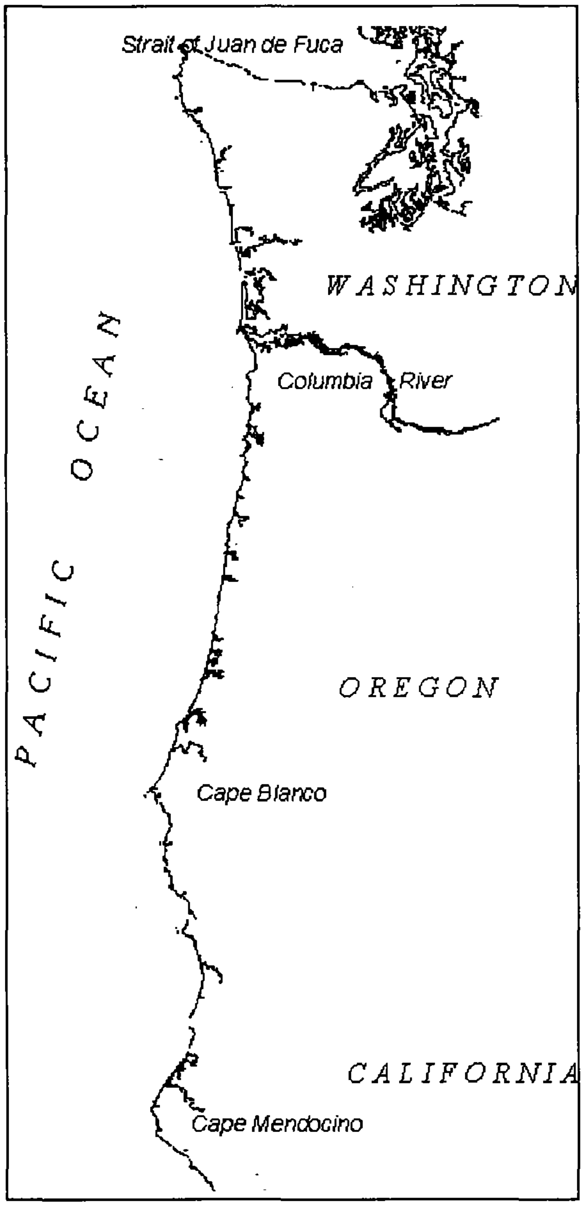


Figure 1.1. Pacific Northwest Coastal Ecosystems Regional Study area.

in Washington and with Humboldt Bay near Cape Mendocino. Other key features are the Columbia and Fraser Rivers, and the Straits of Juan de Fuca and Georgia. The topographically rugged continental slope, dissected by canyons, and offshore reef complexes on the shelf, create a variety of benthic habitats.

Together, these variable and interacting processes, features, and habitats form the basis of highly productive marine and coastal ecosystems that support numerous species of seabirds, marine mammals, and a wide variety of commercially and recreationally important fish stocks. Most species of marine fish and shellfish appear to be relatively healthy despite significant declines in Pacific salmon populations and indications of possible declines in some populations of rockfish.

Although coastal ecosystems are linked to and influenced by variable processes that operate at basin and global scales, coastal natural resources have traditionally been viewed, used, or managed as individual elements in the landscape and as separate activities within the economy of the community. Over the past century, much of the coastal environment, particularly watersheds and estuaries, has been affected by human activities such as logging, road-building, mining, fishery harvest, damming, dredging, water diversion, conversion of coastal wetlands and estuarine areas for agricultural and urban uses, discharge or runoff of a variety of pollutants, and introduction of non-indigenous species. These activities have significantly altered or stressed many ecosystem functions throughout the region. The effects of altered or stressed ecosystem functions can result in adverse economic as well as ecological consequences. For instance, the loss of Pacific salmon fisheries has significantly affected the economy and social structure of Pacific Northwest coastal communities and has resulted in increased catch effort on other marine fish species.

Policy and management related to coastal resources have not always given adequate consideration for the ecosystem context of the resources, the variability of natural systems, or the cumulative effects of resource use and human perturbations over time. Today, increasing demands for coastal resources and the compromised nature of coastal ecosystems require that management and use of resources be far more responsive to the limits and conditions of the ecosystems than ever before. In turn, developing and carrying out management programs that are more ecosystem-sensitive will require better understanding of coastal ecosystem function and variability, the effects of management practices on the ecosystem, and the economic and social consequences of natural ecosystem variability and degradation by human activities.

THE PNCERS PROGRAM APPROACH

The goals of PNCERS are: 1) to improve the understanding of the relative impacts of natural variability and anthropogenic stressors on coastal ecosystems that support Pacific salmon; and 2) to translate that understanding into improved management of resources and activities that affect coastal ecosystems. The scope of the program is broad. It takes an ecosystem approach to both natural processes and human impacts over the Pacific Northwest region in order to understand: how these natural processes operate at different time scales and affect the major coastal ecosystem components of oceanic, estuarine, and riverine environment; how human activities have affected ecosystem processes and; how natural or human-induced change affects social and economic systems. The program recognizes that salmon are found at some point in their life-cycle in all parts of the coastal ecosystem and appear to be susceptible to both natural and human-caused ecosystem change. Thus, while the research goals of this program are broadly conceived, PNCERS considers salmon to be an integrator and indicator of ecosystem health. In understanding the relationship between ecosystem change and salmon survival, PNCERS will also provide a better understanding of how ecosystem change affects many other resources of social, economic, and ecological importance to the Pacific Northwest. Additionally, PNCERS seeks to understand how information on natural variability, human stressors, and broad-scale indicators of change and/or ecosystem integrity can best be integrated and effectively translated for use by managers and policy makers. Ultimately, PNCERS intends that this new understanding will provide a basis for more appropriate and effective management of human activities and coastal resources.

The PNCERS conceptual model (Figure 1.2) recognizes the central role of effective environmental management and sound public policy in conserving the region's coastal resources and sustaining a healthy coastal economy. The model depicts the relationship of ecosystem processes, variability, and stressors with the economic and social values of coastal communities. The model thus establishes a framework for acquiring, utilizing, and assessing information to improve management and policy. From knowledge about the condition of living marine resources (as they are affected by ecosystem processes) and the values that the public holds, public policy is derived and environmental management programs developed that can accommodate the variability inherent in the environment and manage for resilience and sustainability of resources in the Pacific Northwest.

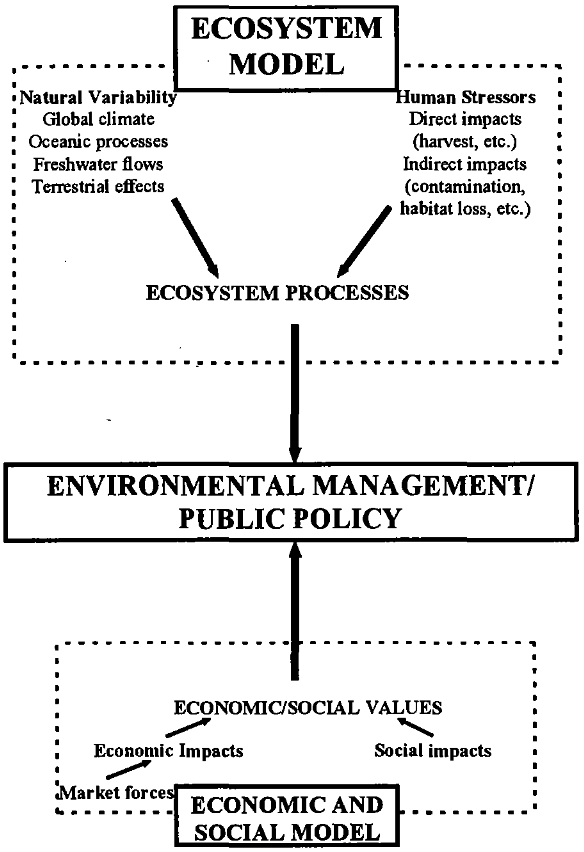


Figure 1.2. PNCERS conceptual model.

PURPOSE AND CONTENTS OF THIS REPORT

Given the extremely broad area covered by the conceptual model, the PNCERS Program Management Team (PMT) chose to delay the implementation of research in order to generate a multidisciplinary synthesis that would act as the technical underpinning for a science plan and serve as a stand-alone reference. During early 1996, theme-oriented synthesis papers (i.e., Chapters 2-6) were commissioned in five topics:

1. The Variability and Stability of Climatic/Oceanic Regimes in the Northeast Pacific Ocean;
2. The Variability of Marine Ecosystems and Relation to Salmon Survival;
3. The Variability of Estuarine and Riverine Ecosystem Productivity;
4. Human Intervention in the Coastal Ecosystem; and
5. The Socioeconomic Causes and Consequences of Ecosystem Change.

Thus, the syntheses (i.e., Chapters 2-6) were intended as a complementary set of syntheses for change in the coastal ecosystems in the Pacific Northwest, as they relate to the habitats of Pacific salmon. While much of the content in the syntheses is specific to the Pacific Northwest region, the general approach and analysis of factors involved should be of interest and value to those in other regions. Chapter 7 reports the results of the workshop held during August, 1996, to critique and discuss the synthesis drafts. The goal of that chapter is to capture and report the ideas discussed during the workshop sessions. There is no chapter on management and policy in this document: the PNCERS program hopes to deal with this component of the conceptual model in future efforts and documents. Because of the interdisciplinary and technical nature of the synthesis papers and the goal of the Decision Analysis Series to reach a wide readership, a fairly extensive glossary and list of acronyms are also included.

CHAPTER 2

HUMAN INTERVENTION IN PACIFIC NORTHWEST COASTAL ECOSYSTEMS

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INTRODUCTION

This chapter highlights some of the major issues related to human intervention in coastal ecosystems in the Pacific Northwest. The review focuses on coastal portions of Washington, Oregon, and northern California, including estuaries, the near coastal ocean, and the watersheds. It is not intended as an exhaustive report on all forms of, or issues associated with, human intervention. Questions that helped to define the scope of this theme include:

- How have riverine, estuarine, and oceanic ecosystems of the Pacific Northwest been affected by human activities?
- Are there interactions among these activities that particularly affect the ecosystem?
- Are there particular activities or interactions that have more effect than others?
- Are there components of coastal ecosystems that are particularly susceptible to human intervention?
- Are there ways to remediate after human intervention?

Two complex questions within this theme require research before they can be adequately answered: 1) how does human intervention affect coastal ecosystem support of salmon and other aquatic resources in view of natural large-scale variability?; and 2) how can effects on aquatic resources caused by human intervention be mitigated in order to restore salmon populations?

HISTORY OF HUMAN INTERVENTION IN COASTAL ECOSYSTEMS

People have lived as a part of, and intervened in, the coastal ecosystems of the Pacific Northwest for many thousands of years. From earliest post-glacial occupation by migrating tribes of Native American peoples, the natural productivity of the ecosystems of this region provided food, fiber, medicine, and shelter. Salmon, especially, were central to the diet and way of life of Native American peoples in most coastal areas, as well as the vast Columbia River basin, but many other plants, animals, fish, and shellfish were important on a seasonal or local basis. While Native peoples actively intervened in natural processes through such activities as setting fires to control brush and building in-stream weirs to trap and harvest fish, the effects of human intervention were relatively limited because of the low population, limited technology, and a cultural view that included people within the natural realm rather than outside.

The influx of Euro-American settlers to the region was initially attracted by the so-called "bounty" of the natural environment, such as the abundance of beaver and other fur-bearing animals, fish, forests, water, the deep soils, and the mild climate. By the mid-nineteenth century, significant numbers of people were migrating into the region and creating significant changes in the patterns, practices, and intensity of human intervention in coastal ecosystems. The enterprise of Euro-American culture brought the clearing of forests for lumber and agricultural use, diking and draining of wetlands, mining of hillsides and streambeds, road-building, and increased fishing pressure. Salmon and other species began to be affected by these changes. As early as 1894, Evermann (1895) documented declines in salmon populations in the Columbia Basin system. The first hatchery on the Columbia was opened by cannery owners in 1878, a strong, early indication of a declining natural resource. The subsequent plight of salmon in the Pacific Northwest has been well documented (e.g., Meggs 1991; Cone 1995; Petersen 1995).

Major events in human interactions with Pacific Northwest coastal ecosystems are summarized in Table 2.1. The major types of events documented include fishery harvest, forest resource harvest, construction of dams, and population increases in urban areas that result in increased sources and volumes of pollutants and loss of habitat.

Human activities in the region have significantly altered, and continue to alter, coastal ecosystems despite the fact that salmon fisheries and forest harvest pressure have been reduced in recent years due to declines or depletion of resources. For example, continued pressure for fishery and forest products has spurred aquaculture and new forestry practices to meet the demand, and construction of major dams has ceased, but new dams are proposed for small streams to supply hydroelectric power to small communities.

IMPACTS OF HUMAN INTERVENTION ON SALMON IN COASTAL ECOSYSTEMS

The various kinds of human intervention in the watersheds, estuaries and shorelands of the Pacific Northwest coastal zone have resulted in physical, chemical, hydrological, and biological

Table 2.1. Chronology of major events in the coastal zone resulting in possible impacts to Pacific salmon.

1793	Alexander Mackenzie explores the Fraser River.
1805	Lewis and Clark explore the Snake and Columbia Rivers.
1808	Simon Fraser explores the Fraser River.
1825	Hudson Bay Company establishes Fort Vancouver, anchoring the fur trade in the Pacific Northwest.
1855	Treaties between the U.S. government and several Northwest Indian tribes are signed relegating them to reservations. Rights to hunt and fish in Tribal traditional places is reserved.
1858	Gold rush moves through the Columbia and Fraser River valleys.
1864	The first salmon cannery in North America is established on the Sacramento River.
1866	The first salmon cannery is established on the Columbia River.
1872	The first salmon hatchery in the northwest is established on McLond River.
1878	Salmon hatchery is established on the Columbia River by cannery owners.
1883	The lower Columbia commercial fishery captures 43 million pounds of chinook, the largest catch ever recorded.
1885	US Department of Agriculture surveys coastal areas suitable for wetland reclamation (i.e., agricultural development).
1894	Decrease in salmon catch in the Columbia prompts an investigation by the U.S. Fish Commission.
1899	The number of fishwheels increases to 76 in the Columbia and traps increase to 121 in the Straits of Juan de Fuca and Puget Sound.
1890	Population of Tacoma is 50,000, up from 3300 in 1880. Between 1880 and 1940, 1900 acres of vegetated wetlands were filled in the Commencement Bay area.
1900	Weyerhaeuser Company purchases 900,000 acres of timberland in the Pacific Northwest.
1913	Hell's Gate blockade, a landslide prompted by road construction, ended the cannery boom on the Fraser River. The previous sockeye run is estimated to have exceeded 30 million fish.
1938	Bonneville Dam is constructed 140 miles upriver from the mouth of the Columbia.
1941	Weyerhaeuser Company established the nation's first tree farm in southwestern Washington.
	550-foot Grand Coulee Dam is completed on the Columbia blocking 1100 miles of salmon habitat.
1974	The Boldt Decision is passed in Washington allotting to native fishing tribes 50% of the salmon catch destined for the tribes' traditional fishing places. Oregon passed a similar ruling in 1969.
1983	El Niño blamed as the cause of low returns of adult coho salmon to Northwest coastal rivers.
1985	Pacific Salmon Treaty ratified between the US and Canada laying out management allocation and conservation guidelines.
1988	Snake River coho salmon become extinct.
1991	American Fisheries Society reports that 214 salmon stocks in the West face extinction.
	Snake River sockeye salmon listed as an endangered species.
1994	Columbia River closed to commercial salmon fishing by non-Indians.
	Snake River chinook salmon listed as an endangered species.

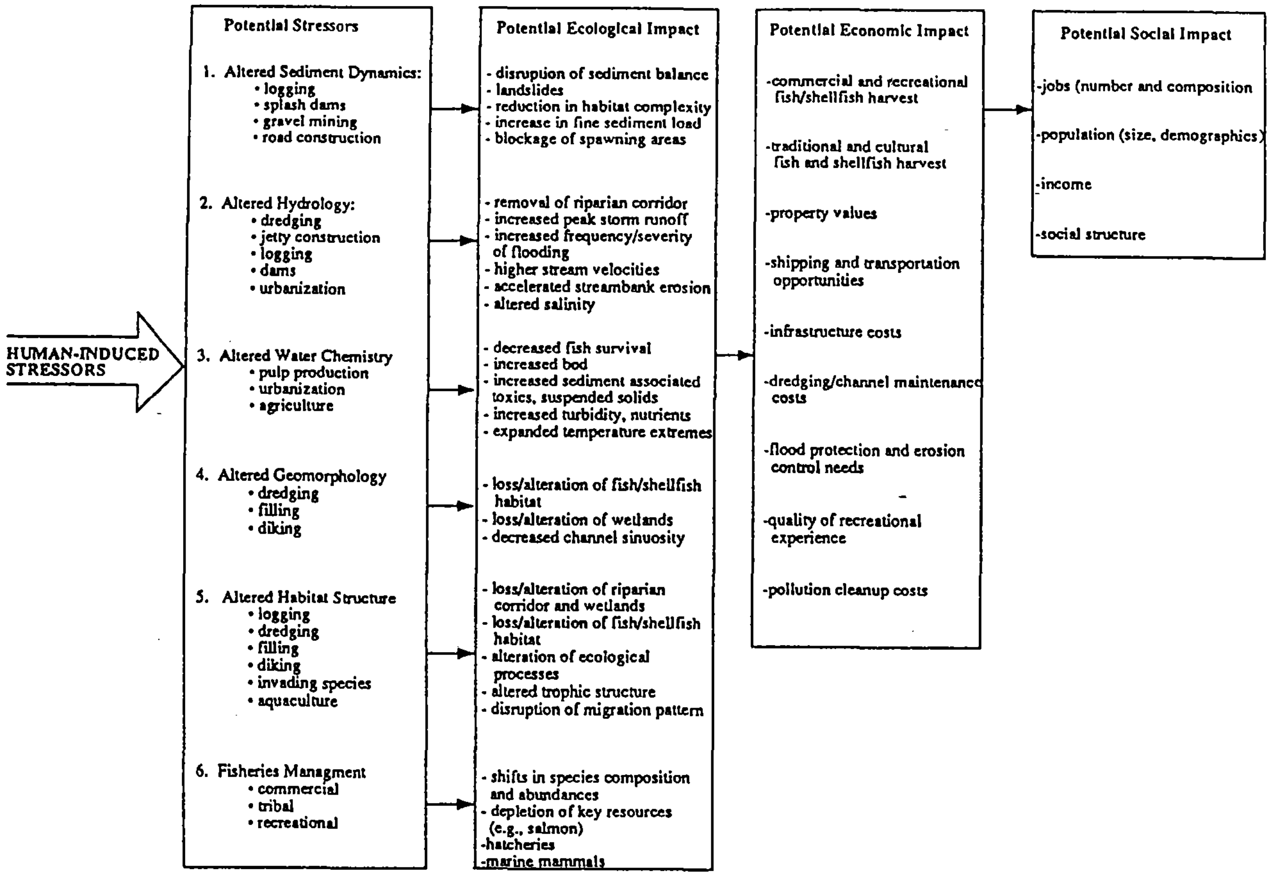

Figure 2.1. Potential stressors in the coastal ecosystems of the Pacific Northwest and associated potential ecological, economic and social impacts.

modifications to coastal ecosystems. Human activities and their effects are often interrelated in complex ways and the cumulative effects of various activities and ecosystem modifications can have equally complex and far-reaching biological results. Figure 2.1 shows the types of modifications that have occurred and the connections between modifications and biological effects, as well as social and economic impacts. This section summarizes what is presently known about the magnitude and distribution of various modifications as well as the linkages between each of them and salmon habitat or production.

Physical Modifications of Coastal Ecosystems

Physical modifications of coastal ecosystems range in scale from obvious habitat losses in coastal forests, wetlands, and estuaries, to subtle changes in such physical parameters as stream diversity or stream complexity. The principal drivers of these modifications are population growth, with resulting urban, suburban, and rural development, and direct economic exploitation of natural resources through such activities as damming streams for hydroelectric power generation and irrigation, logging forests for timber value, cultivating land for agriculture use, and building roads. Among the cumulative effects of these modifications are degraded in-stream habitat conditions, loss or degradation of estuarine habitat, and changes in near-shore sediment transport along the coast. The impacts of forestry practices on stream ecosystems and salmonids are described in the editorial works of Meehan (1991) and Salo and Cundy (1987). The Federal Forest Ecosystem Management Assessment Team (FEMAT) also examined the impacts of forestry management practices on aquatic ecosystems and discussed possible management alternatives to reduce impacts (FEMAT 1993).

Many human activities in coastal watersheds, such as road-building, excavation for construction, agricultural practices, and forest practices, can result in significant loads of sediments in streams and adversely affect in-stream habitat used by salmonids for spawning and rearing. Sediments can cover spawning gravel, suffocate fish eggs, and reduce winter survival of juvenile salmon by filling crevices in the substrate used for refuge from severe cold (FEMAT 1993; Hillman et al. 1987). Fine sediment also fills deep pools, which retain colder water that is important to summer salmonid rearing, and reduces the production of macroinvertebrates that provide critical food sources to salmon (Hillman et al. 1987). Additionally, increased suspended sediment can result in disruptions in social and feeding behaviors of salmon (FEMAT 1993).

Botkin et al. (1995) estimated that the quality of the riparian area adjacent to a stream is the most important habitat characteristic for providing the requirements for salmon production. The overstory trees in the riparian area shade streams during the summer months and help keep water temperatures low enough for young salmonids during periods of low water flow. Riparian areas are important as sources of allocthonous energy (i.e., outside food sources) for in-stream habitats. Insects and other invertebrates, plant material, and even mammal carcasses fall into the stream and contribute potential food energy. The roots of trees and brush of the riparian area help to stabilize the stream channel and filter water draining to the stream. But as stream channels change over time, trees in the riparian area also topple into or across the stream and thus become an essential component of in-stream habitat known as large woody debris.

For many years, large woody debris was considered as unwanted "debris" and was removed after logging to "clean up" a stream (Bryant 1983). However, large woody debris is now understood to provide critical cover to young fish from predation, create hydraulic diversity through riffles, pools, and falls, and support numerous prey species of insects and other invertebrates. Big trees, especially conifers such as western hemlock, cedar, and Douglas fir, provide in-stream habitat benefits over a longer period of time than do smaller-diameter trees or deciduous trees such as red alder and big-leaf maple. Because of timber harvest and associated activities, riparian areas in the Coast Range (outside Federally-designated wilderness areas) are now nearly all populated by red alder or big-leaf maple, with very few trees greater than 10 inches in diameter within 100-200 feet of the stream (FEMAT 1993). This suggests that there will likely be a long-term deficiency of large woody debris and a related deficiency in in-stream habitat quality.

Complex in-stream habitats are important to salmon survival, however many human activities have reduced this complexity. Splash dams were especially effective in scouring away much of the in-stream structure and habitat areas. These dams were temporary log and rock structures that impounded a stream while logs were deposited in the dammed pool. The structures were then destroyed so that logs would be discharged downstream with the resultant flood waters. This practice simplified the physical structure of many coastal streams and changed the frequency and distribution of in-stream habitats through scouring of gravels, loss of large woody debris, and filling of pools (Sedell et al. 1991). In addition, the diversity and frequency of in-stream habitats were lost because dams and other watershed diversions decreased the range and variety of hydraulic conditions that maintained complexity (Reeves and Sedell 1992). Table 2.2 shows an example of the reduction in pool frequency, probably caused by increased sedimentation, splash dams, log drives, and reduced large woody debris.

The removal of gravel from coastal streams for construction and aggregate materials is the center of some controversy regarding the effect on fish. There has been little or no research done on the linkage between this practice and salmon productivity. However, recently, gravel removal was identified by the Oregon Department of Fish and Wildlife as a significant ongoing adverse impact for fish habitat in the Willamette River (Botkin et al. 1995).

Salmon habitat is also lost through obstructions that simply block access by fish to streams that would otherwise support salmonid production. Obstructions can range in scale from a small road culvert that is disconnected from the stream bed, and thus unavailable to fish passage, to a 550-foot dam, such as the Grand Coulee Dam on main-stem Columbia River. In either case, the habitat beyond the obstruction is useless to the salmon stranded below, if they are unable to reach their final destination. The Grand Coulee Dam blocked and eliminated 1100 miles of salmon habitat from the Columbia River system (Table 2.1). Tide gates on tidally-influenced streams flowing into estuaries also prevent returning migrating salmonids from reaching freshwater.

Watershed analysis, a process of determining the health and problem areas of a watershed, is a useful tool for determining the amount of large woody debris in a stream, the health of the riparian corridor, the kind and extent of obstructions to upstream migrating salmon, the pool-to-riffle ratio, the sources and contribution of erosion, the water quality, the amount of water withdrawal, and various other natural inputs (Furniss and McCammon 1994; Washington Forest Practice Board 1994).

Physical modification within and adjacent to estuaries and tidally-influenced coastal streams also has had a deleterious effect on coastal ecosystems that support salmon. Dredging projects, intended to establish or maintain navigation channels, have altered estuarine hydrology, and the sediment removed by dredging was often used to fill estuarine areas and adjacent wetlands, thus removing these areas from natural productivity. In other instances, estuarine and adjacent tidal marshes or freshwater wetlands have been diked and filled for land-uses (Seliskar and Gallagher 1991) thus reducing overall estuarine volume and reducing the ratio of tidal flushing. Table 2.3 shows the loss of saltmarsh habitat in the major estuaries of the Pacific Northwest. Jetties, built at the mouths of estuaries to stabilize the channel to the sea, have interrupted the long-shore ocean transport of sediments and resulted in an inflow of marine sediments into the estuary (Burch and Sherwood 1992). Other effects from these projects include changes in nearshore marine habitats (Thom 1981; Thom and Shreffler 1994), and temporary increases of sediment in the water column (Kehoe 1982).

Table 2.2. An example of changes in the frequency of large, deep pools between 1935 and 1992 in streams on national forest land in coastal Washington and Oregon (FEMAT 1993).

	1935-1945			1987-1992		
Location	Miles surveyed	Number	Number per mile	Number	Number per mile	**Percent change**
Coastal Washington	84.9	283	3.33	58	0.68	-79.5%
Coastal Oregon	25.9	182	7.03	30	1.16	-83.5%

Another of the most detrimental of these physical modifications to salmon populations is the loss of wetlands in stream corridors and around estuaries. These habitats provide important rearing areas for juvenile salmon. Protection and food are provided by these systems, allowing the juveniles to mature before entering the open ocean. As far back as the mid-1880s, surveys were underway to locate and evaluate tidal marshes to be diked for agricultural land development (Nesbit 1885). Since the mid-1800s, major areas of tidal wetlands have been diked and drained for agriculture. In addition, coastal habitat areas have been filled for port development. The total losses of tidal marshes and associated habitats are as high as 99% in urban bays such as Commencement and Elliott bays, in Puget Sound. Whereas filling has been common near major urban centers, tidal marshes in rural areas in Oregon and Washington have been extensively diked. Most of the filling took place during the period of rapid development shortly after World War II (Boule' et al. 1983; Thom and Hallum 1991).

Hydrological Modifications of Coastal Ecosystems

Hydrological modification are changes in the natural flow of water through watershed streams to the sea. The kind and intensity of modifications vary widely among streams and can include decreases in total volume, reduction of seasonal peak flows (such as late spring snowmelt), decrease in daily flow, increases in flows during some seasons (such as winter outflows from the Columbia River) increases in water temperature, and earlier and greater peak flows. In general, these hydrological modifications stem from logging practices, urbanization, dams, and water diversion for agricultural and municipal use.

Table 2.3. Estimated loss of tidal marsh and saltmarsh habitat in specific regions of the Pacific Northwest.

Region	Lost (hectares)	Cause	Source
Commencement Bay	769	Dredging, filling, and development	Boule' et al. 1983
Snohomish Estuary	3642	Diking, log raft storage	Boule' et al. 1983; Congleton and Smith 1976
Skagit River Delta	324	Diking	Nesbit 1885; Congleton and Smith 1976
Fraser River Estuary	1,800	Diking	Levings and Thom 1994
Grays Harbor	625	Diking and dredge disposal	Proctor et al. 1980
Willapa Bay	2,500	Diking and dredge disposal	Hedgpeth and Obrebski 1981
Columbia River Estuary	300	Dredge disposal	Proctor et al. 1980
Coos Bay	831	Diking and dredge disposal	Proctor et al. 1980
Tillamook Bay	(90%)	Diking and dredge disposal	TBNEP 1995
Humboldt Bay	2,750	Diking	Proctor et al. 1980

Forestry practices can affect the hydrology of a stream or a watershed in many ways. Networks of roads that cut across hillsides interrupt the dispersed, slow flow of surface-flowing water and shunt it to ditches and culverts where it discharges rapidly into streams, often with additional sediment derived from the cut-slope of the road or ditch. Where clearcuts have occurred, relatively bare ground lies exposed to rain and snow, instead of dense, complex surfaces of leaves and boughs that once slowed the fall of rain or snow to the ground and allowed slow absorption by forest soils. In early years of regrowth, precipitation accumulates on the ground faster than it can be absorbed by the soil, which, in many cases, has been disturbed by logging activity, and flows rapidly downhill into the stream network. Snow, once shaded by a forest canopy that prevented melting well into the spring, now melts quickly in the sun and rain, and discharges water earlier in the season altering the flow of water into the soil and water-table.

Dams on streams affect salmonids, both upstream migration of spawning adults and the downstream migration of juveniles in several ways. Table 2.4 shows the downward trend in adult returns compared with the construction of hydroelectric dams on the Columbia/Snake system. Maximum spawning discharge and preferred rearing discharge flows are required for optimum spawning and rearing (Hiss 1993). Additional stresses to juveniles caused by hydrological modifications are impaired out-migration due to dam turbines (Mighetto and Ebel 1994), reduced flows carrying the young fish too slowly, concentration at dams making the juveniles easy prey (Shively et al. 1996), gas-bubble disease from high dissolved nitrogen concentrations (supersaturation) in water passing through high spillways (Mighetto and Ebel 1994), and inadvertent inclusion in irrigation diversions (Williams and Tuttle 1992).

Besides the direct obstacles that impoundments create, water diversion can also pose a serious problem to migrating adults. Withdrawals for irrigation, municipal water, industry, and recreation can lead to significant loss of in-stream flows, particularly in summer when demand for water is high and stream flow is naturally low. Specific in-stream baseflows are required to ensure that salmon can reach their upstream destination (Hiss 1993).

Chemical Modifications of Coastal Ecosystems

Chemical contamination of waters in the coastal zone comes from many sources. Some are so-called point-sources, such as industrial or municipal discharges of waste or effluent. Other sources, which are difficult to pinpoint because they occur widely throughout watersheds as a consequence of land-uses, are termed non-point sources. These include urban area stormwater drainage from parking lots, streets, and roads, which carry oils, greases, and chemicals, and runoff from industrial sites that can contain heavy metals and toxic chemicals. More dispersed runoff from agricultural and forestry operations, which occupy wide areas in much of the coastal region, can carry sediments, pesticides, herbicides, fertilizers, and other synthetic chemicals into water bodies (PSWQA 1994).

The direct effects on salmonids from chemical contamination are difficult to assess. However, three studies conducted in the Duwamish watershed near Seattle, Washington, demonstrated that juvenile chinook salmon bioaccumulate substantial amounts of toxic chemicals (McCain et al. 1990), and that this exposure was sufficient to elicit biochemical responses, immune system alterations, and impaired growth relative to juveniles from hatcheries and non-urban areas (Casillas et al. 1995; Figure 2.2). Another study in the Chehalis watershed in Washington concluded that effluent from two pulp mills in the estuary, dredging of the inner harbor, and high parasite loadings were working in concert to cause exceptionally high mortalities in coho salmon (Schroder and Fresh 1992).

Copping and Bryant (1993) discussed the extent of chemical contamination in the Pacific Northwest Region. Most tested areas are in Puget Sound and the Columbia River, with virtually no data available for the open coast. In the lower Columbia River, concentrations of aluminum, cadmium, copper, iron, lead, and zinc exceed water quality criteria in the water column. The pesticide DDT and its derivatives (DDE and DDD) were detected in 98.6% of the samples, and

Table 2.4 Trends in returns of upper river spring and summer chinook salmon in the Snake and Columbia Rivers and hydroelectric dam construction (from Williams and Tuttle 1992).

Four-Year Average	Number of Adults (1000s)	Dam (Year Constructed; Head in meters)
pre-1950	ND	Rock Island (1933; 12.1)
		Bonneville (1938; 14.8)
		Grand Coulee (1941; 85.8)
1950-53	299	McNary (1953; 26.1)
1954-57	401	Chief Joseph (1955; 43.8)
		The Dalles (1957; 21.5)
1958-61	316	Brownlee (1958; 68.0)
		Priest Rapids (1959; 21.0)
		Ice Harbor (1961; 30.3)
		Oxbow (1961; 35.5)
		Rocky Reach (1961; 28.2)
1962-65	270	Wanapum (1963; 24.2)
1966-69	266	Hells Canyon (1967; 66.7)
		Wells (1967; 21.8)
		John Day (1968; 31.8)
		Lower Monumental (1969; 30.3)
1970-73	286	Little Goose (1970; 30.3)
1974-77	152	Lower Granite (1975; 30.3)
1978-81	112	
1982-85	98	
1986-89	139	

ND No data.

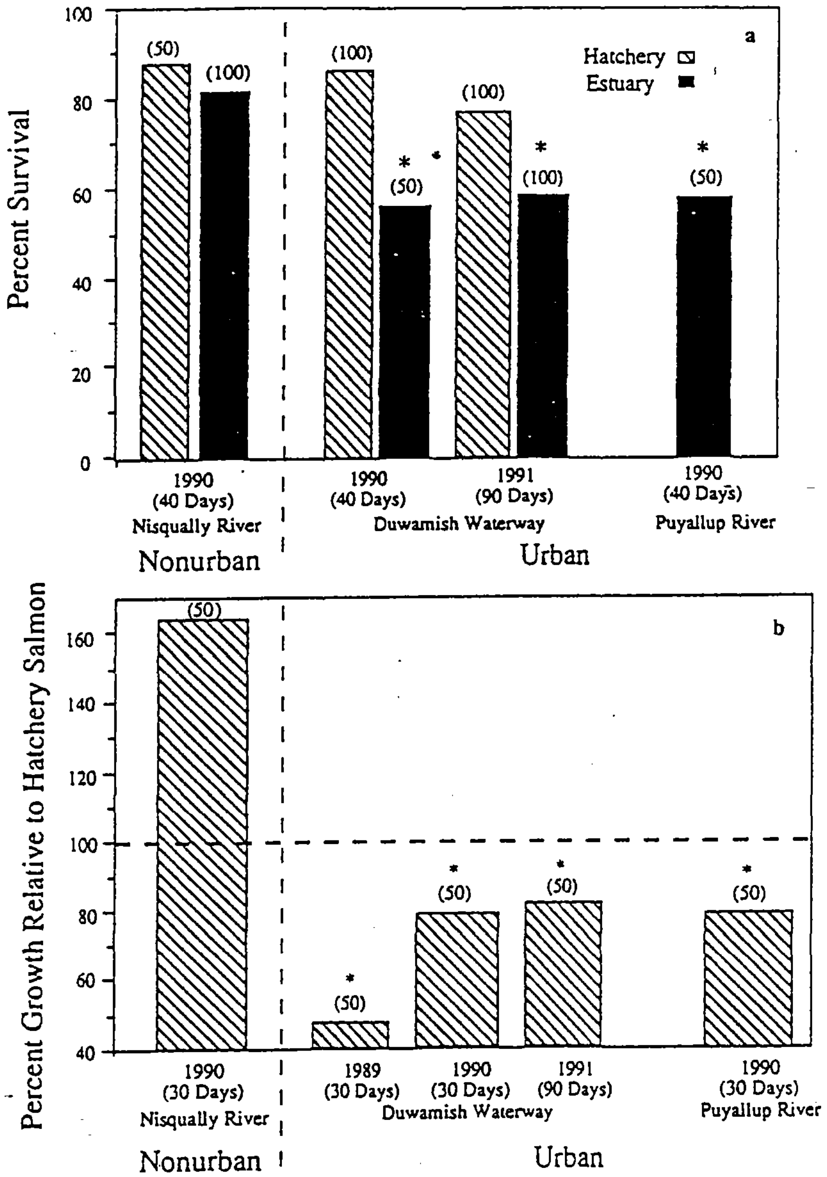

Figure 2.2. Data on (a) percentage survival over a 40-day period in 1990 and a 90-day period in 1991 of juvenile salmon collected from the Nisqually River and the Duwamish Waterway; and (b) percentage growth (length) of juvenile salmon from Nisqually River and the Duwamish Waterway relative to growth of salmon from the respective hatcheries for a 30-day period in 1989 and 1990 and a 90-day period in 1991. Asterisk indicates a significant reduction in survival or growth; numbers over bars are fish sample sizes. Source: Johnson et al. (1994), adapted from Casillas et al. (1993a, b) and Varanasi et al. (1993).

polychlorinated biphenyls (PCBs), formerly widely used in industrial applications, were detected in samples throughout the study area at levels that may affect fish and related wildlife (Copping and Bryant 1993).

Biological Modification of Coastal Ecosystems

In addition to indirect effects on the biota of coastal ecosystems through changes in hydrology, stream structure, or water quality, humans have also directly affected the biological composition and relationships of coastal ecosystems. This form of direct intervention is most manifest in the harvesting of fish for commercial or recreational purposes, however the actual contribution of overfishing to declines or loss in salmon populations is difficult to separate from other impacts. Nehlsen et al. (1991) attempted to assess the condition and status (high risk, moderate, etc.) of 214 stocks in Washington, Idaho, Oregon, and California and the factors contributing to their status (Summary, Table 2.5). Although their information was not complete, a general estimate was made of the contributions of various activities to the status of stocks. Overfishing was considered a factor in the decline of 51 stocks at high risk, 52 at moderate risk, and 13 of special concern, or a total of more than 50% of the stocks examined. The contributing factors are considered to be current problems, not necessarily the historical cause of decline.

Maintaining otherwise declining salmon stocks through hatcheries has been a popular form of mitigation since the first hatcheries were developed in the Columbia River system in the late 1800s (Table 2.1). Hatcheries are now widespread in many river systems throughout the Pacific Northwest. In the 1970s, concerns were raised about the relationship of genetic differences between wild salmon and hatchery stocks and the reduced reproductive success in hatchery stocks (Goodman 1990) (see also Chapters 5 and 6 of this document for discussions of the importance of genetic diversity to survival of salmonid stocks). Several studies have confirmed these possible threats and their effects on wild salmonid stocks (Chilcote et al. 1986; Fleming and Gross 1993). Although these effects are complex, it appears that there are three main consequences: 1) reduced genetic diversity and the lack of natural selection in hatchery fish; 2) increased competition between wild stocks and the frequently higher numbers of hatchery released stocks; and 3) overfishing of mixed (hatchery and wild) stocks resulting in decimation of the wild stocks. Recently, the importance of wild stocks has been realized, and measures are being taken to develop enhancement techniques that mimic the natural processes of selection and reproduction (WDFW 1995). The effect of the negative interactions with hatchery fish is included in the "biotic interaction" category of Table 2.5, along with the introduction of exotic species, hybridization, competition, and predation.

The differences between the geographic scale of salmon life-histories and the geographic scale of management regimes contribute to overfishing and inappropriate management of salmon fisheries. All species of Pacific salmonids cross several political boundaries during their lives and thus swim through areas managed with different philosophies, goals, and techniques. In addition, Canadians and Americans have a long history of conflict over the right to catch fish that may have spawned in the other's country (Jensen 1986). Moreover, Native American coastal tribes in Washington

Table 2.5. Number of stocks affected by various factors contributing to the scarcity or decline of anadromous salmonid populations from California, Oregon, Idaho, and Washington (from Nehlsen et al. 1991).

	Present factors contributing to the scarcity or decline			
Status	*Habitat Loss*	*Overfishing*	*Disease*	*Biotic Interactions*
High risk	95	51	0	41
Moderate risk	53	52	0	34
Special concern	41	13	0	36
Listed as threatened or endangered	1	--	--	1
Total	190	116	0	112

NOTE: Total number of stocks examined is 214. More than one factor may contribute to the status of a stock.

and Oregon have claimed the right to 50% of the catch from their usual and customary fishing grounds, thus complicating management and harvest allocations.

Two other factors contribute to the complication of fisheries management and consequent overfishing. One is the economic push for each fisher to get the largest possible catch from each returning run which requires fisheries managers to determine the levels of catch that satisfy the economic and political demands for fish while still allowing continued escapement of sufficient stock to ensure reproductive success. Harvests in the commercial and sport salmon fisheries from 1972 to 1994 are shown in Tables 2.6-2.8.

The second factor is that different populations of salmonids are mixed together in their ocean feeding grounds. Because the so-called sustainable level of fish harvest varies among species and populations within a species, regulation of harvest of a single population is extremely difficult. Fisheries managed to allow higher catch of the more productive population would likely overfish the less productive one (Schmitt et al. 1994; see also Chapter 5). This issue is further complicated by the previously discussed interception issues between the US and Canada.

Table 2.6. Pacific Coast commercial troll coho salmon landings in millions of pounds round weight (Pacific States Marine Fisheries Commission 1994).

Year	*Alaska	British Columbia	Washington	Oregon	California	Total
1970	2.2	17.3	6.1	8.7	1.5	35.8
71	3.1	21.4	7.9	10.1	3.7	46.2
72	5.7	15.9	3.9	5.6	1.2	32.3
73	4.5	16.2	4.3	5.9	2.3	33.2
74	6.7	15.6	6.4	8.3	4.3	41.3
75	1.5	9.5	5.1	4.7	1.3	22.1
76	4.3	15.3	7.2	10.4	3.3	40.5
77	4.9	14.4	4.3	3	0.2	26.8
78	8	14.9	3.2	3.2	1.5	30.8
79	7.1	17.7	4.2	5.3	1.2	35.5
1980	5	15.3	2.3	2.5	0.3	25.4
81	6.7	12.2	2	3.8	0.5	25.2
82	10.2	15.8	2.2	3.1	0.6	31.9
83	8.5	18.9	0.3	1.3	0.3	29.3
84	10.4	19.2	0.3	0.1	0.4	30.5
85	13.2	14.8	0.6	0.6	0.1	29.3
86	17.3	23.1	0.7	2.2	0.8	44.1
87	7.7	15.5	0.7	2.2	0.3	26.4
88	4.4	13.3	0.3	3.8	0.4	22.2
89	10.4	15.1	0.7	2.3	0.3	28.8
1990	13.8	19.5	1	0.7	0.4	35.4
91	12.5	19.1	1.1	1.6	0.5	34.7
92	15.5	13.8	1	0.2	0	30.5
93	15.3	8	0.4	0	0	23.6
10-yr Mean	12	16.1	0.7	1.4	0.3	30.6
1994**	27.3	11.7	0	0	0	38.9

* Troll caught salmon are landed dressed. Round weights are projected.

** All data are preliminary.

Table 2.7. Pacific Coast commercial troll chinook salmon landings in millions of pounds round weight (Pacific States Marine Fisheries Commission 1994).

Year	*Alaska	British Columbia	Washington	Oregon	California	Total
1970	5.1	9.9	2.5	1.9	6.1	25.5
71	4.9	15.2	3.1	1.2	5.7	30.1
72	3.3	14.1	2.6	1.5	6.2	27.7
73	5.0	12.7	3.8	4	8.7	34.2
74	5.1	13.5	4.3	2.6	5.8	31.3
75	4.4	12.6	3.3	3	6.6	29.9
76	3.5	13.8	4.4	2.2	5.7	29.6
77	4.7	12.1	3.3	4	6.6	30.7
78	6.8	13.2	2.4	2.2	6.0	30.6
79	6.0	11.1	2.0	3.0	7.9	30.0
1980	5.5	11.6	1.9	2.5	6.4	27.9
81	4.7	9.9	1.4	1.8	6.8	24.6
82	4.5	11.9	1.9	2.7	8.5	29.5
83	4.3	9.5	0.8	0.8	2.4	17.8
84	4.4	11.1	0.2	0.6	2.3	18.7
85	4	9.3	0.6	2.3	5.2	21.4
86	4.7	8.6	0.7	3.9	7.6	25.5
87	5.3	10.2	1.1	6	9.5	32.1
88	4.3	11.3	1.5	5	16.5	38.6
89	5.2	8.6	1.2	4.1	6.2	25.3
1990	5.6	9.2	0.6	2.5	4.7	22.6
91	5.2	8.3	0.8	0.8	3.7	18.8
92	3.3	10.1	1	1.2	1.9	17.5
93	4.4	8.7	0.6	0.9	2.9	17.5
10-year Mean	4.6	9.5	0.8	2.7	6.1	23.8
1994**	3.4	5.6	0.1	0.3	3.3	12.6

* Troll caught salmon are landed dressed. Round weights are projected.

** All data are preliminary.

Table 2.8. Salmon and steelhead sport harvest (in thousands of fish) for the Pacific Coast, 1975 to 1993 (Pacific States Marine Fish Commission 1994).

Year	Alaska		British Columbia†		Washington†		Oregon†		Idaho		California†		Total	
	Salmon	*Steelhead*	*Salmon*	*Steelhead*	*Salmon*	*Steelhead*	*Salmon*	*Steelhead*	*Salmon*	*Steelhead*	*Salmon*	*Steelhead**	*Salmon*	*Steelhead*
1975	178	2	948	NA	1298	93	329	186	0	0	125		1930	281
76	201	2	983	NA	1649	89	581	118	0	2	139		2569	212
77	381	4	NA	18	1095	100	261	145	4	13	118		1858	262
78	525	4	NA	15	1022	163	283	201	7	12	114		1950	380
79	361	3	NA	13	1035	95	202	122	closed	6	141		1740	226
1980	532	5	NA	11	747	151	345	204	closed	9	106		1731	369
81	380	3	514	10	702	125	231	155	closed	13	95		1407	296
82	597	4	539	14	645	104	214	135	closed	21	165		1622	264
83	533	5	792	15	752	79	172	84	closed	32	91		1547	200
84	626	7	828	19	419	150	140	198	closed	25	107		1292	380
85	619	5	1096	19	579	166	246	189	3	35	187		1633	393
86	721	6	896	25	715	169	242	149	4	40	160		1842	364
87	970	6	922	17	672	135	241	161	1	30	240		2124	332
88	908	6	1297	15	533	138	265	174	1	21	206		1913	340
89	1,097	6	848	12	711	236	307	113	closed	39	237		2351	394
1990	909	6	927	9	716	103	227	142	1	31	191		2045	282
91	1037	5	933	10	779	103	274	95	closed	26	150		2239	230
92	993	3	1195	11	483	154	198	123	1	37	85		1760	316
10-yr mean	841	6	974	15	636	143	231	143	1	32	166		1875	323
1993	1052	4	1616	7	476	124	66	95	0	35	140	41	1734	298

† Marine salmon fishery harvests only.

* Steelhead not estimated in California before 1993.

NA Not available.

Exotic Species Introductions

The presence of number of non-native or exotic species in coastal ecosystems in the Pacific Northwest, principally in estuaries and streams, is a factor of unknown dimensions. Several plant species have been introduced into aquatic systems occupied by salmon. These species have grown to occupy large areas. Reed canarygrass (*Phalaris arundinacea*) is largely confined to freshwater marshes and riparian zones along rivers. Japanese eelgrass (*Zostera japonica*) occupies formerly unvegetated mudflats and sandflats in estuaries at elevations immediately above the native eelgrass. A brown seaweed (*Sargassum muticum*) that grows on rocky substrates in estuaries within the low intertidal to shallow subtidal zone has been shown to outcompete native bull kelp (*Nereocystis luetkeana*) in some areas (Thom and Hallum 1991). Cordgrass (*Spartina* spp.) has spread from a small area to massive areas in Willapa Bay and Puget Sound (Simenstad and Thom 1995). Cordgrass has also been noted in small patches in other coastal areas in the Pacific Northwest (Mumford et al. 1990).

Some species have been purposely introduced, such as the Pacific oyster (*Crassostrea gigas*), introduced early in this century and since cultured widely in the region's estuaries, and the American shad, an anadromous fish species introduced in the Columbia River where it appears to be thriving in impounded water behind dams. Many other introductions are inadvertent; growing evidence shows that ballast water from ships calling at ports in the Northwest has been the source of numerous introductions of toxic or harmful phytoplankton species (Janet Kelley pers. comm.). There is speculation that the diatom that causes domoic acid toxicity in razor clams was introduced via ballast water.

Effects on the aquatic ecosystems by exotic species have received only marginal attention. Studies in the seagrass system in Padilla Bay indicated that the Japanese eelgrass is an important component of the food web; it is directly eaten by dabbling ducks as well as grazing invertebrates, and forms habitat for juvenile salmon prey resources (Simenstad et al. 1988; Thom 1995). Ongoing research in Willapa Bay by a University of Washington team (Charles Simenstad, principal investigator) is examining the role of the indigenous smooth cordgrass (*Spartina alterniflora*) in the ecology of that system.

Interactions and Cumulative Impacts of Modifications

Teasing apart and understanding the interactions and cumulative effects of various modifications is difficult, time-consuming, and, at this point, inexact. Botkin et al. (1995) identified the leading causes of changes in salmon abundance and distribution in western Oregon and northern California (Tables 2.9 and 2.10). Causes (i.e., human activities) were separated into three categories: major factors, potentially important factors, and minor factors. Components or specific effects of each factor were also identified. Among the major factors, agriculture, forestry, and urbanization have the greatest number of components affecting salmon, almost all of which are categorized as indirect effects (that is, they decrease the quality of the ecosystem conditions

Table 2.9. Components of factors that have caused changes in salmon abundance and distribution in western Oregon and Northern California (Botkin et al. 1995).

A[a]	Loss of riparian vegetation and functions
B	Pesticide exposure
C	Industrial pollutants exposure
D	Increased sediment delivery to streams
E	Stream channelization
F	Habitat destruction
G	Loss of woody debris and channel form
H	Filling of side channels
I	Reduced freshwater flow
J	Exposure to abnormal temperatures
K	Habitat area loss
L	Lack of barriers over diversion canals
M	Reduced upwelling
N	Altered ocean currents and flow
O	Decreased food abundance
P	Reduced escapement
Q	Reduced smolt releases
R	Barriers to fish passage
S	Loss of genetic integrity and diversity
T	Competition between hatchery and wild fish
U	Forest fragmentation
V	Estuary degradation

[a] Letter codes are used in Table 2.10.

for the population), except fish harvest, which has a direct effect on fish abundance and distribution. The major components can affect salmon at all life stages.

When viewed within a particular river system, the cumulative or interactive effects of one or more major factors on fish are clearly shown. For example, systems that have been 1) heavily logged, 2) undergone urbanization, and 3) have high degree of hydrological modifications would be expected to have major losses of salmon. This is particularly true in areas such as Commencement Bay in Tacoma, Washington. The relative degree of impact from each factor also varies among systems in the Pacific Northwest. Nehlsen et al. (1991) concluded that multiple stressors were active in reducing salmonid populations in the region (Table 2.5). Habitat loss was most frequently cited.

Table 2.10. Leading causes of changes in salmonid abundance in western Oregon and northern California (Botkin et al. 1995).

Major Factors	Components of Factors [a]
Agriculture	A, B, D, E, F, H, I, J, R, U, V
Dams	I, K, R
Drought	I, J
Fish Harvest	P, S
Forestry	A, B, D, F, G, J, U, V
Urbanization	A, C, E, F, G, H, I, J, K, U, V
Potentially Important Factors	
Gravel Harvest	F
Irrigation	I, L
Legal Bycatch and Noncatch Mortality	P, S
Hatchery Fish Interference	S, T
Unfavorable Ocean Condition	M, N, O, P
Unregulated Harvest	P, S
Minor Factors	
Bird Predation	Q
Marine Mammal Predation	P, Q

[a] Components of factors are from Table 2.9.

Ecosystem Components Most Susceptible to Human Intervention

The coastal ecosystems most susceptible to human intervention have historically been those with resources of economic value (e.g., forest products), that are amenable to transportation (e.g., deep estuaries), or that permit economical food production (i.e., agriculture). Where two or more of these conditions exist, human intervention has typically been greatest, such as in Puget Sound, the lower Willamette Valley, Grays Harbor, and Coos Bay. After so many years of such widespread and pervasive alteration, ecosystems that have already suffered the greatest losses are presently most susceptible to further or continued human intervention. Where salmon populations are near extinction, small changes in ecosystem conditions, whether human-caused or from natural forces, may result in permanent loss of salmon from the system.

Likewise, within a system that has been especially altered, specific areas may be more susceptible to intervention than others. For example, critical remnants of salmon spawning habitat may be within a forested area of high commercial value. If these remaining areas are damaged, the salmon run may cease to exist or be so reduced that it has little resilience in the face of natural climatic variations.

INTERACTION BETWEEN NATURAL VARIABILITY AND HUMAN INTERVENTION

Natural variability in ecosystems is largely a function of climate variability. Changes in temperature, precipitation, and irradiance are major controllers of hydrology, erosion, and sedimentation, as well as of the growth and reproduction of plants and animals. As these factors vary, so do the components of the ecosystem affecting aquatic resources. For example, years with higher than normal temperatures and low precipitation can result in droughts. Droughts can affect spawning habitats in streams that during periods of average rainfall contain marginal quantities of water capable of supporting a spawning population.

Human intervention can exacerbate the effects of short-term climatic variations as well as effects of longer-term shifts in climate. For example, human development patterns have fragmented suitable habitats and created barriers (e.g., highways or farm fields) to dispersal (Orians 1993). Hence, species are not as free as they once were to shift geographically to more suitable areas of habitation in response to climate changes. Extinctions caused by climatic changes are likely to increase due to such habitat alteration and isolation in the landscape (Orians 1993).

Retrospective Analysis of Climate Variability and Human Activity

Retrospective analysis is an important technique for understanding natural variability and the history of resource use and development in coastal ecosystems. Existing literature and statistical analysis can be used to correlate such factors as salmon production, climatic and geologic variability, and human activities in certain areas of interest. To date, little has been done to link these areas of research. One study on the Coquille River estuary on the Oregon coast used archaeological data to try to determine possible links between the process of tectonic uplift and catastrophic subsidence and effects on biological resources (Hall 1996). Another study examined the effects of sea level rise on intertidal salt marshes in the Pacific Northwest by examining sediment cores to determine the sediment accretion rates that resulted from known historical events (Thom 1992).

More recent historical analysis can help to link the advent and use of certain technologies to physically modify the landscape with changes in distribution and abundance of natural resources and the composition and function of coastal ecosystems. The Coquille estuary study, as well as other historical and archaeological studies along the coast, was able to link such human activities as jetty-building, stream-channeling, land-use changes, exotic plant introductions, and sea mammal hunting with changes in natural resource availability (Hall 1996). Although the Coquille study did not focus specifically on changes in salmon populations, an analysis of this type would certainly be feasible.

While retrospective studies can reveal historical patterns of change, they can be especially useful if compared against more contemporary data about ecosystem conditions. Such contemporary data about certain baseline conditions can be useful in identifying emerging problems and distinguishing natural from human-caused change. For instance, the Washington Department of Ecology's Puget Sound Ambient Monitoring Program (PSAMP) monitors numerous marine stations within Puget Sound to establish baseline water quality data (Newton et al. 1995a) and includes focused projects of 6 months to 3 years with increased resolution of data to assess the existence or extent of problems. One such project in Hood Canal indicated reduced dissolved oxygen in 1994-1995, as compared with historical data (Newton et al. 1995b). Such findings are the basis for intensified data collection and analysis to determine the causes and find possible solutions.

Impacts of Climate Variability on Coastal Ecosystems

Understanding the effects of climatic variability on aquatic and coastal resources is a major focus of research globally (e.g., Ballentine and Stakhiv 1991; Pernetta and Milliman 1995; National Science and Technology Council 1996). At least two studies have indicated a strong linkage between climate variability and salmon survival (Neitzel et al. 1991; Francis and Sibley 1991).

Two programs in the Pacific Northwest that relate to the PNCERS mission are planning to address the issue of climate variability and effects on fisheries resources. One, the Joint Institute for the Study of Atmosphere and Oceans (JISAO), has initiated a program to assess the dynamics and effects of climate variability and policy response for the Pacific Northwest, with an emphasis on the changes in the regional climate due to greenhouse forcing (Miles 1995). The second program is the US Global Ocean Ecosystems Dynamics (GLOBEC) study (Hollowed 1996) that will examine oceanic processes and the effects on oceanic species, such as salmon and crab, in the northeast Pacific Ocean. This program has specifically centered on climate change and the "carrying capacity" of the North Pacific Ocean.

Evidence indicates that decadal shifts occur in the climate of the Pacific Northwest and that a warming trend currently exists (Tangborn et al. 1991). The change in geographic distribution of various Pacific fish species in response to warm periods have long been known (e.g., Radovich 1961). Climatic warming, and consequent changes in ocean conditions, has been linked to changes in the rocky intertidal fauna in California (Barry et al. 1995) and the decline of zooplankton biomass in the California Current (Roemmich and McGowan 1995). Modeling of the effects of climate-induced changes on spring chinook salmon in the Yakima River system suggests that slight warming could result in conditions that severely diminish that population (Chatters et al. 1991).

Sea-surface temperature and salinity data collected in Puget Sound by the Washington PSAMP (discussed above) were assessed in relation to El Niño-Southern Oscillation (ENSO) events to determine the effects of climatic forcing on Puget Sound waters (Newton 1995). That assessment concluded that climatic conditions noticeably affect both sea-surface temperature and salinity; sea-surface temperature appears to co-vary with air temperature, and salinity co-varies with river flows which, in turn, may be affected by ENSO events (e.g. decreased rainfall).

Sea level rise, which can result from climate change, can affect salmonid populations by destroying feeding and rearing areas in tidal portions of riverine systems. Although there have been very limited investigations, loss of tidal marshes would be predicted as a consequence of sea-level rise due to major climatic warming (Thom 1992).

Changes in the concentrations of atmospheric gases due to human-caused loading could also affect coastal ecosystems. One study has investigated the effects of increased CO_2 concentration on two coastal aquatic plant species, eelgrass (*Zostera marina*) and bull kelp (*Nereocystis luetkeana*), that create important habitat for numerous estuarine or nearshore fisheries (Thom 1996). The study showed that plant production increased with lower increases in CO_2 concentration (2.5 times), and was variable at higher levels of CO_2 enrichment (5 times).

RESTORATION OF COASTAL ECOSYSTEMS FOR SALMON

Although humans have historically intervened in and adversely affected coastal ecosystems in many ways, humans also purposefully intervene in order to protect and restore habitat or resource functions. As the decline of salmon populations has been increasingly linked to isolated, degraded or destroyed habitat, many citizen groups and government agencies have begun programs to try to restore habitat and rebuild populations of coastal salmon. The process of mitigating human-caused effects on salmon is complex. Research is beginning to determine the steps and considerations for successful restoration efforts. The FEMAT (1993) report identifies habitat management strategies to minimize further damage to salmon populations and provides guidance on the restoration of salmon habitat. In addition, the Washington Department of Fish and Wildlife (WDFW) has developed a wild salmon policy that provides a comprehensive plan for restoring salmon populations (WDFW 1995). A new report (Thom and Wellman 1997) provides guidance to the US Army Corps of Engineers on monitoring the performance of restored aquatic ecosystems.

Restoration Goals

Restoration begins with the creation of a visual image in the minds of people (Thom and Wellman 1997) which, stated formally, is the goal that provides the direction for the restoration effort or program. Goals and related subgoals or objectives are most useful when converted into conditions that can be evaluated with appropriate measurements (Thom and Wellman 1997) to assess restoration success. Monitoring programs should therefore be developed during the planning phase of any restoration effort so that unrealistic goals can be modified into more realistic or measurable goals.

Conceptual and Numerical Models

Specific restorative actions require an *unambiguous understanding of cause and effect*, and *proven restoration technologies*. These can be accomplished through focused research, conceptual model development, and design, assessment, and reporting of the performance of restoration projects. A conceptual model allows the restoration project to identify: 1) direct and indirect connections among the physical, chemical, and biological components of the ecosystem; and 2) principal components upon which to focus restoration and monitoring efforts (Thom and Wellman 1997).

A conceptual model for habitat restoration typically follows the general form:

Controlling Factors ⟶ Habitat Structure ⟶ Habitat Function.

Restoration Activities

A wide range of specific restoration activities has been tried in the Pacific Northwest. Restoration has been directed at improving migration, reproduction, rearing, and riparian habitats (Adams and Whyte 1990; Koski 1992; Reeves et al. 1991). Adams and Whyte (1990), Reeves et al. (1991), and Koski (1992) summarized the primary restoration actions used in streams affected by logging activities. Williams and Tuttle (1992) summarized activities for restoring salmonids affected by dams in the Columbia River system. Simenstad and Thom (1992) provide alternatives for restoring estuarine habitat used by salmon. The use of hatcheries and harvest management for maintaining and restoring salmon has been reviewed by the WDFW (1995) in their wild salmon policy report.

Restoration activities have included: simply allowing natural recovery; removal of barriers; improving and replacing culverts; cleaning stream gravel; constructing spawning and egg-incubation channels; building or placing in-stream structures; and planting trees to restore riparian habitat and function. The restoration of Columbia River habitat has focused on improving conditions for the passage of salmon through dams during both upstream and downstream migrations (Williams and Tuttle 1992). Estuarine restoration has centered on constructing shallow-water juvenile feeding and rearing habitat. Such habitat projects have been successful in increasing food resources and residence time for juveniles in estuaries

Assessing Performance

Reeves et al. (1991) concluded that the "future success of habitat restoration will depend on the ability and willingness of current practitioners to continually update their methods and to incorporate new information as it becomes available." Research is also needed to quantify the fitness of salmon and ultimate increase in population size and viability in response to restoration programs. Research is needed to determine the time required for various restoration strategies and technologies to achieve full function and whether the function is maintained.

Only one study (Levings and MacDonald 1991) has attempted to experimentally release juvenile salmonids in various locations in a restored estuary and then recapture these salmon as returning adults. This study showed that restoration of estuarine habitats was effective and can enhance salmonid survival to adulthood and the return of the fish to the stream of origin. These types of studies provide credibility to potentially expensive restoration projects; however, post-restoration monitoring studies are still very rare.

Adaptive Management of Restored Systems

Because scientifically-derived information and understanding of ecosystems is often incomplete, the principles of adaptive management must be incorporated into administration of restoration project (e.g., Boesch et al. 1994). Walters (1986) outlined three ways to structure adaptive management: 1) evolutionary or "trial and error"; 2) passive adaptive; and 3) active adaptive. In the evolutionary method, early choices are made in a haphazard manner and later choices are made from a subset of choices that may give more desirable results (Walters and Holling 1990). The passive adaptive method uses the best available information to select a single response model through which decisions are made. Finally, active adaptive management involves manipulations carried out to evaluate which model is best for enhancing the performance of the system. This latter method may provide the most meaningful information to help make decisions that will assure the ultimate success of the project and provide meaningful data that will help in the design

Although there is wide interest and impetus (NRC 1992; Kentula et al. 1992; Thom and Wellman 1997), implementation of adaptive management has not been accomplished on a systematic basis. This may be a key research area for PNCERS in the Pacific Northwest. Thom (1997) has designed a system-development matrix for use in systematic planning of adaptive management of restoration projects in coastal areas. The matrix can be used to assist planners and managers in determining when adjustments in their system may be needed.

SUMMARY AND PRELIMINARY RESEARCH QUESTIONS

Human intervention in coastal ecosystems is widespread and significant. Yet, there is very little understanding of how to quantitatively partition the cumulative effects of many different stressors on the ecosystems that support salmon. Previous reports have concluded that major impacts to salmon have been from a variety of sources, but questions remain as to specific impacts in any particular watershed. A lack of long-term monitoring adds to the uncertainties regarding impacts to salmon populations. Susceptibility to human intervention varies among systems, and varies within each ecosystem. As compared with relatively pristine areas, salmon populations in highly damaged systems may be more vulnerable to additional insults or natural variations in climate.

Although more must be done to understand the effects of human intervention on coastal ecosystems, restoration of these systems is long overdue. The PNCERS program should consider a strong program to enhance the capabilities of users and managers to successfully restore salmon and other coastal aquatic resources in the region. Restoration planning and implementation of restoration programs could benefit from research in specific areas under PNCERS.

Areas for potential research under the PNCERS program might be directed at the following seven major topics:

1. retrospective analysis to correlate salmon production, climatic and geologic variability, and human-induced stressors;
2. development of methods to assess cumulative effects of multiple stressors on coastal ecosystems (i.e., natural variability, climatic variability, human intervention);
3. assessment of the ecological role and development of methods for the control of undesirable introduced species;
4. further refinement of GIS technologies coupled with numerical models for assessing damaged areas and for planning restoration actions;
5. identification of the vulnerability of ecosystems and components of ecosystems to natural variability;
6. quantification of the ecological and resource response to restoration activities, cost/benefit analysis of various restoration strategies, and examination of restoration case studies; and
7. development of a systematic, highly objective, adaptive management system.

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CHAPTER 3

SOCIOECONOMIC CAUSES AND CONSEQUENCES OF COASTAL ECOSYSTEMS CHANGE

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INTRODUCTION

This review investigates the methodologies available to the Pacific Northwest Coastal Ecosystems Regional Study (PNCERS) program to: 1) determine the linkages between social and economic causes and consequences, both direct and indirect, of ecosystem changes in coastal areas; and 2) the linkages between ecosystem change and responses by institutions and organizations, and formal decision processes that may or may not appropriately interpret these changes and initiate planning to improve the pattern of ecosystem changes.

Consideration of socioeconomic consequences focuses on a limited number of economic and social components related to coastal ecosystem variables. These include salmon fishing and related recreation, shellfish culture, coastal tourism/recreation, the forest products industry, agriculture, land-use practices and regulation, and coastal land-use (harbors, beaches, wetlands).

Concept of Interacting Social and Biogeochemical Systems

A simple schematic diagram (Figure 3.1) conceptualizes the key linkages among and between components of the biogeochemical system (the natural-resource, ecosystem-related realm) and the social (human-centered) system. There are three main areas in the diagram, each with related elements. This chapter is concerned mainly with the social side (the right-hand side) of the diagram which is therefore more fully elaborated than is the biogeochemical system (the left-hand side), which is elaborated in other chapters in this document. The center of the diagram refers to the ways that people affect the biogeochemical system and the ways that the biogeochemical

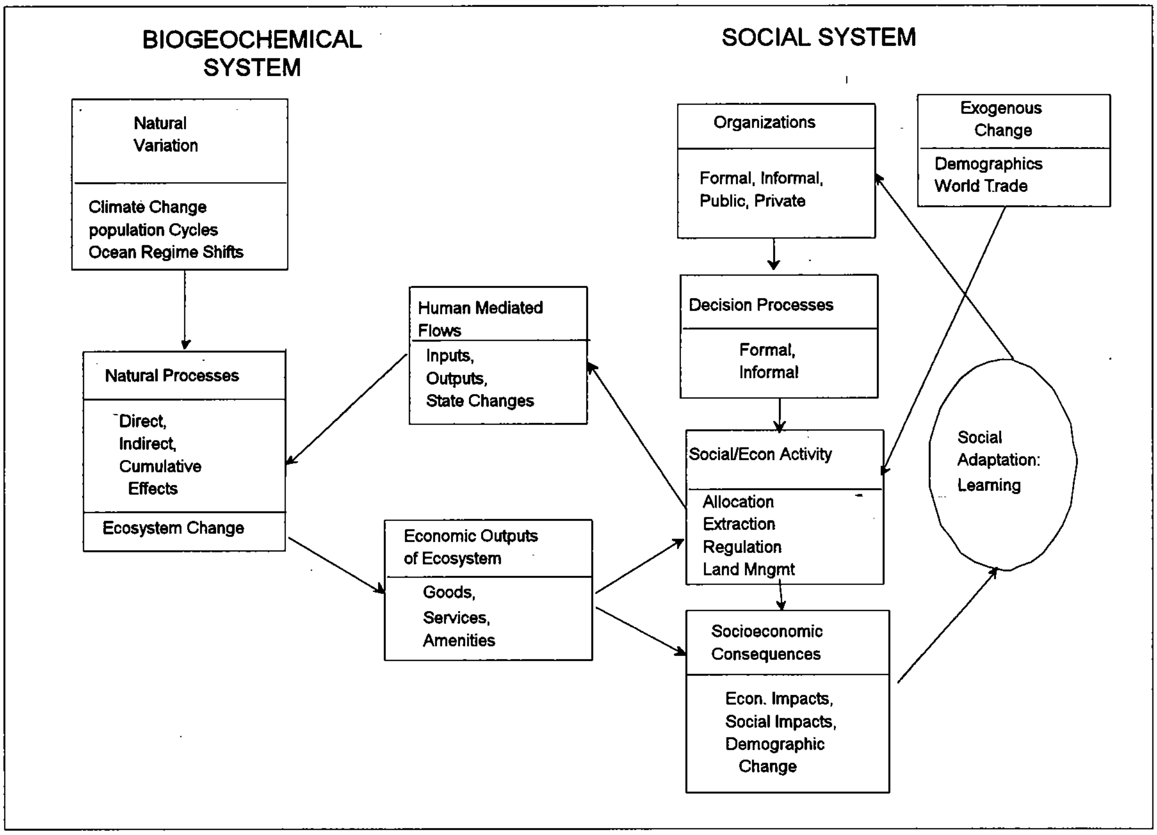

Figure 3.1. Schematic model of ecosystem interactions.

system serves and influences people. This diagram should also be compared to the overall PNCERS conceptual model presented in Chapter 1.

On the left hand side, elements of the biogeochemical system are driven by exogenous variables such as climate change, ocean regime shifts, and slow geologic processes (see Chapters 4, 5, and 6). Human activities have also caused changes in the structure and functioning of some components of coastal ecosystems (see also Chapters 2, 5, and 6). Biogeochemical system response to human activity results in a dynamic process of change in availability of goods and services (e.g., fish harvests, water supply, and raw timber) and in the state of the biogeochemical system as perceived by people. Some biogeochemical conditions may have direct socioeconomic consequences, for example, the scenic or aesthetic character of ecosystem components is of direct value to people. So, in combination, human-mediated and exogenous driving forces cause the ecosystem to change in character and function over time, and these changes in turn provoke responses in the social system.

In the upper center box, human-mediated influences on the ecosystem include the flows of materials from humans to the environment (e.g., pollutants, solid waste, etc.) and actions that directly change the ecosystem (e.g., harvesting fish, dredging harbors, damming rivers, mining gold, clearing land, planting crops, etc.). In the lower center box are the economic outputs that contribute to human welfare (e.g., fish, timber, metallic ores, agricultural crops, scientific information, etc.). In addition to material flows, the natural environment produces amenities that are important to humans such as recreation, aesthetic experiences, clean air, and spiritual renewal. The conceptual framework is structured to indicate the flow of materials and actions from society to the ecosystem and of the flow of goods, services, and amenities flowing from the ecosystem to society.

On the right side are the major elements of the social system that affect or interact with the coastal ecosystem. The process of transforming materials and distributing them through the society is largely the subject of economics, and the roles of markets, competition and governments are predominant. At any given time, the structure and behavior of the economy is constrained and guided by social conventions and norms, formal governmental regulations, legal rules, traditions, habits, and ethical commitments. As social activity affects the biogeochemical system and then receives feedback as a consequence of changed conditions, changes in human well-being, both real and perceived, are reflected in a variety of quantitative and qualitative ways, collectively called socioeconomic consequences. These consequences are summarized as economic impacts, social impacts, and demographic change.

Adaptation, personal as well as social, occurs as a result of conflicts between people or between expectations and realization that generate dissatisfaction. Some adaptations are simply individual coping actions, some involve organized local efforts to plan better, some involve state and Federal agencies, and others are litigation or legislative action. The institutions through which public action occurs are numerous, overlapping, and inconsistent. Hence, the decision processes that ultimately shape the rules, conventions, and technologies that guide social activity are difficult to characterize. Also, the ways in which rules and conventions actually modify human behavior are often complex. Finally, the social system is driven by such exogenous variables as broad demographic changes (including population growth and immigration), technological shifts, and world trade patterns.[1] Coastal communities have little control over these trends, but are strongly affected by them.

As a result of the feedback loops described here, the social system is constantly adapting as people perceive and react to the consequences (both positive and negative) of changes in the goods, services, and amenities flowing from the ecosystem. The chain of action from perception of consequences to altered use of ecosystem resources is long, complicated, and multistaged. It involves both informal and formal organizational efforts to redirect human activities in ways that reflect the present understandings of causes and consequences of human use of the ecosystem.

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[1] Many of these "exogenous" forces in coastal systems would be endogenous at larger geographic and longer time scales (e.g., State or national policy).

Connecting Science to the Policy Process

A basic premise of PNCERS is that improved understanding of coastal ecosystems, processes, and variability will enable the public, resource-users, policy-makers, and managers to maximize benefits to society while minimizing costs to the ecosystem (Bailey 1995). The socioeconomic causes and consequences of ecosystem change may be better accounted for as economic and social changes and conceptualization of the institutional/organizational processes are more clearly understood.

Because humans and their activities are components of the ecosystem (Fig. 3.1), studies of coastal ecosystems must address not only biogeochemical relationships, but also the social processes that ultimately cause anthropogenic effects in the environment and the socioeconomic consequences of these effects. This can best be accomplished if social science and policy studies are conducted in tandem with natural science investigations. The information generated from policy studies can then be incorporated into the broader conceptual model of interactions among economic and policy decisions and the ecosystem functions. The complementary nature of these efforts will also be important to identifying key scientific questions and refining management strategies.

SOCIOECONOMIC RESEARCH APPROACHES

There are three prevailing approaches or research domains to understanding social system structure, how it adapts or changes over time, and how this process of adaptation may incorporate concerns related to the social-biogeochemical system linkages. These three are: 1) legal or institutional analysis; 2) social studies; and 3) economic studies. All of these focus on an *understanding* of the existing system (through description, measurement, and investigation of causal links) as well as identifying *intentional actions* that could alter the social system's relationship to the biogeochemical system. The pursuit of understanding is the province of science; the choice of social response to that understanding necessarily involves ethics, institutions, and politics as well as science.

Legal/Institutional Approach

DOMAIN OF STUDY

Several kinds of organizational actors can be described: public agencies with land-management, regulatory or educational missions; private non-profit organizations representing a spectrum of perspectives on the role of human actions in coastal ecosystems; private for-profit organizations, representing tourism, fisheries, agriculture (including forestry and aquaculture), transportation, and other sectors; and informal citizens' groups and individuals. These classes of social entities differ in their goals and motives, sources of authority, geographic and other constraints on their scope of action, organizational structure (bureaucracy), and the types of collective action in which they engage (e.g., "resource management" vs. "resource use").

The amount of research on the various roles of these organizations in coastal regions, in general, and in the study area, in particular, varies widely. The legal basis for the action of public entities is well understood, but the roles of private organizations and individuals is less well documented, and informal interactions across the entire public-private continuum have been infrequently studied.

APPROACHES

Several methods, descriptive as well as theoretical, have been used to study the organizations, legal institutions, and decision processes that influence collective, (i.e., public) action in coastal environments. The most widely-adopted study approach has been a process of identifying "stakeholders" whose input is sought in a formal planning process (e.g., various state or Federal agencies, local watershed councils or working groups, port districts, local governments, citizen organizations, businesses, property owners or leaseholders, etc.). An iterative process of professional judgment and public input is often used to identify gaps, overlaps, differences, and commonalities among these various stakeholders. A fairly large body of "gray" literature exists that explores reports this method of "stakeholder" participation in environmental impact, natural resource damage assessment, and planning studies conducted in coastal regions.

A more analytical approach, "institutional mapping," has been used to systematically describe the formal institutional framework for coastal management (Sorensen et al. 1984) and for watershed planning (Fischer 1994; Fischer et al. 1994). In this two-step approach, a comprehensive survey is first conducted of various programs, implementing agencies, and sources of legal authority in the policy arena in which elements of coastal ecosystems are managed (Table 3.1, Fischer et al. 1994). The geographic scope, problems addressed, actions taken (or authorized), and the legal foundation are summarized. Second, jurisdictional constraints, gaps, overlaps, and conflicts are identified by inspecting legal documents and interviewing agency personnel (Table 3.2, Fischer et al. 1994).

Institutional mapping has been used to compare regional planning programs (Fischer 1994). Using GIS to map the geographic extent of jurisdiction for various programs helped identify institutional constraints that could potentially affect restoration activities at various habitat sites. Table 3.2 illustrates some of the constraints on planning in a fragmented jurisdictional framework. Indicated are the problem types, an example of each problem type, the legislation behind each of these examples and a brief description of the constraint.

A third approach, the study of "advocacy coalition frameworks" goes beyond institutional mapping to investigate decision processes within "issue networks" and other informal associations of persons (Lee and Miles 1992). It is in these coalitions and networks that change in the behavior and policies of formal organizations may originate. "Advocacy coalition frameworks" depicted in Figure 3.2 (Sabatier 1988; Sabatier and Jenkins-Smith 1993; Mazmanian and Sabatier

Table 3.1. Watershed planning framework in the state of Washington.

Plans	Geographic Scope	Agency	Problems to Address	Focus	Actions to Consider	Legal Foundation		
						Federal	State	Local
Non-point Pollution Watershed Action Plans	biographic area: watershed	PSWQA and WDOE; citizen involvement	non-point pollution: stormwater and CSOs, agriculture practices, on-site sewage, boats and marinas	source control protection	plan including: BMP's ordinances, permits, education	CWA §319	WAC 400-12; cigarette tax funding	plan using ordinances, agreements
Stormwater Basin Plans	distinctive geographic areas within the comprehensive plan having a unified interest	WDOE, cities, and counties	flood zones, aquifer recharge, fish and wildlife habitat, wetlands	technocratic; engineering approach	stormwater facilities, habitat enhancement, sensitive area protection, regulations, source control		GMA; RCW 36.70.330 36.70.340 36.70.350	stormwater utility funds; agency task force
Storm Water Mgt.	political districts: urban cities, counties, municipalities	PSWAQ and WDOE (administer programs and NPDES permits)	shellfish beds, fish habitat, sediment contamination, water and sediment quality	control of quantity and quality of water	SWM programs; NPDES permits for watershed; ordinances for erosion control; education; technical assistance; draft legislation (HPA)	CWA §319; NPDES; CZMRA §6217 (Non-point pollution control program)	PSWQA plan, RCW 90.48 (state water quality standards)	stormwater management plan, permits
Development Regulation Land-use	urban, cities, subdistricts	WDCTED, counties	private land development, roads, other public services	development goals, zoning	zoning ordinances, building and development permits		state statutes	planning and zoning ordinances
Growth Management	political districts: fastest growing counties and cities (stops at HW mark)	local jurisdiction	conservation of resources and protection of critical areas	growth planning	impact fees, sanctions, incentives, grants excise tax		GMA:ESHB 292	local comprehensive plans
Shoreline Management SMP	Federal, tribal, county/city shorelines to 200	WDOE, county and city planning commissions, shoreline hearings board	shoreline development, riparian and floodplain mgt., fish and wildlife habitat protection, public access and recreation	"protection" of shoreline through management of uses	environmental designations (natural, conservancy, rural, semi-rural, urban); substantial development permits; performance standards	Public Trust, CZMA	SMA (1971), SEPA	Jurisdictional shoreline management Master Program

Table 3.2. Illustrative jurisdictional constraints in the state of Washington.

Problem type	Example Constraint	Legislation	Problem Description
Overlap	Watershed Action Plans and Basin Plans	WAC 400-12 and RCW 36.70.330, 36.70.340, 36.70.350	Two plans address similar issues
Regulatory Inadequacies	§404 wetland mitigation	§404 CWA, §10 RHA	weak and incomplete regulation
Legal Issues Regulatory Programs	Shoreline Management Master Program; Growth Management	SMA GMA	Property rights exemption diminishes public trust goal
Constitutional Rights	Dolan v. Tigard Lucas v. South Carolina	Takings Clause of the 5th Amendment	Interferes with state and local efforts to plan for citizen's best interests
Goal Conflicts	Tribal Fisheries and Growth Management Act	US v. Washington (384 F Supp. 212) and ESHB 2929	Conflicting interests interfere with project goals
Agency Coordination	Elliott Bay/Duwamish Restoration Program	NRDA	Time consuming consensus building
Insufficient Information Base	Kitsap County Shoreline Management	SMA	lack of comprehensive shoreline inventory
Insufficient Funding	Tribes	Federal Treaties	unable achieve restoration goals

1980), have been used to analyze "policy subsystems" organized around particular issues in the Pacific Northwest (e.g., wetlands, Martz 1993; sediment contamination, Lind 1994).

The advocacy coalition framework is designed to test a set of hypotheses (Lee and Miles 1992; Martz 1993) about the probability that organizational learning, that is, changes in belief systems, (Table 3.3) will take place. In such studies, a preliminary model of the basic advocacy coalition structure is constructed. Advocacy coalitions within a policy subsystem may cross formal institutional boundaries (Table 3.4), providing a mechanism for incorporating the roles of private institutions and individuals and informal interactions into a model of decision-making.

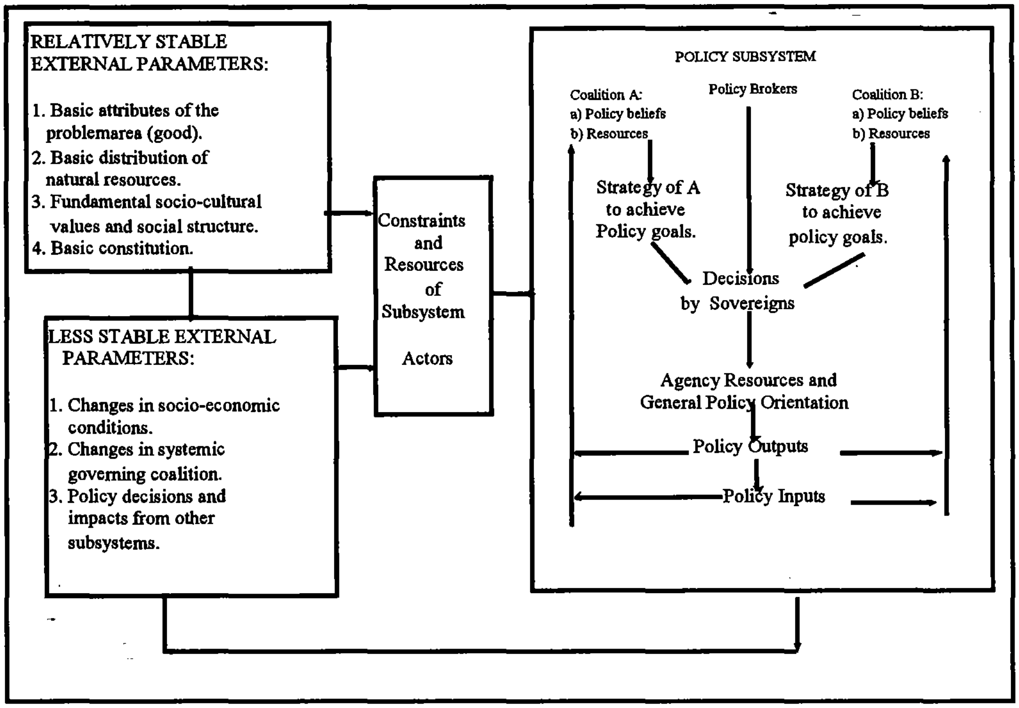

Figure 3.2. Model of policy evaluation with competing advocacy coalitions (adapted from Sabatier 1987).

Table 3.3. Classes of belief systems (Sabatier 1987; Martz 1993).

Type of Beliefs	Description	Likelihood of Change (Learning)
Deep (normative) core beliefs	Fundamental normative and ontological axioms defining the personal philosophy of an actor	Low
Policy core beliefs	Fundamental policy positions that define the strategies that will satisfy the deep core beliefs	Intermediate
Secondary beliefs	Instrumental strategies to implement the policy core positions in the policy arena of concern	High

Table 3.4. Two identified advocacy coalitions in the wetland policy subsystem.

Preservation Coalition	"Wise Use" Coalition
most regulators	some regulators
most academics	some academics
most agency technical staff	some agency technical staff
most agency researchers	many consultants
many consultants	some Congressional representatives
some Congressional representatives	developers
environmentalists	farmers/ranchers/loggers
some farmers	many private landowners
hunters/fishers	property rights advocates
some private landowners	some journalists
some journalists	Presidents Reagan & Bush
President Clinton?	general public
general public?	

Sociological Approach

The role of social systems in natural processes and landscape change has been the subject of study for more than 60 years (Lee 1992). Studies concentrating on the interaction between social systems and biogeochemical systems are characterized by three distinguishing factors (Burch and DeLuca 1984; Lee 1992):

- a holistic perspective regarding the interaction between humans and the environment, that sees these two systems as two parts of one larger system;
- flexible approaches to study, using either the human system or the natural system as the dependent variable; and
- over sixty years of accumulation of an extensive body of knowledge regarding societal consequences of interactions with natural systems.

Burch and DeLuca (1984) characterized the social dimension of natural resource issues as the interaction of the resource flow (including the flow of energy, materials, and information), the distribution of the resources (as a result of social order), and the demand for those resources (as a result of social cycles such as life cycles and work/non-work cycles). Figure 3.3 shows a conceptual diagram of the interaction of these elements.

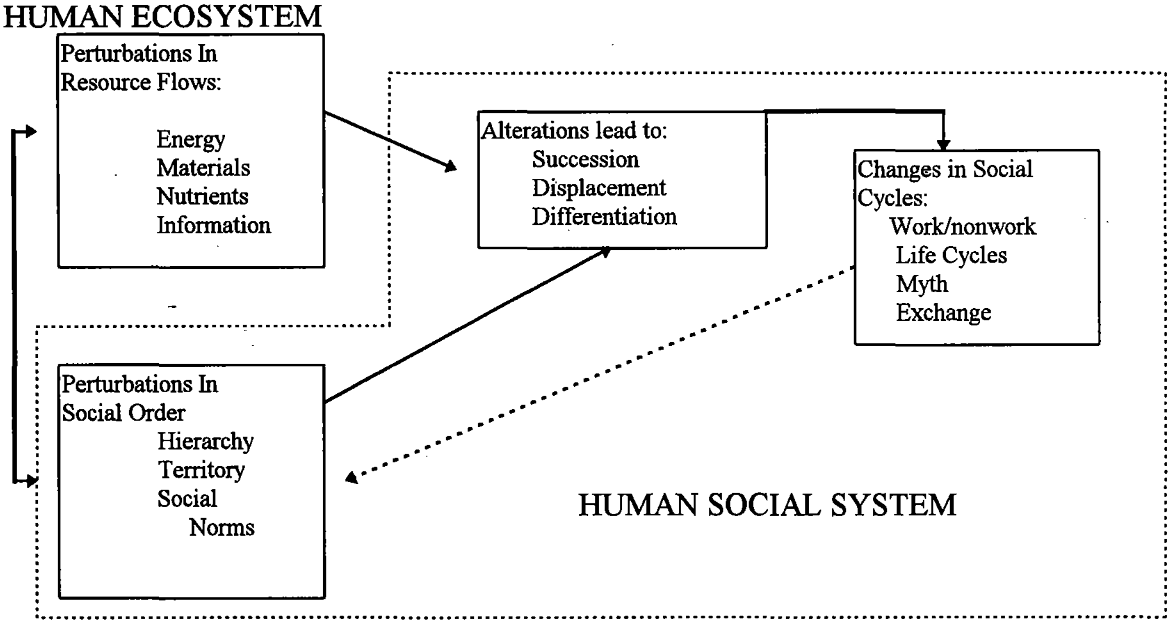

Figure 3.3. The interaction of the human ecosystem and the human social system (Burch and DeLuca 1984).

Burch and DeLuca suggest that the nature and types of resources, social cycles, and social order should be considered in impact analysis. The four resources in Fig. 3.3 (energy, materials, nutrients and information) are examples of resources that are distributed in some way to the human social system. The "Alterations" box shows how a particular action or policy, resulting from perturbations in resource flows or perturbations in social order, can alter the existing social system. Changes of this type may lead to succession, for example, cultural alterations from old land-use patterns to new land-use-patterns. The resulting new procedures, occupations, persons and industries will displace existing procedures, occupations, persons and industries. Finally, these changes will result in differentiation in social roles and values that lead to changes in such social cycles as changes in work/nonwork cycles, life cycles, myth cycles (the pattern of persistence and replacement of myths), and exchange cycles (mechanisms of exchange that link social and political groups such as families, political constituencies or corporations). Changes in social cycles can indirectly cause further perturbations in social order that affect, and are affected by, perturbations in resource flows (Burch and DeLuca 1984).

SOCIAL IMPACT ASSESSMENT

Since the early 1970s the interaction of human activity and natural systems has been studied through a social science methodology called Social Impact Assessment (SIA; Gale 1987). SIA is generally used to aid decision-making by measuring the range of results from alternative proposed actions (Burch and DeLuca 1984) and is often required as part of an Environmental Impact Statement under the Federal National Environmental Policy Act (NEPA). Although most SIAs to date have been anticipatory (used to predict response to changes), the method can be used to determine impacts after the fact (Burmingham 1995). SIA can be employed to measure the potential or resulting effects of a particular policy or event on *individuals* (e.g., on economic welfare, transportation, leisure, public participation, health and safety, attitude, etc.), on *organizations* (e.g., on profitability, changes in employment levels, etc.), or on *communities* (e.g., on the effect on the capacity of the community to provide a high quality of life; Finsterbusch and Wolf 1981).

The three objectives of SIA are to determine: 1) what social effects are to be measured; 2) how these effects should be measured; and 3) how the measured effects are to be evaluated (Finsterbusch and Wolf 1981). Burch and DeLuca (1984) have identified seven theoretical approaches to SIA methodology, as it is applied to natural resource policies (Table 3.5). Although this list is by no means exhaustive, it provides an excellent example of the extent and variety of SIA approaches. These theoretical approaches may use a variety of evaluative methods including such techniques as weighting schemes, discrete dimension evaluation, objective or subjective metrics, or utilizing informal political inputs such as public choice (Finsterbusch and Wolf 1981).

There are several important reoccurring themes in the SIA literature that have direct applicability to coastal issues. Among these themes are the interaction between community and ecosystem stability, the idea of social carrying capacity, and analysis of issues of biogeochemical and social temporal and spatial scales.

Table 3.5. Theoretical approaches for assessing social impact (adapted from Burch and DeLuca 1984).

Approach	Unit of Analysis	Data Source	Possible Applications
Time Budget	Individual	Diaries/Logs	Determining individual demand/ response to variation in resource
Family Life Cycle	Individual/ Households	Census/ Interviews	Determining effectiveness of community environmental programs
Adoption of ideas/practices	Individual/ Household/Firm	Interviews/ Records	Determining constraints on or opportunities for introducing new resource policies or techniques
Community	Neighborhood/ Town	Interviews/Documents Observation/Records	Determining collective response to variation in resource use
Regional	Region	Documents/ Census	Determining efficiency and equity factors in inter-regional exchange of resource costs and benefits
Social Survey	Demographic Categories	Interviews/ Questionnaires	Determining categories of population samples who are most/ least susceptible to variations in resource use
Social Indicators	Political Subdivisions/ Nation-state	Records/Documents/ Census	Determining distribution effect of variation in national resource budget: monitoring effects of policy

Community Stability. Ecological and community stability are often measured when determining the effect of ecosystem change on social systems (or vice versa). The definition of community stability varies throughout the literature (not unlike the definition of ecological stability), but it is generally agreed to be either the preservation of the status quo, or the ability of a community to react to change (i.e., the existence of a diversity of functions that facilitates adaptation to change; Schallau 1987; Burch and DeLuca 1984). The US Forest Service guidelines define community stability as "the rate of change with which people can cope without exceeding their ability to deal with it" (Schallau 1987).

Measurements of community stability often center on economic factors, but may also include measures such as social conflict, population change, environmental perceptions, or structural change (Burch and DeLuca 1984). Community stability can be affected by the nature of the ecosystem (see the below discussion on scale), and ecosystem change can directly impact the stability of a community, hence, it is often useful to study the two simultaneously. Community stability is an especially important part of the sociological analysis of coastal communities because of changing demographics and the shift of coastal economics from traditional resource-extractive industries, such as fishing, to newer non-extractive resource-based industries, such as tourism.

Social Carrying Capacity. For the past 30 or so years, social scientists have grappled with the idea of a social carrying capacity as a parallel to the concept of ecological carrying capacity (Graefe et al. 1984). Social carrying capacity has traditionally been applied to recreational experiences, and is generally defined as the level of sustained recreational use deemed acceptable by some predetermined criteria, taking into account both the quality of the resource and the quality of the experience for the user (Shelby and Heberlein 1984). It is generally agreed that there is no one level of carrying capacity, as the level of acceptable impact will vary among experiences and uses (including location, time, type of activity, previous experience, etc.; Graefe et al. 1984).

Despite the variation and elusiveness of the concept, social or recreational carrying capacity is a useful construct for managers. In fact, several Federal agencies, such as the National Park Service, US Forest Service, US Forest Service, and US Fish and Wildlife Service require determination of social carrying capacity when evaluating the effects of some program actions (Moore and Brickler 1987). Recreational carrying capacity can be used to determine social thresholds for many types of activities including beach-going, boating and canoeing, and sport fishing. A methodology for management to achieve sustainability of resources and quality of recreational experiences may be quite useful to managers of high use coastal areas.

Scale. Although not consistently investigated, examination of scale issues, both temporal and spatial, can greatly increase the understanding of a given complex biological and social problem. For example, ecological studies show that populations of organisms with short generation times are more susceptible to environmental variation than organisms with longer generation times (Lee et al. 1990). These populations are considered relatively unstable because they are more dependent on environmental influences and reproductive rates than on influences such as interspecies interactions.

Analogies have been drawn between ecological communities and the social communities of natural resource “boom” towns (Lee et al. 1990). The relatively short length of job opportunities is influenced by the longer time scale of environmental conditions of the resource, and these types of communities are considered unstable (see above). Interactions between people become more complex and more important for community stability than the condition of the environmental resource when the job opportunities are extended and ties are formed to people and place (Lee et al. 1990). These patterns have been most frequently observed in timber dependent towns, where the social patterns of "boom and bust" are correlated with changes in the nature of the resource (Lee et al. 1990). However, the nature of some coastal communities dependent on unique and perhaps finite resources (such as extractive recreational activities) may display similar types of patterns.

The Economics Approach

Economics typically focuses on the material side of human welfare and activities. Economic research is concerned with describing, understanding, and predicting the structure of economies, prices and economic production levels; the material welfare attained under various circumstances; and the effectiveness of collective rules to modify voluntary contracting in markets. Description involves selecting pertinent variables, and defining, measuring, and summarizing them in ways that provide meaning and substance to people. Common descriptive variables include personal incomes, production levels, price levels, trade flows, magnitude of recreational use, and funding levels for public goods and services.

Understanding and predicting the structure and process of economies require a causal model relating economic variables to exogenous influences and policy changes. As in ecology, such models reveal complex and sometimes obscure linkages among variables. For a study of coastal ecosystem change, the pertinent models should focus on causal linkages between ecosystem states, resource-extraction rates, and policy efforts with the aim of predicting economic consequences of changes in the rules governing private markets and collective institutions. The simplest models are linear models of economic structure (such as input-output models) that typically focus on regional economic "impacts" such as aggregate and sectoral shifts in production, income, and employment. More complex and data-demanding models of markets focus on the inter-sectoral shifts in resources, incomes, and employment caused by relative price changes, shifts in resource availability, shifts in demand, and environmental regulations.

Economic evaluation necessarily relies on a specific ethical stance, typically utilitarian or contractarian ethics. Because there is no generally accepted ethical system, different economists reach different conclusions. The most broadly used method, benefit-cost analysis, focuses on the aggregate net economic benefits of a particular policy or exogenous change. The aggregate benefit is defined with respect to the existing distribution of incomes and is typically insensitive to the distribution of incremental benefits among various people, communities, or interest groups. Because it ignores important economic equity issues, benefit-cost analysis is a partial and incomplete summarization of economic consequences for decision makers. In practice, net benefits are combined with numerous other data summaries by policy analysts. For example, the Water Resources Council's "Principles and Guidelines" (1983) for project evaluation calls for evaluation in four "accounts:" 1) national economic benefits; 2) environmental quality; 3) regional economic development; and 4) other social effects.

ECONOMIC DESCRIPTION

Descriptive Statistics. Routine economic variables are used to describe and analyze the structure and processes of the economy, including market value of production (price and quantity) by industrial category, payments to labor, shipments of goods, income levels and distribution of income across functional and statistical categories, employment levels by industrial classification, unemployment rates, etc. Standard Industrial Classification (SIC) is used in the United States to provide a common set of categories for reporting of production, sales, prices, employment, and payments. The main sources of these data are the US Census Bureau's reports (both the population census and the census of manufacturers), and the US Bureau of Economic Research. Detailed information on agriculture comes from the US Department of Agriculture, Economic Research Service; information on the forest products industry is published by the US Forest Service; and information regarding fisheries is from the US Department of Commerce, National Marine Fisheries Service, and from the Oregon and Washington Departments of Fish and Wildlife.

To supplement the volumes of routine data, large amounts of economic descriptive information are generated periodically by special surveys of specific areas or issues. For example, economics surveys frequently focus on the structure of production costs in a particular industry. Fishing costs have been surveyed and documented for salmon fishing in Oregon. Another example would be surveys of public values for non-market goods, such as recreational fishing and the existence of salmon populations in specific rivers. The US Fish and Wildlife Service (1988) funds a National Survey of Fishing and Hunting that estimates the magnitude of outdoor recreational activities, expenditures, and fish and game harvests. Some of these applications are reviewed below in the section on Causal Models.

Input-Output Tables. Input-output tables provide a more detailed picture of the economy than do the simple economic aggregate variables. An input-output table (called by its creator W. Leontieff a "Tableau Economique") describes a static flow of outputs from each sector of the economy through other sectors (where used as inputs), to final outputs of goods and services. It also quantifies the payments from firms in each sector to households (wages, salaries, rents, interest payments, and profits), and payments among sectors of the economy (the inter-industry transactions). For example, an input-output model of Tillamook County, Oregon, will show the market value of sales of goods from fishing, agriculture, manufacturing, tourist services, wholesale and retail trade, and government agencies. It will also show the degree to which those goods are sold locally or exported; and it will show the degree to which each purchase category is based on imports to the county. For each sector of the economy, the input-output model will show how much of the total expenditures in sector "i" goes to sector "j," and how much to households. For example, the fishing industry buys inputs from fuel suppliers, boat repair yards, insurance companies, etc., and pays wages, salaries, and other labor payments. It sells its output to retail firms, wholesalers and brokers, and food processing firms. Quantification of the transactions flows in a regional economy in an input-output table, combined with appropriate assumptions and motivation, support the analysis of economic effects of sectoral changes on the regional economy.

CAUSAL MODELS

Economic Impact Analysis. Economic impact analysis predicts gross changes in incomes, market value of goods and services, and employment levels in a regional economy resulting from policy choices, such as the expansion of a local seaport, relocation of a major employer, an influx of tourists and visitors seeking outdoor recreation, increased social costs of water treatment or storm surge protection due to coastal pollution or sediment regimes, or declining production in a natural resource-based industry. Popular methods of economic impact assessment typically rely on simplified linear models of the economy that assume constant prices and constant costs per unit of output. With this simplified model, a rise or fall in any economic sector generates a proportional change in that sector's purchases from other sectors, a proportional change in employment and household earnings from that sector, and a secondary proportional change in regional incomes and employment affecting the whole economy. By accepting the simplification of linearity, these models make possible a simultaneous examination of dozens of overlapping and competing economic activities. More sophisticated versions incorporate trade and product flows between regions in order to trace the indirect effects of economic changes in one region on those of a distant region.

While input-output models are developed at the national scale, much economic impact analysis focuses on smaller economic regions. For example, income and employment effects of forest management options have been evaluated for rural logging communities or counties. Three kinds of economic impact are often estimated using regional economic models: 1) direct (or primary) effects; 2) indirect (or secondary) effects; and 3) induced effects. Direct effects are the increases in the value of final goods and services (or of income) in the sectors directly affected. Indirect effects are the increases in the value of final goods produced (or income) in sectors linked through purchases or sales to the directly affected sector. Induced effects are the broad effects on the local economy due to increased incomes and spending by households directly and indirectly affected. By the usual conventions of income and product accounting, the value of goods and services equals the local income generated (e.g., wages, salaries, rents, interest payments, and profits) plus cost of inputs purchased from elsewhere. Thus, the regional income impact will always be a fraction of the regional sales generated.

Davis and Radtke (1994) estimate that net incomes for Columbia River gill net fishermen equal 36 to 55% of gross revenues. Hence, an increase of $100 in fish sales could generate a direct local income impact of between $36 and $55. The remaining 64 to 45% percent of gross sales revenue represents purchases of fuel, gear, insurance, etc. To the extent these inputs to the fishery are produced in the local economy, there will be some indirect income impact as well. Indirect effects occur through "forward linkages" (firms that purchase from the directly affected sector) and through "backward linkages" (firms that sell inputs to the directly affected sector). To continue the commercial fishing example, if 10% of fishing expense is for services produced locally (gear and vessel repair), the indirect income impact will consist of increased income in these related economic sectors. So, if service sectors generate $0.60 of direct local income (via wage payment) per dollar of sales, each $100 dollar of fishery output generates an indirect income impact of: [10% × $100 × (74% to 45%)] = $7.40 to $4.50. The indirect effect described here is a "backward linkage." A forward linkage occurs, for example, when an increase in salmon harvest results in expanded fish processing or retailing in the region. The increased incomes in those "forward linked" sectors would be another form of indirect income impact of fishing harvesting. The full indirect income impact is the sum of such indirect effects across all economic sectors that supply goods and services to the fishery. The induced income impact occurs as the households experiencing greater incomes (direct and indirect) increase their spending on a wide array of consumer goods. This induced effect is spread across many sectors of the economy.

Market Models. In contrast to impact analyses based upon input-output models, an analysis of market models will focus on changes in prices due to shifts in supply and demand curves. The simplest market models examine one market (good or service) at a time, using the assumption that other markets are unaffected. For example, a decline in fish harvest due to a fish population decline will constitute a leftward (i.e., downward; see Fig. 3.4) shift in the supply curve of fish, and, assuming the fish market clears at a price that equates quantity supplied with quantity demanded, this will cause an increase in the price of fish. In reality, the reduced fish supply and increased price causes a shift of consumer expenditures to other food products (e.g., poultry), which would be depicted as a rightward shift (upward) in demand for these other products. Depending upon the slopes of the supply curves for these other products, their prices would rise as well. The degree to which supply shortages in one sector transmit through the markets to affect prices in other sectors depends critically on the shapes of demand and supply curves in linked markets. Hence, research on market-demand systems tends to focus on the functional relationships between quantity demanded and own price, income, and prices of substitute commodities. Research on supply curves tends to focus on factors that influence the costs of production and the pricing behavior of firms. In a full-blown multimarket model, one could trace out the sequence of linked changes in prices and quantities across markets due to a particular initial shift in policy, resource availability, population growth, or technological change.

Dynamic Models Linking Market Economics to Natural Resources. A third type of economic model pertinent to understanding coastal ecosystems is the model that explicitly includes the dynamics of natural systems. For example, bioeconomic models of fishing often append an industry cost and consumer demand analysis to a fish population model. Similar economic models of forestry combine tree-stand dynamics models and market value models to show how harvest timing affects timber revenues. As the simpler single-species or single use economic models were developed, it became clear that more complex models were needed to deal with the real world complexities of multispecies harvesting (in both fisheries and forestry), and to properly account for the numerous competing uses of the resources (recreation, aesthetic appreciation, as well as consumption). Some explicit models have been developed to incorporate non-harvest uses in forestry and to explore the implications of competing recreational and commercial harvest in fisheries. Yet a greater level of generality may be needed in order to capture the economic aspects of linked effects due to the transformation of coastal ecosystems by expanding human populations and economies.

ECONOMIC EVALUATION OF ECOSYSTEM SERVICES AND CHANGES

Alterations of coastal ecosystems can have a variety of effects on economic values. Three conceptual categories of economic value are: 1) the value of using products supplied in markets (like meals in seafood restaurants) made from ecosystem components; 2) the value of using the ecosystem directly for recreation and aesthetic enjoyment; and 3) non-use value, the value of simply knowing that features of the environment exist (existence value) or are being preserved for future generations (bequest value). There has been a huge volume of research in this area during the past two decades. Much of the accepted practice is summarized by Freeman (1993) and

Braden and Kolstad (1991). Economic values arise in all three categories in Pacific Northwest coastal ecosystems.

Indirect use-values flow also from coastal ecosystems through such activities as commercial fisheries, forestry, agriculture, and land development. These values are generally estimated using market equilibrium models. Environmental degradation affects both the production of economic goods (reduction in fish catch) and perceptions of quality or safety in consumption of economic goods (seafood wholesomeness and recreational fishing success). In this circumstance, both supply and demand for ecosystem-related goods are affected. A theoretical discussion of economic values associated with complex changes of this sort has been summarized by McConnell and Strand (1989) for the case of commercial fishing.

The resulting economic valuation data can be helpful in three ways: 1) the estimated total economic value places the subject ecosystem into perspective alongside other environmental and capital assets; 2) the estimated values of recreation, commercial fishing, and existence reflect relative economic values of various components of the ecosystem; and 3) detailed analysis of the economic valuation data can reveal incremental values associated with various ecosystem changes. The analysis of incremental values shows how agency decisions can affect the economic value of the ecosystem, and this is useful information, for example, for screening alternative projects when agency budgets for marine ecosystem management are limited.

Benefits and Costs. The first step in evaluating the "benefits" and "costs" of ecosystem changes is to determine how goods and services are affected. The second is to assign an economic value to the change in goods and services, most often based upon the consumer's "willingness to pay" (WTP) for an increase or decrease in goods. For marketed goods, we normally assume that the existing price equals the marginal value or WTP for an additional unit of the good.

Figure 3.4 depicts the downward sloping-market demand curve, and two upward sloping market supply curves. The total WTP for the entire quantity supplied equals the area under the demand curve. At a uniform market price, the total sales value equals price times quantity (P_1xQ_1). The net WTP or "consumer surplus" is the total WTP minus actual payments. If the price offered by suppliers at a given quantity equals marginal cost of producing and selling the good in question, the upward slope of the supply curve implies increasing marginal costs. Consequently the area under the supply curve at any given quantity is a measure of the total cost of producing that quantity.

The *producer surplus* is the area over the supply curve and below the price; for quantity Q1 in Fig. 3.4 this producer surplus value equals the area of the triangle DBP1. In practice, the producer surplus is reflected in profits to business enterprises and rents earned by owners of land or other scarce natural resources (e.g., water, forests, minerals). For direct uses of the ecosystem that are not sold in markets (e.g., shoreline recreation, beautiful sunsets, clean water for swimming and fishing), the value to the public may be estimated using surveys to obtain price-like information. In outdoor recreation economics, for example, a variety of techniques (travel cost demand estimation, contingent behavior or value survey) is used to estimate the demand for recreational sites or conditions. These methods have been used extensively to determine fishing and other recreation values in the Pacific Northwest. When a specific estimate of WTP for

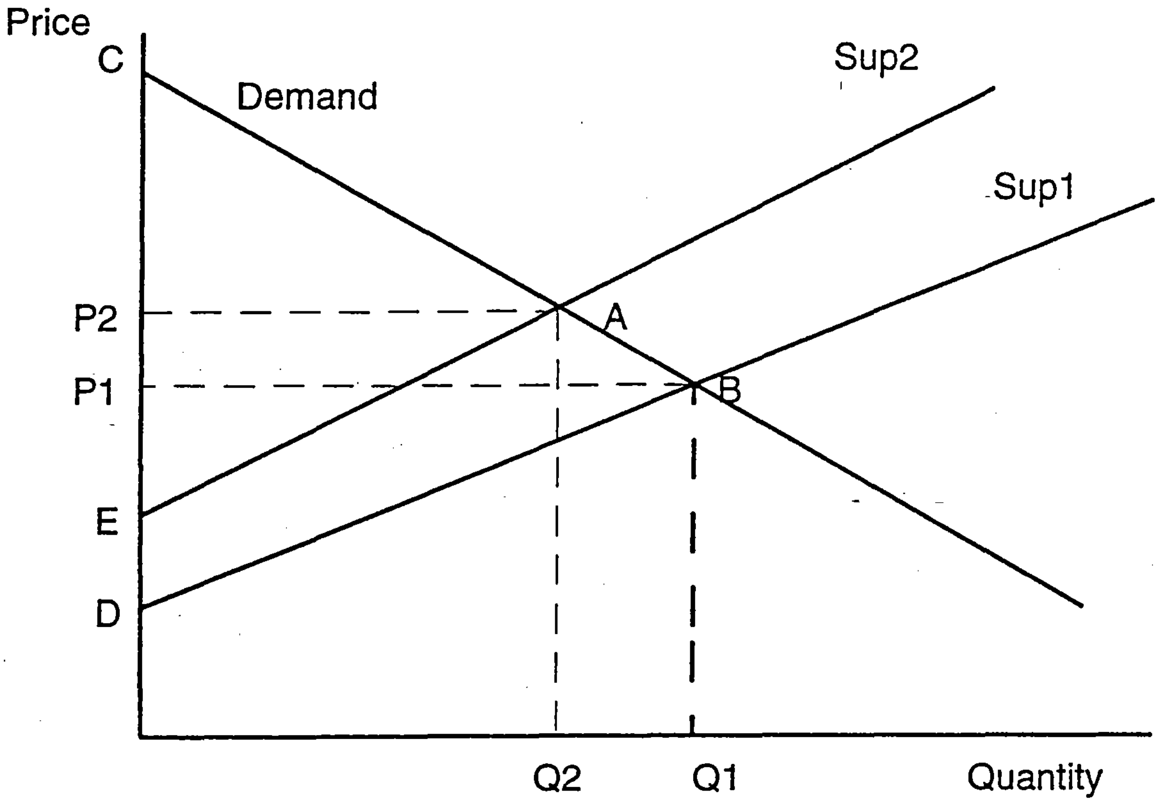

Figure 3.4. A simple market supply and demand diagram (see text).

recreation days or visits is available for a site, this value is used to evaluate a decline or increase in recreation caused by a salmon conservation measure. When studies have not been completed for the species, river, beach, or coastal port in question, estimated values for similar recreational sites are often used as proxies. This necessarily involves some subjective choice and results in some error.

The non-use values of coastal ecosystems (such as the value knowing that salmon continue to migrate up coastal rivers) can be measured by the amounts people are willing to pay to preserve them. This value is variously named "existence" value, "non-use" value, or "passive use" value. Measurement of existence value is a growing field of application for environmental economists, and there are still major controversies over technique and the meaning of the measurements. Because little existence value information is available concerning most coastal resources, the incremental existence values associated with ecosystem changes are difficult to assess without the mounting of a specific study.

Complicated ecosystem changes and human policy responses will increase supplies of some goods and services while decreasing the amounts of others. For example, changes in forest harvest practices to protect riparian habitats may reduce annual timber harvest while improving long-run anadromous and resident fish populations, improving water quality, reducing peak runoff volumes, and improving recreational quality. Where several consequences are linked by the ecosystem functions or are connected due to constraints on resource management policies, the economic effects are always a combination of costs and benefits. Evaluation and selection of management actions that achieve maximum net economic benefits is one way of balancing these competing ends. But, as already noted, the benefits and costs are frequently distributed unfairly through the population of regional residents. For example, unemployed timber industry workers may suffer, while commercial and recreational fishing industry workers prosper. Even if the net benefits of a fish enhancement program are positive (i.e., the fishing industry gains more than the timber industry loses), the public decision to help one group at the expense of another is not strictly supported by the ethical stance of economics. Only programs that help some people, while harming no one, meet the strict standards of the economic welfare test.

Distinction Between Effects and Net Benefits. A simple example helps to explain the difference between net economic benefits and effects. Suppose a coastal salmon stock declines precipitously and the management authorities close the fishery. Commercial landings of that fish will decline, resulting in reduced direct sales and incomes in the fish harvesting and processing sectors. Reduced tourism and angling activity will cause additional reduced sales of goods and services (e.g., motels, restaurants, gas stations, bait shops) in the coastal community. This will cause lower incomes, employment, and total economic output in the affected community. The economic *impact* in the community would be measured as the loss in regional sales, personal income, or employment.

The change in net economic value due to the salmon stock decline would be measured as the loss in net commercial and recreational values, as measured by the consumer surplus and producer surplus concepts. The economic value of salmon fishing (depicted as the consumer surplus under a recreational fishing demand curve) represents the amount the recreationists would be willing to pay for fishing. Even though other species (e.g., rockfish, albacore tuna) may be available, recreational fishermen would be willing to pay some amount to have salmon to catch. This value is lost when salmon are removed from the suite of available fishing options. The lost value would be counted as an economic cost in a benefit/cost analysis. From the perspective of a community dependent upon expenditures by recreational fishers, the lost economic value of recreation may be of little interest; however, the negative regional economic impact would be of great concern. The prosperity and stability of a coastal community may be adversely affected by a loss of recreational business. However, the recreational participants are likely to shift their expenditures to other locations, species, or alternative outdoor activities (like freshwater fishing or hiking). These shifts in activity and expenditures will cause offsetting positive economic effects, some in the original locations and some in new locations.

There is no necessary linkage between regional effects and net national benefits. For example, negative economic effects in a town distressed by reduced US Forest Service timber sales will be balanced to a large extent by expansion in other logging communities or in communities producing substitute building materials. One community's secondary negative impact is linked to another community's positive secondary impact. The "other community" is likely to be a geographically dispersed and diffuse group of people, while the losers are often concentrated in the specific community. It would be deceptive to focus only on the negative effects where the natural ecosystem is protected, while ignoring the linked positive secondary effects elsewhere. Such a practice would systematically overstate the net economic costs of ecosystem protection. Still, a real reduction in timber output would result in real reduction in national net benefits generated in the forest sector. But the accurate measure of that net cost would be the reduction in consumer and producer surplus aggregated across all the regional economies affected.

INTEGRATIVE STUDY APPROACHES

As research on human management of real ecosystems has progressed, integrative approaches have been developed that use insights and knowledge from several social science disciplines or that combine social and natural science. Two of these are represented by the burgeoning literature on management of common property resources and natural resource accounting.

Common Property Management and Co-management. The classic literature on management of common-pool resources focuses on two options: privatizing resource rights and regulation through formal government institutions. The economic theory of common property resources, as initiated by H. Scott Gordon (1954) and elaborated via the use of game theory (Dasgupta and Heal, 1979), emphasizes the difficulty of achieving an efficient natural resource conservation regime when numerous parties use a depletable resource. Each individual's incentive to conserve the resource is diluted by inability to control resource use by others, which can lead the collection of resource users to overexploit and deplete the common resource. This problem was labeled the "tragedy of the commons" by Garrett Hardin. Since this "tragedy" is cast as a necessary outcome of uncontrolled access to common pool resources, those seeking institutional solutions have focused on either: (1) eliminating the common pool characteristic (e.g., by privatizing the resources); or (2) placing external controls on the resources users (e.g., giving authority to a governmental agency to control resource use).

Both of these solutions raise other problems. Privatization requires that control of the resource be granted to individuals as "property rights" or "usufructuary rights" and that standard legal processes be used to defend those rights. As many natural resources (such as salmon) are fluid and cross geographical boundaries, a private owner might need to control an enormous area in order to gains the benefits of privatization. This could lead to excessive market power or political control. Regardless of market power issues, the private owner would be expected to attend only to those aspects of the common resource that generate benefits for her. She would likely ignore other ecological linkages that generate no private benefits. Salmon predators, like bald eagles, and salmon competitors, like resident trout populations, might fare poorly at the hands of a private salmon owner. Hence, placing ecosystem resources in the hands of private owners could lead to what economists call "market failure": an improper balancing of marketable and non-marketable service from multidimensional ecosystem resources.

Government agencies may also be unable to effectively manage a complex of ecosystem resources. While an agency could be given broad authority to optimize ecosystem outputs and functions (salmon, trout, eagles, assimilation of pollutants, etc.), bureaucratic organizations tend to strive for internal objectives that often differ from broader social objectives. Increasing budgets and larger workforces tend to be signals of success in government organizations. Further, government agencies survive at the pleasure of political processes that have relatively short time horizons, in contrast to the long-term processes that govern ecosystems. Agency stewards of ecosystems may be compelled to satisfy relatively short-term demands for economic benefits rather than longer term conservation objectives. Hence, some analysts are concerned that placing important natural resources and ecosystems in the hands of politically-driven bureaucracies can lead to "government failure" (Anderson 1983).

Contemporary literature on common property governance and co-management departs from the classic approach. The key is to view the problem as one of reconciling individual incentives to conserve resources and to control externalities with collective and long-term conservation objectives. The new approach seeks solutions that involve collective commitment to ecosystem management objectives without formal approval and enforcement by "outside" forces. As developed by Ostrom (1990), the theory has been expanded to examine conditions under which individuals will voluntarily conform to collective rules of resource use and monitoring systems that lead to sanctions for noncompliance. Besides expanding the theory of collective action, empirical research in this field has broadened our understanding of the prevalence of self-organized and self-governing common pool resource regimes. The numerous successful and unsuccessful examples of self-governance in Ostrom's (1990) book suggest the following criteria for determining the applicability of self-governance:

1) Most ecosystem users share a common judgement that they will be harmed if they do not accept some rules;

2) Most users will be affected in similar ways by the new collective rules;

3) Most users highly value the continuation of the common pool resources in the ecosystem (i.e. have long time horizons);

4) Ecosystem users face relatively low costs of information and enforcement;

5) Most users share generalized norms of reciprocity and trust that can be used as initial social capital; and

6) The group of users is relatively small and stable.

Where these criteria are not met, simple institutional changes may help to satisfy them. For example, a fishing fleet meeting all criteria but (6), might be able to develop self-governance under a license limitation system. In other cases, it is clear that one or more of these requirements will not be met without more formal organization or external enforcement. Hence, these conditions can be used to screen specific common pool resource regimes for specific shortcomings in collective decision-making. The result is a better organized and structured concept of what is needed to resolve problems of resource conservation.

A companion development in the natural resources management field is "co-management": a form of resource governance involving negotiated agreements and other legal or informal arrangements between resource-using communities and various levels of government. The discussion of fishery co-management emphasizes the need for fishery managers to include local communities and groups of fishermen in the management process in a meaningful way (Rettig et al. 1989); sharing of information, objectives, authority and responsibility are all part of the co-management regime. The co-management systems incorporate both community-level and broader governmental authorities to assure acceptance and compliance by local fishers in the management regime. Pinkerton (1989) collected a series of papers that relates the experiences of numerous fishing communities with co-management. These focus on agreements between centralized government authorities and Native American tribes and villages on the Pacific coast of North America. Most of the examples concern salmon fishing, but marine mammal management and lobster fishery management in Nova Scotia are also included.

Co-management themes have been extended and elaborated in a recent report by Pinkerton and Weinstein (1995) and in two collections of papers edited by Hanna and Munasinghe (1995a, 1995b). The expansion of these themes examines the nature of social institutions that shape the use of environmental resources. As applied to problems of the developing world, this work attempts to supplement development efforts focused on investment projects by improving the institutional framework within which resources are used. Pinkerton and Weinstein describe Japanese inshore fisherman co-operative associations, Peruvian fishing villages on Lake Titicaca, a watershed working group in Queensland, Australia, Korean seaweed fisheries, and several community level organizations focused on watershed management for fisheries conservation. Hanna and Munasinghe spread a broader net to include air pollution control systems in the United States, enforcement of nitrogen fertilizer regulations in Sweden, using incentives to preserve biodiversity in India, and problems of deforestation in Nepal Himalaya. Lessons from this field of study should be applicable to coastal ecosystem management in the Pacific Northwest, particularly in areas with networks of small fishing communities. In particular the assessment of watershed councils, that are increasing in number in the Pacific Northwest, would benefit from these insights.

Natural Resource Accounting (Natural Capital). Because economic production often transforms natural materials into final products or capital equipment (e.g., buildings, machines, tools), ecological economists claim that ecosystem services and natural materials are *complements* to human skills and capital equipment. This is in contrast to the view that technology, capital, and skill are *substitutes* for natural resources. The "substitutes" view allows for the possibility that economic growth could continue through technological innovation and use of more capital as natural resources are depleted. The ecological economics view is that opportunities to substitute manufactured capital for natural resources are very limited, and that further growth (or even maintenance of current economic output) requires careful conservation of the natural features that make economic production possible. "Natural capital" was coined to represent the value of ecosystem functions and natural materials needed to support economic production.

Accounting for the value of manufactured (man-made) capital in business and in the national accounts helps economists and policy-makers to note whether the stock of capital is rising or falling. But no such accounting is normally done for natural capital. According to Costanza and Daly (1992) "natural capital produces a significant portion of the real goods and services of the ecological economic system, so failure to adequately account for it leads to major misperceptions about how well the economy is doing." A number of economists have tackled the problems of accounting for natural capital, and the United Nations Environmental Program and World Bank convened an international symposium on the subject (El Serafy 1989; Ahmad et al. 1989). Attempts to value the natural capital of wetlands (Costanza et al. 1989) show that the concept is feasible.

Applying these accounting concepts to coastal ecosystems would involve measuring contributions of various ecosystem features and functions to the economic system. Natural capital would include values of fish stocks, freshwater supplies, pollutant assimilation capacity, riparian and in-stream habitats, etc. Each capital item represents the accumulated future value of ecosystem goods, services, and amenities; hence, these represent an extension of conventional economic valuation of market goods and services to non-market ecosystem goods and services. Implementation of this research agenda would be taxing, because the ecosystem involves complex interactions that obscure the individual contributions of various components to human economic welfare. Thus, the unit values of natural capital stocks would be difficult to measure. This difficulty may explain the absence of a single quantified measure of natural capital in a recent compendium of papers on the topic (Jansson et al. 1994).

Natural capital accounting for coastal ecosystems could contribute to a more reasonable and equitable balancing of current versus future benefits, because depletion of natural capital would signal declining potential economic welfare for future generations. The new accounting conventions cannot resolve the problem of choosing a proper level of preservation and a reasonable mix of natural assets. Because not all natural capital can be preserved, an important aspect of sustainability policy involves choice about what to preserve and what to sacrifice. These choices may be better informed in the presence of comprehensive natural resource accounting.

STATUS OF RESEARCH ON OREGON/WASHINGTON COASTAL ECOSYSTEMS AND COMMUNITIES

Legal/Institutional Research

Two aspects of the jurisdictional framework affecting coastal ecosystems are important. The first is a set of changes occurring in the decision process that alters the criteria for decision-making. These changes have occurred recently and are subject to much debate and research. Often they conflict with each other. For example, the increased power of Native Americans over coastal resources conflicts with the increased deference to private property rights, especially when shellfish resources are at stake. These changes have altered how we think about public resources and environmental management (Ehrlich and Daly 1993).

The second aspect affects the process of decision-making. The large number of agencies with power over coastal resources and environments has led to pressure for reform. The goals of reform are to simplify the process, to eliminate redundancies and conflicts in rules, and to introduce a more holistic perspective. Further, the desire for holism has led to planning processes involving a wide range of users. This is done to create ground rules for change and predictability in decisions (Brower and Carol 1987).

CHANGES IN CRITERIA FOR DECISION-MAKING

Private Property Rights. One of the most difficult aspects of crafting large-scale environmental regulations is coordinating actions across public and private property boundaries. Private property owners may be seen as obstacles to successful management, or they may be tools to create efficient ecosystem protection. Understanding more about how programs have dealt with private property issues is critical to planning any ecosystem level management program. It is important to consider a broad spectrum of property rights, from access rights based on customary use to rights of lessees of tidal lands to rights secured by treaties. This section focuses on recent court decisions interpreting rights of private land owners in coastal areas; common property issues, the public trust doctrine and tribal rights are covered later in this paper.

In the past ten years, the courts have made significant changes in the laws constraining how public agencies can regulate private lands. Many of these decisions have found in favor of property owners, and governments that draft planning regulations must now navigate through a complex web of legal decisions. For example, the relationship between the regulatory requirement and the goal of the statute must be very close (the "nexus" rule). The regulation may not deprive owners of all beneficial use, otherwise compensation must be paid.

The recent Supreme Court decision in *Lucas v. South Carolina Coastal Council* (1992) generated several in depth articles reviewing the issue of "takings" (Babcock 1995). In *Lucas*, the US Supreme Court found that South Carolina's Beachfront Management Act deprived the plaintiff of the economic value of his land, that this constituted a "taking" of his land, and thus the state was obliged to compensate him. In light of this decision, state and local land-use regulators reviewed their statutes and regulations and acted more conservatively to avoid payments. The Lucas decision also provided ammunition for property rights activists, as seen in 1995 when the Washington legislature passed Initiative 164. That initiative, which was subsequently repealed by Referendum 48, would have required the state to compensate owners for any decrease in property value caused by a state regulation. Property rights bills have emerged in many states and will likely continue to be proposed in future years.

Wetland Mitigation and Habitat Restoration. Coastal ecosystems depend on functioning wetlands for a wide range of environmental benefits. For close to two decades environmental agencies have sought "mitigation" for unavoidable effects on wetlands with the goal of no net loss to the resource. This has been an elusive goal for a variety of technological and administrative reasons. For example, the piecemeal legal framework that covers wetlands focuses on a project-by-project evaluation, and agency resources are not available to define and monitor mitigation requirements adequately. As a result far more wetlands are lost than are replaced through mitigation. Additionally, the coordination of regulatory actions is time consuming and sometimes impossible (Strand 1993).

Much of the existing research on wetlands restoration has focused on the physical aspects of creating wetlands, with any institutional analysis being secondary. Nationally, Kusler and Kentula (1990) and Thayer (1992) provide case studies of restoration in a variety of ecosystems. Several of these case studies discuss the regulatory framework that facilitated restoration efforts. The US Army Corps of Engineers (1994) published an annotated bibliography examining the tradeoffs required for successful environmental projects, including wetlands. And a 1992 workshop (Martz et al. 1994) held in Seattle, examined wetland restoration in sites across the country, with a substantial body of work from Washington and Oregon.

The Pacific Northwest region also figures prominently in the emerging literature on mitigation banking. Washington and Oregon have recently tried to integrate wetlands mitigation and restoration into planning processes through mitigation banking. Federal and state agencies in Washington have entered into a Memorandum of Agreement for wetland mitigation banking when Washington Department of Transportation projects are proposed (Hershman and Green 1995). Oregon authorizes wetland conservation plans which include mitigation banks (ORS.196.668 - 692). Programs designed to look at wetlands on a statewide or watershed scale also offer the possibility of long range urban planning; by identifying wetlands before areas are slated for development, a county could conceivably avoid effects and/or offset unavoidable effects by setting aside some portion of the area as a "wetland mitigation bank" (Environmental Law Institute 1993). This has implications for integrating growth management with environmental regulations, although Thomas and Perkins (1995) argue that, in Washington, wetlands may fall though the cracks of the broad EPA and state Growth Management Act (GMA) regulations.

Habitat restoration is a requirement of the Federal Endangered Species Act. Habitat Conservation Plans (HCPs) must be prepared to protect and restore the ecosystem supporting an endangered or threatened species. A major HCP was prepared for the endangered salmon in the Columbia River system (National Marine Fisheries Service 1995). Similar steps would be needed should additional listings of salmon occur in the Pacific Northwest.

Native American Treaty Rights. The legal history of Native American access rights to fish begins with the original treaties. These treaties have been interpreted in a number of Supreme Court cases starting with *United States v. Winans* (1905). The ruling in that case determined that treaty tribes could not be prevented from harvesting fish from their usual and accustomed fishing grounds. The Boldt decision (1974) ruled that treaty tribes had the right to fifty percent of all harvestable fish, not just the fish that arrived at customary fishing sites. Most recently, the Rafeedie shellfish decision (1994) expanded the definition of "fish" to include shellfish, giving tribes access to shellfish resources whether in the intertidal (often privately owned) or the subtidal zone. These decisions have been highly controversial: judges have been threatened and natives have been fired upon while harvesting fish (Bentley 1992). An unanswered question is whether the treaty tribes have rights to protect the habitat that supports the fishery. Though not clearly answered as a matter of law, the tribes have become active participants in the coastal decision processes that might affect the fish and their habitat.

Growth Management and Coastal Management. Both Oregon and Washington have statewide land-use/growth management laws as well as coastal management statutes and regulations. In Oregon the two are closely related since the coastal laws and policies are specific "goals" of the statewide land-use program. In Washington State the legislature has only recently required a closer integration between the state's Growth Management Law dating from 1991, and the 25 year-old Shoreline Management Act.

These land-use laws are important for coastal ecosystem management for two reasons. First, they try to deal with sprawl through imposition of urban growth boundaries. Land-use can intensify within the urban growth areas but natural resource protection is mandated outside the urban areas. The coastal regulations, on the other hand, tend to be based on zoning and performance standards requiring water-dependent uses, setbacks, vegetated buffers, view corridors, public access, and other controls to achieve environmental protection and public use. In theory, these regulatory mechanisms provide ample authority for controlling development so that coastal habitat can be protected. Little research has been undertaken to determine the long-term effect of these programs on habitat. Social scientists have found significant effects on fisheries from population growth and gentrification (Murdock et al. 1992; Gale 1991). One study in Oregon found that the growth management controls in a coastal county were not achieving their intended objective (Moore and Nelson 1993). A study in Washington State found that wetlands were not well-protected under the Growth Management and Shoreline Management Act (Thomas and Perkins 1995).

Public Trust Doctrine. The public trust doctrine is a common law rule of law that has received considerable attention from judges and legal scholars in recent years. It establishes the principle that owners and managers of tidal and navigable waters, and the lands beneath them, are under a duty to protect public interests in the use and management of these resources. Courts define these interests and determine the extent of the obligation to protect. For example, in Washington State, in the case of *Orion Corp. vs. State of Washington*, the Court concluded that the owners of the tidelands never had a right to fill those tidelands for housing development because, under the public trust doctrine, the state was not legally able to convey that right to private interests: the right resided in the public. Archer et al. (1994) have done an excellent job summarizing the development of this field of law for the nation, and Johnson et al. (1992) have summarized the law in Washington State. New decisions are reached frequently, however, and this area of law should receive additional research attention.

EMERGENCE OF COLLABORATIVE MODELS FOR PLANNING AND REGULATION

The National Estuary Program (NEP). The Federal Water Quality Act of 1987 created the NEP in order to facilitate collaborative estuary management (EPA 1987, 1989, 1990, 1992). Administered by the US Environmental Protection Agency (EPA), the NEP provides Federal funds and technical assistance to estuaries that choose to participate; Puget Sound, the Columbia River estuary, and Tillamook Bay are all NEP sites. The NEP is one of a few programs attempting interjurisdictional "ecosystem" scale management (DeMoss 1987), and as such it has received significant attention from policy analysts (Imperial and Hennessey 1996; Tuohy 1994; Crum 1992; Hiller 1991; Imperial et al. 1992). Much of this work has focused on developing evaluative criteria for the NEP, and the majority of the case studies have involved NEP sites on the Atlantic Coast. Day (1990) and Elder (1989) have compared the management of British Columbia estuaries with programs in Washington and Oregon. There are no studies specifically focused on the NEP's influence on management in the Pacific Northwest.

Regulatory Negotiation and Mediation. The Federal Negotiated Rulemaking Act of 1990 brought regulatory negotiation (commonly called "reg neg") to the Federal government (Lassila 1992). Through this Act, environmental regulations could be crafted with input from industry and environmentalists, hopefully ensuring better compliance and more cost-efficient regulations. Based on the success of "reg neg", consensus-based or mediated agreements became popular solutions to contentious debates, particularly those surrounding land-use and environmental quality (Rowland 1992; Rose-Ackerman 1994). Environmental mediation has become a growing field, and an increasingly viable option even in situations where alternative dispute resolution is not mandated. The presence of mediation has changed the quality of environmental debates by offering an alternative to litigation; however, the trend to mediate may overlook failings in mediation that make it inappropriate for some situations (Campbell and Floyd 1996). As the popularity of mediation grows in the Pacific Northwest, it will become more important to understand the possible implications of mediated settlements over coastal resources.

Special Area Management Plans (SAMP). The SAMP process emerged in the mid-1970s as a planning tool in the implementation of coastal management programs (Brower and Carol 1987). SAMP was first used in San Francisco Bay, Grays Harbor, and Coos Bay, as a way to make coastal planning more specific. It is a collaborative planning process used in a geographically distinct area such as a bay or estuary, resulting in increased specificity in protecting critical natural resources and providing for coastal dependent economic development. In the mid-1980s the Corps of Engineers authorized the SAMP process and linked it closely to the Federal permit process. A regional "general" permit could be issued as a way to implement a Corps SAMP. This would greatly expedite the Corps permit process and assure the implementation of the SAMP. Research into Corps SAMPs is now underway.

Washington and Oregon have been leaders in the use of SAMPs. In Washington State, Grays Harbor is the "granddaddy" of the SAMPs, finally receiving Federal approval in 1992 after a 17 year development period (Lind and Hershman 1993). In Oregon, many estuary plans are the same as SAMPs (Dull 1983). This planning tool can be especially useful where there are extensive wetlands and considerable development pressure. It affords the opportunity to consider tradeoffs at an estuary (or bay) scale.

Watershed Planning for Pollution Control. In the United States, pollution from point sources has been rigidly controlled and progress has been made in reducing the quantity of pollutants entering the water from those sources. However, non-point sources of pollution (i.e., surface water run-off from streets, farms, forestry operations, etc.) are still a very serious problem. Watershed management has been introduced as a way to better control non-point sources of pollution. The goal is to reduce the amount of sediments, chemicals, animal wastes, and other foreign materials from entering the streams or the bay/estuary by capturing and treating at the source. Additionally, proper land-use practices in agriculture, forestry and urban development can reduce runoff. Wetlands, which perform a water storage and filtration function, are critical for a well-functioning watershed (Clark 1996).

Because watershed management involves land-use practices, there is great societal resistance to a heavy regulatory approach to resolving the problem. Many people do not want this level of governmental intrusion into their daily life and work. Agencies have published recommended "best management practices" (EPA 1993) and considerable public education has been undertaken with industries and the general public to reduce sources of non-point pollution. McCreary et al. (1992) studied the capacity of local governments to implement nonpoint pollution controls in the San Francisco Bay region, and Hennessey (1994) analyzed the Chesapeake Bay Program's "adaptive management" strategy for watershed management. The Bonneville Power Administration has sponsored a number of watershed plans to protect salmon resources in the Columbia River system (LSC 1995).

In Washington State, the Puget Sound Water Quality Authority and state Department of Ecology promote the use of best management practices. However, they have no power to require local governments to impose strict standards. Considerable energy has been put into watershed action programs to seek voluntary compliance (Shiginaka 1987).

Ecosystem Management. The ecosystem concept expands watershed-based management by concentrating on an interconnected set of ecological goals that often cross watershed boundaries. This new breed of management began as a terrestrial tool. As a result of the Pacific Northwest Forest Conference (1993), President Clinton created an Ecosystem Management Task Force (EMTF) to address issues of sustainability and diversity in forest management. The two watersheds identified for ecosystem management were the Willamette River Basin and the Washington Coastal Ecoregion. Currently, Federal agencies under the EMTF Memorandum of Agreement are developing research strategies. There is also a focus on ecosystem management in Oregon's Territorial Sea Plan (Oregon Ocean Policy Advisory Council 1994), which proposes five main ecological goals that management should strive to achieve. From an ecological point of view, the expanded boundaries of ecosystem management are advantageous since they do not constrain management plans to the artificial boundaries imposed by humans. However, ecosystem management may be hampered by disjointed institutional cooperation, precisely because it crosses these boundaries. Most of these programs are still in their infancy, and thus the evaluative literature is slim. As ecosystem management plans are implemented it will become possible to examine their effects on human communities and biological dynamics.

THE ROLES OF PRIVATE ORGANIZATIONS, NON-GOVERNMENTAL ORGANIZATIONS (NGOs), AND INDIVIDUALS

Policy-makers are well aware of the impact of public opinion, and of the influence of a concerted lobbying effort. In recent years, more and more advocacy groups have developed, leading to their prominence as a major force with which to be dealt in creating and implementing regulations. These groups, and the actions of their members, can also influence community dynamics by creating bonds or driving wedges between neighbors. They also articulate values, policy preferences and alternatives, and likely effects. Thus, the actions of coalitions have important effects at all levels of government, and may be especially important in small-scale, place-based management regimes (King et al. 1996).

Little is known about the status of NGOs in the Pacific Northwest. Some work has been done on the dynamics within and among these groups, primarily using the advocacy coalition or issue network frameworks (Miller 1989; Martz 1993; Lind 1994; Leschine et al. 1997). The interactions of coalitions in areas with a high degree of community based management initiatives, notably Willapa Bay, have also been examined (Eng 1994, in press; Wing 1996). Few of these works look at the demographic information and methodology of NGOs. Information is still scarce surrounding private organizational activities in coastal areas, and in particular, no work has been done on recreational fishing groups.

Sociological Research

Social Impact Assessment (SIA) has had little historic application to coastal communities and processes as compared to those of uplands. One reason is the historic use of SIA in the US Forest Service versus the relatively new inclusion of social sciences in the National Marine Fisheries Service (NMFS), an agency that has existed for a short time in comparison to the Forest Service, and that employs few social scientists (Miller pers. comm.; Gale 1987). Although in the determinations of "optimum yield" for fisheries, NMFS is charged with the consideration of social factors, but their inclusion in assessments of fishery management policies has been minimal to date (Vanderpool 1987, Miller and Gale 1987). SIA is more routinely applied in the NEPA process, in Environmental Impact Statements. Unfortunately, studies involving coastal issues are difficult to locate and review. The following section provides a brief description of the methods and sources of current studies that could be located.

As previously mentioned, SIA is applied more routinely to environmental issues in terrestrial upland environments, most notably in forested areas. However, some of the Washington and Oregon coast is forested and studies of these areas may include specific mention of coastal issues. For example, the Forest Ecosystem Management Assessment Team (FEMAT) recently completed an extensive ecological, economic, and social assessment of the Pacific Northwest, including much of the Washington, Oregon, and California coasts. In analyzing several different policy options, the report measured each option against "community capacity", a measure of the community's ability to respond and adapt to change. The report concluded, based on a rating by panelists in the three states, that in general, coastal communities have higher capacities than inland communities, due in large part to more diverse economies and a more developed tourism industry (FEMAT 1993).

Visual impact assessment, often used to determine social impact from a proposed policy or action, measures aspects of scenic beauty, viewer preference, viewer perception, or aesthetic values, and has been used to determine the effects to coastal recreation and tourism from such activities as oil and gas development (Kruger et al. 1991). Although data collection for a Pacific Northwest project was discontinued due to lack of funding, the report does provide an excellent literature review and extended bibliography on the subject of visual impact assessment. This type of tool may be used more extensively as the accompanying technology, (i.e., computer-based photo manipulation) becomes more refined, cheaper, and easier to use.

There may be a source for sociological studies within local or national coastal research centers. The National Coastal Resources Research and Development Institute (NCRI) funds many projects directed towards both coastal business/community economic development and coastal tourism and recreation. NCRI's mission for funding coastal tourism and recreation projects includes that for the development of community-wide capacities to respond to changing social, political, and environmental conditions.

Last, a source of data for Social Impact Assessment can be found in various demographic and economic descriptions. For example, Cook and Jordan (1995) compiled social and demographic characteristics and trends over the past decade for seven county groups in Washington. Social variables included population change, age structure, living arrangements, education, source of income and income change, poverty, industrial change, working men and women, commuting, and housing. Although these reports do not make any comparisons between ecosystem and sociological change, they do serve as a useful baseline. Similarly, Davis and Radtke (1994) contains a description of the demographics and economics of the Oregon Coast, including description of social characteristics (e.g., well-being, housing, finance, labor force, occupations, industries, and wealth). Again, these data may provide a useful starting point for analysis of sociological consequences of ecosystem change. Like the Cook and Jordan (1995) report, Davis and Radtke do not suggest how these data may be used in a sociological study of consequences of ecosystem change.

Economics Research

Summary statistics on population, production, and income for Washington State and coastal counties (Table 3.6) and for Oregon State and coastal counties (Table 3.7) show that the coastal economy is a relatively small part of the state economy, and that the coastal counties experience lower incomes per capita, lower rates of population growth, and have relatively small manufacturing sectors. In addition, transfer payments (e.g., social security payments and pensions) are a greater proportion of personal incomes on the coast than in the rest of the states. The income contribution of aggregate industrial sectors (Table 3.6) illustrates the difficulty of using broad SIC categories to determine coastal county dependence upon specific natural resource industries (e.g., forestry, fishing, agriculture). Fisheries and forestry are lumped with agriculture, and some manufacturing income in Clallam and Gray's Harbor counties is likely earned in sawmills and wood processing. More detailed, disaggregated data are needed to link the natural resource base to level of economic activity in Washington counties[2]. Davis and Radtke (1994) have accomplished the requisite work to show (Table 3.7) the economic contributions of resource industries in Oregon. Those data indicate that agriculture accounted for 3.4% of coastal county incomes, fisheries for 4.8%, tourism for 7.4%, and the timber industry for 12.3% in the year 1991. In addition to calculating these aggregate contributions, the Davis and Radtke study provides the results of an input-output type impact assessment.

Similar, recent economic impact studies of natural resource industries on the Washington coast have not been found, but various studies provide part of the picture. For example, the ICF Technology, Inc. study for Washington Department of Community Development (1988) provides a thorough (if dated) assessment of income contributions and economic effects of commercial and recreational fishing for salmon and sturgeon in Washington State. Radtke (1984), Carter and

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[2] I thank Miranda Wecker for this point.

Table 3.6. Population and income by source in Washington state and coastal counties, 1993.

Source: Washington Economic and Revenue Forecast. June 1995. Vol. XVII, No.2

	Unit	Washington St.	Clallam	Jefferson	Gray's Harbor	Pacific	Wahkiakum	Coastal County Totals
Resident Population, 1993	*1,000s*	5258.6	60.8	23.4	66.2	19.9	3.5	173.8
Resident Population, 1973	*1,000s*	3477.2	39	11	60.1	16	3.6	129.7
20-yr Percent Pop. Increase	%	51%	56%	113%	10%	24%	-3%	34%
Personal Income, 1993	mil. $	$114,501	$1,148	$452	$1,154	$329	$63	$3,146
Farm Income	mil. $	$1,839	$5	$1	$7	$10	$3	$26
Total Non-Farm Earnings	mil. $	$80,740	$589	$184	$697	$153	$24	$1,646
Agric. Serv., fish, forestry	mil. $	$1,131	$9	$6	$20	$15	$4	$55
Mining	mil. $	$168	$1	$0		$1	$0	$3
Construction	mil. $	$5,288	$41	$18	$43	$5		$107
Manufacturing	mil. $	$14,471	$118	$34	$181	$32	$6	$370
Transportation & Utilities	mil. $	$4,949	$26	$5	$39	$3	$1	$73
Wholesale Trade	mil. $	$5,079	$16	$6	$25	$1		$49
Retail Trade	mil. $	$8,277	$86	$28	$90	$23	$2	$229
Finance, insurance, real estate	mil. $	$4,836	$18	$5		$5	$0	$28
Services	mil. $	$21,514	$120	$35	$142	$27	$3	$327
Government	mil. $	$15,027	$153	$45	$132	$43	$5	$378
Other (1)	mil. $	$0	$0	$0	$26	($1)	$1	$26
Total Earnings by Place of Work	mil. $	$82,579	$594	$185	$678	$164	$25	$1,646
Dividends, Interest, Rents	mil. $	$17,390	$312	$126	$174	$65	$12	$689
Transfers	mil. $	$18,542	$282	$101	$322	$102	$15	$821
Less Contributions for Soc. Ins	mil. $	$5,157	$41	$13	$48	$11	$2	$114
Total Income, by place of work (2)	mil. $	$113,353	$1,147	$399	$1,127	$319	$50	$3,043

(1) "Other" is defined to include those sectoral earnings figures that are non reported to avoid disclosure of confidential information.

(2) Income by place of work differs from income be residence due to adjustment for earnings of foreign workers in US & US resident work outside US.

Table 3.7. Population and income by source in Oregon state and coastal counties, 1991.

	Oregon	**Clatsop**	**Tillimook**	**Lincoln**	**Coastal Lane**	**Coastal Douglas**	**Coos**	**Curry**	**Coastal County Totals**
Resident Population, 1990 *(1,000s)*	2842	33	25	39	5	5	60	19	186
Resident Population, 1970 *(1,000s)*	2091	28	18	26	2	4	57	13	148
20-yr Percent Pop. Increase	36%	17%	36%	51%	130%	19%	7%	49%	26%
1991 Personal Income, mil. $	$51,111.9	$569.0	$321.4	$658.8	$203.7	$123.7	$931.4	$307.4	$3,115.4
Agriculture		$7.2	$64.9	$4.4	$1.3	$0.8	$27.7	$6.3	$112.6
Fishing		$45.8	$6.9	$60.5	$1.5	$2.0	$20.9	$10.6	$148.2
Forestry		$58.5	$51.1	$80.1	$18.3	$10.4	$120.1	$45.8	$384.3
Tourism		$48.6	$27.3	$65.9	$12.7	$5.5	$52.5	$19.4	$231.9
Paper		$17.9		$34.9	$10.4	$18.9	$16.4		$98.5
Marine Transportation		$8.3		$0.9			$26.7	$0.0	$35.9
Boat Building				$2.6		$0.9	$6.8		$10.3
Spec. Educ. and military		$7.0	$0.8	$4.5			$1.8		$14.1
Other		$156.5	$14.0	$100.7	$57.5	$21.4	$261.2	$55.9	$667.2
Transfers		$113.6	$84.1	$156.8	$51.0	$31.9	$226.6	$80.4	$744.4
Investments		$105.7	$72.3	$147.4	$51.0	$31.9	$170.7	$88.9	$667.9
Total Income		$569.1	$321.4	$658.7	$203.7	$123.7	$931.4	$307.3	$3,115.3

Source: Shannon Davis and Hans Radtke. 1994. *A Demographic and Economic Description of the Oregon Coast.* Prepared for the Oregon Coastal Zone Management Association, Inc.

Table 3.8. Economic values for recreational salmon fishing.

	Average Net Value per Trip	Marginal Net Value per trip of doubling salmon runs	Average Net Value per fish caught	Marginal Net Value of doubling Runs per fish
Salmon location:				
Puget Sound	$75.88	$26.89	$51.27	$18.17
Washington-Oregon coast	89.47	54.31	41.61	25.26
Coastal rivers	58.39	25.55	36.72	17.81
Columbia River Basin	111.46	45.07	45.68	18.47
Steelhead location:				
Coastal rivers	59.58	23.21	64.06	24.96
Columbia River Basin	$90.08	$37.29	$132.47	$54.84

Source: Table 4 (p.53) D. Olsen et al. (1991).

Radtke (1988), Radtke et al. (1987), and sections of the Pacific Fishery Management Council's Annual Review of Salmon Fisheries (1995) provide a long series of coastal economic impact estimates at various degrees of spatial aggregation for salmon fisheries.

Recreational fishing information useful for economic description and evaluation has been collected in a consistent and comprehensive manner by the NMFS-sponsored Pacific Coast Marine Recreational Fisheries Statistics Survey (MRFSS). Rowe (1985) used the MRFSS data to construct a broad travel-cost model of angler demand for marine fishing, including estimates of WTP values for particular species of fish. Similar demand estimation has been accomplished using the US Fish and Wildlife Service's National Survey of Fishing and Hunting database (Brown and Hay 1987). Numerous special surveys have been completed to provide estimates of fishing trips per angler, catch rates, expenditures, and various other data (Brown et al. 1980; Brown and Shalloof 1986; and most recently Olsen et al. 1991).

The summary table from Olsen et al. (1991) shows several pertinent facts about salmon and steelhead recreation in the Pacific Northwest (Table 3.8). First, the economic values per fishing trip vary significantly among fishing areas, ranging from about $58 to $111. Second, these values are for fishing, not for fish, per se. The reported average value per fish simply equals the value per trip divided by the number of fish caught per trip, and this does not represent the amount that an angler would pay to catch a fish. Further, Olsen et al. (1991) analyzed survey responses to estimate the amounts anglers and non-anglers would pay to double the salmon runs (which would presumably double the fish availability to anglers).

There are few useful references to economic values for other coastal ecosystem goods and services, such as recreational values for other marine species, beach use values, amenity values for coastal watershed characteristics, coastal stream hydrologic regimes, etc. A promising study by Loomis (1988) constructively approaches the evaluation of forest-supported commercial and recreational fishing values alongside commercial timber industry values. He shows that greater protection of forest streams for fish habitat would generate more overall value than aggressive timber harvest strategies. In addition, there are few pertinent studies of the direct costs of ecosystem protection and recovery strategies or of the opportunity costs inherent in the tradeoffs between salmon and other uses of the coastal ecosystems. For the Snake River, Huppert and Fluharty (1995) take a broad approach to opportunity costs of salmon recovery, examining the effects of hydropower system modification, flow enhancement, and tributary stream protection on agriculture, electricity, river navigation, flood controls, and public land management. In other regions of the country there have been in-depth studies of ecosystem costs; for example, Shulyer (1995) examines the costs of reducing nitrogen inputs to the Chesapeake Basin via nine different operational methods, and displays the information usefully for a cost-effectiveness analysis. Similar studies of Pacific Northwest coastal ecosystems may be more difficult due to the multivariate nature both of the ecosystem functions and the program objectives.

Existence Value for Salmon Recovery[3]. The existence value for salmon (also known as non-use or passive use value, or as intrinsic value) is expressed as a willingness to pay to preserve salmon even when the payer does directly use salmon (e.g., to catch or eat). Expressing an existence value is not the same as a expressing a "policy preference" for salmon protection over other river uses. The policy preference is often equivalent to a willingness for *someone else* to pay for salmon preservation. A person holding existence value for salmon is willing give up a quantity of money or to sacrifice other aspects of personal material welfare. Existence value has been estimated for some specific salmon stock improvements. For example, the non-use value for a doubling of the Columbia River salmon runs under the Northwest Power Planning Council's 1987 plan was estimated by Olsen et al. (1991).

Based upon the responses from over 2,000 regional residents, Olsen extrapolates the willing-to-pay for doubled salmon runs to all Pacific Northwest households[4]. The residents of the region fall into three categories: (1) no probability of future use (1,599,360 households); (2) non-users with some probability of future use (304,640 households); and (3) users of salmon (1,496,000 households). The average non-use values per household for these three categories of households were $2.21 per month ($26.52 per year), $4.88 per month ($58.56 per year), and $6.18 per month ($74.16 per year), respectively. Extrapolating from the sample average WTPs to all households in the region, the total value for doubling the Columbia River basin anadromous fish runs would be about $170 million. Of this total, the amount attributed to non-users ($42,415,027

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[3] This section adapted from Huppert and Fluharty. Draft "Economics of Snake River Salmon Recovery: A Report to the National Marine Fisheries Service". March 1996.

[4] Also reported in the study were estimates of willingness to accept compensation. We do not report the willingness to accept compensation numbers here due to the high refusal rate (83 to 85%) for those questions.

per year) would clearly be existence value. Some of the remainder is existence value as well. These non-use values pertain to the Columbia basin as a whole, and are not necessarily transferable to salmon populations in coastal drainages.

Another piece of information concerning the public's willingness to pay for recovery of Pacific Northwest salmon runs was provided by the Elway Poll of May, 1994. Elway Research is a Seattle survey firm that periodically surveys Washington State registered voters across congressional districts. One of the many questions posed in the poll asked whether respondents were willing to pay at least $1 per month more in electric bills "if you thought it would help restore salmon". A follow-up question asked whether they would pay $5 per month. Responses are displayed in Table 3.9. As with the Olsen et al. (1991) estimates, these responses do not pertain specifically to salmon in coastal ecosystems. Elway's survey invited respondents to think about whatever salmon run was important to them, including coastal rivers, Puget Sound rivers, Oregon rivers, and Canadian rivers. Further, the Elway survey question does not distinguish between use and non-use values. But the Elway study does reaffirm that most households attach a value to recovery of salmon that is likely in the neighborhood of $1 - $5 per month ($12 - $60 per year)[5]. Extrapolating over all 3.4 million households in the region, yields a total value for "salmon restoration" of between $40.8 million and $204 million per year. By the way the survey was constructed, many respondents were undoubtedly thinking of Puget Sound and other non-coastal fish runs; and, of course, it is not correct to extrapolate the Washington State values to other states.

Table 3.9. Responses to May 1994 Elway Poll.

Category of Response	Willing to Pay $1/month?	Willing to Pay $5/month?
No Answer	9%	16%
Yes	73%	39%
No	18%	52%

Loomis (1996) estimated regional and national existence values for restoration of salmon in the Elwha River. While the Elwha is one small river on the Olympic peninsula, the restoration value may reflect values held for other coastal salmon-bearing rivers. Two dams have blocked off most of the historical salmon spawning and rearing habitat in the Elwha. Based upon a carefully crafted mail survey using the referendum voter format, Loomis sought to estimate the annual willingness to pay for removing the dams and restoring the salmon runs. For Clallam County, where the

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[5] If the distribution of value per household is highly skewed towards high values, the average value could easily be much greater than $60 per household.

dams are located, Loomis estimates an average WTP of $59 per year per household. Household values are $73 per year in the rest of Washington State, and $68 per year in the rest of the nation. These per household values for Elwha River restoration are similar to Olson et al.'s (1991) estimate of value for the Columbia basin salmon doubling, and similar to the Elway poll's results for general salmon enhancement. Some analysts suspect that surveys of the sort Loomis used encourage people to express very general values (e.g., for all salmon) even when the question is narrow (Elwha salmon).[6] If so, one could interpret the results as the value for generalized salmon enhancement and preservation in the Pacific Northwest. More study of these issues is needed in order to sharpen our understanding of salmon existence values.

While the existence value information available does not directly pertain to the suite of coastal ecosystems of concern to PNCERS, it suggests that existence values for various salmon stocks and habitats could be a significant portion of the overall economic value held by residents of the Pacific Northwest. It is important not to ignore values associated with people's willingness to sacrifice for the benefit of salmon in addition to their value for harvesting salmon. Further, the lack of extensive quantitative documentation of these existence values should not be permitted to imply their unimportance.

Economic Growth and Environmental Protection in the Pacific Northwest. Natural resource industries like mining, forestry, grazing, fishing, and irrigated farming have been the economic backbone of rural communities throughout the western United States, and they have accounted for much of the economic growth supporting regional metropolitan centers. However, in recent decades personal income growth in the Pacific Northwest has come largely from non resource-based industries. Rasker (1995) shows that during the period 1969 - 1993 personal income in the interior Columbia basin grew from $ 29.1 billion to $ 58.2 billion, while income from resource extraction and agricultural industries grew from $ 5.1 billion to $ 6.5 billion. The resource-based economy expanded slightly, but shrank as a percentage of the region's income from about 17% to 11.1 %. Whether gauged by personal income or by total employment, the resource industries are growing little and becoming less significant as a source of economic development in the region. Some major legal institutions (e.g., the General Mining Law of 1872, the Taylor Grazing Act) and much of the Federal and State support for economic development and economic stabilization (e.g., irrigation projects, agricultural price support and land banking programs) continue to emphasize these industries.

A shift from established interests in mining, grazing, and forest industries to the less land- and water-intensive high technology and service industries is reflected in growing regional interest in preservation for amenity and other purposes. This is considered by some a harbinger of the future of the Pacific Northwest. The increasing reliance of the Pacific Northwest on the new industries will place greater importance on providing the natural amenities and outdoor recreational experiences that the increasingly white-collar and urban work force seeks. Forests, riparian areas, beaches, and coastal wildlife habitats are some of the natural environments that newcomers will demand be preserved and enhanced. So, the economic transition occurring in the Northwest is directly connected to political, social, and economic pressure to shift from extraction and use of

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[6] This is termed a an "embedding effect" or "whole-part bias" in the contingent valuation literature.

natural resources to preservation and enhancement of natural environments. The extractive industries and the communities dependent upon them continue to fear the negative economic effects of decreased mining, logging, and grazing. As many ex-mining, fishing, and logging towns convert to tourist, recreational, and high technology economic bases, the weight of economic concern is tilting toward environmental protection.

Recent regional economic analyses (Rasker 1995; Niemi et al. 1995) have taken the next logical step to suggest that continued economic development in the Pacific Northwest depends upon maintenance of a high-quality natural environment. Rasker (1995) suggests that "local and regional economic development should emphasize preservation of scenic quality and ecosystem health." A recent report signed by 34 Pacific Northwest economists (Anonymous 1995) goes even further to suggest that the fast growth in the regional economy is due in part to the region's quality of life and increasing mobility of people and businesses. Niemi, et al. (1995) suggest that businesses now relocate to regions that have the environmental amenities for which workers are looking. The "old regional economics" focused on basic industries-like aerospace, agriculture, manufacturing, and extractive industries that provide an employment base and export products to drive the development of other economic sectors. The "new regional economics" suggests that economies develop by attracting firms to workers who choose to live where environmental amenities are in good shape. The driving force is now choice of living conditions, not conglomeration around basic industries. While the sharp contrast between these two visions of economic prosperity may be overblown, protecting the environment, including coastal ecosystems and salmonid habitats, could be a source of economic prosperity.

Still, it is not clear how specific coastal ecosystem protections (such as salmon habitat restoration programs) will affect the process of economic growth. No one has demonstrated a strong link between ecosystem functions and perceptions of "environmental quality" in the Pacific Northwest, nor is there a strong empirical link between level of economic growth and ecosystem state. While there must be a connection between coastal ecosystems and perceived environmental quality, it remains to be seen whether we can draw a credible direct connection between particular ecosystem characteristics, immigration, and economic development.

Finally, the National Research Council (1995) notes that "growth in human populations and economic activity threatens the continued existence of salmon in the Pacific Northwest." Expanding housing, shopping malls, and light industrial areas is destructive to riparian habitats, wetlands, and forests. Hence, if improved salmon populations attract greater economic development, the economy-environment connection may contain the seeds of its own destruction. Economic development has many different dimensions. To some residents, the expanding Pacific Northwest economy is a dis-benefit, to others it is a largely zero-sum game in which some regions lose jobs and income to other regions, and to yet others it is a source of increased prosperity that makes environmental protection affordable. The complex connections between environmental protection, particularly protection of coastal ecosystems containing salmon, and the level of economic growth and welfare are not fully understood.

IMPLICATIONS FOR FUTURE RESEARCH

Social science research projects that contribute significantly to the design of policy strategies and options for managing coastal ecosystems are needed. Overall, the focus must be on research that either: 1) reveals important underlying relationships crucial to formulating ecosystem management objectives; 2) predicts socioeconomic consequences that will provoke significant response (positive or negative) from the public and decision makers; or 3) provides insight into the working and structuring of organizations and decision processes that deal with coastal ecosystems. Prediction of socioeconomic consequences is largely a matter of data collection, model formulation, and integration with ecosystem thinking. It is as yet unproved that an integrated model, even one that incorporates significant social science component, will possess enough precision and accuracy to provide useful policy advice. Hence, this project must be viewed as a research and development process, not as a simply an application of existing knowledge to engineer a better model and a better system.

Legal and Institutional Research

DEVELOP A BETTER UNDERSTANDING OF THE ROLES OF PRIVATE ORGANIZATIONS AND NGOs

A wide variety of private organizations influences activities in the coastal zone. These organizations have agendas that range from very broad conservation goals to single economic issues. It would be useful to build a database of private organizations, particularly those that work with salmon issues, and look at their membership and activities. This would provide information on the evolution and behavior of these organizations, leading to a better understanding of how policy and private groups work together.

ANALYZE THE INFLUENCE OF INTER-JURISDICTIONAL MANAGEMENT

Much of the research on coastal institutions has sprung from an analysis of a statute and led to a localized case study. However, there is a growing emphasis on place-based management, which necessitates starting with a location and then examining the web of institutions that strives to agree on policy for that area. An important question relates to the authoritativeness of the agreements reached among these many jurisdictions: “What is needed to make interjurisdictional management longlasting and enforceable?”

EVALUATE THE EFFECTIVENESS OF MARINE HABITAT MANAGEMENT

The management of nearshore marine habitats is not well developed compared to the management of public lands, such as forests and parks, fisheries or shorelands. Nearshore habitats play a critical role in protecting salmonids and broader ecological values. Greater knowledge of the strengths and weaknesses of submerged lands management regimes by natural resource and fisheries/wildlife agencies could identify directions for reforms, if needed.

LOOK AT THE AGGREGATE EFFECTS OF CHANGES IN UPSTREAM WATER USE

Using the model of the Columbia River, a study of the changes in upstream water use could reveal discrepancies in current management regimes. The regulation of activities upstream cannot often be coordinated with regulation on the coast, and yet the quality and quantity of river runoff has an impact on coastal ecological functions. It would be useful to know more about the present state of river run-off, its amounts and composition, in conjunction with the mechanisms by that it is regulated. Combining this knowledge with an understanding of coastal regulatory mechanisms would lead to a more complete picture of where problems exist and where solutions could be created.

IDENTIFY TRENDS IN DECISION CRITERIA AS "RIGHTS" AS ARTICULATED BY THE COURTS

Rights claimed by private property owners, treaty tribes and the general public lead to changes in the decision process. These can be subtle, such as greater leniency with private parties to avoid takings claims, or overt, such as the addition of tribes to the management framework. Knowing more about these trends can better inform the decision process.

ASSESS THE IMPACT OF FURTHER "LISTINGS" ON COASTAL ECOSYSTEMS

Additional listings of salmon under the Endangered Species Act in the near future are a distinct possibility. This could have important ramifications for protection of coastal habitats in affected streams. Habitat conservation plans would be needed and these would have substantial impact on existing management regimes. Lessons learned from the Columbia River recovery efforts could be assessed to determine optimal directions in other streams and watersheds.

EXAMINE HOW INSTITUTIONS HANDLE EFFECTS ON ETHNICALLY AND SOCIOECONOMICALLY VARIED COMMUNITIES

Decisions made about coastal access may affect certain groups disproportionately. As coastal populations increase and diversify, the issue of inclusiveness will become increasingly important. Attempts are being made to explicitly include members of affected communities in decision-making; thus, avoiding charges of "environmental racism" and hopefully increasing regulatory compliance among community members. Consensus-based regulations and mediation are two of the main tools, however more may be in use in areas outside the Pacific Northwest. Future research could include examining the efficacy of these tools and expanding the toolbox by including procedures developed in other areas.

Social Research

Sociological research in Pacific Northwest coastal communities could focus on the role of ecosystem components in the changing communities. Although few studies to date use sociological methodology to determine the consequences of Pacific Northwest coastal ecosystems change, the methodologies currently available can be molded to answer these types of questions. A first-cut analysis could use the descriptive county level data collected and reported by Davis and Radtke (1994) and Cook and Jordan (1995) in conjunction with data on local ecosystem state and resource-based industries to seek patterns that could generate hypotheses regarding causal relationships. Two categories of social characteristics seem pertinent: (1) the paths or mechanisms by which changing ecosystems affect the stability and health of coastal communities; and (2) the degree to which coastal communities have adaptive capabilities that encompass the types of ecosystem changes likely to occur.

Economic Research

Existing research on coastal economies focuses heavily on descriptive data and linear models, possibly because the basic information is available at relatively low cost while research funds are scarce. This review found adequate research on economic contributions and economic effects of standard industry sectors in Washington and Oregon. For Oregon, the Davis and Radtke (1994) study goes further than simple economic description to investigate specific coastal resource-based sectors. A similar resource-based study for the Washington coast would help to gauge the importance of ecosystem changes to the local economies.

For particular resource-based economic sectors, like commercial fishing, forestry, and agriculture, there appear to be adequate economic data on economic outputs and market values. The review found less information for the outdoor recreation, tourism, and other non-commodity production sectors. A fuller investigation of economic structure would explore causal links between resource use, tourism, recreational visitor rates, and coastal ecosystem features. The objective is to explain and predict how coastal economies can adapt to changes in the ecosystems and how ecosystem state affects the economic status of people on the coast. The methods of analysis would range from multi-market models for coastal economies to dynamic ecological-economic models to contingent valuation surveys.

The structure of economic values attached to the full range of ecosystem elements has apparently not been estimated for coastal ecosystems. Economic valuation and assessment is relatively well developed for outdoor recreational uses of ecosystems, but these values are highly variable through time and space. Hence, focused study of specific ecosystem uses in the coastal ecosystem are needed. Opaluch et al. (1995) are beginning to document their extensive research effort on the multitude of resource and environmental values in the Peconic estuary system on New York's Long Island. They are measuring levels of use, attitudes, values, and policy preferences across a broad range of estuary management issues. Efforts similar to this should be integrated with broader studies of Pacific Northwest coastal ecosystem functions.

Economic cost and benefit data need to be developed in conjunction with ecosystem protection and enhancement strategies. For example, strategies to reduce non-point source pollutants from urban, agricultural and forest land in coastal ecosystems will entail both direct program costs and opportunity costs of reduced economic outputs, at least in the short run. Selection from a menu of possible pollution reduction measures should pay some attention to the economic effects.

Models that explain and predict causal relationships between economic consequences and ecosystem changes seem to be developed only for narrow purposes, for example, examining the optimal yield of a commercial fishery, balancing recreational and commercial catch of limited salmon runs, or developing a multi-purpose forest management plan. We did not investigate the voluminous literature of forest plans and environmental impact statements for coastal land-use. There may be more research there, but we suspect that causal models, especially ones that incorporate social and ecosystem dynamics, are absent. This is an area in which more research would be appropriate.

SUMMARY OF SOCIOECONOMICS RESEARCH TOPICS

The review of available research on socioeconomic consequences of coastal ecosystem change, and comparison to the menu of research issues leads us to suggest the following list of research needs. These issues would be applied specifically to habitat important for salmonids.

Role of Coastal Ecosystems in Society

Study whether demographic trends reflect the "pull" of coastal community jobs and amenities or the "push" of jobs and amenities elsewhere.

Detailed baseline study of social and economic structures of coastal communities focusing on the degree of dependence on coastal ecosystem elements, and time and space scales over which these dependencies are important.

Expanded study of the nature and role of coastal recreation and tourism activities, and determine how these activities tied to salmon, salmon habitats, and other features of the coastal ecosystem.

Develop an inventory of public uses, attitudes, and values pertaining to ecosystem services using focus groups, broad surveys, and other social research methods.

Compile and document the direct, programmatic costs of existing ecosystem protection, enhancement, and management activities.

Through collaboration with biogeochemical systems researchers develop ecological-economic models for specific watersheds; demonstrate the capability to analyze trade-offs between ecosystem functions and categories of economic benefits.

Coastal Ecosystem Management Policy: Structure, Process, and Effectiveness

Develop an institutional map of ecosystem management for selected coastal watersheds and use these to explore pathways for management actions and to identify bottlenecks.

Assess the importance of recent changes in decision criteria (property and treaty rights, endangered species listings) and organizational structure for coastal ecosystem management.

Document the role of private, non-governmental organizations in determining the nature of the policy dialogue and in the design of conservation strategies.

Examine how salmon fishery management is affected by jurisdictional structure (international treaties, Federal management in ocean, state and local controls over estuarine and river), and assess the appropriateness of the current structure.

Evaluate the role of decision makers managing submerged lands (e.g., owners, fish and wildlife agencies, US Army Corps of Engineers) in protection of coastal ecosystems.

Explore the utility of cost-effectiveness analysis in evaluating salmon habitat protection strategies.

Develop a multi-dimensional analysis of net economic benefits from alternative mixes of land-use and water quality management regulations.

Examine how institutions handle effects on ethnically and socioeconomically varied communities.

Study aggregate effects of changes in upstream water use.

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CHAPTER 4

VARIABILITY AND STABILITY OF CLIMATIC/OCEANIC REGIMES IN THE PACIFIC NORTHWEST

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INTRODUCTION

This chapter addresses the variability and stability of climatic / ocean regimes of the Pacific Northwest. A physical template is first presented that consists of a set of principles and a set of conceptual models. Within the template, conceptual models include the consideration of a nested hierarchy of scales, spatial and temporal scales, and geographic / temporal gradients in Pacific Northwest coastal ecosystems. A scale treatment is applied to both the atmospheric and the oceanic regimes of the Pacific Northwest and is also used in Chapters 5 and 6. Some of the more important linkages between the atmosphere and the ocean are emphasized, and comments are made regarding the development of comprehensive models for the Pacific Northwest Coastal Ecosystems Regional Study (PNCERS). The chapter concludes with some of the questions that have arisen from the body of the chapter and the PNCERS workshop. Appendices include some technical information and a list of data sources.

During the PNCERS workshop (see also Chapter 7) participants suggested improvements to this chapter. First, more attention would be given to large scale models of the atmosphere and ocean and their usefulness. More emphasis would be given to the operation of the climate and ocean in the Pacific Northwest within a larger geographic framework. The region immediately encompassed by the PNCERS program is the coastal terrestrial ecosystem, from about Vancouver Island to Cape Mendicino in northern California, and marine ecosystem out to the edge of the continental shelf. However, it is important to recognize that the region should be extended northwards to include British Columbia and southern Alaska, and that the extended concept of the Pacific Northwest is affected by events within a hemispheric and, most likely, on a global scale. Treatment of these large scales would reveal teleconnections other than El Niño-Southern Oscillation (ENSO)-related ones that should be taken into account. Second, this paper probably does not do justice to the richness and importance of all the phenomena acting on time scales of a year or less by dealing with them in a single section. A truly comprehensive treatment would examine these scales separately. Third, the mesoscale features of the ocean are particularly important. Fourth, a comprehensive treatment would also give more attention to the past, present, and potential future, use of technology such as satellite use and electronic tracking. Finally, and very important for a program that attempts to provide information to managers, it should be emphasized that, although a certain amount of predictability is possible, an inescapable fact is that the atmosphere and ocean are inherently variable and their non-linear dynamics makes them a system about which perfect predictions are not possible.

CONCEPTUAL FRAMEWORK: PHYSICAL TEMPLATE AND SCALES OF VARIABILITY

Principles

Variability in Pacific Northwest Coastal Ecosystems Reflects Interaction of Multiple Scales of Processes. Pacific Northwest coastal ecosystems display an enormous amount of variability. By definition, these ecosystems lie at the interface of the planet's largest ocean and one of its largest continents. A wide variety of atmospheric, oceanic, hydrologic, and biospheric processes intersects at this location. The richness of the resulting land- and ocean-scape reflects the operation of all of these processes through time scales ranging from billions of years to seconds, and space scales ranging from planetary to sub-millimeter. Scientists attempt to make sense of this complex reality in a number of ways. Two of the most common are first, to recognize the existence of these scales and endeavor to sort out their interaction, and second, to apply the concepts of general systems theory. The first of these approaches is emphasized in the following discussion.

Hierarchy Theory. Hierarchy theory was introduced in the 1980s to address linkage between scales and general complexity in ecological systems. The theory, which sees different scales of ecosystem operation forming a hierarchy, was introduced in great detail by Allen and Starr (1982) and is frequently applied to ecosystems. Among others, O'Neill (1988) has outlined some important practical applications of the theory. He suggests that the understanding of one hierarchical level in a system is enhanced by reference to those immediately above and below it, but not so much by those a long way from it. An important principle of hierarchy theory for the PNCER study is that higher levels set constraints, and in some cases provide control, for lower levels of the hierarchy. The application of this principle is implicit in much that follows.

Heterogeneity in Basinwide Processes. The manner in which oceanic and atmospheric processes function across the whole Pacific Ocean basin has important results for both aquatic and terrestrial ecosystems. There is a continual shifting of habitat conditions. Occasionally successional and developmental processes are reset by high impact events. Often, in marine ecosystems, there are found opposing regions of abundance and scarcity. These phenomena make it impossible to understand coastal ecosystems without a good knowledge of its larger planetary setting and the way that biophysical processes work on all scales.

Nonlinear Behavior and Feedback Systems. Many, if not most, processes in the abiotic and biotic parts of the coastal ecosystems are nonlinear. This fact makes it difficult to understand the processes, to model them, and to fit together the various pieces of sub-models, and finally to make predictions from the resulting comprehensive models. Although there can be some certainty about the way in which a particular part of the ecosystem functions, there is increasing uncertainty when fitting the operation of that part with the functioning of related parts. Furthermore, there are important feedback mechanisms at work. There are many feedbacks between the ocean and the atmosphere in terms of mass, energy, gas, and momentum exchange. There are also many feedbacks of the same properties between the land surface and the atmosphere. These feedbacks also frequently do not act in linear ways.

Interfaces Between Adjacent Ecosystems. A further complexity in Pacific Northwest coastal ecosystems is introduced by the interfaces between the many sub-ecosystems, which are themselves often very distinct and complex. Such interfaces exist between the upland and lowland terrestrial ecosystems, between the terrestrial and freshwater aquatic ecosystems, between the freshwater and marine ecosystems, and between the land and the ocean systems. These interfaces offer discontinuities in abiotic and biotic fluxes and *the degree to which the various sub-ecosystems are coupled or decoupled at the interfaces is a major topic for investigation.*

Press and Pulse Disturbances. Although this review concentrates on processes that work more-or-less continuously in time it recognizes that certain events, which might be regarded on some scales as either directional or discontinuous, are sometimes very important to the ecosystem. Press disturbances, such as increasing toxicity of an estuary due to an anthropogenic cause, may occur in a directional sense. Pulse disturbances, such as a high magnitude, low frequency floods or wind storms, are discontinuous but sometimes have repercussions that filter through all the related parts of the sub-ecosystems.

Models

The complexity of coastal ecosystems demands that rather than one model, a suite of models and modeling approaches is necessary. Such a suite includes the following:

Nested Hierarchy of Scales. Critical biological and physical processes act at different scales of reference; the smaller of these scales are nested within increasingly larger scales. This relates closely to basic hierarchy theory and has many other advantages discussed in the climate section below. Figure 4.1 illustrates how this concept may be applied to the oceanic and atmospheric systems and to understanding some other systems as well.

Spatial and Temporal Scales. A number of authors have investigated the organization of biophysical and even anthropogenic processes as they co-vary across spatial and temporal scales. One of the first investigations, and still one of the most helpful, was the concept of Delcourt et al. (1983) shown in Figure 4.2. The hierarchy relates a large number of environmental disturbance regimes, which includes far more than climatic disturbance, through biotic responses and into resulting vegetation patterns. The investigators are careful to quantify the scales involved by

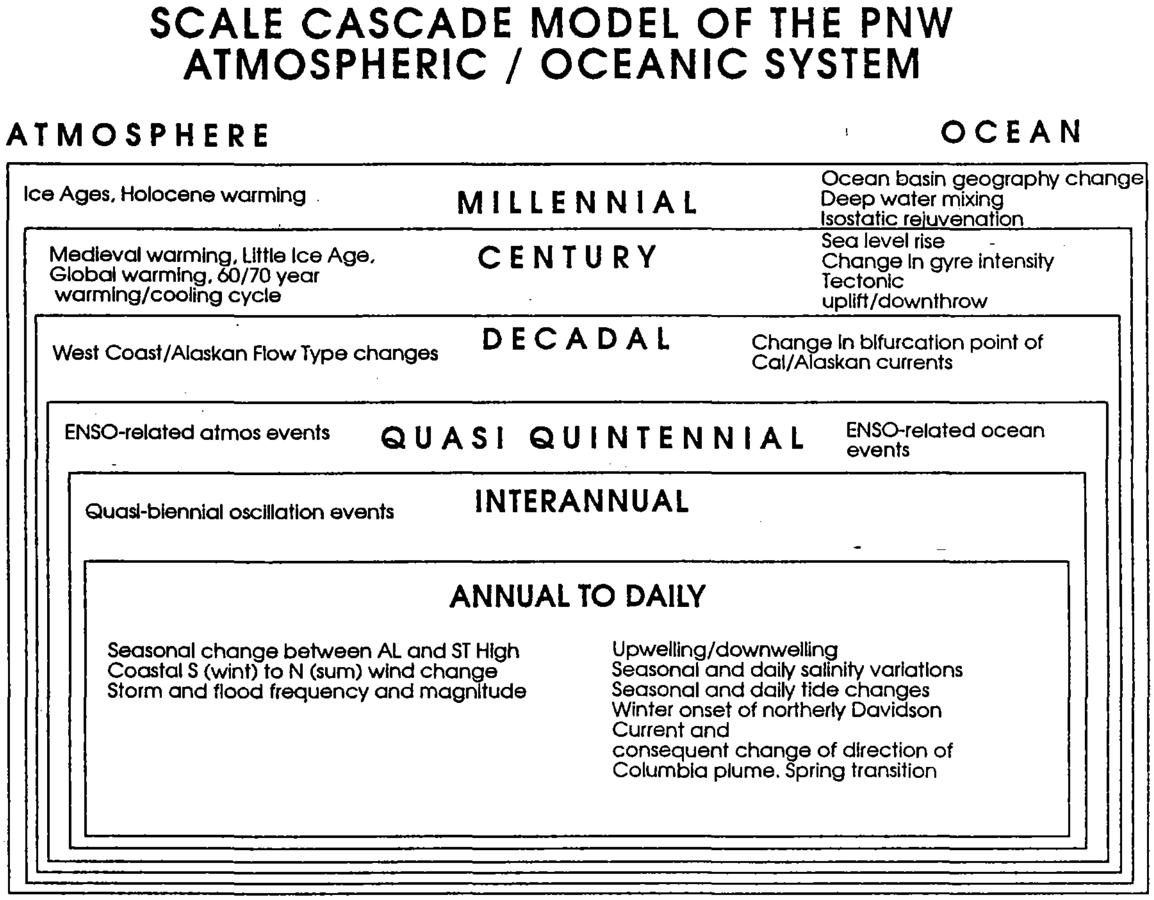

Figure 4.1. Concept of nested hierarchies of scales as applied to the atmospheric and oceanic systems. AL = Aleutian Low pressure, ST High = SubTropical High pressure, S = southerly winds, N = northerly winds.

giving specific limits for mega, macro, and micro scales, their sub-scales, and related vegetation units. The overall pattern is one in which the larger the temporal scale of the disturbance, the larger is the spatial scale of the disturbance, its associated biotic processes, and vegetation response. There is a general semi-linear pattern of increase along both the logarithmic scales of time (in years) and space (in meters). Similar patterns are found in a later study by McDowell et al. (1990) that concentrates more on climatic forcing functions. The McDowell et al. study, unlike others, uses equally-spaced logarithmic units on both time and space axes. The relationships in time and space of climatic episodes and events, on the one hand, and ecological and evolutionary units, on the other hand, show the different phenomena tend to be located towards the spatial, as opposed to the temporal, axis, and thus demonstrate that the temporal scale of the climate-vegetation system is virtually unlimited, but the spatial scale hierarchy is bounded by the finite size of the Earth. Additional scale diagrams have been provided by Graetz (1990) and by Clark (1985), who brings in an anthropogenic component. Exciting new

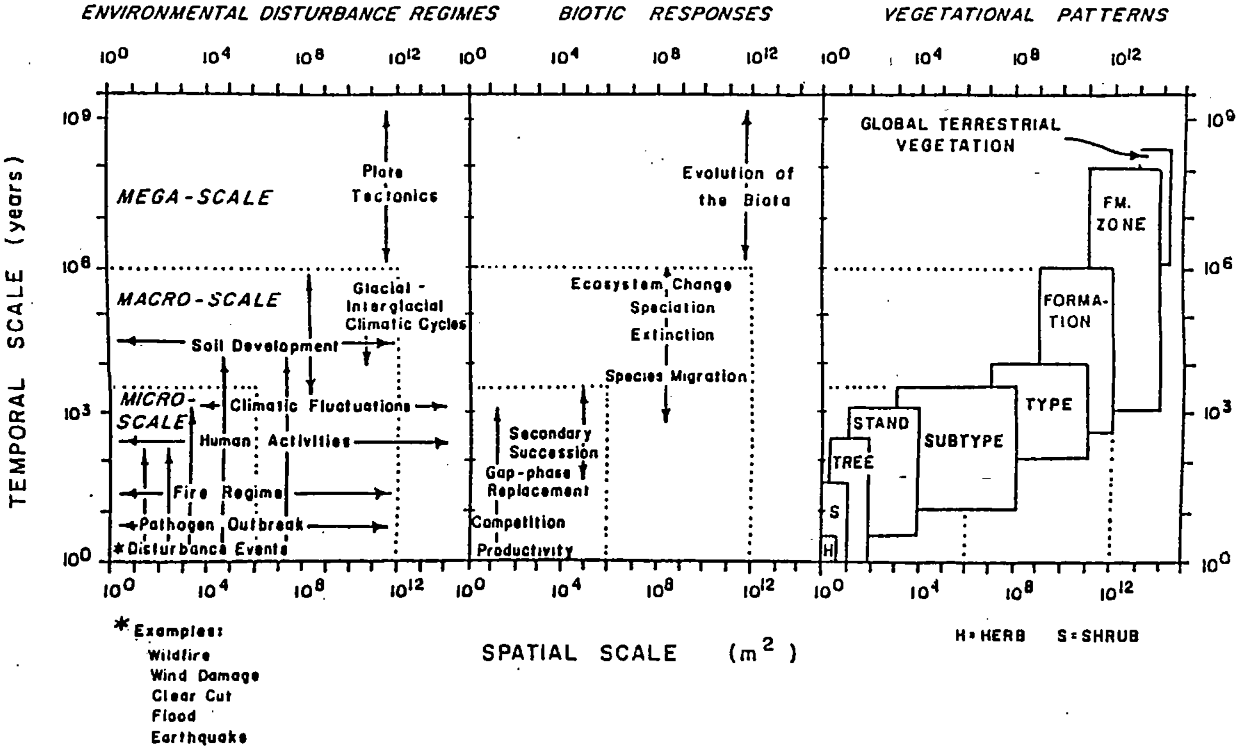

Figure 4.2. Environmental disturbance regimes, biotic responses and vegetational patterns viewed in the context of space-time domains in which the scale for each process or pattern reflects the sampling intervals required to observe it. The time scale for the vegetational patterns is the time interval required to record their dynamics. (Source: Delcourt, H.R., P.A. Delcourt, and T. Webb. 1983. Dynamic plant ecology: the spectrum of vegetational change in space and time. *Quaternary Science Reviews* 1:153-175. Reprinted with permission, courtesy Elsevier Science.)

semivariance analysis and fractal techniques are becoming available in order to link different biophysical phenomena together at mutually important scales (Bian and Walsh 1993).

Geographic/Temporal Gradients in Pacific Northwest Coastal Ecosystems. The geography of the Pacific Northwest gives rise to well-marked gradients in values of biophysical variables in both the latitudinal (north-south) direction and in the longitudinal (west-east) direction. In addition, a third dimension of time is conceived as running perpendicular to these spatial dimensions. Within this three-dimensional view we can imagine "temporal time-dependent slices" of variability in one or more biophysical variables at any geographic point on the plane formed by the two spatial dimensions (Figure 4.3). This is somewhat analogous to the world line or Feynman diagram concept used by particle physicists (Zukav 1979: p. 232). In the reality of the Pacific Northwest, some of these "temporal slices" are known and it is probable that there are others about which we do not yet know.

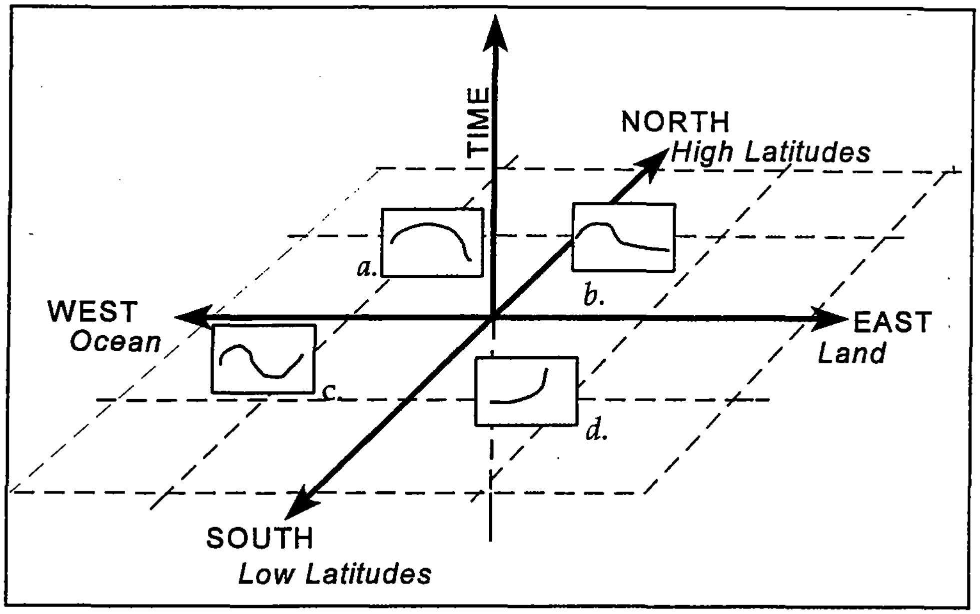

Figure 4.3. Conceptualization of geographic/temporal gradients in Pacific Northwest Coastal Ecosystems. A plane of geographic gradients is formed by the horizontal East-West and North-South axes. A vertical Time axis forms the temporal gradient. Four conceptual examples of "temporal slices" of biophysical variability across geographic gradients are shown as graphs a, b, c and d.

CLIMATIC AND OCEANIC REGIMES IN THE PACIFIC NORTHWEST

Background

DEFINITION OF THE THEME TOPIC

Overview of the Atmosphere/Ocean System in the Region. The Pacific Northwest Region is defined for the purposes of this review as generally including the Washington and Oregon coasts and the California coast to Cape Mendocino. The coastal ecosystem at the center of attention includes the linked components of rivers and streams in coastal watersheds; estuaries including Puget Sound, and the Pacific Ocean to the seaward edge of the continental margin (PNCERS

1995). The coastal ecosystem is nested within the larger oceanic and atmospheric setting of the northeast Pacific Ocean and because of the way in which the atmosphere and ocean operate, this setting itself can extend to large parts of the planet as a whole.

Climatography/Oceanography. The climate of the Pacific Northwest is mostly marine West Coast climate but includes some Mediterranean climate in the south (central and northern California) and sub-arctic climate in Alaska. East of the Cascade Range, where lies a large part of the Columbia-Snake river drainage area, the climate is mainly one of Middle Latitude Steppe (Akin 1991). The ranges of monthly mean temperatures and monthly total precipitation demonstrate both the north-south latitudinal gradient and the west-east, coast to interior gradient for the greater Pacific Northwest area (Figure 4.4). The terrestrial part of the Pacific Northwest climate has a precipitation maximum in winter, much of it falling as snow in the higher elevations. Snowmelt potentially leads to a June maximum of discharge for the Columbia River but since the damming of the river its flow has much less seasonal variation. Papers in Small (1990) show that the peak flow of the Columbia at Astoria can now occur in January. The other coastal rivers have a maximum discharge to the ocean in December and January (Landry et al. 1989). The summer tends to be hot and dry in all areas of the Pacific Northwest.

Winter sea surface temperatures range from 8°C in the north to 10°C in the south. Summer sea surface temperatures range from 17°C well off shore to 11°C near the coast in areas of upwelling (Figure 4.5). Values of summer and winter distributions of salinity and density (Figures 4.6 and 4.7) show the huge impact that the Columbia river discharge has on large areas of water over the continental shelf, especially in summer (Landry et al. 1989). The winter storms give intense vertical mixing and alongshore northward advection which, for the most part, is not impeded by the straight coastline of much of the Pacific Northwest. The Columbia provides about 80% of the river discharge to the ocean between San Francisco and the Strait of Juan de Fuca (Hickey 1989). The Fraser river, which has fewer dams than the Columbia, is also a major contributor of fresh water to the ocean off Washington and Oregon (Huyer 1983). The important features of the ocean/atmosphere system in this region are the frequent and strong winter storms, strong wind stress, seasonal wind reversals, moderate upwelling in spring and summer, significant freshwater input, relatively smooth coastline, major estuaries and nursery grounds, moderate advection, and mesoscale oceanic activity (GLOBEC 1994).

The atmosphere/ocean system in NE Pacific and Pacific Northwest is extremely dynamic. Driven initially by solar energy, the system plays its part in the general planetary circulation of atmosphere and ocean that attempts to balance heat energy between low and high latitudes. The system is composed of a variety of atmospheric and oceanic currents together with interrelated processes of heat, mass, moisture, and momentum flows and exchanges. Typical ocean and atmospheric movement throughout the year is summarized by a schematic diagram of surface atmospheric pressure and ocean currents (Figure 4.8). The summer atmosphere of the North Pacific and Pacific Northwest is dominated by a subtropical high pressure system (termed the North Pacific High in Chapter 5) with accompanying clockwise-flowing anticyclonic winds that brings a northerly (southward) air flow over the region. During winter, the high pressure system is much reduced in size and replaced in the north by the Aleutian Low pressure system with its associated counter-clockwise, cyclonic winds that bring air from the west, southwest and

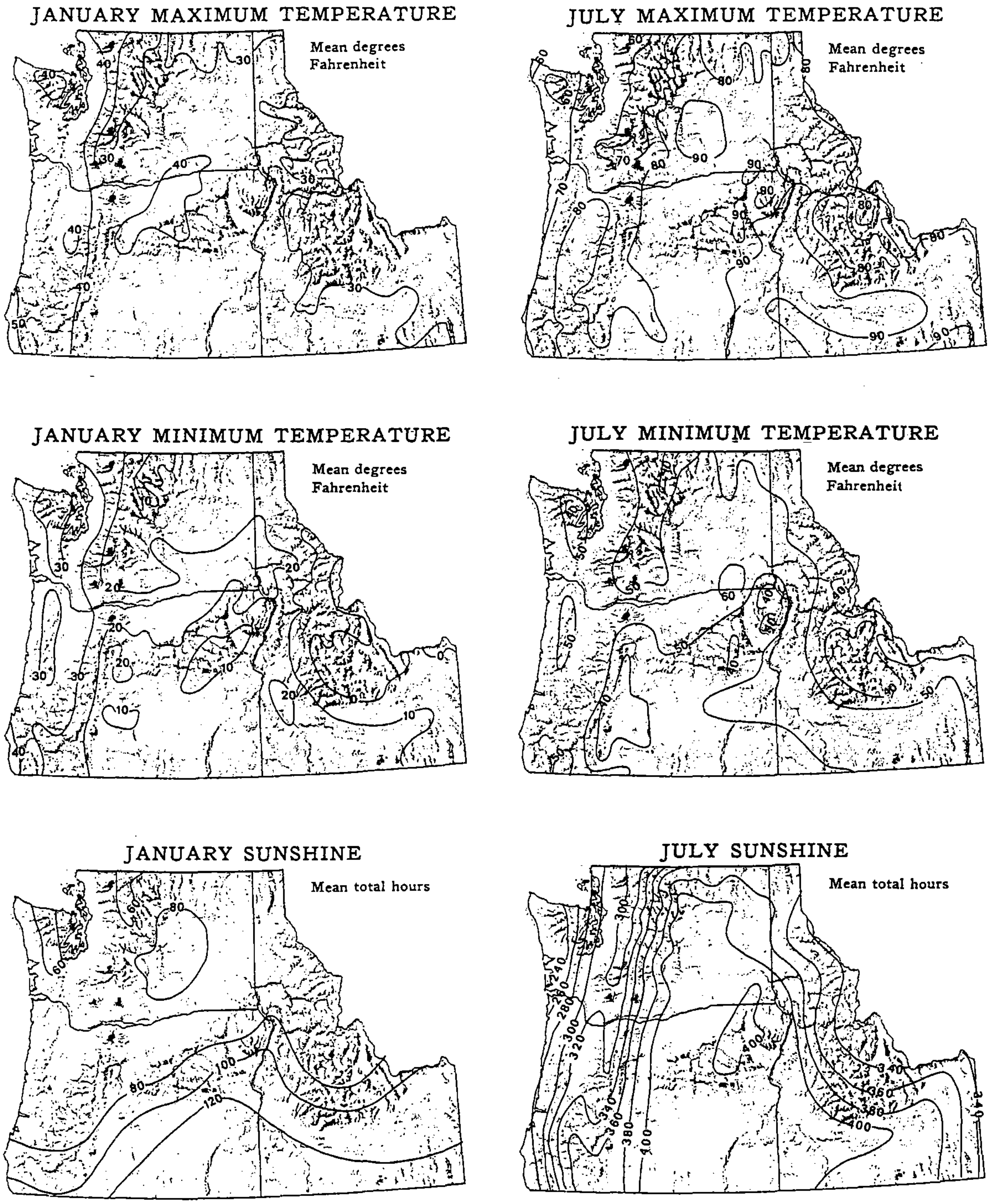

Figure 4.4. Maps of selected climate variable values for the Pacific Northwest. (Source: Jackson, P.L., and A.J. Kimerling. 1993. *Atlas of the Pacific Northwest*, 8th Ed. Corvallis: Oregon State University Press. Reprinted with permission, courtesy OSU Press.)

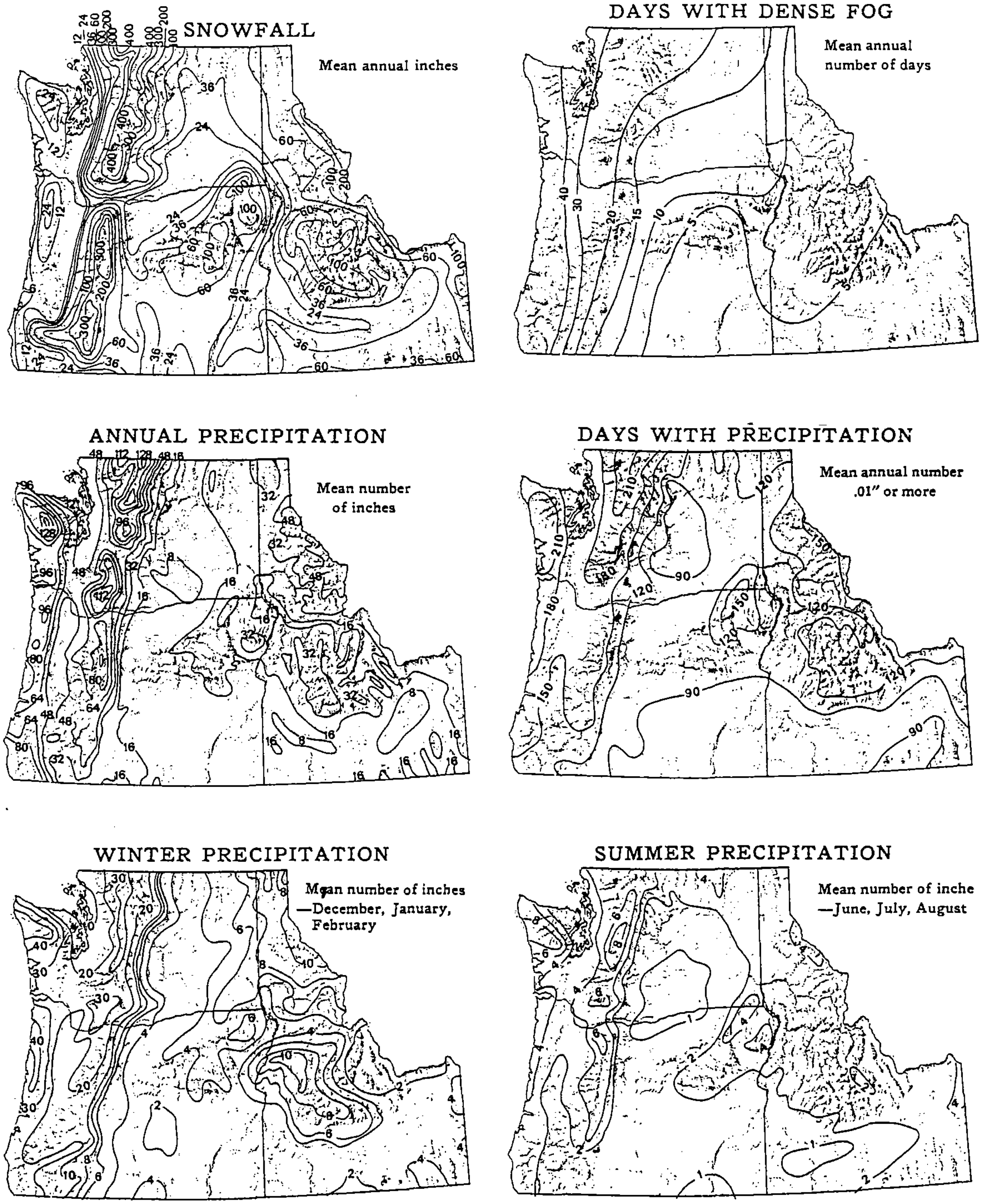

Figure 4.4 (continued). Maps of selected climate variable values for the Pacific Northwest. (Source: Jackson, P.L., and A.J. Kimerling. 1993. *Atlas of the Pacific Northwest*, 8th Ed. Corvallis: Oregon State University Press. Reprinted with permission, courtesy OSU Press.)

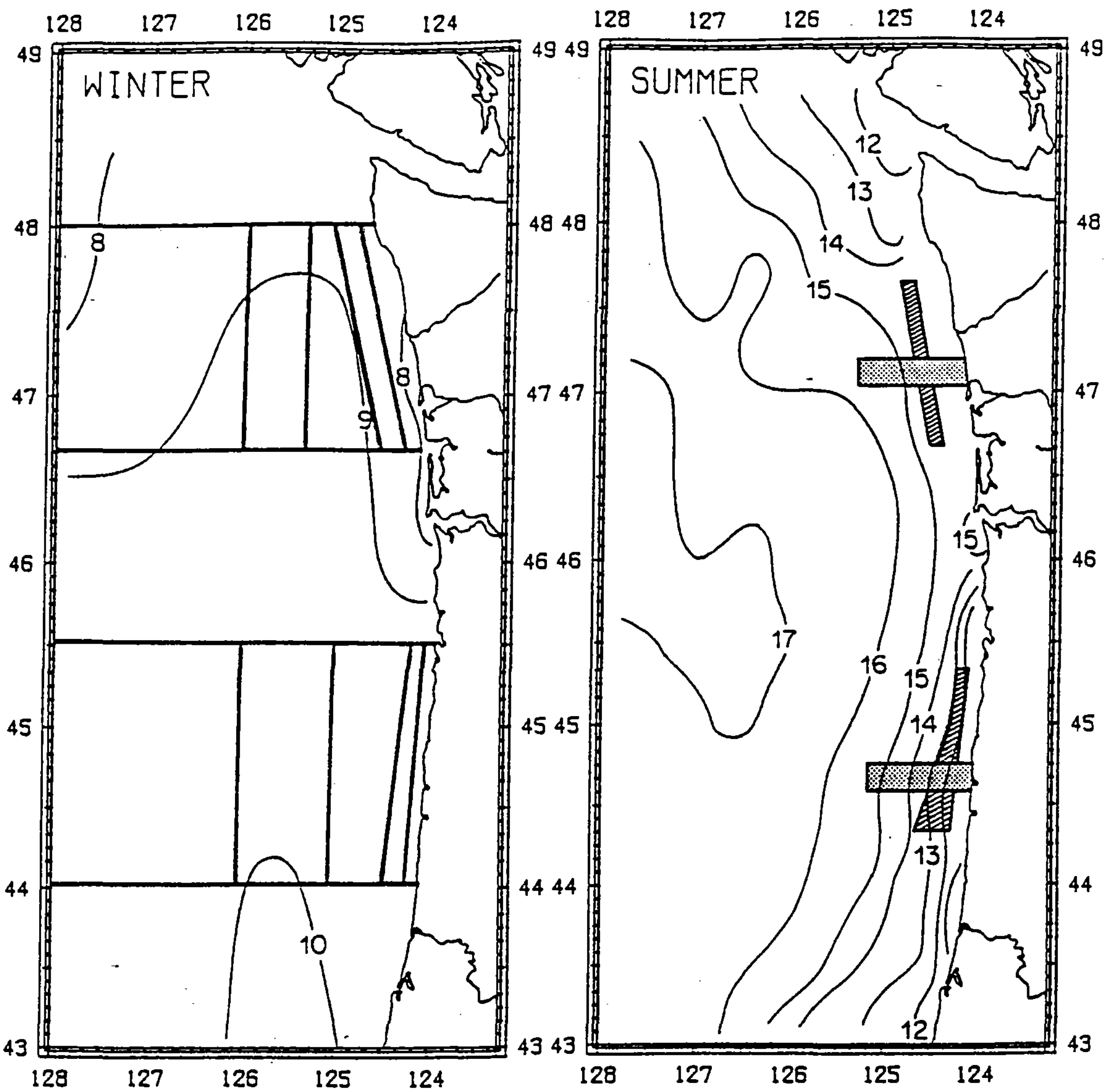

Figure 4.5. Summer and winter distributions of sea surface temperature in °C over the ocean of the Pacific Northwest. Also shown are areas of previous intense study. (Source: Landry, M.R., J.R. Postel, W.K. Peterson, and J. Newman. 1989. Broad-scale distributional patterns of hydrographic variables on the Washington / Oregon shelf. In *Coastal Oceanography of Washington and Oregon*, eds. M.R. Landry and B.M. Hickey, 1-40. New York: Elsevier. Reprinted with permission, courtesy Michael Landry.)

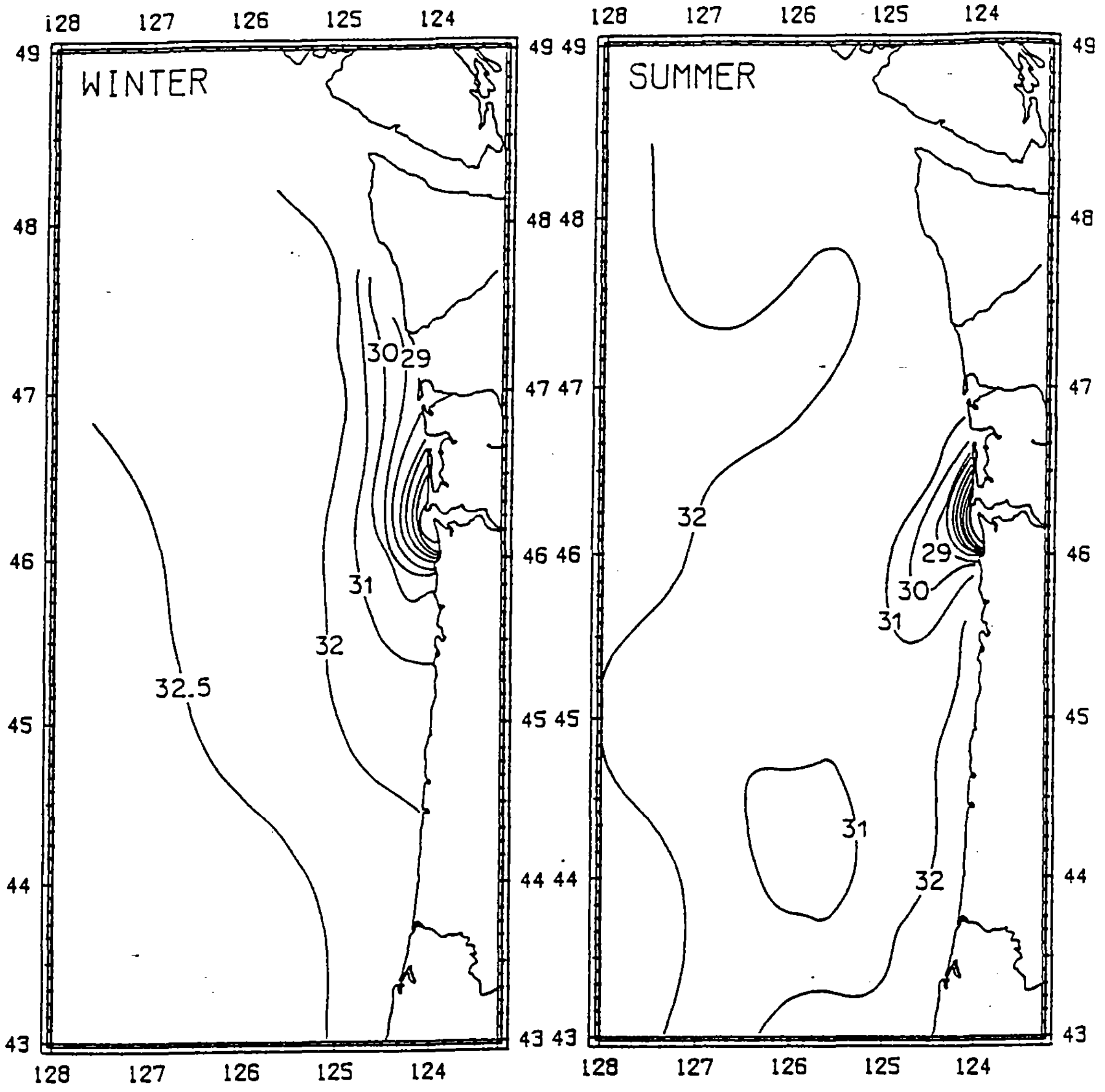

Figure 4.6. Summer and winter distributions of salinity over the ocean of the Pacific Northwest. (Source: Landry, M.R., J.R. Postel, W.K. Peterson, and J. Newman. 1989. Broad-scale distributional patterns of hydrographic variables on the Washington / Oregon shelf. In *Coastal Oceanography of Washington and Oregon*, eds. M.R. Landry and B.M. Hickey, 1-40. New York: Elsevier. Reprinted with permission, courtesy Michael Landry.)

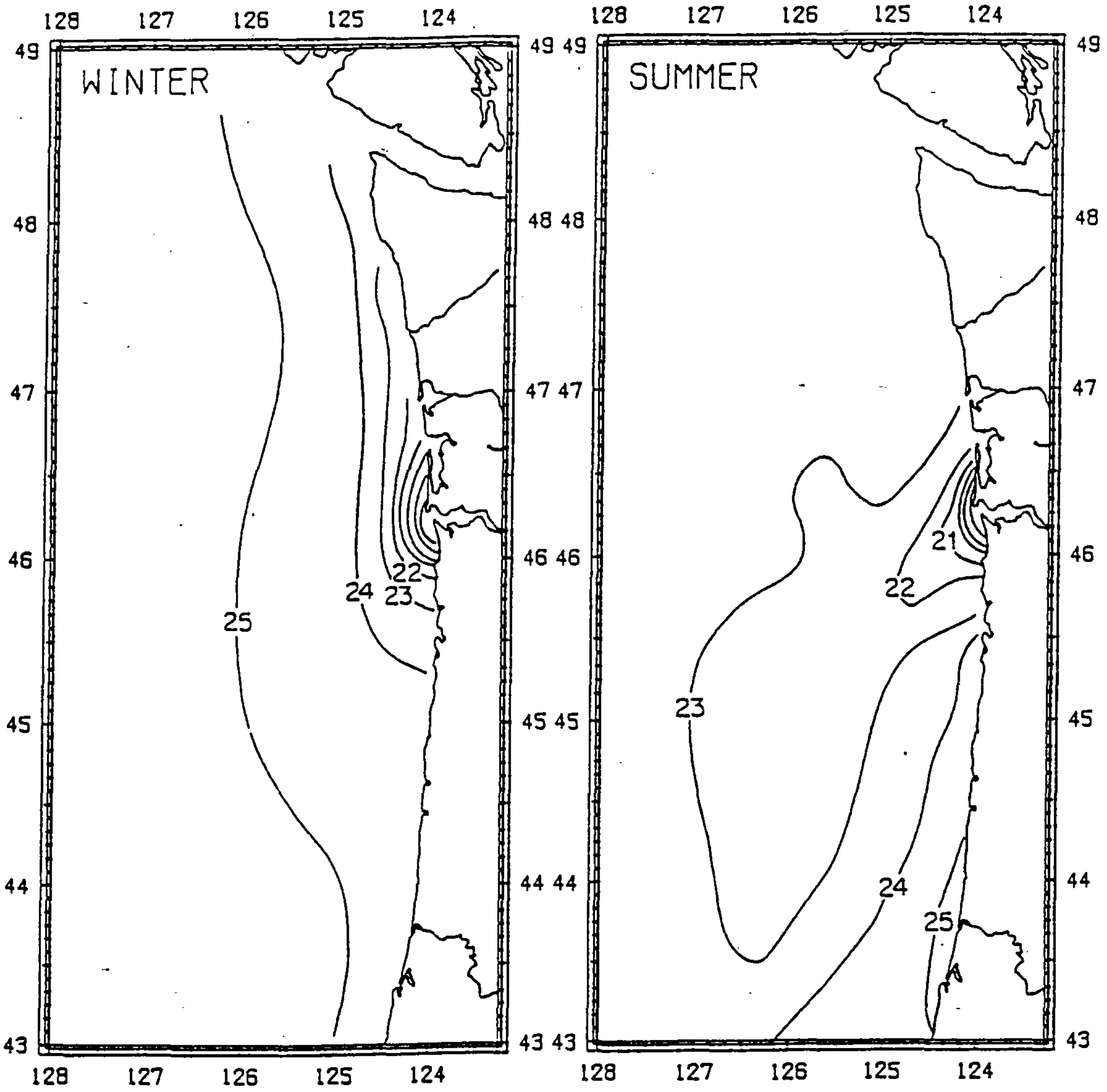

Figure 4.7. Summer and winter distributions of density (σt) over the ocean of the Pacific Northwest. (Source: Landry, M.R., J.R. Postel, W.K. Peterson, and J. Newman. 1989. Broad-scale distributional patterns of hydrographic variables on the Washington / Oregon shelf. In *Coastal Oceanography of Washington and Oregon*, eds. M.R. Landry and B.M. Hickey, 1-40. New York: Elsevier. Reprinted with permission, courtesy Michael Landry.)

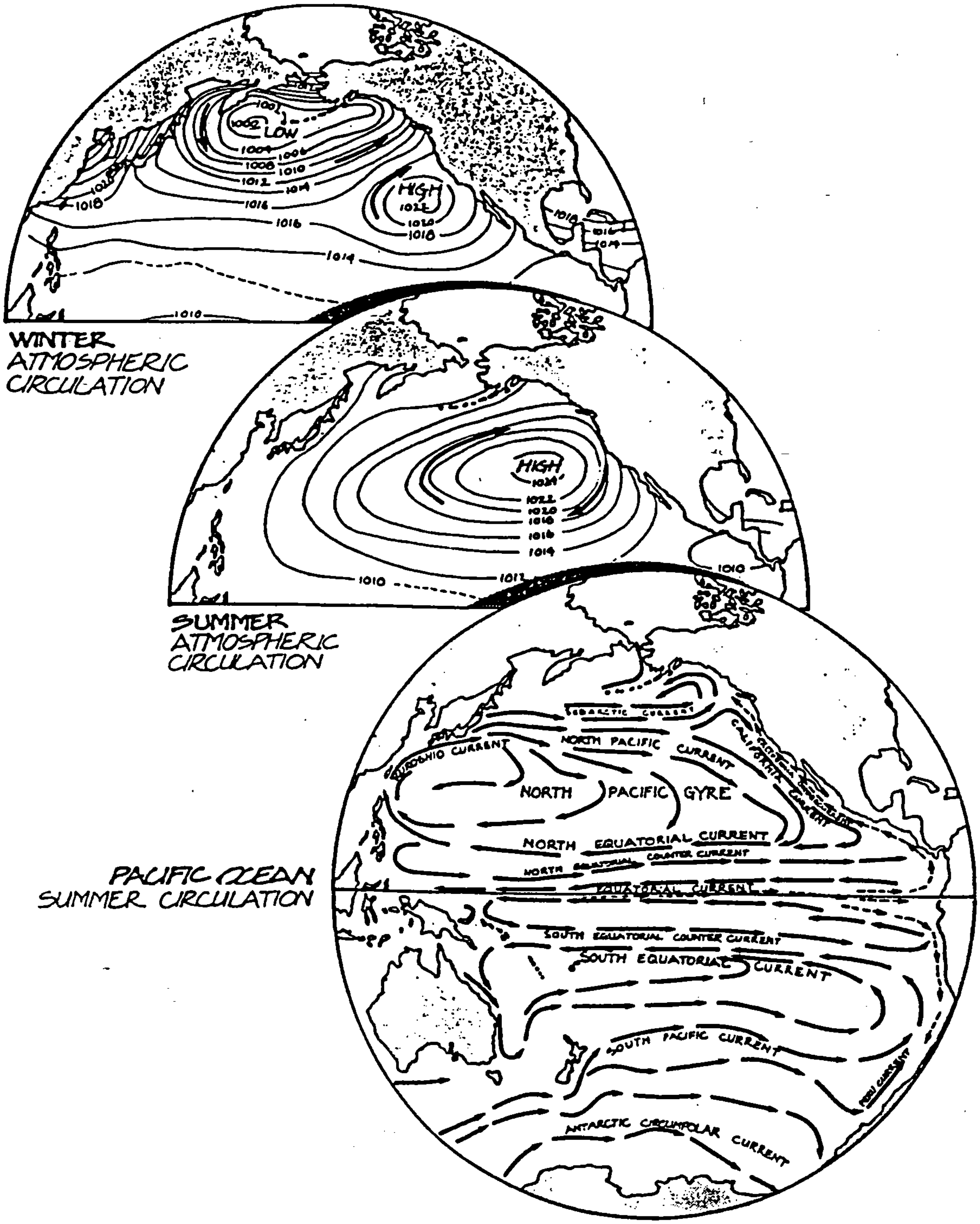

Figure 4.8. Major circulation patterns in the atmosphere and the ocean. (Source: Parmenter, T., and Bailey, R. 1985. *The Oregon Ocean Book*. Salem: State Printing Office. Reprinted with permission, courtesy Robert Bailey.)

south to the region. In the upper atmosphere, generally westward flowing air in the mid- to high-latitudes comprises the northern hemisphere circum-polar vortex. This vortex is marked by the presence of long or planetary (Rossby) waves that can guide surface storms, and by geographic expansion and greater vigor in the winter season compared to the summer. The surface winds associated with the Aleutian low and subtropical high pressure provide the principal force that drives the major ocean currents shown in Fig. 4.8. The North Pacific Current (sometimes called the West Wind Drift) and the Sub-Arctic Current flow eastward across the North Pacific and bifurcate to form the northward flowing Alaskan Current and the southward flowing California Current in the NE Pacific. Both currents continue to become parts of oceanic gyres (basin-wide horizontal circulations).

SCOPE OF VARIABILITY

An effective way of approaching the complexity of this system is to identify the principal temporal scales on which phenomena operate. These scales actually range from the instantaneous to the lifetime of the planet but for this review are identified as including the daily, monthly and seasonal, annual (calendar and water year), interannual, quasi-quintennial (here defined as 3-7 years), decadal, century, and millennial. The range between seasonal to century scales is particularly important to the goals of the PNCERS because larger temporal scales are related to larger spatial scales and *vice versa*. The identification of the scale of a process is very important because phenomena at different scales often have different processes operating and different causes for changes of rates or manner of operation. In addition, variability of biophysical phenomena at different scales frequently carries different implications for the way in which an ecosystem is managed. Scale is so important as an organizing framework that the bulk of this review is taken up by a consideration of atmospheric and oceanic phenomena on the scales listed above.

The Atmosphere

The principal processes operating in the atmosphere are ones of *physical climatology*, which involves the transfer and exchange of heat and moisture within the atmosphere and between the atmosphere and the Earth's surface, and *dynamic and synoptic climatology*, which treats the movement of air and its properties in the atmosphere and across the surface. These types of climatology assume varying degrees of emphasis on the different time scales outlined above. Atmospheric processes and phenomena are reviewed according to the scale most appropriate for them. In some cases there is a certain degree of sharing of scales as, for example, changes in intensity over a period of a century of the quasi-quintennial scale El Niño-Southern Oscillation (ENSO).

ATMOSPHERIC VARIABILITY AT THE MILLENNIAL SCALE

The millennial time-scale, which here focuses on the Holocene but which can also involve the Pleistocene and some preceding geological epochs, does not play such an important role for present-day ecosystem managers. But it does help to be aware of changes on this time scale for three reasons. First, the changes on the millennial scale can give information concerning the extremities to which the system can move and provide some feel for the degree of homeostasis of the system. Millennial-scale changes set the "limiting values" on the natural system changes in a practical and hierarchical sense. It is conceivable that human influence can help exceed these limits but it is useful to have some idea for where they are or have been in the past. Second, many of the floral and faunal species presently found in the ecosystem, or close relations of current species, have survived throughout all these extremities, thus indicating the degree of resilience of the ecosystem to natural changes. Third, it helps to recognize that many atmospheric phenomena that are important today have been present for a long time. Radiolarian records from the Santa Barbara basin, for example, indicate that El Niños have been occurring for at least 5.5 million years (Casey et al. 1989).

The occurrence of the major ice age of the Pleistocene epoch [approximately 2 million to 10,000 years before present (BP)] may be due to the changing geography of land and ocean distribution related to the continental drift forced by plate tectonics. Within the Quaternary period [i.e., the Pleistocene plus the Holocene (10,000 years BP to present)] variations of solar radiation reaching the Earth are important and are generally believed to be a major cause of continent-scale waxing and waning of ice sheets and cold and warm periods. The major orbital variations of the Earth include changes in the eccentricity of the planet's orbit around the sun (100,000 years periodicity), changes in the tilt (obliquity) of the Earth's axis to the plane of orbit (40,000 years periodicity), and changes related to a 'wobbling' of the Earth's axis (20,000 years periodicity). The combined effects of the three orbital parameters can cause variation in seasonal insolation as large as ~ 30% in high latitudes (Hartmann 1994). At the millennial time scale solar input at 45°N (the approximate latitude of the Pacific Northwest) can vary by about 70 Watts per square meter (Wm^{-2}) during the summer solstice, which may be compared to a present day mean of about 475 Wm^{-2} arriving at the top of the atmosphere and approximately 225 Wm^{-2} (Landry et al. 1989) which arrives at the surface of the Pacific Northwest in June.

Warona and Whitlock (1995) used pollen analysis from Little Lake in the central Oregon Coast Range and climatic reconstructions (COHMAP 1988) to determine five major climate periods during the past 42,000 years. The period between 42,000 and 24,770 years BP, a nonglacial interval, was cooler and wetter than today. From 27,770 to about 16,000 BP there was a full glacial period in the area marked by parkland, lodgepole pine, fir and mountain hemlock. During this period, the mean annual temperature was likely to have been 7°C lower than today with the January temperature 14°C lower. Conditions were also probably drier than today with the jet stream flowing well to the south. The Late Glacial period occurred between 16,000 BP to 10,000 years BP and was marked by an increase in temperature and effective moisture. There is some evidence for a reversal to a Younger Dryas climate between 11,000 and 10,000 years BP but this is not certain. Between 10,000 and 5,600 years BP (Early Holocene) temperature is believed to have increased and effective moisture decreased as summer droughts became a climatic feature associated with an expansion of the subtropical high pressure area in the eastern Pacific Ocean. The Cooperative Holocene Mapping Project (1988) noted that the time between 12,000 and 6,000 years BP was one of enhanced solar radiation in summer which would lead to a greater thermal contrast between land and sea. If the line of reasoning of Bakun (1990) is correct then this would also have increased coastal upwelling during this period. The Late Holocene, 5,600 years BP to the present, showed a trend toward cooler, moister conditions. Most of these changes are echoed to some extent by evidence from the Olympic Peninsula and the Puget Sound area and in the Cascades (Sea and Whitlock 1995).

ATMOSPHERIC VARIABILITY ON THE CENTURY SCALE

Apart from approximately the last 150 years, which are treated in the next section, not much is known concerning century-scale climate variability in the Pacific Northwest. During the last 1500 years the general climate of the northern hemisphere saw a warm period in Medieval times from about 1000 to 1300 AD, and a colder period variously described as occurring somewhere between 1300 and 1900 AD and known as the Little Ice Age (Lamb 1995). It is reasonable to assume that the Pacific Northwest was subject to these trends but in a less extreme way owing to its maritime location. The small amount of available evidence is either consistent with this suggestion or does not contradict it.

A tree ring chronology for Lost Forest (northeastern Lake County, eastern Oregon) from 1460 clearly shows that interannual variability is the norm on the century scale (Hatton 1989). Graumlich (1987) performed an excellent analysis for whole of the Pacific Northwest and concentrated on precipitation. A principal component analysis of the precipitation record identified three regions: Southern Valleys, Columbia Basin, and Western Lowlands. There are some north-south contrasts, especially in 19th Century. Between 1810-1838 it was wet in the Columbia Basin and dry in Southern Valleys while between 1850-1890 it was wet in Southern Valleys and dry in the Columbia Basin. Graumlich suggests that: 1) cool season droughts occur when there is a blocking high pressure sending storm tracks north of the Pacific Northwest; 2) cool season precipitation occurs when the polar front jet stream is over the Pacific Northwest; and 3) summer drought is due to expanded influence of subtropical high pressure ridge. Leavett et al. (1991) looked at tree rings near the Collier Glacier in the Oregon Cascades and found the glacier had not moved very far down the valley in the last 500 years. Sorenson (1983) found evidence for smaller advances in the Little Ice Age about 500 BP when new and high moraines occurred in the Cascades. The most exciting dendrochronological work related to PNCERS is the coastal tree ring and density records of Buckley et al. (1992) and Wiles et al. (1995) that extend records of both Pacific Northwest and Alaskan coastal air temperatures and Gulf of Alaskan and coastal sea surface temperatures back to about 1750. The Graumlich, Buckley et al. and Wiles et al. records display high variability but do not seem to have been examined for trends or cyclicities some of which can be seen in the latter (Figure 4.9).

Beyond the issues of the Medieval warming (1000-1300 AD) and the Little Ice Age (1300-1900 AD) some investigators have concentrated on cycles and on shorter time scales. Sediment cores from anoxic basins reveal a 60-70 year cycle of warming and cooling over the past 1500 years (GLOBEC 1994). The last cycle in this pattern, which ecologically is associated with sardine dominance over anchovy and *vice versa*, is seen with warming around 1925, cooling at 1948, and a return to warming about 1977. Ware and Thompson (1991) regard the 60 year cycle in

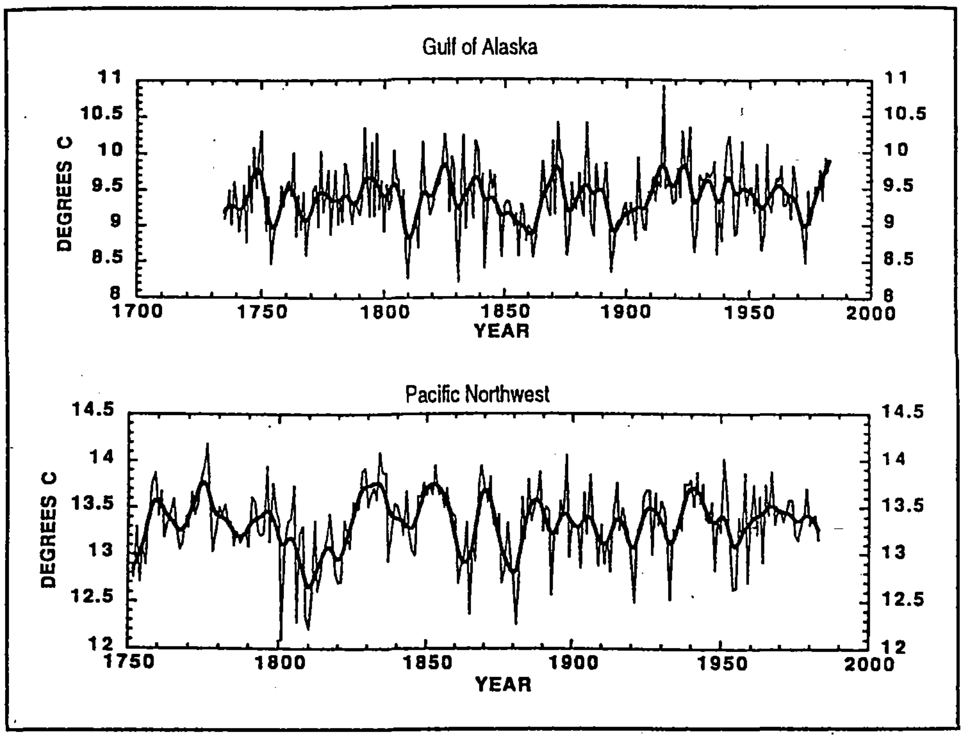

Figure 4.9. Summer temperature reconstructions from dendrochronological data for the Gulf of Alaska and the Pacific Northwest. (Source Wiles, G.C., R. D'Arrigo, and G.C. Jacoby. 1995. Modeling North Pacific temperatures and pressure changes from coastal tree-ring chronologies. In Proceedings of the Eleventh Annual Pacific Climate (PACLIM) Workshop, eds. K.T. Redmond and V.L. Tharp, 67-78. California Department of Water Resources, Interagency Ecological Studies Program for the Sacramento-San Joaquim Estuary. Technical Report 40. Reprinted with permission, courtesy California Department of Water Resources.)

Southern California data as being consistent with their belief that pelagic fish are responding to a 40-60 year oscillation in primary and secondary production that, in turn, is being forced by a long-period oscillation in wind-induced upwelling. They report evidence, some of which goes back to 1910, and several findings in other investigations, that is consistent with an approximate 50 year cycle. *A search for cyclic behavior in the range 40 to 70 years should be a research topic of some importance.* On yet another temporal scale, Sharp (1992) uses the evidence from fish scales buried in sediments in the Santa Barbara basin to identify a 250-350 year climatic cycles and a major change, at or near, the end of the Medieval Warm period (which he dates at 1050-1100 AD) tending away from warmer and wetter conditions with greater upwelling activity.

Trenberth (1993) reviewed coupled General Circulation Model output and suggested, under current projections of CO_2 increase, that the western coast of North America is expected to warm by about 1.0-1.5 °C by the year 2030 and that northern regions will warm more rapidly than southerly regions. The hydrologic cycle is expected to intensify by about 10%, leading to greater amounts of evaporation and precipitation. Trenberth (1995) has also suggested that the relative frequency of the El Niño mode in the past decade "may well be one of the primary manifestations of anthropogenic global warming". Some analyses have shown the possibility of century-scale oscillations in El Niño frequency (Endfield 1988; Anderson 1992). Anderson's (1992) analysis reveals a pattern in which El Niños are more frequent in cycles of about 90, 50, and 24 to 22 years periodicity. El Niño events were most frequent around AD 800 and least frequent during the Medieval Warm period (1100 to 1300 AD) when they had a periodicity of about 90 years.

It seems that there is a good opportunity to re-examine old proxy data and acquire new proxy data in an attempt *to learn more about climatic variability in the Pacific Northwest on the century scale* and this should be taken as a research task of some importance. In contrast to the century scale, the decadal scale has been given a great deal of attention in the last few years.

ATMOSPHERIC VARIABILITY ON THE DECADAL SCALE

Initial studies on the decadal scale concentrated on investigating whether there had been any 100 year-long warming or cooling trends in temperature data (precipitation data have been somewhat neglected in terms of trends on this scale). Roden (1989) found no such trends except for significant warming at large city stations which he attributed to heat island effects. Some other studies support this conclusion for parts of the Pacific Northwest (Greenland 1994a). More importantly, a highly sophisticated study by Dettinger et al. (1995) for the US as a whole for the period 1910-1987 concluded that the first three factors in a mulitvariate analysis (called empirical orthogonal functions), which collectively explain 75% of the spatial temperature variability of the US, had less importance in the Pacific Northwest area indicating relatively low temporal variability. They found, however that the Pacific Northwest did share somewhat in a general national trend for a warming from 1910 to the 1940s and a cooling to minimum in the 1970s. A nationwide study of 10- to 20-year climatic fluctuations showed that such fluctuations were frequent between 1931-1982 (Karl and Riebsame 1984). This national trend pattern and the tendency for marked interdecadal variation is part of a pattern noted by Wallace et al. (1996), that the best-marked interdecadal variation in temperature is a land (continental) -based, cold season phenomenon. Wallace et al. also found that the mixed-layer of the ocean has a "memory" (at least 12 months long) that masks warm season/cold season changes. This "memory" masking implies that interdecadal changes in temperature in the Pacific Northwest are likely to be rather smaller in size than those in continental interiors.

A great deal of attention has been given to the possibility of a certain degree of regularity in the operation of the atmosphere on the interdecadal scale and the possibility of fast changes between one decadal regime and another. Initial time series studies, although sometimes displaying these changes, did not emphasize them (Roden 1966, 1987; Bradley 1982). However, the remarkable winter of 1976-77 stimulated climatologists to pay more attention to the climatic conditions before and after this time. Several investigators (Trenberth 1990; Ebbesmeyer et al. 1991) noticed a "step" change, and in some cases, recognized that there had been earlier such changes of this kind in the observed environmental records of about 100 years in length (Ebbesmeyer et al. 1989).

Trenberth and Hurrell (1994) concentrated on the atmospheric part of the interdecadal change. Compared to the decadal-scale period preceding it, they found the troposphere over the North Pacific during the period 1976-1988 displayed a deeper and eastward shifted Aleutian low system in the winter half of the year, which advected warmer and moister air along the west coast of North America and into Alaska and advected colder air over the North Pacific Ocean. This period was also associated with a southward shift in storm tracks. Cayan and Peterson (1989) showed that when the Aleutian low was deep, storm tracks were guided northwards towards Alaska tending to result in anomalously high stream flows in Alaska and anomalously low stream flows in the Pacific Northwest (Figure 4.10). It seems reasonable to generalize these processes and their hydrological implications as being integral parts of regime shifts. Thus, during a West Coast flow regime (see below, Francis 1993) the Pacific Northwest has above-average precipitation values and is cooler while during an Alaskan regime the region has above-average temperatures and below-average precipitation leading to persistent droughts such as those of the late 1980s. This regime shift has recently been termed the Pacific Decadal Oscillation (PDO; Mantua et al. 1997).

Teleconnective or circulation indices are used on a number of scales to summarize the state of the atmosphere at a given time period on a quasi-hemispheric spatial scale. A number of these indices has been defined for the Pacific Northwest. The most relevant ones for the Pacific Northwest include the North Pacific Index, Pacific North American Index, Central North Pacific Index, and the Southern Oscillation Index. (SOI) These are defined and their operations explained in Appendix 4.1. The values of most of the indices are well correlated among each other (Cayan and Peterson 1989; Trenberth and Hurrell 1994). Figure 4.11 clearly identifies four decadal-scale periods, centered at about 1925, 1940, 1962, and 1984, of anomalously low values of the North Pacific Index, indicating a strong Aleutian low at these times. Other investigators have used their own indices (e.g., Beamish and Bouillon 1993), but most time series results of this kind are quite similar.

Ebbesmeyer et al. (1989) developed a very interesting measure called the Pacific Northwest Index (PNWI), composed of information on: 1) the coastal ocean temperature anomaly; 2) the annual average Puget Sound main basin temperature; and 3) the March 15 snow depth in the Cascades. The PNWI is extended back to 1916 and shows well the interdecadal pattern with 4 cycles in the period 1915-1987 (Figure 4.12). Spectral analysis of these data showed that 40 % of the variance could be explained by a peak with a period of about 16 years. Ebbesmeyer et al. (1989) suggest that there may be approximately five cycles in the period from 1889 to 1987. Different variables were used to develop an index called the PNI (Ebbesmeyer et al. 1995), made up of the annual precipitation at Cedar Lake, Washington, snow depth on Mount Ranier, air temperature at Olga, Washington, the percentage of salmon returning to the Fraser river around the northern end of Vancouver Island, the oyster condition index in Willapa Bay, and the maximum PSP toxin concentrations in June in butter clams in Sequim Bay. The PNI can be extended back to about 1946 (Figure 4.13) and, according to Ebbesmeyer et al. (1991), equals the average of the standard normal deviates (also called standardized anomalies) of the 1989 PNWI.

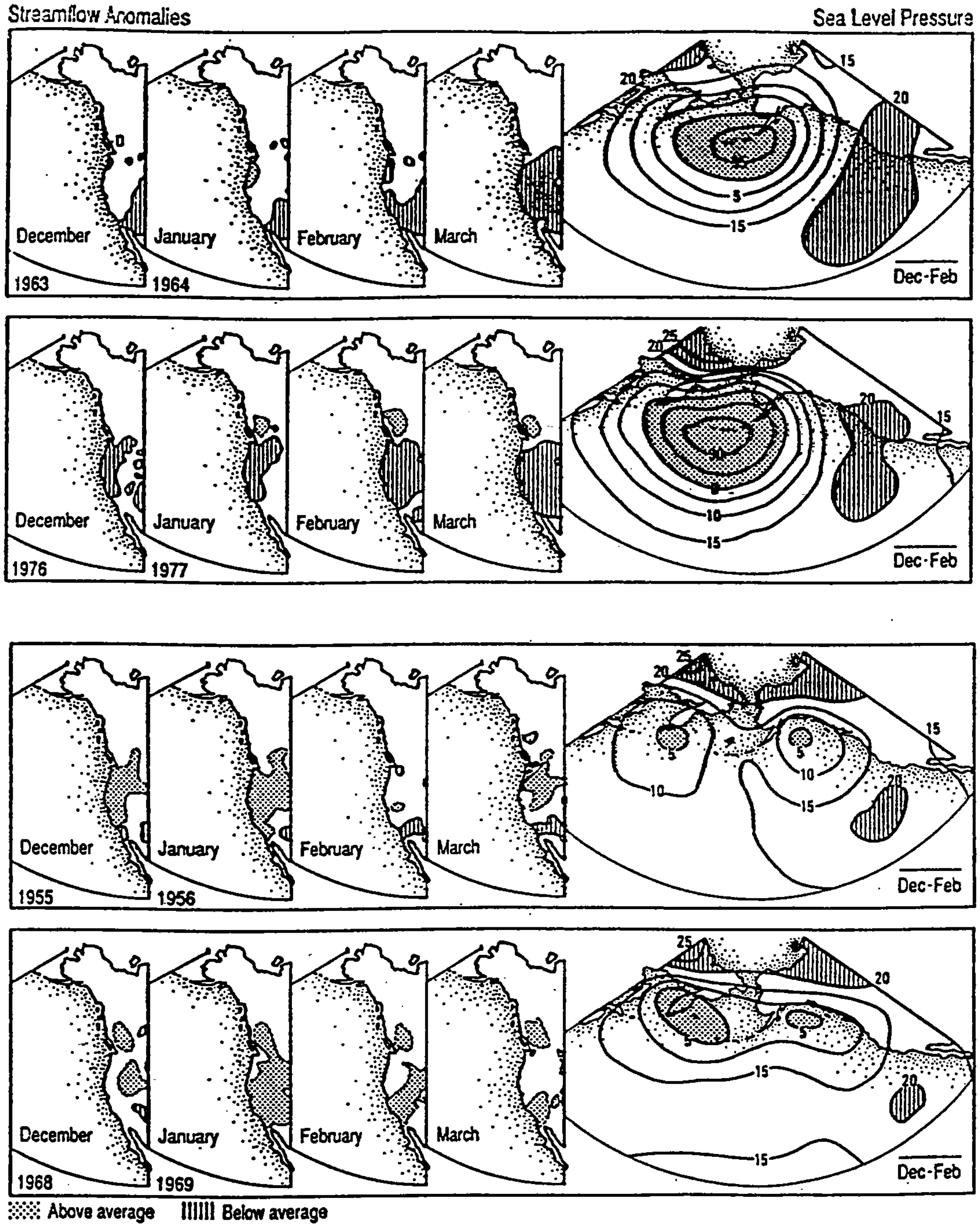

Figure 4.10. Stream flow anomalies under different atmospheric flow patterns. Upper panel are Alaska flow regimes; lower panels are West Coast flow regimes. (Source: Cayan, D.R., and Peterson, D.H. 1989. The influence of North Pacific atmospheric circulation on streamflow. In *Aspects of Climate Variability in the Pacific and the Western Americas*, ed. D. H Peterson, 375-397. Washington, DC: American Geophysical Union. Reprinted with permission, courtesy American Geophysical Union.)

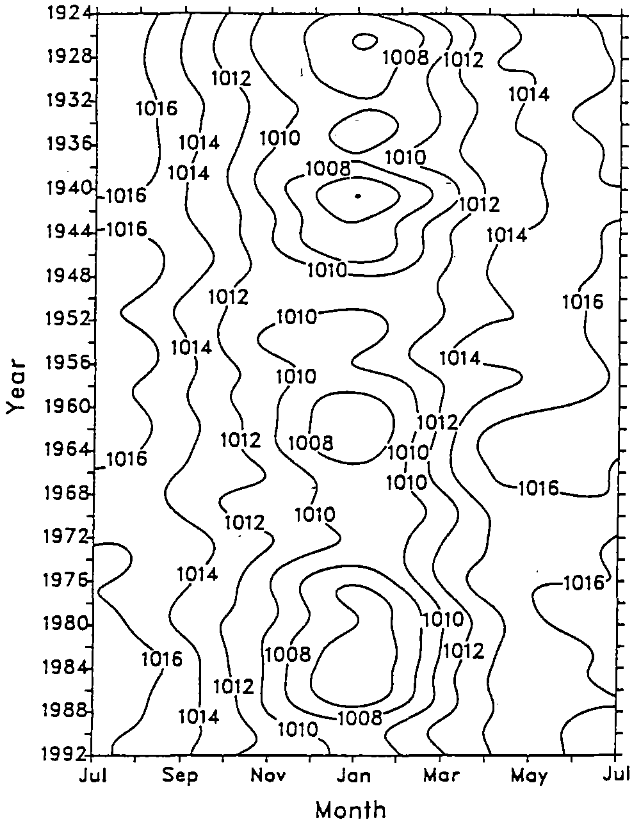

Figure 4.11. Changes in the North Pacific Index over the last century. Time series of the mean North Pacific sea level pressures (in millibars) averaged over the area between 30°N to 65°N, 160°E to 140°W as a function of month and year. Note four decadal-scale periods centered on 1925, 1940, 1962, and 1984 of very low values for the Aleutian low. (Source: Trenberth, K.E., and J.W. Hurrell. 1994. Decadal atmosphere-ocean variations in the Pacific. *Climate Dynamics* 9:303-319. Reprinted with permission, courtesy Springer-Verlag, New York, Inc.)

Regime changes may occur suddenly. Ebbesmeyer et al. (1991) identified 40 environmental variables from the ocean, atmosphere and biosphere and demonstrated a significant difference, which they called a step jump, in their deviate values between the periods 1968-1975 and 1977-1984. It is important to examine the nature of the cycles seen in the PNWI and PNI, and the strength of the evidence for them to determine whether or not they are cycles rather than modal regime changes separated by step jumps. Step jumps have been suggested by Francis (1993) who, following a model of Hollowed and Wooster (1991), only used one index, the Central North Pacific Index (CNP), to propose four modal changes between what he calls a West Coast Type and Alaskan Type circulation pattern (Figure 4.14). Greenland (1996) showed how the CNP was well-related to other atmospheric indices for the two circulation patterns (Figure 4.15). In particular, the Alaskan Type is a form of the positive Pacific North American Index (PNA) pattern and the West Coast Type is related to negative PNA values. The existence of regime changes is now well established for the last hundred years in the Pacific Northwest. Dell'Arciprete et al. (1996) assembled a comprehensive data set of Pacific Northwest air temperature, precipitation, streamflow, snowpack, and sea surface temperatures and found that 79% of the multi-variance could be explained by two statistical factors. The first factor (principal component, PC1) they called the "cool-and-wet / warm-and-dry" winter mode with values that parallel the PNW index. The second factor was labeled the "cool-and-dry /warm and wet" winter climate mode and is

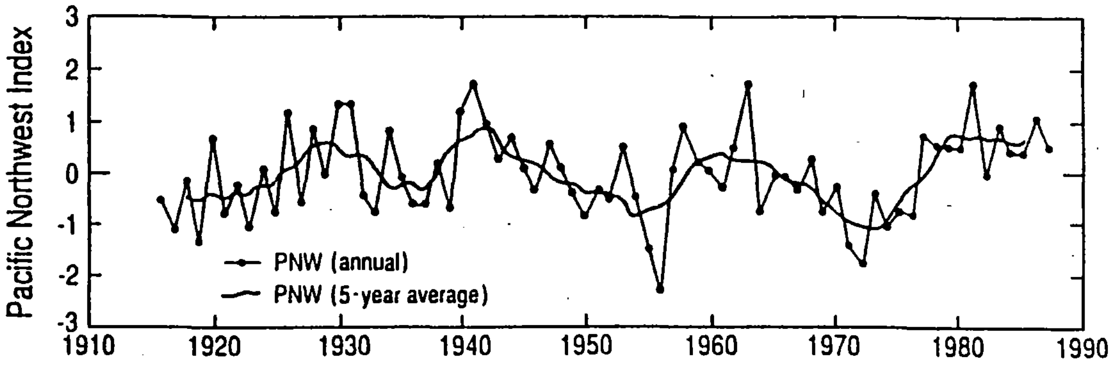

Figure 4.12. Changes in the PNW Index over the last century. The 5-year average shows four cycles of oceanic-atmospheric circulation between 1916 and 1987. (Source: Ebbesmeyer, C.C., C.A. Coomes, G.A. Cannon, and D.E. Bretschneider. 1989. Linkage of Ocean and Fjord Dynamics at Decadal Period In *Aspects of Climate Variability in the Pacific and the Western Americas*, ed. D. H Peterson, 399-417. Washington, DC: American Geophysical Union. Reprinted with permission, courtesy American Geophysical Union.)

dominated by interannual variability. Principal component 1 was well correlated with the Pacific Basin-wide variables of North Pacific sea surface temperature, North Pacific Index, and SOI. Re-examination of earlier comprehensive investigations (Roden 1989) of coastal air temperatures and sea surface temperatures demonstrates decadal changes well (Figures 4.16 and 4.17). Roden has also found some discontinuous West Coastal station data that could be used to establish a hypothesis of how the decadal regimes might be extended back into the beginning of the 19th Century. Royer (1993) found a clear 18.6 nodal (lunar tide) signal in Sitka, AK, air temperatures, and presumably, sea surface temperatures, going back to 1828. He suggests that this lunar signal is best found in high latitudes. A possible research task would be to *use discontinuous early coastal air and sea surface temperature data to build a suggested picture of decadal regime behavior extending back to the early 1800s.* Such a picture might tell us important information about the degree of "stationarity" of this type of change.

Since interdecadal changes seem to be related to the catch of some fish species (Francis and Sibley 1991; Francis 1993; Greenland 1996) it is important to find out more about them. Unfortunately the instrumental record is not long enough to ensure that the time-series is stationary. Because of this an important *research area would be to look at longer time-series of proxy data* (possibly the dendrochronological data going beyond that of Graumlich and Brubaker 1986; Graumlich 1987; Wiles et al. 1995) to see if these phenomena persist beyond the last century.

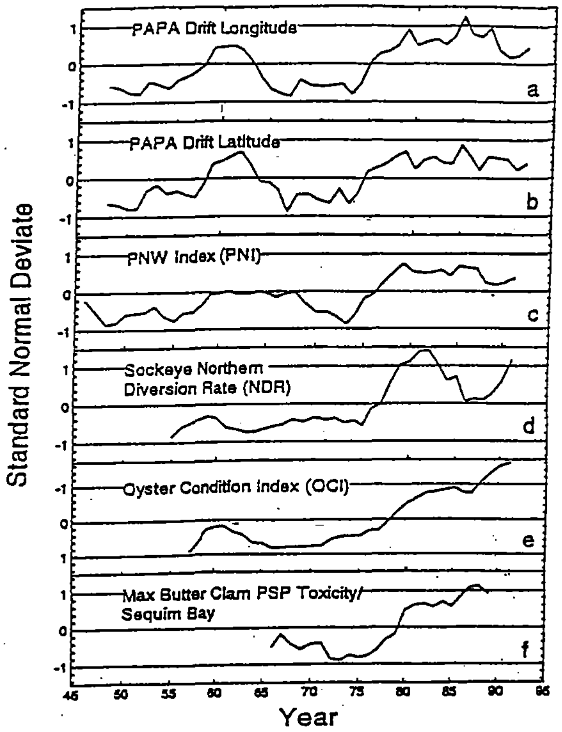

Figure 4.13. Changes in the PNI (c) back to 1945, along with five other environmental parameters. (Source: Ebbesmeyer, C.C., R. Chiang, A. Copping, G.M. Erickson, R. Horner, W.J. Ingraham, and L. Nishitani. 1995. Decadal covariations of Sequim Bay paralytic shellfish poisoning (PSP) with selected Pacific Northwest environmental parameters. *Puget Sound Research* '95:415-421.)

Schwing (1994) has pointed out that the variations in coastal temperature and salinity time-series could be interpreted as either decadal periods of slightly increasing (or decreasing) temperature followed by rapid increases (or decreases) of temperature, *or* as a series of "regime shifts" where the mean annual temperature over a short period makes a rapid shift following a decadal period of relatively level temperature. This is consistent with the ideas of Francis (1993). Another research area, then, is *to determine whether the changes are quasi-cyclic in form or quasi-modal punctuated by step functions*. Dettinger et al. (1995) found peaks in spectra of US air temperatures at 10 and 7.4 years with strongest oscillation in the Western US and with noticeably step-like transitions. Another research area is to find out *what causes the change between one part of the cycle or modal type and another*. Francis (1993) has implied a relationship between shifts from West Coast Type to Alaskan Type (now being termed the Pacific Decadal Oscillation) and the occurrence of El Niño winters that have the highest sea surface temperatures in the far western Pacific. Trenberth (1995) and Trenberth and Hoar (1996) have suggested that the decadal time-scale variations are linked to recent changes in the frequency and intensity of El Niño versus La Niña events and related forcing from the anomalous sea surface temperatures of the tropics. An intense investigation on this general topic is justified, and is all the more urgent since other studies have shown well-marked decadal variation in the Atlantic sector of the Northern Hemisphere (Hurrell 1996) and the fact that the North Atlantic Oscillation has remained in one extreme phase over the last decade (Hurrell 1995). Another research question related to all these issues is, *given the fact that the changes are somewhat statistical in nature (i.e., they show up best when the data are aggregated for the whole winter and in standardized anomalies rather than 'raw' data), how can this knowledge best be transferred to, and used by, decision makers?*

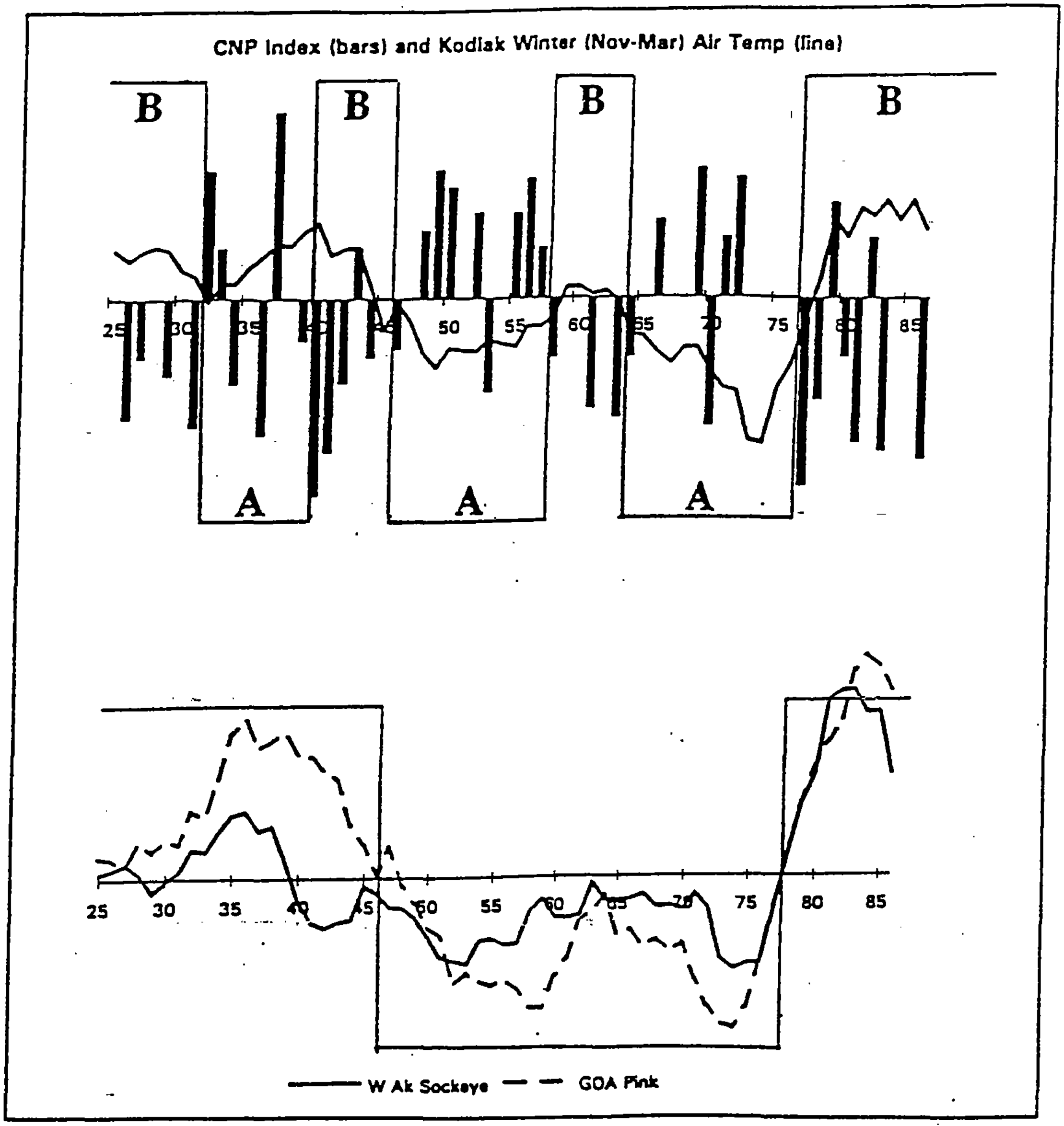

Figure 4.14. Changes and possible regimes in the Central North Pacific (CNP) over the last century. The upper graph plots the CNP Index and the winter air temperature in Kodiak, Alaska, to suggest West Coast Type (A) and Alaska Type (B) circulation regimes between 1925 and 1985. The lower graph shows distinct, related shifts in abundance of Alaska sockeye salmon and Gulf of Alaska pink salmon. Note the "regime shift" apparent in both graphs in 1976. (Source: Francis, R.C. 1993. Climate change and salmonid production in the North Pacific Ocean. In Proceedings of the Ninth Annual Pacific Climate (PACLIM) Workshop, April 21-24, 1992, eds. K.T. Redmond and V.L. Tharp, 33-43. California Department of Water Resources, Interagency Ecological Studies Program, Technical Report 34. Reprinted with permission, courtesy California Department of Water Resources.)

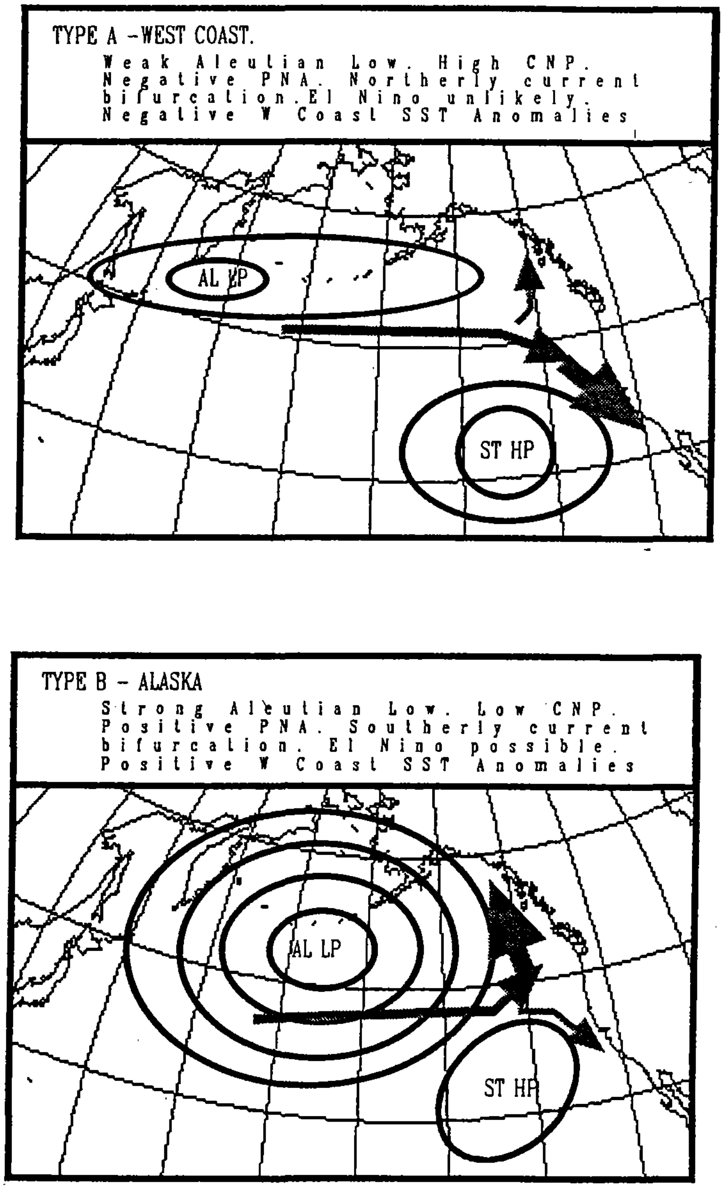

Figure 4.15. Schematic diagram of the West Coast and Alaskan flow types with their relation to several teleconnective indices. AL LP is Aleutian low pressure; ST HP is subtropical high pressure; arrows show relative magnitude of strength of oceanic surface currents. This suggests the relationship between atmospheric conditions and ocean currents. (Source: Greenland, D. 1996. Offshore coho salmon populations near the Pacific Northwest and large scale atmospheric events. In Proceedings of the Twelfth Annual Pacific Climate (PACLIM) Workshop, May 2-5, 1995, eds. C.M. Isaacs and V.L. Tharp, 109-119. California Department of Water Resources, Interagency Ecological Program. Technical Report 46. Reprinted with permission, courtesy California Department of Water Resources.)

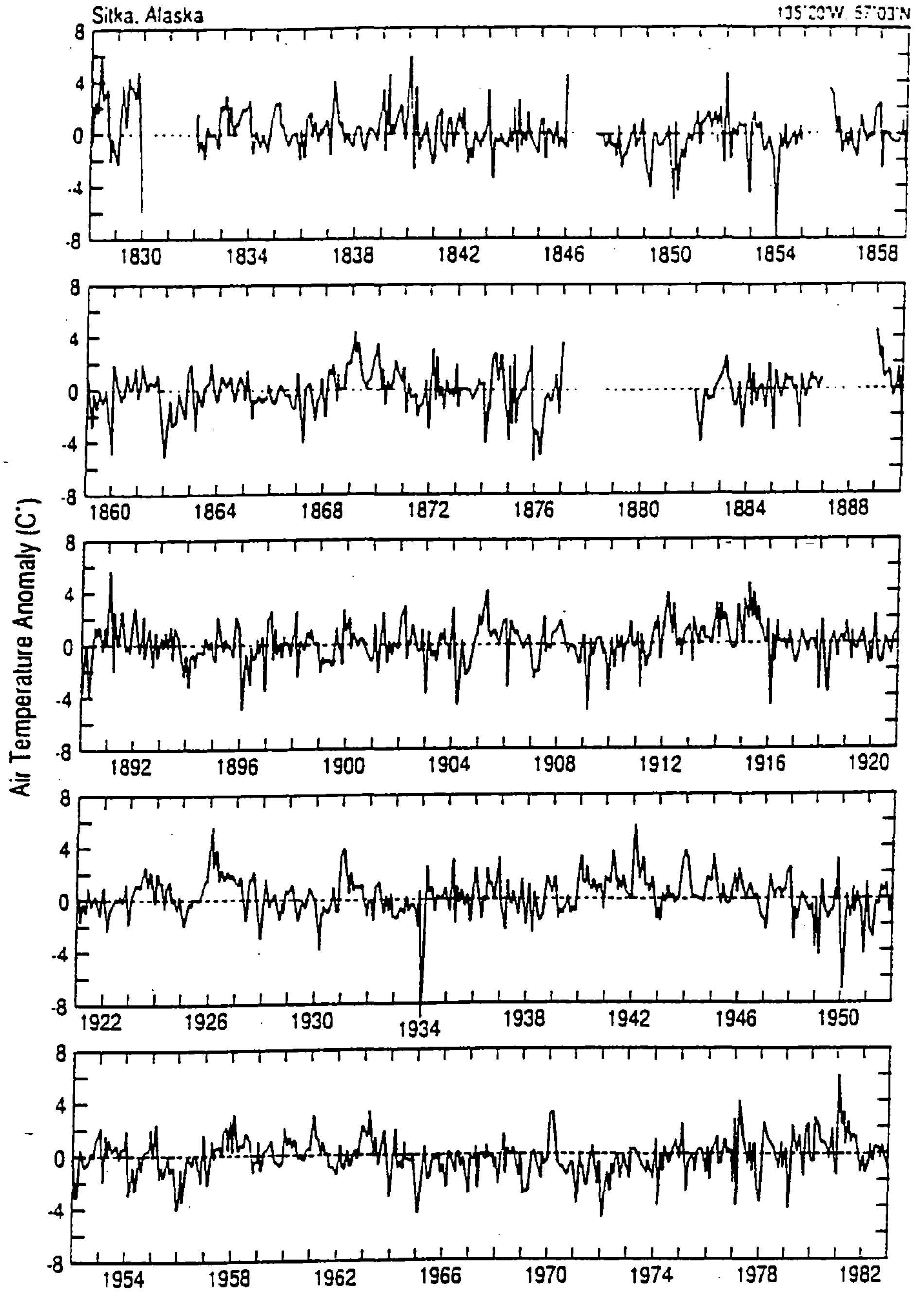

Figure 4.16. Air temperature anomalies from long-term monthly means at Sitka, Alaska. (Source: Roden, G.I. 1989. Analysis and interpretation of long-term climatic variability along the West Coast of North America. In *Aspects of Climate Variability in the Pacific and the Western Americas*, ed. D. H Peterson, 93-111. Washington, DC: American Geophysical Union. Reprinted with permission, courtesy American Geophysical Union.)

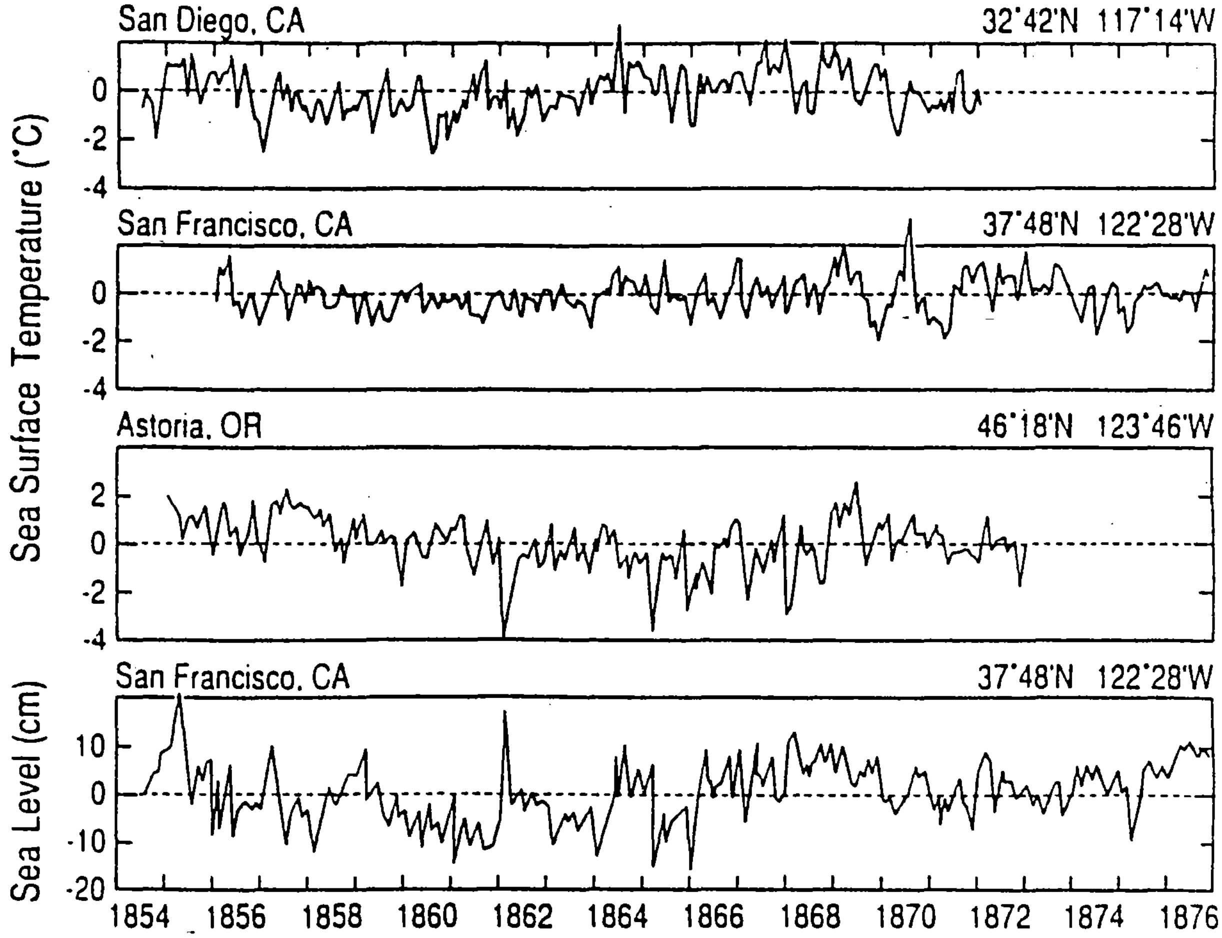

Figure 4.17. Sea surface temperature anomalies from 1854-1876 at California and Oregon tide stations. (Source: Roden, G.I. 1989. Analysis and interpretation of long-term climatic variability along the West Coast of North America. In *Aspects of Climate Variability in the Pacific and the Western Americas*, ed. D. H Peterson, 93-111. Washington, DC: American Geophysical Union. Reprinted with permission, courtesy American Geophysical Union.)

ATMOSPHERIC VARIABILITY ON THE QUASI-QUINTENNIAL SCALE - ENSO

The dominant source of variation on the quasi-quintennial scale is related to the El Niño-Southern Oscillation (ENSO). El Niño refers strictly to a warming of sea surface temperatures in the eastern tropical Pacific Ocean but is usually associated with a basin-scale warming extending from the coast of South America to the International Dateline. An important hypothesis suggests that the ENSO system, which is primarily driven by the ocean, is a natural result of interactions between oceanic Kelvin and Rossby waves in the tropical part of the Pacific Ocean (Graham and White 1988). El Niño is linked in the atmosphere to times of low sea level pressure in the area of Tahiti and high sea level pressure near Darwin, Australia. The atmospheric part of El Niño is embedded in the Southern Oscillation in which the difference of pressure between these two places oscillates between high and low on a 2-7 year time scale. The Southern Oscillation is itself part of a larger oscillation in the strength and direction of flow of the "Walker Cell", which is a cell of air with rising and falling limbs near Tahiti and Darwin, respectively, and surface and upper air flows moving either east or west to provide continuity of mass. Most commonly, the state of the Southern Oscillation is measured by the departure from the long-term monthly mean sea level pressures at Tahiti minus those at Darwin in an index called the Southern Oscillation Index (SOI). However, there are many other ways of measuring the phenomena of the oscillation. Indeed, Murphree (1996) has pointed out that the SOI may not be the most appropriate measure of the ENSO phenomena as they are related to the Pacific Northwest. He has identified monthly mean 200 millibar (mb) pressure anomalies over the North Pacific as a useful tool because it is at this level where much of the tropical-extra tropical ENSO-scale connection may be found (Murphree and Reynolds 1995). Other measures of ENSO more applicable for the Pacific Northwest than are tropical sea surface temperatures, may be available for the ocean as well. McGowan et al. (1996) have suggested the use of North American West Coastal sea surface temperatures and changes in sea level heights. Consequently, an important research topic is *what are the most appropriate measures of both the atmospheric and the oceanic manifestations of ENSO in relation to the Pacific Northwest?*

The SOI is not the only measure of El Niño phenomena. Cayan and Webb, (1992) following earlier workers, grouped years into El Niño and La Niña years from 1901. Quinn (1992) made a classic reconstruction of El Niño years classified in five classes of strength, three classes of time within the year, and five classes of confidence in the data used for any particular year. The record goes back five centuries to 1497 and encompasses both large-scale and regional El Niños. Quinn has also extended the record back to 622 AD using data on Nile River flooding. Tree-ring records have been employed to reconstruct SOI values back to 1607 by Lough (1992). The ENSO signal is also the dominant signal in a 1500 year ice-core record from Peru (Thompson et al. 1992). The major El Niño (warm event) and La Niña (cold event) episodes between 1877 and 1988 have been identified by Diaz and Kiladis (1992) as shown in Table 4.1. The atmospheric manifestation of El Niño and La Niña in the Pacific Northwest, as measured by SOI values, is well marked. Low SOI values (El Niños) are correlated with reduced precipitation (Redmond and Koch, 1991), snowpack and streamflow in the region (Cayan and Webb 1992; Figures 4.18, 4.19 and 4.20). The Pacific Northwest also tends to display warmer winter temperatures and drier than usual conditions (Redmond and Koch 1991). Redmond and Koch (1991) used a four month lag to correlate June to November SOI values to precipitation and temperature values in the following October to March for western climate divisions. The results for the Pacific Northwest, both east and west of the Cascades in Washington and Oregon, show mostly a very clear ENSO signal (Table 4.2), although the signal on the west is somewhat more clear. This is consistent with results found for the Andrews Forest Long-Term Ecological Research site in the foothills of the Cascades in Oregon (Greenland 1994a). Ropelewski and Halpert (1996) demonstrated the most consistent El Niño response is decreased precipitation at 4 to 12 months after the peak of the ENSO warm event with the largest response occurring in the November after the June in which the El Niño peaked. The highest El Niño-related temperatures in the Pacific Northwest

Table 4.1. Major El Niño (warm event) and La Niña (cold event) episodes between 1877 and 1988. After Diaz and Kiladis (1992).

Warm Event (El Niño) Years	Cold Event (La Niña) Years
1877	1886
1880	1889
1884	1892
1888	1898
1891	1903
1896	1906
1899	1908
1902	1916
1904	1920
1911	1924
1913	1928
1918	1931
1923	1938
1925	1942
1930	1949
1932	1954
1939	1964
1951	1970
1953	1973
1957	1975
1963	1988
1965	
1969	
1972	
1976	
1982	
1986	
Total = 27	Total = 21

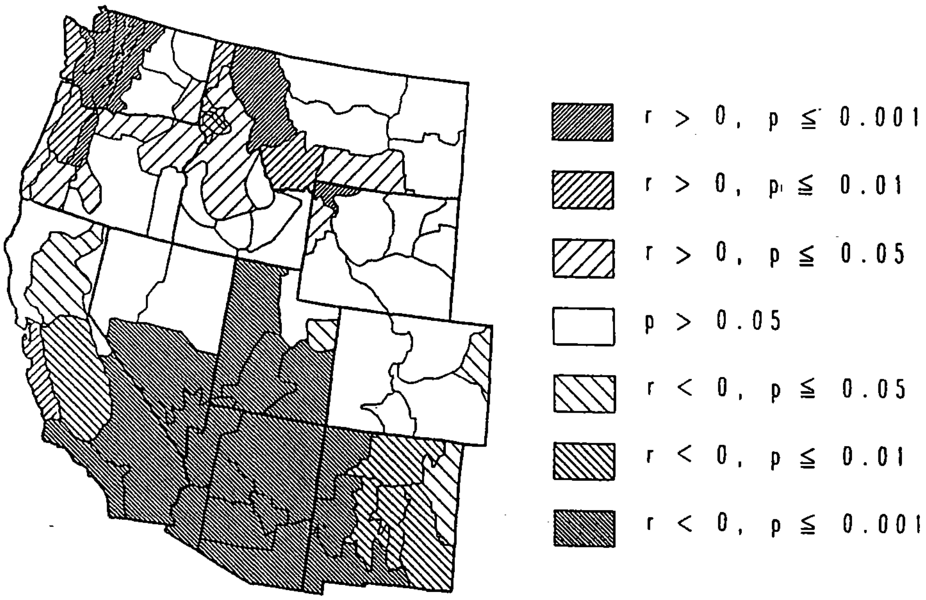

Figure 4.18. Relationship of Southern Oscillation Index (SOI) to precipitation values in the western US. r is the correlation coefficient and p is the probability of random occurrence. (Source: Redmond, K.T., and R. Koch. 1991. ENSO vs. surface climate variability in the western United States. *Water Resources Research* 27:2381-2399. Reprinted with permission, courtesy American Geophysical Union.)

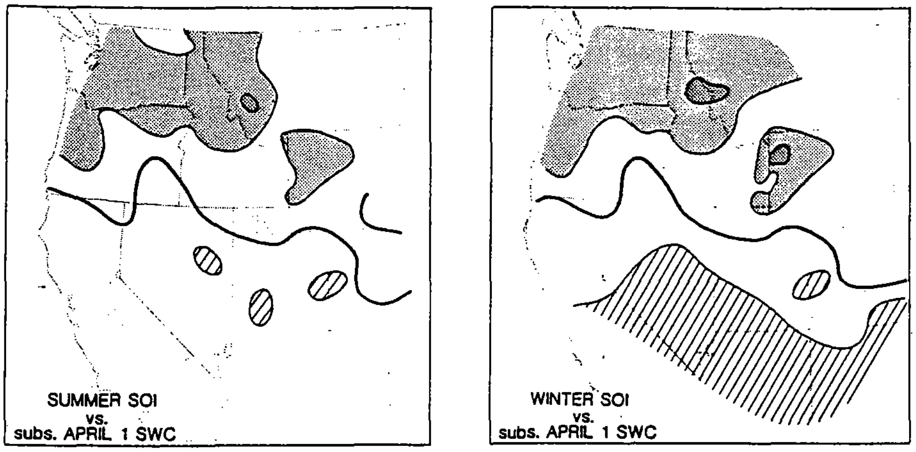

Figure 4.19. Relationship of Southern Oscillation Index (SOI) with snow water content (SWC) in the western US. Stippling represents positive correlation and hatching represents negative correlation. (Source: Cayan, D.R., and R.H. Webb. 1992. El Niño/Southern Oscillation and streamflow in the western United States. In *El Niño: Historical and Paleoclimatic Aspects of the Southern Oscillation*, eds. H.F. Diaz and V. Markgraf, 29-68. Cambridge: Cambridge University Press. Reprinted with permission, courtesy Cambridge University Press.)

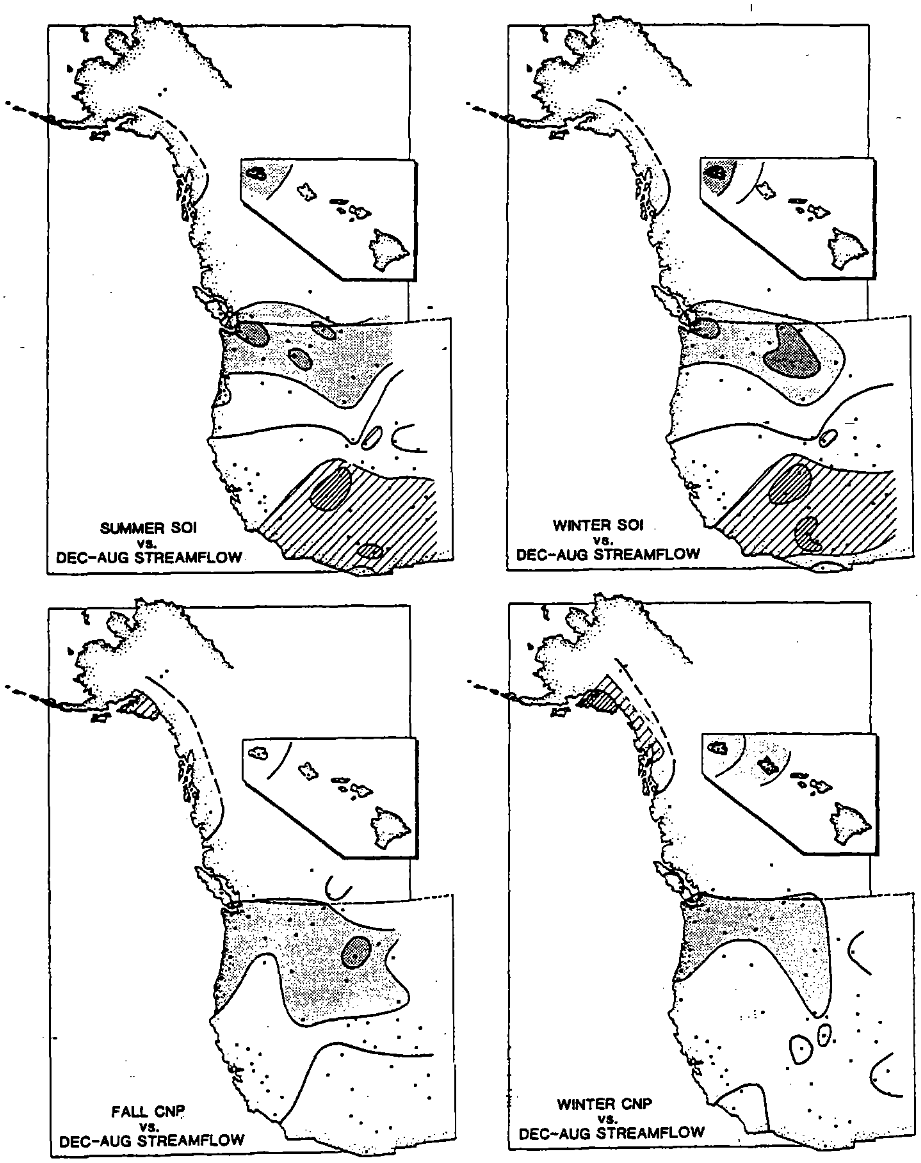

Figure 4.20. Relationship of Southern Oscillation Index (SOI) and Central North Pacific Index (CNP) with streamflow in the western US. Stippling represents positive correlation and hatching represents negative correlation. (Source: Cayan, D.R., and R.H. Webb. 1992. El Niño/Southern Oscillation and streamflow in the western United States. In *El Niño: Historical and Paleoclimatic Aspects of the Southern Oscillation*, eds. H.F. Diaz and V. Markgraf, 29-68. Cambridge: Cambridge University Press. Reprinted with permission, courtesy Cambridge University Press.)

Table 4.2. Statistics from analyses of June-November Southern Oscillation Index (SOI) and October-March Climate Divisional Precipitation and Temperature. The correlation coefficient, r, shows positive correlations between SOI and precipitation, and negative correlations between temperature and SOI. Ratio is the quotient of the average precipitation for years with SOI > 0.5 divided by that for years with SOI < 0.5. Difference in temperature is the average difference also between years with SOI > 0.5 and those for years with SOI < 0.5 (from Redmond and Koch 1991).

Division	Precipitation	Ratio	Temperature	Difference °C
	r		r	
Washington				
West Olympic Coast	0.363	1.22	-0.399	-1.1
NE Olympic San Juan	0.455	1.36	-0.384	-1.0
Puget Sound Lowlands	0.416	1.27	-0.357	-1.0
E Olympic-Cascade Foothills	0.481	1.30	-0.355	-1.0
Cascade Mts. west	0.512	1.35	-0.344	-1.1
E Slope Cascade	0.428	1.42	-0.246	-0.9
Okanogan-Big Bend	-0.007	1.06	-0.254	-1.2
Central Basin	0.125	1.19	-0.171	-0.8
Northeast	0.183	1.14	-0.265	-1.1
Palouse-Blue Mts.	0.301	1.23	-0.165	-0.7
Oregon				
Coastal area	0.268	1.19	-0.304	-0.8
Willamette Valley	0.341	1.25	-0.229	-0.6
Southwest Valleys	0.261	1.29	-0.186	-0.6
Northern Cascades	0.471	1.38	-0.203	-0.9
High Plateau	0.252	1.23	-0.083	-0.3
North central	0.239	1.22	-0.112	-0.5
South central	0.171	1.16	-0.080	-0.3
Northeast	0.301	1.26	-0.185	-0.7
Southeast	-0.047	1.01	-0.028	-0.2

occur between November and June, peaking in March, following an El Niño of the previous June. Yarnal and Diaz (1986) also determined that the west coast temperature and precipitation anomalies during warm ENSO events are associated with a strong Pacific North American Index (PNA) pattern, while during cold events there is a reversed-polarity PNA pattern. More recently Ropelewski and Halpert (1996) showed the value of expressing ENSO-related shifts in median precipitation amounts expressed as percentiles with respect to climate normal values. This approach can be potentially useful for managers interpreting ENSO forecasts but the authors did not apply the approach to the Pacific Northwest. Consequently a research question would be *what are the sizes of ENSO-related shifts in precipitation and temperature median values to climatic normal values in the Pacific Northwest?*

The 1982/83 El Niño is the largest one recorded (this was written before the 1997/98 El Niño). It was more noteworthy for its oceanic effects in the Pacific Northwest than for those in the atmosphere. Even so, the SOI value was the lowest recorded since modern records began in 1935. There was the greatest negative 700 mb seasonal mean height anomaly since the beginning of records in 1948 (see Appendix 4.1) and the second lowest monthly mean sea level pressure for February in the NE Pacific since records started in 1899. Temperature anomalies in the Pacific Northwest for the winter of 1982/83 ranged between 1 and 2°C above the 30 year mean. But instead of being dry, the precipitation for the winter was between 100-150% above normal in the Pacific Northwest mainly because of a wet February (Quiroz 1983). Although this year appears as an outlier in a scattergram of winter water-year precipitation at the H. J. Andrews Forest, Oregon, it is more an outlier because of its SOI value rather than its climatic value (Greenland 1994a).

La Niña events also have important effects on the Pacific Northwest climate. Kahya and Dracup (1993) are among several investigators to demonstrate that high precipitation and high streamflow values in the Pacific Northwest are often associated with La Niña years. We mention below that severe floods may also be associated with such years. A more systematic investigation of La Niña climate in the Pacific Northwest is justified.

Whatever measure is used, the nature, intensity, and geographic extent of effects vary from one El Niño to another. Nevertheless, the similarities between one event and another are large enough to permit model predictions and seasonal forecasts. Emery and Hamilton (1985) noted empirically that not only are ENSO episodes often coincident with a well developed Aleutian low, but also that the episodes often follow a year of poorly developed Aleutian low pressure. Graham and Barnett (1995) used 6 month lead forecasts of tropical Pacific sea surface temperatures to predict 700 mb height-anomalies for the Northern Hemisphere. The forecast worked best for extreme episodes but had substantial success in 23 consecutive winter predictions; however the results for the Pacific Northwest were not as good (Figure 4.21; Graham and Barnett). The National Center for Environmental Prediction (NCEP) uses a combination of a number of different forecast methods to provide long-range forecasts for the US. As an example of the wording used in the forecast we present the following:

> The forecast issued December 1995 for the period January, February, and March, 1996 using statistical methods called for cold temperatures in the Pacific Northwest, forecasts of temperatures from dynamical methods did not mention the Pacific Northwest. Dynamical methods called for wetness in the Pacific Northwest while statistical methods called for a dry Pacific Northwest.
>
> The forecast issued March 1996 for the period April, May, and June 1996 using statistical methods called for warm temperatures in the Pacific Northwest, forecasts of temperatures from dynamical methods called for "cool on northern tier for spring and summer 1996". Dynamical methods said nothing about the Pacific Northwest while

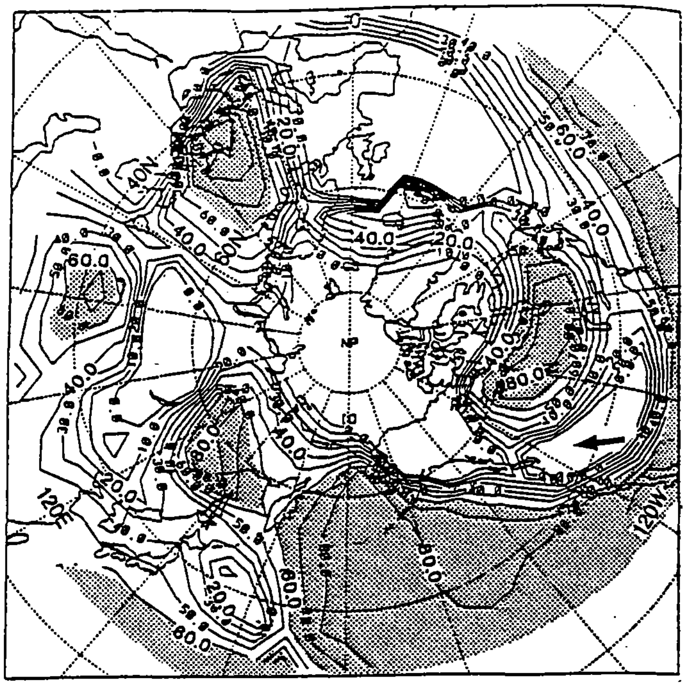

Figure 4.21. Polar-view global map showing areas (shaded) of 90% success in predicting winter weather conditions (700 mb) using 6-month lead forecasts of tropical sea surface temperature. The Pacific Northwest (arrow) is at the edge of areas where this technique is successful. (Source: Graham, N.E., and T.P. Barnett. 1995. ENSO and ENSO-related predictability. Part II: Northern hemisphere 700 mb height predictions based on a hybrid coupled ENSO model. *Journal of Climate* 8:544-549. Reprinted with permission, courtesy American Meteorological Society.)

> statistical methods called for wetness in the Pacific Northwest for April, May, and June.
>
> Both forecasts generally believed La Niña conditions would continue through the summer but some (of 12) forecasting methods suggested that it would end by fall and winter would see rising sea surface temperatures in the equatorial Pacific (NOAA 1996).

Two potential research projects arise from these efforts. First, model forecasting studies should be reviewed, and their efficiency assessed, with regard to their specific Pacific Northwest area forecast. Second, the best methods for use of National Weather Service (NWS) Long-lead forecasts by Pacific Northwest managers should be determined. At the same time NOAA should work on educating the forecast users on how to assess the forecasts, particularly at times when different forecast methods render different prognostications. Because an El Niño event leads to warming in the Pacific Northwest area, there is a belief that it can, to some extent, be used as an analog for global climate warming conditions. This may be true in some areas but Bakun (1990) has pointed out that this may not be true as far as coastal upwelling is concerned.

As mentioned above, Francis (1993) has implied a relationship between shifts from West Coast Type flow mode to Alaskan Type flow mode and the occurrence El Niño winters that have the highest sea surface temperatures in the far western Pacific. He points out that three of the four hypothesized shifts from West Coast to Alaskan flow regimes occurred during the high west Pacific sea surface temperature El Niño times of 1925/26, 1941/42 and 1976/77. An interesting research topic would be *to see if this West Coast to Alaskan Type flow regime switch also occurred in earlier decades*. The earlier data of Roden (1989) and earlier El Niño occurrence data (see Diaz and Markgraf 1992) could be used to test this hypothesis. A related question would be to find out *what causes the switch back from Alaskan to West Coast Type flow regimes*?

Wang (1995) has shown that atmospheric and oceanic conditions prior to an El Niño event have changed since the 1970s. Prior to this, the onset was preceded by a large anomalous cyclone (low pressure) over Australia and a relaxation of the easterly Trade Winds leading to an increase of sea surface temperature off the South American coast prior to an increase in sea surface temperatures in the central tropical Pacific. Instead, from 1980, the onset phase of El Niño has been preceded by an anomalous cyclone over the Philippines Sea, enhanced Trade Winds in the southeast Pacific, and central Pacific sea surface temperatures warming before those on the South American coast. Recent studies have also suggested that the unusually long El Niño event of the early 1990s is related to anthropogenic-induced global climate change since it is statistically unlikely to be part of decadal time scale variation (Trenberth and Hoar 1996). It is certain that ENSO related phenomena will be the focus of much research attention for many years to come.

ATMOSPHERIC VARIABILITY AT THE INTERANNUAL SCALE

Preliminary analyses of precipitation variations by Greenland (unpublished) indicate considerable variability at a biennial scale for the Northern Cascade Climate Division of Oregon. But on a national scale Dettinger et al. (1995) found that biennial scale variability in air temperature is much more marked in many other parts of the country. Dettinger et al. explain how the temperature variations across the country are associated with the Quasi-Biennial Oscillation (QBO). The QBO is best seen in the mean zonal-winds of the equatorial stratosphere, which have zonally symmetrical easterly and westerly regimes alternating regularly with periods varying from about 24 to 30 months (Holton 1992). Atmospheric circulation patterns in the North America area related to the QBO include stationary centers at about 40° latitude off both coasts that fluctuate in phase opposition. The centers bring warm air to the Southwest and cool air to the Northeast and *vice versa* about 12 months later (Dettinger et al. 1995). Barnston et al. (1991) have postulated a relationship between ENSO and the QBO such that during a warm ENSO event there is a preference in January and February for a strong Pacific North American Index circulation pattern in the west QBO phase.

Another feature that should be considered at this scale is the effect of major explosive volcanic eruptions. Such events tend to be stochastic and time-scale independent but their effects play out on a biennial scale. Portman and Gutzler (1996) have shown that at various times in the two years after a major eruption the Pacific Northwest tends to be anomalously cool in winter and spring and wet in summer. Based on the work of these authors and Lamb (1995) the most significant eruptions in recent times are listed in Table 4.3.

Table 4.3. Important volcanic eruptions which have effected the atmosphere. After Portman and Gutzler (1996) and Lamb (1995). MA and MI indicate major and minor eruptions, respectively.

Volcano	Year	Severity
Krakatau	1883	MA
Pelée	1902	MA
Soufrière	1902	MA
Santa Maria	1902	MA
Ksudach	1907	MA
Katmai	1912	MA
Hekla	1947	MI
Bezymyannyy	1956	MI
Agung	1963	MA
Awu	1966	MI
Fernandina Island	1968	MI
Fuego	1974	MI
Mount St. Helens	1980	MA
El Chichón	1982	MA
Mount Pinatubo	1991	MA

ATMOSPHERIC VARIABILITY AT THE ANNUAL SCALE

The seasonal changes of the Pacific Northwest include a long winter rainy season and a hot, dry summer. Alsop (1989) has identified the seasons of Oregon as follows. On the average, the winter season runs from November 5 to March 12. Spring is between March 19 and May 14. Summer lasts from May 21 to September 17 while the short fall season is between September 24 and October 29.

Monthly and Seasonal. More detail of the principal changes in the typical seasonal variations in surface pressure are provided in Figure 4.22 (Terada and Hanzawa 1984). Between latitudes 42-46°N is found the greatest poleward energy flux in the northern hemisphere. The Pacific Northwest lies, on the average, in the latitude of the main Polar Front Jet Stream (PFJ) in summer and just north of PFJ in winter. While the surface pressure is dominated by subtropical high pressure in summer and a mixture of high and Aleutian low in winter, the upper air (700 mb) over the Pacific Northwest is dominated by a zonal jet in January with a ridge over western Alaska. In July the influence of upper air high pressure is seen. The climate in the coastal region is markedly maritime with lower temperatures than the interior continent in July and higher than the interior continent in January. There is a very marked gradient of annual temperature range between maritime and continental areas that makes climatic modeling difficult in this part of the world. Most cyclonic centers in winter track north of the Pacific Northwest but trailing fronts affect the

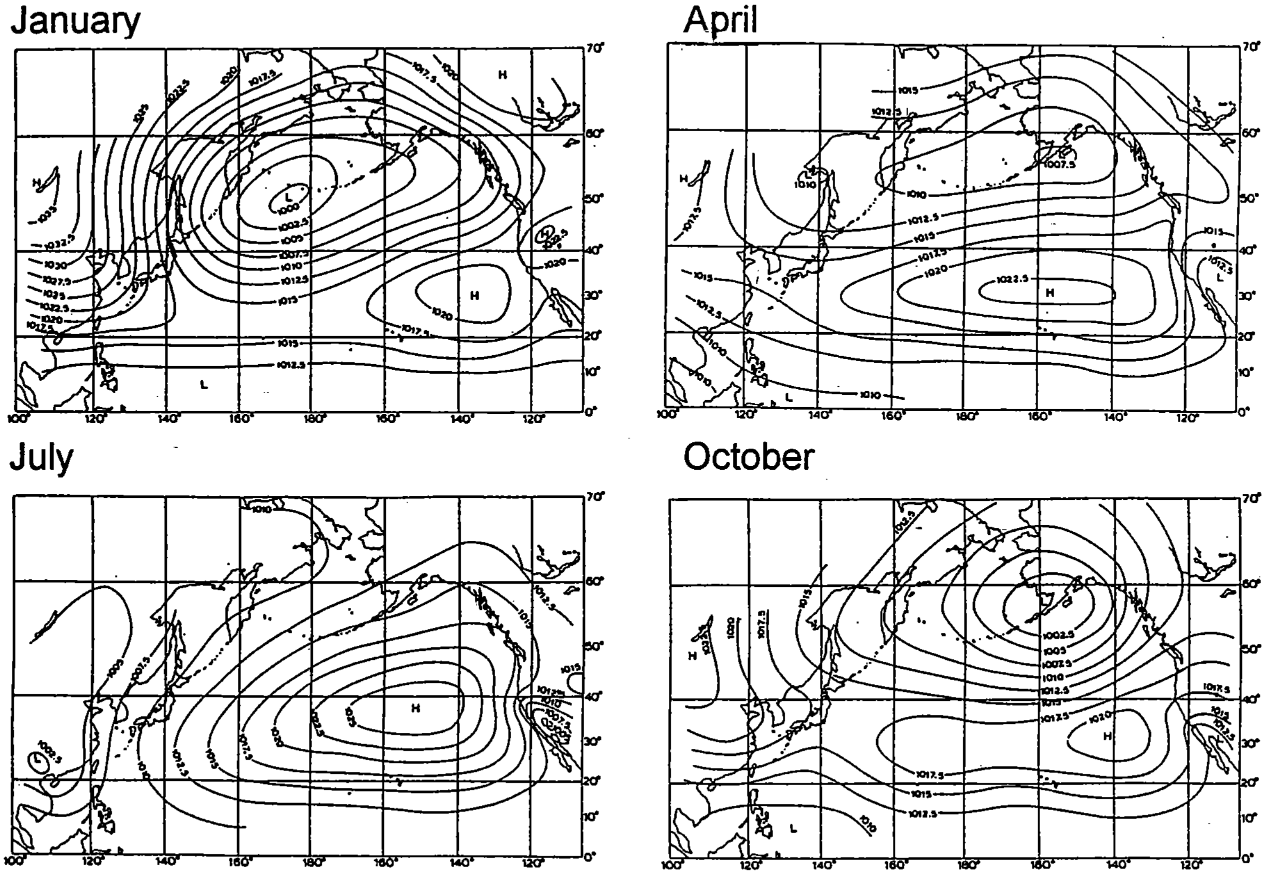

Figure 4.22. Mean sea level pressure (millibars) over the North Pacific Ocean in January, April, July, and October. Note the strong Aleutian low and weak subtropical high in January compared to the dominance of the high pressure in July. April and October show transitions between theses extremes. (Source: Terada, K., and M. Hanzawa. 1984. Climate of the North Pacific Ocean. In *World Survey of Climatology,* ed. H.E. Landsberg Vol. 15, 431-477. *Climates of the Oceans*, ed. H. Van Loon. Amsterdam: Elsevier. Reprinted with permission, courtesy Elsevier Science - NL.)

area. In July, storm tracks are in the latitude of Alaska. Pacific airmasses dominate all year round (Barry and Chorley 1992; Bryson and Hare 1974).

Within the Pacific Northwest the warmest month near the coast is August. This delay is due to the peak of cold offshore currents in July and the associated fog. The annual average snow fall is between 2.5 and 7.5 cm. Several times each year winds may exceed 33 m s^{-1} (74 miles per hour, or hurricane force). Higher elevations in the Coastal Ranges have little effect on temperature because maritime air masses in winter are not much colder at 1000 m compared to sea level while in summer continental heating balances an expected altitudinal cooling (Sternes 1960).

Teleconnective Indices. Wallace and Gutzler (1981) provided the first "type description" of the Pacific / North American Pattern (PNA). They described it as one in which "...(winters are) characterized by below normal temperatures over the eastern United States and strong ridges in the 700 mb height field extending from the Pacific Northwest of the United States to the Alaska-Canada border." Greenland (1994a) noted that when the PNA index is positive and high, a meridional circulation in the westerlies with a ridge of high pressure shunts storms to the north of the Pacific Northwest giving rise to relatively dry and warm winters. When the PNA is negative, the zonal circulation in the westerlies brings in storms from the Pacific Ocean giving rise to wetter and cooler weather. Cayan and Peterson (1989) found that streamflow fluctuations show correlations (0.3-0.6) with sea level pressure anomaly patterns over the North Pacific. For streams on the West Coast, positive streamflow is associated with low pressure off the coast (to the west or northwest) leading to increased west and southwest winds and storms. Higher interior streamflow is associated with a positive sea level pressure anomaly over the central North Pacific.

Stream and River Discharges. As mentioned above, snowmelt potentially leads to a June maximum of discharge for the Columbia river but the existence of dams has smoothed out this seasonal pattern. The Columbia provides about 80% of the river discharge to the ocean between San Francisco and the Strait of Juan de Fuca (Hickey 1989) and the Fraser is also a major contributor. The other coastal rivers have a maximum discharge to the ocean in December and January (Landry et al. 1989). The amplitude and phase of the annual cycle of monthly precipitation and streamflow varies markedly along the West Coast and the strict Pacific Northwest area is just part of this gradient of variation.

In, and south of the San Francisco Bay area, maximum stream flow occurs between April and July following maximum precipitation (falling as snow) in January and February (Figure 4.23; Cayan and Peterson 1989). This pattern is followed in the Pacific Northwest by the Columbia River but coastal rivers peak with coastal precipitation maxima in January and February. In British Columbia and Alaska, summer, fall or early winter precipitation tends to give rise to streamflow peaks in various parts of the summer. Further details on stream and river discharges are provided in Chapter 6.

Stream and River Temperatures. Few reports exist of systematically collected long-term stream and river temperatures. This is partially because of the large natural spatial variability of stream temperatures, which are a function of solar radiation and other energy inputs and outflows, advection, convection, evaporation rates, and tributary inflow (Fuhrer et al. 1996). However, Fuhrer et al. (1996) report a general uniformity in the lower Columbia River with daily mean water temperatures for the period 1968 to 1994 ranging between 6°C and 18°C with a median value of approximately 12°C. August is the month of highest values and either January or February has the lowest. An Oregon Department of Environmental Quality (1995) report shows selected samples of Oregon stream temperatures in summer ranging from 15.4°C to 28.9°C and temporal changes from May to November with a range of approximately 17°C and a maximum annual range in mean monthly temperatures of about 15°C in eastern Oregon with smaller values in western Oregon. The rivers tend to warm as they flow downstream. Stream temperatures may potentially be strongly affected by a wide variety of human activities.

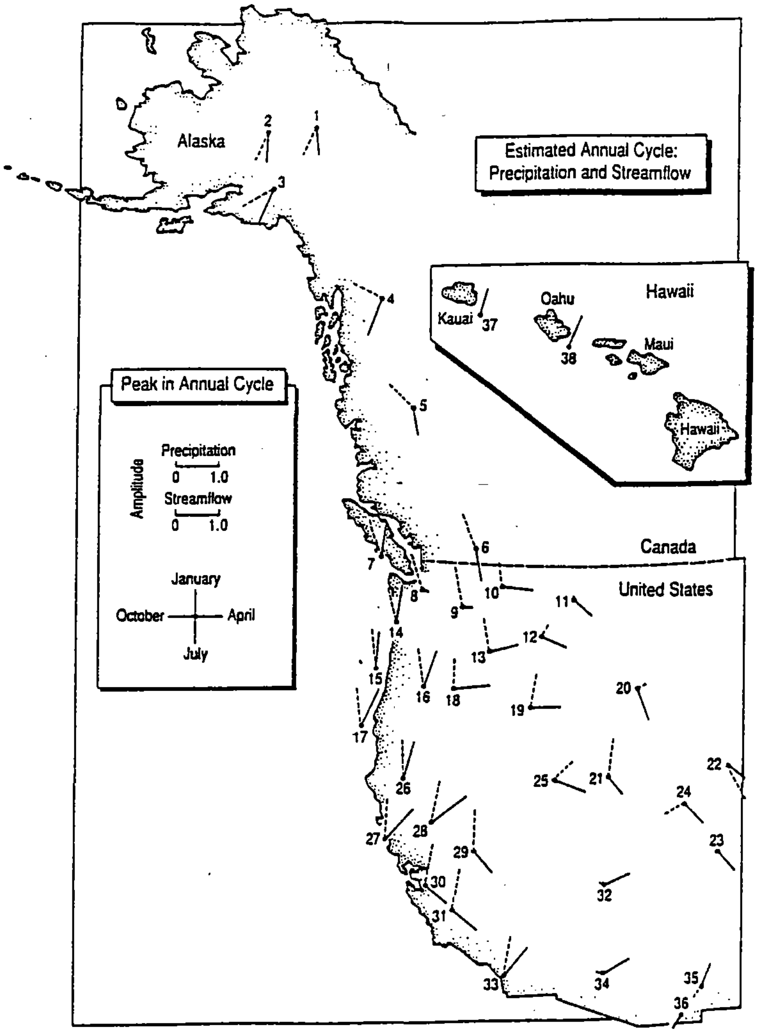

Figure 4.23. Amplitude and phase of the annual cycle of monthly precipitation and streamflow along the West Coast and in the West. Numbers indicate station identification; the direction and length of the vectors indicate the season and amount, respectively, of maximum rainfall (dotted) and streamflow (solid). For instance, at Boise (19), most precipitation falls during January/February and sreamflow peaks during late March. (Source: Cayan, D.R., and Peterson, D.H. 1989. The influence of North Pacific atmospheric circulation on streamflow. In *Aspects of Climate Variability in the Pacific and the Western Americas*, ed. D. H Peterson, 375-397. Washington, DC: American Geophysical Union. Reprinted with permission, courtesy American Geophysical Union.)

Daily. Usually any extremes of temperature are of small duration and associated with continental air flows. Low temperatures are found when the air flow is from the northeast and high temperatures occur when air flow is from the southeast. Very extreme seasonal values occasionally occur related to unusual situations. An example of this is the extreme winter of 1861-62 when temperatures reached - 30°C at the Dalles, Oregon, and both the Fraser River at Vancouver and the Columbia River at Vancouver, Washington, froze over. Floods of great magnitude occurred in California at the time and the Sacramento River took on the appearance of "an inland sea" (Roden 1989). These events are believed to be associated with a large jet stream meander that caused a blocking high pressure zone over the Pacific Northwest and allowed Arctic air to penetrate into the region and forcing storm tracks southward into California. This is also the scenario that led to widespread flooding in 1964. According to Sternes (1960), major floods have occurred at the coast in 1861, 1890, 1909, 1927, 1953, 1955. A further major flood occurred in February 1996 which was due to a rain-on-snow event accompanied by a large stream of atmospheric moisture arriving from the direction of Hawaii that flowed over a long strip of positive sea surface temperature anomalies in the Pacific. *The role of extreme events such as floods and droughts on the ecosystem should be identified as well as the relation between extreme events and longer term cycles.*

Wind storms are also a feature of the Pacific Northwest area. Two of the largest wind storms to affect the Pacific Northwest this century occurred on October 12, 1962 and December 12, 1995. The former, named the Columbus Day Storm was more severe than the latter in virtually every respect (Knight, 1996). Peak wind gusts were recorded at 75 m s^{-1} (170 miles per hour) for the former and 53 m s^{-1} (119 miles per hour) for the latter. Over 51 mm (2 in.) of precipitation were recorded for the former and almost twice as much was observed for the latter. Forest blow-downs were large in both storms, particularly the former. Similar storms affected the area in 1880, 1921, and 1951.

Published data on the magnitude and frequency of severe storms are lacking. One of the most useful data sources is that of Brunengo (unpublished, 1989) who examined the record of the largest 48 hr precipitation events at five sites in the Cascades from 1940 to 1987. He found 47 events during this period with a mean precipitation of 107 mm. The greatest storms were concentrated in the November to February period. Storms of this kind generally affect most of the Pacific Northwest. He identified a tendency for winters in the Pacific Northwest to be stormy at time of low values of the North Pacific Index. Brunengo developed a "Storminess Index" (SI) that reflects the number of storms and the amount of precipitation. Cumulative values of the SI index show some parallels to interdecadal variations noted in other sections of this report and are worthy of further investigation. *More data sets like Brunengo's SI data set should be developed and analyzed for short-term and interdecadal variability.*

Both wind storms and high precipitation events can have the effect of "resetting the ecosystem clock". February 1996 saw a fairly large flood event in the Pacific Northwest with over 305 mm (12 in) of rain in many coastal locations between February 3-9. Similar flood events occurred in 1933 and 1964. Local residents in the coastal town of Waldport, Oregon blame the February 1996 flood for a very low clam catch in their estuary area. It might take some species of clams up to 7 years to reach previous population levels (R. Malouf pers. comm. 1996). Thus short period events may have long-lasting ecological consequences. Evidence (Cayan and Redmond 1994; Greenland 1994a) suggests that some of the largest precipitation values in the Pacific Northwest, and by implication large storms, are associated with La Niña events. This, in turn, suggests once more that further attention should be given to the La Niña- related climatic events in the Pacific Northwest and to answer such questions as *are flood events more likely to occur in the Pacific Northwest during La Niña times?*

Ocean

OCEANIC VARIABILITY AT THE MILLENNIAL SCALE

Paleoclimatic estimates from proxy data suggest that at the height of the last ice advance at 18,000 year Before Present (BP), the majority of the North Pacific had approximately the same temperatures as at present but that areas off Mexico and in a zone between latitudes 45°N to 60°N across the ocean had sea surface temperatures about -2°C or more lower than at present (Hartmann 1994 p. 316; CLIMAP 1981). Radiolarian data from the Santa Barbara basin tend to suggest a decrease in ocean temperatures at 5400 BP that lasted with minor interruptions until 1,500 BP (Pisias 1979), but Roden (1989) has questioned how spatially representative this finding may be.

Generally there seems to be a dearth of information on ocean changes in the Pacific Northwest on this time scale. A general research area would be to improve the information base of ocean data on the millennial time scale.

OCEAN VARIABILITY ON THE CENTURY SCALE

One of the more important potential changes on the century scale are those of coastal sea level rise and fall. Within the general global warming hypothesis of this century it might be expected that there would be a gradual sea level rise along the West Coast. However, partly because of tectonic and isostatic activity, recorded sea levels vary widely from region to region and according to Roden (1989) and others, "any global sea level change, if it occurred at all, is small and masked by land uplift and subsidence." The corollary of this is that tectonic changes are potentially important for future sea level changes at coastal areas and such changes should be recognized as a random variable in any future model that includes sea level. Some investigations performed after Roden's warning about interpretations of sea level data have provided interesting results. Ware and Thompson (1991) report a fall in sea level for Victoria, British Columbia, between 1915 and 1940 followed by a rapid rise at the time of the 1940-41 El Niño. They attribute the fall between 1915 and 1940 to be mainly a function of intensifying northerly winds.

An increase in sea surface temperature is the most commonly expected century scale result of 20th Century global warming. No direct evidence of this is so far reported for Washington and Oregon. But south of the PNCERS study area, along the southern US West Coast, Roemmich (1992) has documented a general ocean warming of about 0.8°C and a rise in sea level. According to Barry et al. (1995) the central California coast has seen a 0.75°C rise in sea surface temperature between the early 1930s and 1994.

It has been suggested that potential global climate warming will increase land-sea temperature differences (Trenberth 1993), intensify equatorward winds in summer and lead to stronger coastal upwelling (Bakun 1990). An examination of West Coast nearshore sea surface temperatures and salinity (Schwing 1994) and sea level change at Vancouver island (Ware and Thompson 1991) is consistent with this suggested increase in upwelling. Bakun (1990) has noted that several major coastal upwelling areas of the world have been growing in intensity. Bakun also makes the very important point that it is not always possible to project direct physiological effects of climatic warming on organisms. In this case, a simple projected increase in coastal sea surface temperatures would neglect the biological effects of increased upwelling. On the larger spatial scale, Manabe et al. (1991) suggest that carbon dioxide-related warming in the northeast Pacific would be on the order of 1-2 °C at the sea surface. The warming is projected to increase by half that amount at a depth of 700m.

GLOBEC (1994) planners make the following hypotheses regarding projected global warming: boundaries between distinct physical and biological regions will move; there may be a change in strength, timing or even occurrence of the spring transition; greater upwelling and increased stratification will create stronger upwelling fronts and jets as well an increased vertical shear within these jets; global warming will cause the thermocline and nutricline to be depressed. The overall hypotheses of GLOBEC (1994) planners are summarized in Table 4.4.

Table 4.4. Hypothesized physical changes in the California Current-PNCERS region under a global warming scenario (from GLOBEC 1994).

Physical Process	Hypothesized Change
West wind drift intensity	decrease
West wind drift location	shifted north
Freshwater input	increase
Coastal wind stress	increase summer, no change or decrease winter
Mean sea surface temperature	increase all months
Stratification	increase
Mean transport of CCS	decrease
Alongshore transport upwelling jets	increase
Turbulent mixing	increase summer, no change or decrease winter
Transport in eddies and meanders	increase
Offshore transport	increase
Upwelling (vertical transport)	increase
Mixed layer depth	unknown
Winter storm frequency	decrease
Winter storm intensity	decrease
Timing of spring transition	unknown

Apart from global warming issues, the 60/70 year cycle mentioned in the atmosphere section was first found through its effect on the ocean in terms of the relative abundance of sardines and anchovies. This particular cycle has continued for at least 1,500 years (Baumgartner et al. 1992). *The 60/70 year cycle is an important cycle and deserves to be studied much more closely.*

OCEANIC VARIABILITY AT THE DECADAL SCALE

As was the case in the atmosphere, a great deal of attention has been given recently to decadal variability in the Pacific Ocean. Several studies investigated the spatial variability of ocean parameters at this scale, especially concentrating on sea surface temperatures. Also parallel to the atmospheric case, attention is focused on the changes centered on 1976 but then is also expanded to a longer time period. Trenberth and Hurrell (1994) and several others have pointed out that, in terms of dynamics, there is a fairly sluggish response of the mid-latitude ocean to changes in the ocean forcing through the surface momentum and heat fluxes. This effectively serves as a low-pass filter for short-term variability, and emphasizes the longer time scales. Many features of the interdecadal fluctuations in ocean climate have been modeled by Miller et al. (1994 a, b).

The spatial variation of sea surface temperatures across the Pacific from 1961 to 1989 was subjected to a multivariate analysis by Wang (1995). He found that one principal component (having the most power in the north eastern tropical Pacific) explained 62% of the variance at the interdecadal time scale, and also made a major change from negative to positive values around 1976. An ocean circulation model demonstrated the 1976-77 oceanic regime shift was caused by a unique concurrence of sustained heat flux anomalies during a multi-month period preceding the shift both in the central Pacific and in the California coastal region (Miller et al. 1994b). Graham (1994) suggests that the 1976-77 regime shift is best regarded as a change in the background mean state of the tropical Pacific.

As a result of atmospheric changes, after 1976 sea surface temperatures increased along the west coast of North America and Alaska but decreased over the central North Pacific (Trenberth and Hurrell 1994). Associated changes in wind stress on the ocean altered the transport associated with major surface currents, which relate directly to one of the key features in Francis' (1993) modal-decadal model (Fig. 4.15) of the Eastern Pacific. This feature is the proposed decadal shift of the point where the Sub-Arctic Current (sometimes called the North Pacific Current; Pickard and Emery 1990) bifurcates to form the Alaskan and California currents. The bifurcation point varies on an annual scale between 45°N in the winter and 50°N in the summer (Pickard and Emery 1990: p. 253). According to the Francis model, during the Alaskan flow mode the bifurcation point is further to the south and more water goes into the Alaskan current with the opposite being the case in West Coast flow years (see also Figure 5.10). The movement of the bifurcation point is critical both on an annual scale and a decadal scale. Francis notes that some investigators (e.g. Chelton 1983) suggest that the north-south shift is due to physical factors at or upstream from the bifurcation point but that Tabata (1991) suggests the shift may be due to in-phase coastal currents along the western coast of North America. Trenberth and Hurrell (1994) demonstrate that during the period 1976-1988 (an Alaskan flow regime period) storm tracks in the North Pacific were shifted southwards (Figure 4.24). Cyclonic circulation around these storms would probably increase the velocity and mass of the flow of the Alaskan current.

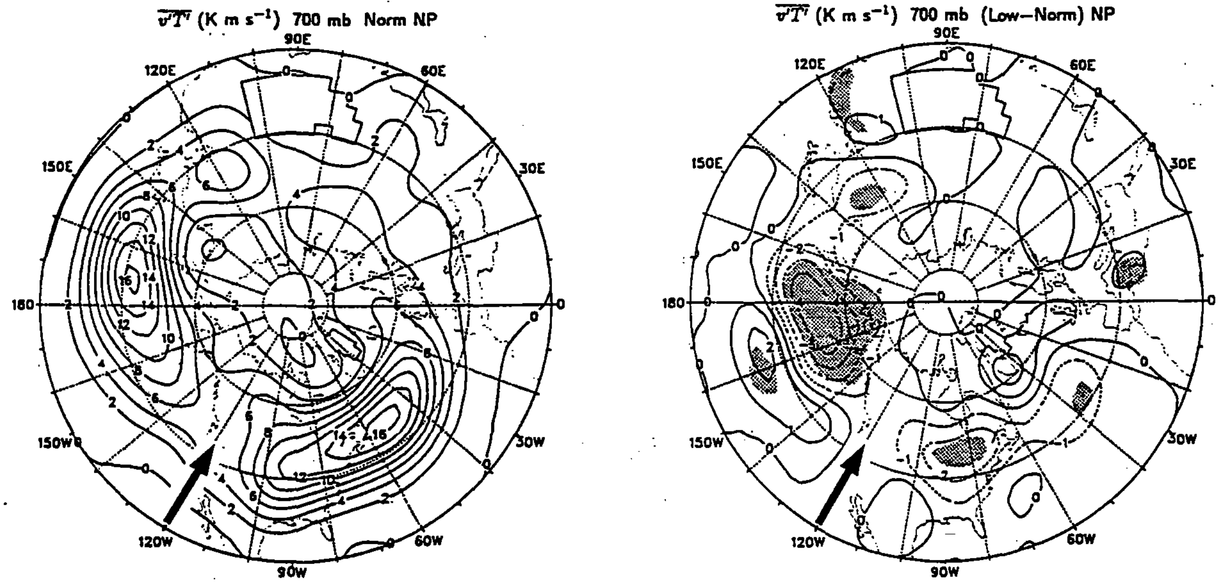

Figure 4.24. Location of storm tracks in the 1976-1988 period (an Alaskan flow regime period) compared to the preceding period. Negative values are dashed; values significantly different from zero are stippled on the right panel. Pacific Northwest region is indicated by arrows. (Source: Trenberth, K.E., and J.W. Hurrell. 1994. Decadal atmosphere-ocean variations in the Pacific. *Climate Dynamics* 9:303-319. Reprinted with permission, courtesy Springer-Verlag, New York, Inc.)

Since the shift of this bifurcation is critical both on the annual and the decadal scale, a prime research topic is *to find out what controls the position of the bifurcation point on scales from the annual to the decadal.* Realizing the importance of this, Ebbesmeyer et al. (1995) used a winter drift latitude and longitude end point (modeled by an ocean current simulation model) in the construction of their PNI index. The decadal changes (as well as El Niño effects) in sea surface temperatures can be seen in a time series of Eastern North Pacific winter sea surface temperatures constructed by Wooster and Hollowed (GLOBEC 1994; Figure 4.25). Tabata's study of baroclinic transports across Line P (145°W) indicated that there was a small out-of-phase relationship between the Alaska Current and the coastal component of the California Current which was consistent with the bifurcation proposal, but he thought the relationship was more likely to be due to an in-phase relationship of coastal currents along the Pacific coast (Tabata 1991). *More research is needed and it would seem a fruitful area for more investigations of the Ocean Weather Ship P data as well as remote sensing studies.* On a more local spatial scale, Ebbesmeyer et al. (1989) link decadal changes in the atmosphere to phenomena of the marine water of Puget Sound. At times when the Aleutian low is eastwards (positive PNA Index), storms deposit less precipitation in the Cascades. The decreasing freshwater input controls a rearrangement of the distribution of water density in the Strait of Juan de Fuca and increases the

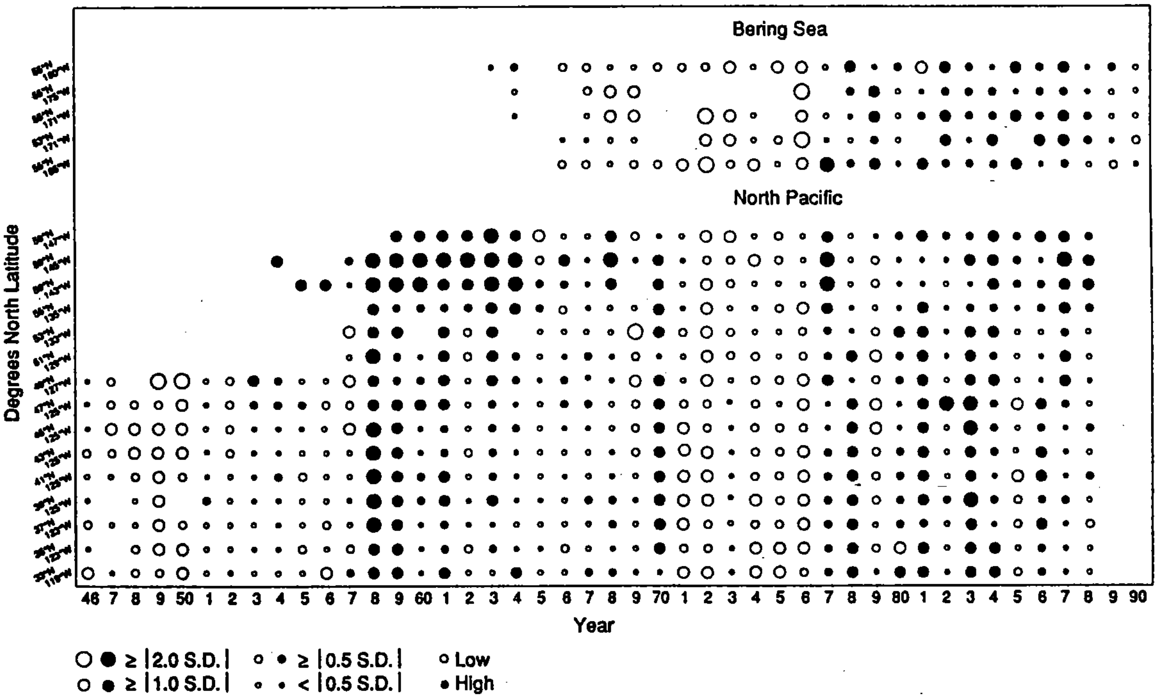

Figure 4.25. Time series of Eastern North Pacific winter sea surface temperatures. Dark circles indicate temperatures higher than normal; open circles indicate temperatures lower than normal. Size of circles shows departure from normal in terms of standard deviations (S.D.) from the mean. The 1976-77 transition from cooler to warmer is readily apparent. (Source: constructed by Wooster and Hollowed in: US GLOBEC. 1994.. Eastern boundary current program: A science plan for the California Current. US Global Ecosystems Dynamics. Report Number 11. Reprinted with permission, courtesy US GLOBEC.)

density difference across the entrance sill zone of the Puget Sound main basin. The increased density difference drives the fastest inflow in the basin from mid-depth to bottom. The basin waters of Puget Sound are very sensitive to the decadal changes and thus could be used as an indicator of such changes. The data of Ebbesmeyer et al. show the decadal regime changes going back to the turn of the century. It may be seen from Fig. 4.17 that decadal regimes in sea surface temperatures quite possibly existed in the last century.

Decadal shifts, however, are not necessarily seen along the whole of the West Coast. Considering the shifts centered around 1941 and 1975, Schwing (1994) concluded that there was considerable inter-regional difference in the timing (or even presence) of the shifts. Marked latitudinal variations in such variables as poleward wind stress and sea surface temperature trends have been identified by Schwing et al. (1996). They note the high variability of the California Current and the danger of oversimplifying present climate change as a constant linear trend or in terms of records from a single location. Similar spatial variability has been found with the values of upwelling indices (Parker 1996). Schwing (1994) suggests an important research task that *future studies should focus on what mechanisms may be responsible for such shifts and how the effect spreads along the coast (i.e., how a sudden shift off southern California "diffuses" northward).*

The fact that these decadal changes do not just occur at the surface was demonstrated in the classic study by Tabata (1989) on 27 years of data (1956 to 1983) on the properties of ocean water at Ocean Weather Station P. Despite not being interpreted as such at the time, these data taken at depths of 400m and below, clearly show evidence for the last two regime shifts with colder water temperatures between the early 1960s and the mid-1970s and warmer water after that to the mid-1980s (Figure 4.26). Comparable changes occur in salinity values but somewhat

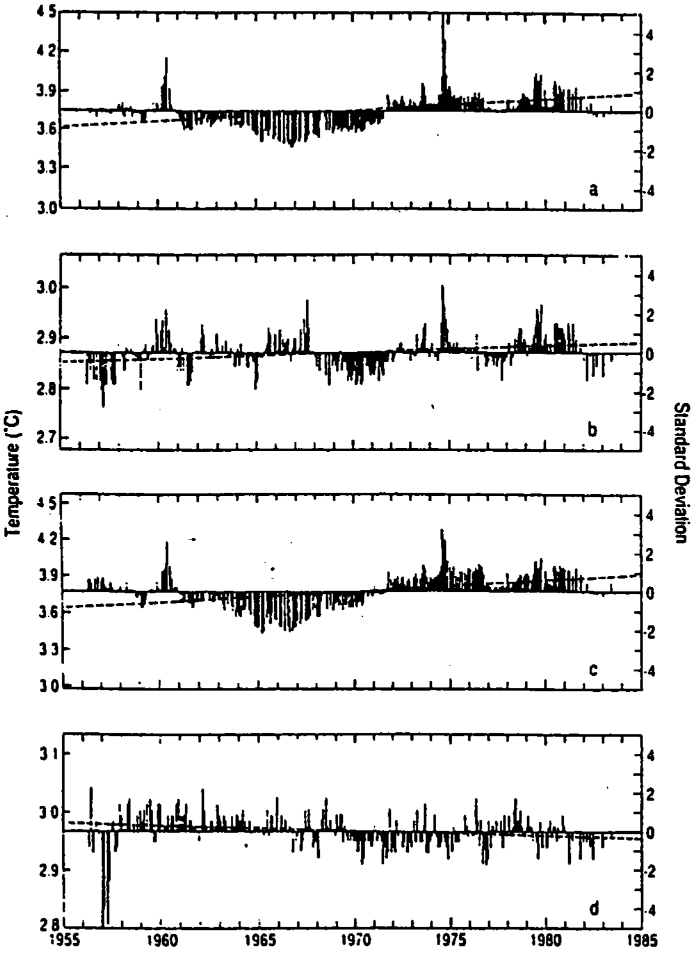

Figure 4.26. Ocean temperature data taken four depths at Ocean Weather Station P (50°N 145°W). Panel (a) 400 decibars, (b) 1000 decibars, (c) $\sigma_t = 27.0$, (d) $\sigma_t = 27.4$. All but the bottom panel show a warming trend over the 27 year time period. (Source: Tabata, S. 1989. Trends and long-term variability of ocean properties at ocean station P in the northeast Pacific Ocean. In *Aspects of Climate Variability in the Pacific and the Western Americas*, ed. D. H Peterson, 113-132. Washington, DC: American Geophysical Union. Reprinted with permission, courtesy American Geophysical Union.)

different decadal changes are seen in dissolved oxygen concentration and the depth isopycnal surfaces. It is interesting to note that the length and particular time of the data period investigated by Tabata leads him to conclude that the ocean was warming over the period. Although he is careful to point out the need for an even longer data record before making more firm conclusions. Tabata concluded that the changes taking place at this scale were mainly due to vertical motion in the water and were not influenced much by shifts in the position of the center of the Alaskan gyre.

While keeping in mind the variations in timing or presence of decadal shifts, further long-term retrospective studies of coastal sea surface temperature could take advantage of the spatial coherence of temperature. Roden (1989) has suggested that the sea surface temperature records of La Jolla, California, and Langara, British Columbia, could be used as benchmark stations to investigate changes in the California and Alaskan Current thermal properties, respectively. GLOBEC (1994) planners also noted the spatial representativeness of the Scripps Pier (La Jolla) record. From about 1920, this record shows a period of warm sea surface temperatures ending about 1945, a cool period (with the exception of the 1957-1958 El Niño) up to 1976, and a warm period from 1977 to the present. Abrupt transitions of about one to two years took place between these periods (Roden, 1989; Figure 4.27). During the part of this period for which observations are available, high temperatures coincide with diminished northerly winds. The interior of the central North Pacific Ocean area has cooled between 1968 and at least 1985 (Venrick et al. 1987). In addition, Royer (1993) has drawn attention to long period tides that may affect sea surface temperatures and be related to their quasi-20 year cyclicity. *The relation of these long period tides should also be investigated in the context of interdecadal regime change.*

OCEANIC VARIABILITY ON THE QUASI-QUINTENNIAL SCALE (ENSO)

Following the phase of warm sea surface temperatures in the tropics the observed effects of an El Niño arrive on the West Coast by both oceanic and atmospheric paths (GLOBEC 1994). GLOBEC planners describe how the oceanic path occurs along the eastern margin of the Pacific Ocean basin, when Kelvin waves propagate poleward (i.e., northward along the Pacific Northwest coast), depress the thermocline (i.e., push cold water deeper), and result in anomalously warm waters. The atmospheric path follows later when the Aleutian Low is displaced to the south and/or west, and winds enhance the flow of water from the south, thus trapping upwelling conditions nearer to the coast.

The effects of El Niño events are more marked in the coastal ocean of the Pacific Northwest than in its atmosphere. Several investigators have noted that positive anomalous changes in sea surface temperatures of the California Current take place virtually simultaneously along the whole north-south area of the coast (Roden 1989; McGowan et al. 1996). An analysis by Breaker (1989) using sea surface temperature off Monterey showed that between 1971 and 1985 there had been four El Niño-related warming events. The warming is strongest in the fall and winter and weakest in the spring. The warming can be up to about 4°C higher than the long-term average sea surface temperature (Figure 4.28). The oceanic manifestation of the large 1982/83 El Niño off the Pacific Northwest coast was initially in the form of poleward-propagating Kelvin waves, followed by onshore transport of low-salinity California Current waters from increased southerly

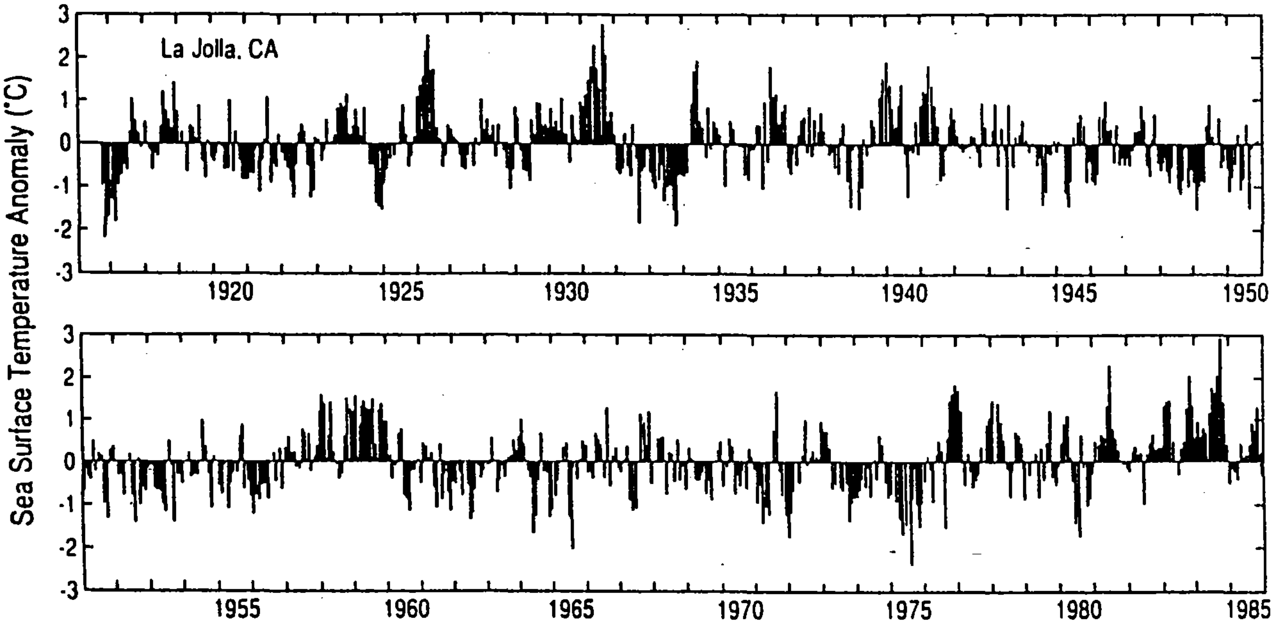

Figure 4.27. Sea surface temperature anomalies at Scripps Pier (La Jolla) from about 1917. The vertical bars show the deviation of the observed temperatures from the long term average. See text for explanation. (Source: Roden, G.I. 1989. Analysis and interpretation of long-term climatic variability along the West Coast of North America. In *Aspects of Climate Variability in the Pacific and the Western Americas*, ed. D. H Peterson, 93-111. Washington, DC: American Geophysical Union. Reprinted with permission, courtesy American Geophysical Union.)

winds associated with the intensified Aleutian Low and the intensified poleward California Counter Current. The result was a depression of the thermocline - nutricline inshore and ineffective upwelling (Pearcy 1992). The waters became anomalously warm and the sea level was raised. Thermal and salinity anomalies were greatest about 80 to 100 m below the surface (Rienecker and Mooers 1986). These effects occurred within one month of the El Niño appearance off Peru and 2 to 3 months *before* any atmospheric effect in the North Pacific. Later oceanic effects of the El Niño were enhanced by the atmospheric effects (Huyer and Smith 1985). The onset was probably also accompanied by an increased poleward flow in a 30 km wide undercurrent at 130 dbar depth with an increased subsurface temperature 50 km off the coast. Eventually temperature anomalies penetrated to 300 m and could be found 270 km off the coast (Huyer and Smith 1985). Newton (1995) has identified clear El Niño effects during the years 1991-1993 in the Puget Sound area. Here salinities, sea surface temperatures, and air temperatures increase during a moderate El Niño year. From a basin-wide perspective Trenberth and Hoar (1996) have shown that the SOI is well related to sea surface temperature anomalies both in the tropics and off the coasts of North and South America.

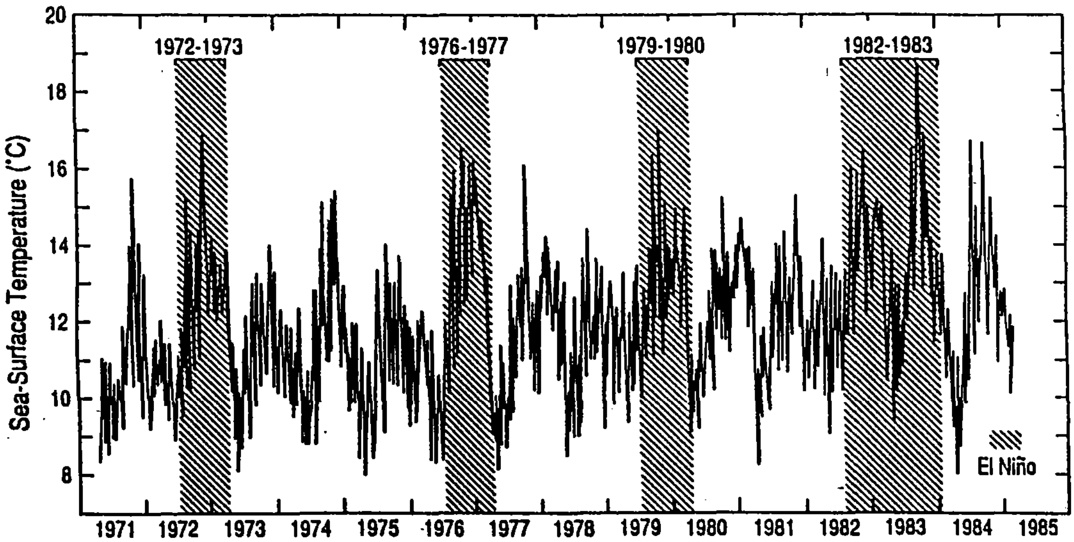

Figure 4.28. Ocean warming during El Niño events (shaded). (Source: Breaker, L.C. 1989. El Niño and related variability in sea-surface temperature along the central coast. In *Aspects of Climate Variability in the Pacific and the Western Americas*, ed. D. H Peterson, 133-140. Washington, DC: American Geophysical Union. Reprinted with permission, courtesy American Geophysical Union.)

As with the case of the atmosphere it has been shown that ENSO phenomena in the ocean are not stationary. Gu and Philander (1995) demonstrated that the amplitude of ENSO, as judged by tropical sea surface temperatures, is found to be large between 1885 and 1915 and small between 1915 and 1950 increasing rapidly again after 1960. Also parallel with the atmosphere, ENSO phenomena have existed in the ocean for millions of years.

Efficient methods now exist for forecasting tropical Pacific sea surface temperatures six months ahead and researchers are optimistic that the ability to predict lead times of a year or more can be achieved. The leading groups in this field are the Lamont-Doherty Group (Zebiak and Cane 1987) and the Scripps Institution of Oceanography Group (Graham and Barnett 1995). Combination forecasts of tropical Pacific sea surface temperatures are published monthly in the NOAA Climate Diagnostics Bulletin. Both groups use a coupled ocean/atmosphere model which is much simpler than full-scale general circulation models. *A major research project is to investigate how the information contained in these forecasts can be applied to practical use by ecosystem managers.*

A periodicity of 6-7 and 2 years in ocean events in the North Pacific, which may or may not be associated with ENSO type events, is believed to be related to atmospheric forcing on the same scale (Tabata 1991). Tabata believes that *information on the barotropic component of the* *circulation is lacking and that such data are needed to understand the coupling between the atmosphere and the ocean in both annual and interannual scales.*

OCEANIC VARIABILITY AT THE INTERANNUAL SCALE

There does not seem to have been so much attention given to ocean variations at this time scale. However, with the greater availability of satellite-derived data it is likely that this situation will be rectified in the future. Ocean-based measurements tend to be limited to those made by research vessels and the Comprehensive Ocean-Atmosphere Data Set (COADS) data (see Appendix 4.2 for description) has not been fully exploited at this time scale.

A permanently moored weather and ocean observing station, Ocean Weather Station P, provides a rich source of oceanographic data. Tabata (1989) notes temperature and salinity changes throughout the mixed layer at Ocean Weather Station P varying with a periodicity of about 2.5 years. Levitus et al. 1994 (quoted by Levitus and Antonov 1995) have documented the spatial changes in temperatures at 125 m depth in the North Pacific. These investigators suggest that the interior mid-latitude of the North Pacific Ocean seems to be characterized by an anomaly that is opposite in sign to an anomaly in the periphery of the Subtropical Gyre. The maximum temperature change between the periods 1960-1962 and 1965-1969 was about 0.5°C but shorter period changes can also happen. Levitus and Antonov (1995) noted an increase in temperatures of up to 1.5°C between 1986 and 1989. They identify an important research problem as an attempt *to determine what, if any, air-sea interactions are involved in these changes.* They also point to the various ideal components of a comprehensive subsurface ocean observing system.

The "memory effect" of the ocean is important on the interannual and annual time scales. Davis (1976) and others have found the temporal persistence of sea surface temperature anomalies in the North Pacific such that sea surface temperature anomalies could be predicted from previous anomaly conditions.

The bifurcation point of the Sub-Arctic Current varies on an annual scale between 45°N in the winter and 50°N in the summer (Pickard and Emery 1990). Another important annual change is in the southern boundary of Ekman upwelling (see Glossary) in the North Pacific Ocean. Pickard and Emery (1990: p. 163) show this boundary to be at about 30°N in the winter and almost 50°N in the summer. This is important since the upwelling can provide nutrients which are the first step in the food chain. According to Brodeur and Ware (1992) upwelling occurs especially in the core of the Alaskan Gyre because of wind-induced divergence in the upper oceanic layer. Presumably this upwelling would be intensified at times of a well-developed Aleutian Low.

Considerable interannual variability over the continental shelf has been noted in the relatively few years of data that have been gathered. Figure 4.29 shows the current variations for the spring time in the years 1973 to 1978 (Hickey 1989). Although the timing of the spring transition was within 1 or 2 weeks of March 25 for three of the four years, the conditions that lead up to it were highly variable. The transition occurs simultaneously in the Pacific Northwest region. *The timing of the spring transition and its relation to atmospheric conditions on a variety of scales is a fertile research area.*

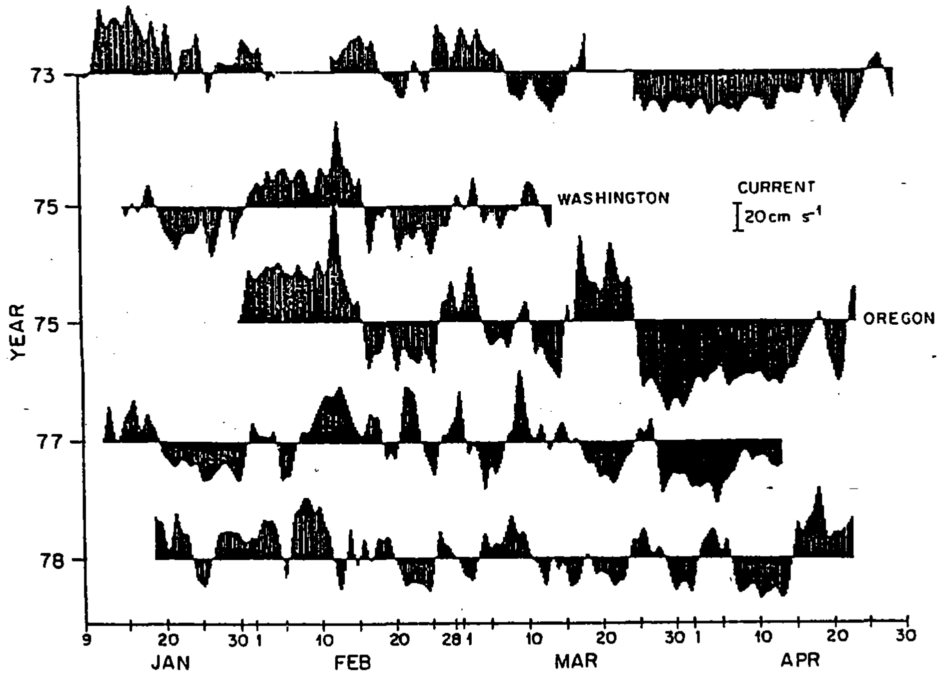

Figure 4.29. The current variations for the spring time in the years 1973 to 1978. Lines above the abscissa indicate flow to the north; below the abscissa to the south. The figure shows the year-to-year differences in the overall transition from a north-flowing to a south-flowing nearshore current in spring. (Source: Hickey, B.M. 1989. Patterns and processes of circulation over the coastal shelf off Washington. In *Coastal Oceanography of Washington and Oregon*, eds. M.R. Landry and B.M. Hickey, 41-115. New York: Elsevier. Reprinted with permission, courtesy Barbara Hickey.)

ANNUAL SCALE

Summary of Typical Seasonal Changes Throughout the Year. A simple description of seasonal changes in currents over the continental shelf was given by Parmenter and Bailey (1985; Figure 4.30). The summer circulation is comprised of the California Current moving under the influence of the northerly summer winds while below it the California Undercurrent travels northwards. In winter the California Current is found offshore but close to the shore the northward-flowing Davidson Current appears. The change from winter to summer conditions occurs very abruptly and is called the spring transition. The change back in the fall is much more gradual. GLOBEC (1994) planners describe extremely dynamic seasonal changes in the California Current in a little more detail. After the onset of northerly winds in spring, upwelling raises isopycnals next to the

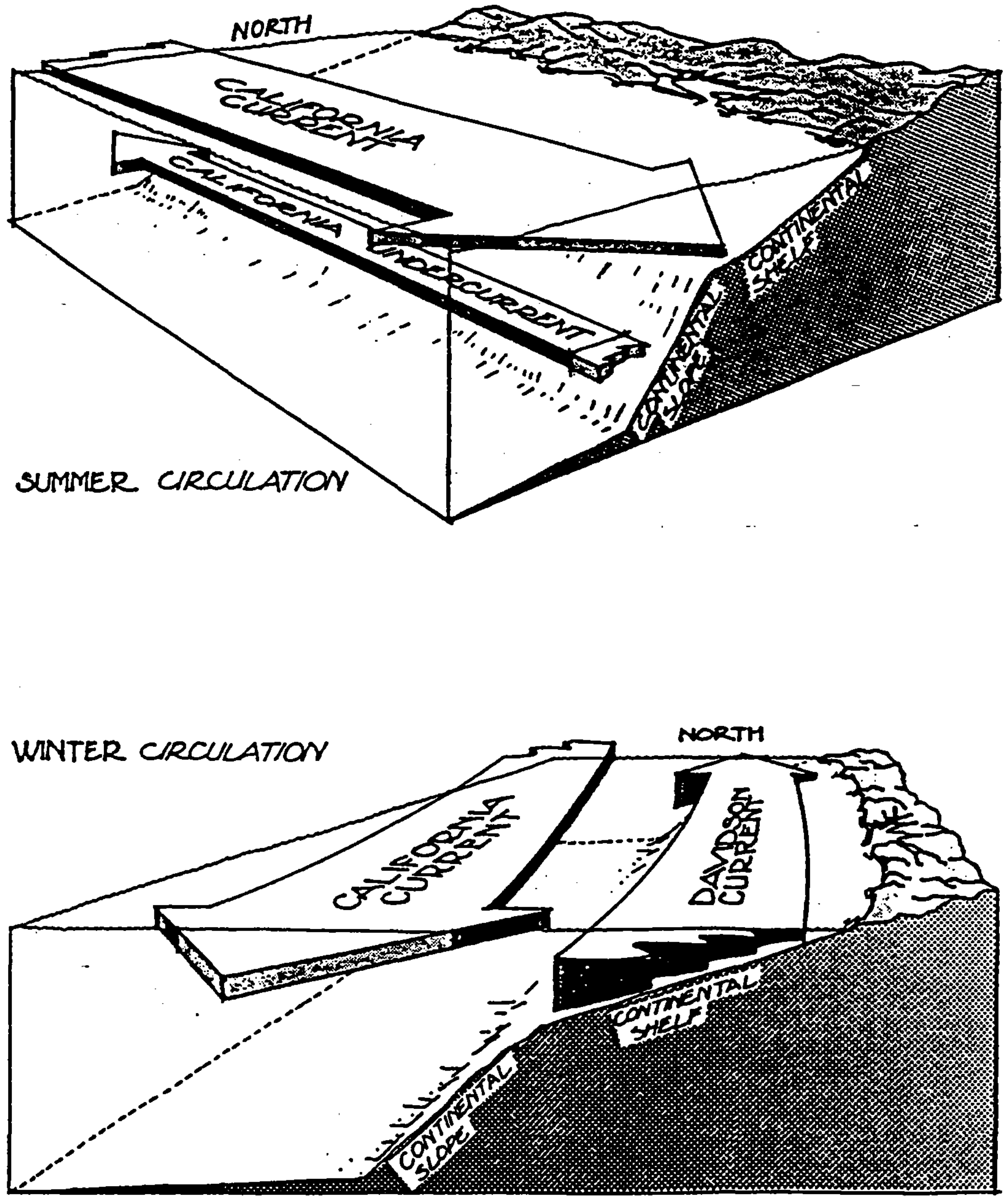

Figure 4.30. Summer and winter ocean currents off the coast of Oregon. (Source: Parmenter, T., and Bailey, R. 1985. *The Oregon Ocean Book.* Salem: State Printing Office. Reprinted with permission, courtesy Robert Bailey.)

coast (i.e., denser, saltier water moves upwards), creating a density front and an equatorward (southward-flowing) jet over the continental shelf. The front and the jet move further offshore in response to stronger northerly winds and return onshore when the wind relaxes or reverses. The southward jet moves further offshore to about 100 km in mid-summer and poleward nearshore counter-currents are often found. During winter, eddies are found offshore and the poleward Davidson current develops over the shelf and slope.

The rather linear and laminar concept of the flow of the California and Davidson currents (and presumably the Alaskan Current also) has been, in recent years, replaced by one of a very turbulent flow with jets, filaments and eddies superimposed on the slow, generally southward flow of the Californian Current. One of the most remarkable advances in recent years is the use of satellite imagery to show the rich structure of the coastal upwelling and eddy formation (Figure 4.31; GLOBEC 1994: p. 15). Present day concepts of the seasonal changes in the California Current System (Figure 4.32; GLOBEC 1994: p17; see also Lynn and Simpson 1987) diverge greatly from our initial laminar conceptualization (Fig. 4.30). Whereas some of these flow phenomena may be geographically anchored by topographic features of the coastline or seabed morphology, other flow phenomena may change with time and changing atmospheric conditions.

Monthly and Seasonal Ocean Currents and Their Boundaries. The most detailed and authoritative review of the circulation over the continental shelf of the PNW area has been provided by Hickey (1989). She and other investigators used a series of models and observations to establish the fundamental features of the circulation and, in many cases, their causes. They investigated: 1) seasonal patterns over the slope, which they divide into inner, middle and outer sections; 2) forcing mechanisms; 3) event - scale variability and forcing; 4) the existence of eddies meanders, squirts, and jets; 5) coastal upwelling; 6) interannual and tidal variability; and 7) the effects of submarine canyons and circulations associated with them. Denbo and Allen (1987) have also provided an insightful discussion of this topic.

Hickey and others have discovered that 70 to 90 % of the fluctuation in alongshelf flow at the mid-shelf, and of coastal sea level, can be explained as "first-mode" coastal trapped waves. The percentage falls to 50% for the outer shelf. Denbo and Allen (1987) find that the fluctuations in alongshore currents occurring on the time scale of about 4 days and longer are more highly correlated with the wind stress value 100 to 300 km to the south than with local winds but short period fluctuations are better correlated with local winds. In the mid and outer shelf, event-scale fluctuations are of the same magnitude as the seasonal mean-scale flow change.

The timing and duration of the periods of equatorward or poleward flow are not constant across the shelf or with depth. As mentioned above, the equatorward coastal jet moves progressively offshore in spring and summer as the upwelling season proceeds. The maximum velocity of the California Undercurrent and the large-scale California Current occurs in the late summer. In the Washington inner shelf, flow in the summer is equatorward to depths of about 100 m and poleward at deeper depths with a subsurface maximum of about 10 to 20 cm s^{-1} in the California Undercurrent. Poleward seasonal mean flow decreases with depth and occasionally reverses to equatorial seasonal mean flow, sometimes called the Washington Undercurrent. According to Hickey (1989) the dynamics of the mean and fluctuating currents on the inner shelf have not received so much attention. *A possible research task is therefore to understand better the*

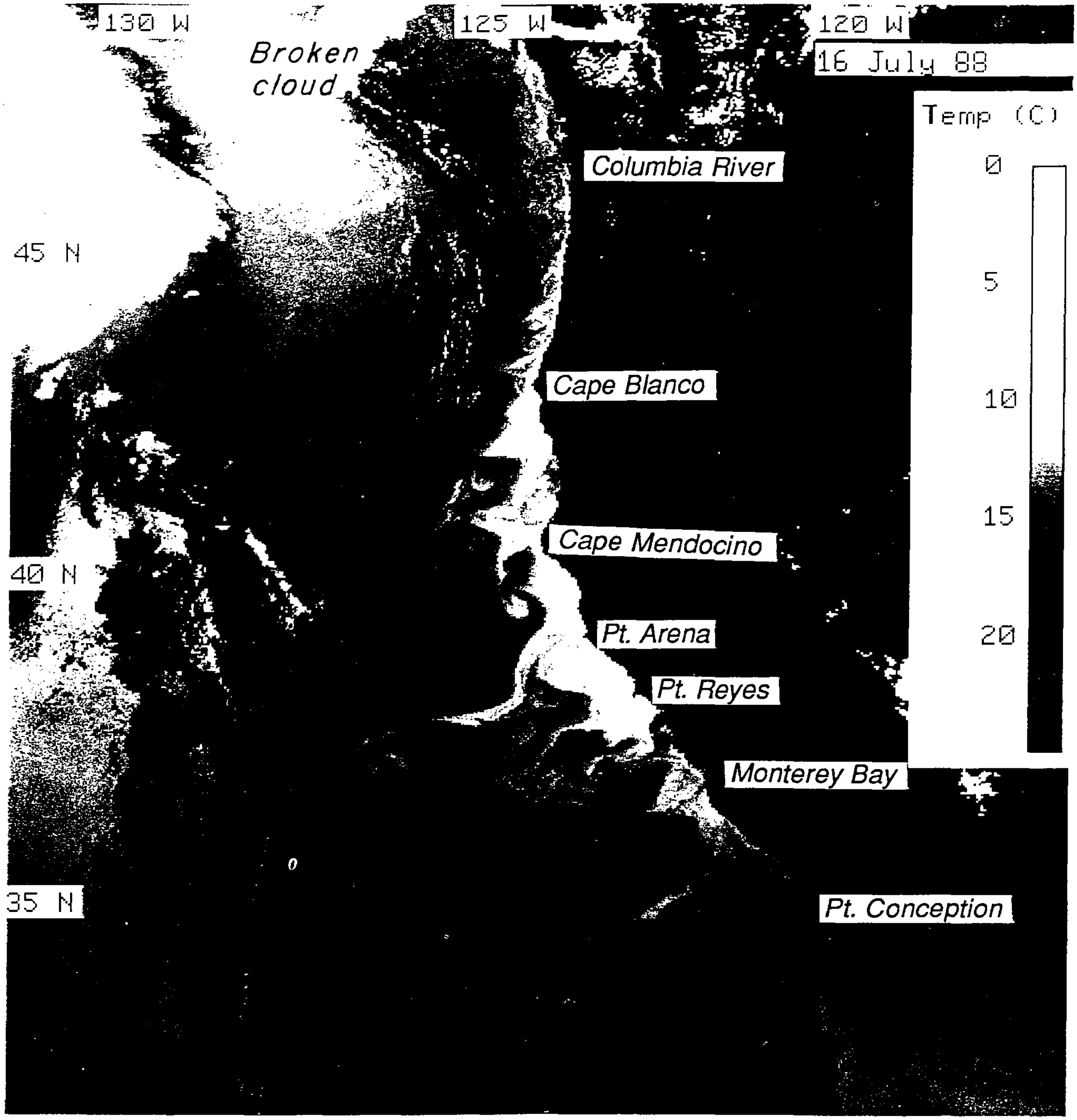

Figure 4.31. Satellite imagery indicating the rich structure of the coastal upwelling and eddy formation in the California Current system. (Source: US GLOBEC. 1994. Eastern boundary current program: A science plan for the California Current. US Global Ecosystems Dynamics. Report Number 11. Reprinted with permission, courtesy US GLOBEC.).

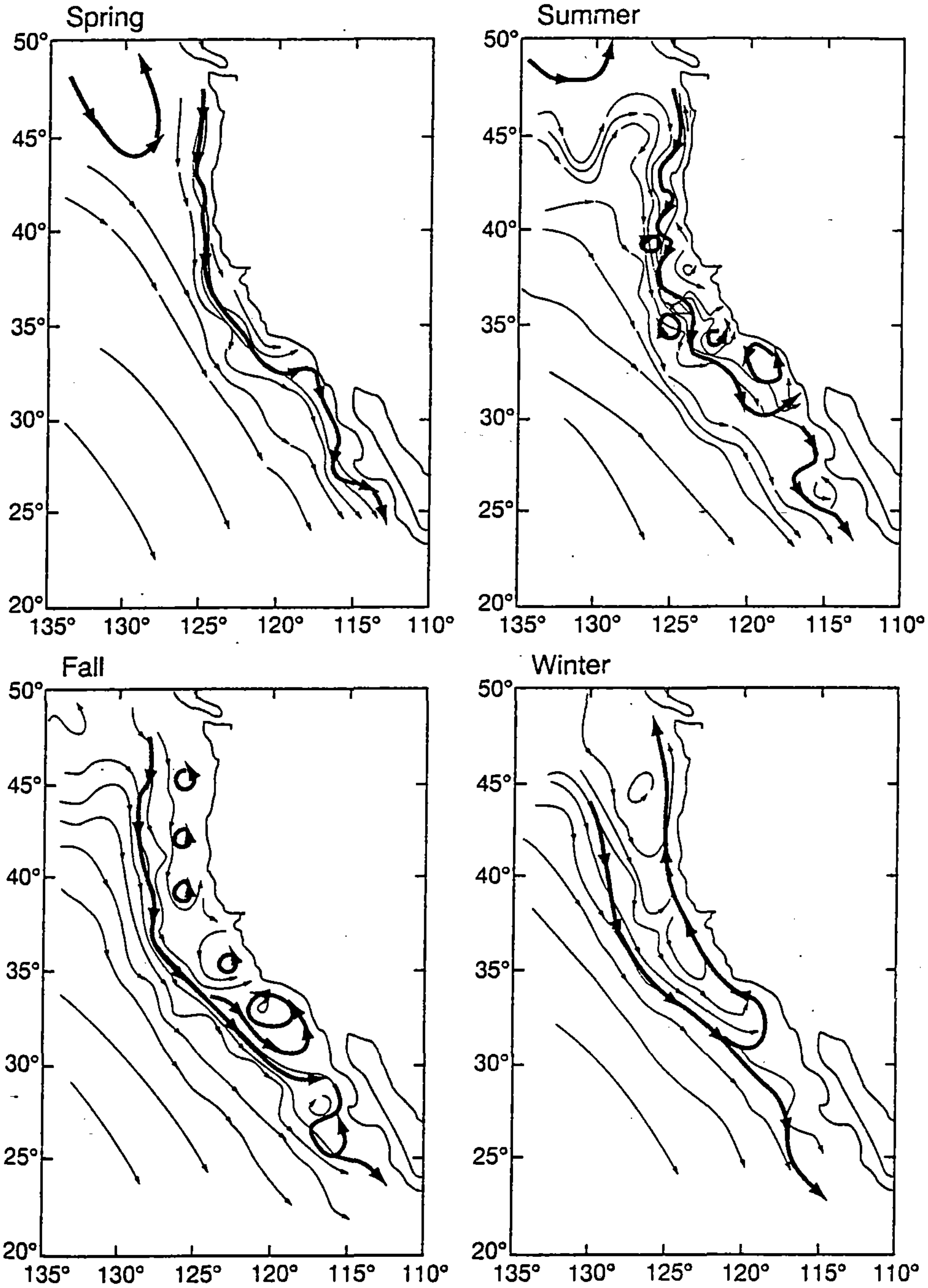

Figure 4.32. Schematic diagram of present day concepts of the seasonal changes in the California Current System (CCS). (Source: US GLOBEC. 1994. Eastern boundary current program: A science plan for the California Current. US Global Ecosystems Dynamics. Report Number 11. Reprinted with permission, courtesy US GLOBEC.).

dynamics of the inner continental slope flows. The principal local forcing mechanisms for the seasonal currents over the Washington shelf and upper slope are combinations of the alongshelf wind stress and a poleward alongshelf pressure gradient force. The principal forcing mechanisms for the seasonal and long-term pressure gradient force are generated by remote wind stress particularly in spring. The effect of submarine canyons is to: enhance upwelling in their vicinity, especially on the downstream side; amplify internal tides; encourage axial (i.e., circular) flow; and, within 50 m of the shelf bottom for narrow canyons (< 6 km), induce counterclockwise eddies when there is equatorward flow.

The spring transition is of interest on the interannual, annual, and daily time scales because it is about a week in length and is often accompanied by a sharp decrease in sea surface temperatures of about 3°C (Breaker 1989). Holtby et al. (1990) have noted that early and abrupt transitions not only produce conditions favorable to upwelling but also delay the formation of, and weaken, the northward flowing coastal current. Future studies on the timing of the spring transition may be informed by the suggestion of Huyer et al. (1979) that the transition is the result of a large cumulative offshore Ekman transport caused by local wind stress. Strub and James (1988) identified the atmospheric pattern associated with the spring transition. The sea level pressure pattern that most often coincides with the spring transition is the formation of a high pressure system centered at 45°N and 140°W together with the development of a low pressure over the southwestern continental US. After transition this is followed by a ridging pattern and diffluent (i.e., not convergent) flow off the western US. The less abrupt fall transition involves the development of a low pressure system off western North America centered at 50°N and 140°W associated with the development of storms in the region. These patterns were based on 9 years of data. Further studies of these weather patterns could show the interannual variability of the sea level pressure situations.

The sum of all the annual events causes regional differences in the ocean. Francis (1993) reviews four of the Northeast Pacific Ocean domains (specified by Ware and McFarland 1989; Figure 4.33) where water properties influenced by seasonal heating and cooling, precipitation and evaporation, and by wind mixing, are critical to fish production. Physical ocean phenomena in some of these domains is discussed in other sections. However, Francis (1993) defines a research question for the Coastal Downwelling Domain. He implies that we should investigate *how the dynamics and intensity of the Alaska Current respond to a very large annual signal in wind and precipitation in the Gulf of Alaska.*

With respect to the larger geographic scale, Roden (1989) has documented how extreme seasonal variations of atmospheric pressure in the area normally occupied by the Aleutian Low are accompanied by a consistent pattern of sea surface temperature anomalies across the North Pacific (Figure 4.34). In January 1931, when a -31 mb sea level pressure anomaly occurred centered on the Alaskan Peninsula, large negative sea surface temperature anomalies were found over the northern and northwestern Pacific. In January 1937, when a +24 mb "Aleutian High" occurred, large positive anomalies took place in the subarctic central Pacific and off Japan while large negative sea surface temperature anomalies appeared off the North American coast. Emery and Hamilton (1985) have argued strongly and presented evidence that sea surface temperature anomalies on seasonal time scales are maintained largely by anomalous wind-driven advection in

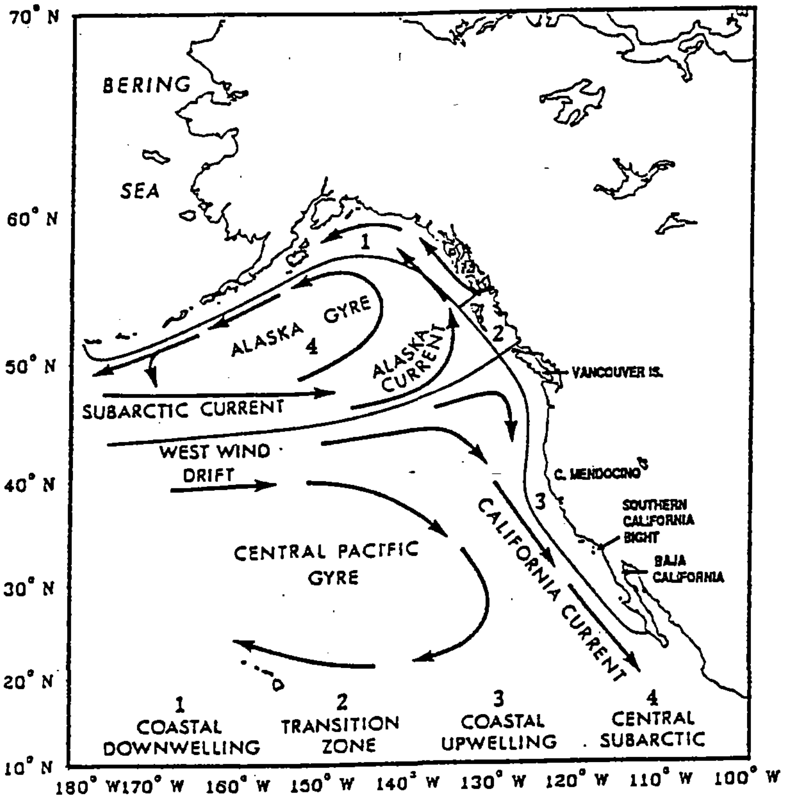

Figure 4.33. Northeast Pacific Ocean domains, showing that the California Current off much of the Pacific Northwest is a domain of coastal upwelling. (Source: Ware, D.M, and G.A. McFarlane. 1989. Fisheries production domains in the Northeast Pacific Ocean. In *Effects of ocean variability on recruitment and an evaluation of parameters used in stock assessment models*, eds. R. J. Beamish and G. A. McFarlane, 359-379. *Canadian Special Publication in Fisheries and Aquatic Sciences* 108. Reprinted with permission, courtesy of National Research Council of Canada.)

the near surface waters of the ocean. Sea level high pressure in the northeast Pacific may also be controlled by the wind circulation over the ocean and this, in turn, may well be controlled by atmospheric changes in the tropical ocean.

When wind blowing across the ocean surface drives ocean movement there are also dynamic cells of water movement formed perpendicular to the surface. These are known as Langmuir cells and start to be generated at wind speeds of 1.5 m s^{-1} (about 3 miles per hour). The convergence part of these cells at the surface can cause local downwelling jets of 2 to 7 cm s^{-1} (Leibovich 1983). Downwind and downcurrent, the downwelling jet speeds reach a maximum at depths between 6 and 20 m beneath the convergence (Shanks 1995). The corresponding associated upwelling is much slower.

Upwelling and Filaments. The simplest conceptual model of two-dimensional coastal upwelling calls for vertical movement of water adjacent to vertical topographical boundaries (the shore), driven by alongshore wind stress from northerly winds and the consequent advection of surface water offshore. Smith (1995) has provided a comprehensive review of upwelling in the region and identifies upwelling as having inherent scales on the order of days and tens of kilometers while the interaction of coastal upwelling with the offshore ocean occurs over of seasons and

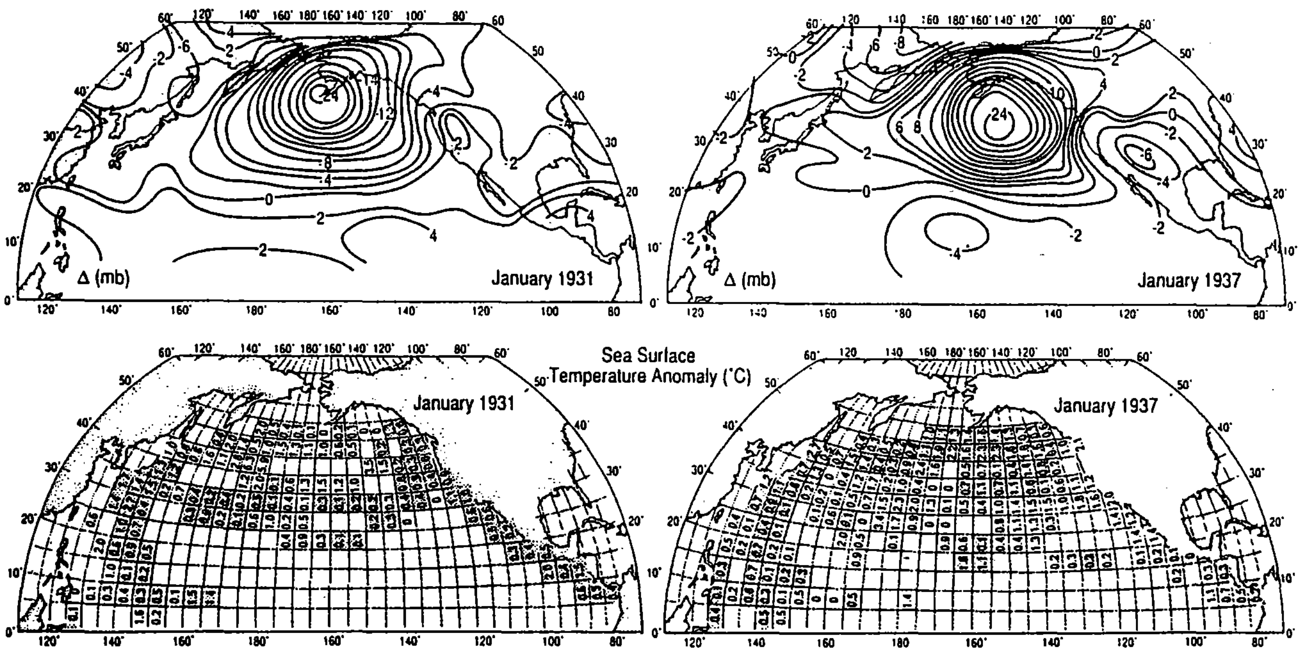

Figure 4.34. Examples of seasonal basin-wide sea surface temperature anomalies and associated atmospheric pressure relations. (Source: Roden, G.I. 1989. Analysis and interpretation of long-term climatic variability along the West Coast of North America. In *Aspects of Climate Variability in the Pacific and the Western Americas*, ed. D. H Peterson, 93-111. Washington, DC: American Geophysical Union. Reprinted with permission, courtesy American Geophysical Union.)

hundreds of kilometers. It is observed that offshore flow during upwelling is confined to a shallow layer at the surface less than 10 m thick.

Hickey (1989) notes observed departures from the strictly two-dimensional classic upwelling model. Two dimensional mass balance has not been observed. Much of the cross-shelf flow beneath the pycnocline occurs in or just beneath the pycnocline rather than deeper in the bottom boundary layer. Alongshore divergence is invoked to explain the lack of mass balance in the cross-shelf plane. Satellite imagery has shown that stronger upwelling occurs at and downstream from capes and promontories (Hickey 1989). Modeling studies have demonstrated that the existence of cape geometry as well as southward surface flow appears to be necessary to produce filament generation (Haidvogel et al. 1991). The topographically-anchored upwelling centers appear to generate jets that carry filaments of coastal water several hundred km offshore (see Fig. 4.31). The Pacific Northwest has fewer marked promontories than California. Satellite and surface observations have shown that the filaments have small-scale horizontal eddies superimposed on them (Flament et al. 1985). Maximum dynamic height ranges and velocities of the filaments occur in summer while minimum height ranges and velocities occur in late winter or early spring. Between May and July in the latitudinal band between 36° and 43°N, a meandering surface jet intersects with an eddy field (Strub et al. 1991). Larger-scale horizontal eddies can focus upwelled water into streams/filaments as schematically represented by Roughgarden et al. (1988; Figure 4.35). Several investigators have noted an optimal velocity of water and air velocity in upwelling situations with respect to biological recruitment. Ware and Thompson (1991), for example, mention a wind speed of 7-8 m s^{-1}. *An interesting research topic would be to investigate the frequency and controlling factors for biologically optimal upwelling conditions.*

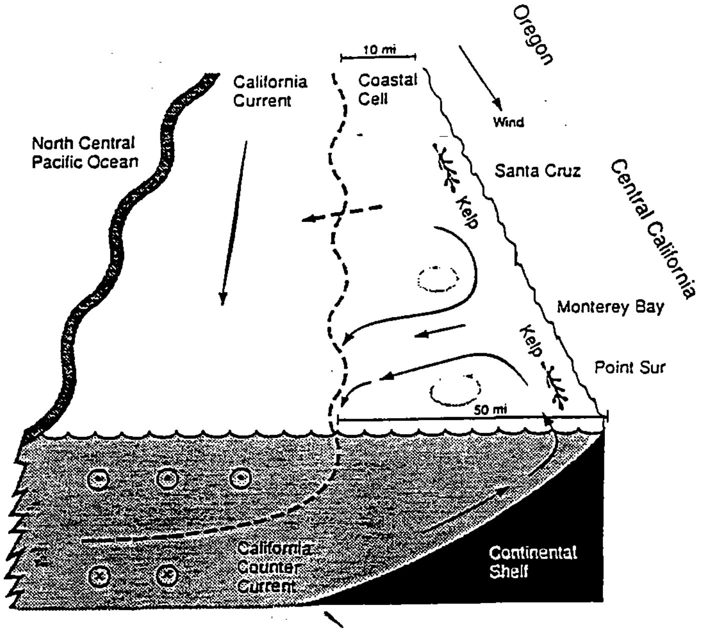

Figure 4.35. Schematic diagram of two dimensional upwelling system with horizontal eddies and streams/filaments. (Reprinted with permission from Roughgarden, J., S. Gaines, and H. Possingham. 1988. Recruitment dynamics in complex life cycles. *Science* 241:1460-1466. Copyright 1988 American Association for the Advancement of Science.)

It is useful to outline the terminology employed for the various mesoscale features. Davis (1985) provided some useful definitions for a variety of mesoscale features. The *eddies* are swirling flows. *Convergences* are regions to which drifters coalesce and frequently coincide with fronts. *Jets* are narrow high speed flows and squirts are localized energetic off-shelf flows often associated with cold-water plumes extending off the shelf. More recently, Strub et al. (1991) used the term *filament* to include many types of surface, cross-shelf, usually cold water flow. They suggested three conceptual models of the filaments (Figure 4.36). First, *squirts* are defined as-one way jets that transport coastally-upwelled water to the deep ocean, sometimes terminating in a counter-rotating vortex pair. The ideal squirt is caused by near-shore convergence. Second, a number of mesoscale eddies embedded in the generally southward-moving current can entrain coastally-upwelled water and move it away from the coast. A third model is one of a continuous southward jet meandering onshore and offshore.

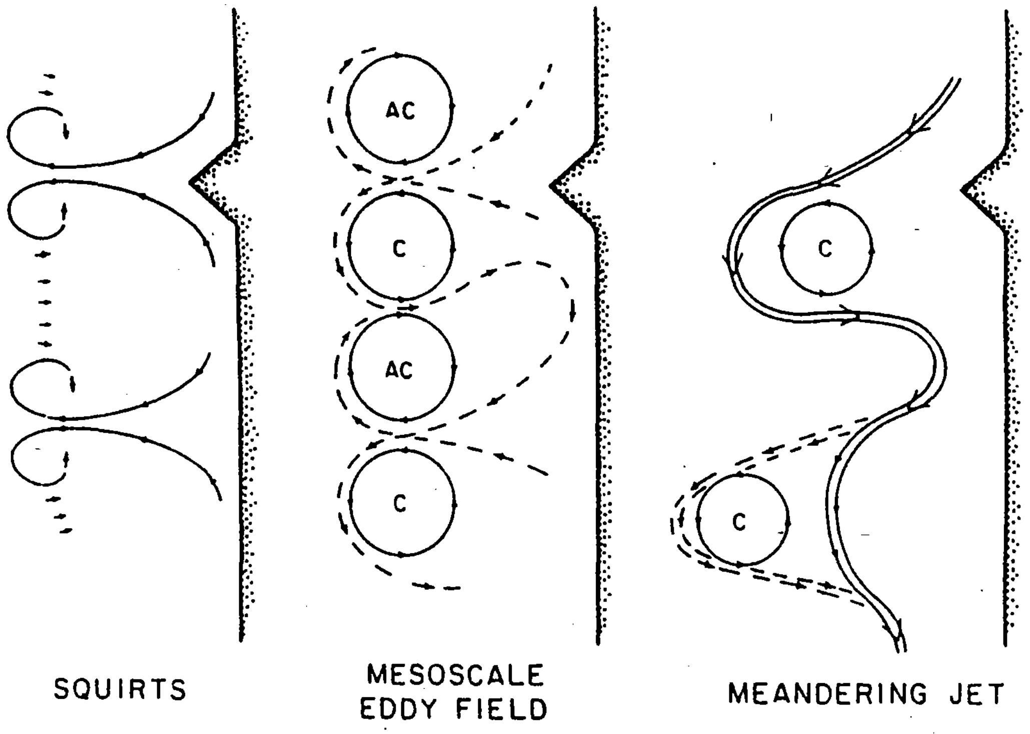

Figure 4.36. Conceptual models considered for the flow structure associated with cold filaments. (Source: Strub, P.T, and C. James. 1988. Atmospheric conditions during the spring and fall transitions in the coastal ocean off the western United States. *Journal of Geophysical Research* 93:15,561-15,584. Reprinted with permission, courtesy American Geophysical Union.)

Eddies and Jets. A very obvious feature of the satellite imagery of the Pacific Northwest ocean (Fig.4.31) is the turbulent flow in the CCS and its mesoscale eddies. Although these are best observed off California and have been described off Vancouver Island, they also exist in the PNCERS study area. They have not been well-studied off Washington and *the study of mesoscale eddies in the Pacific Northwest area is an important research topic.* Hickey (1989) discovered that small-scale eddies are not the principal source of variance at mid-shelf, mid-water column locations but are expected to be of greater significance in the near-surface layers and in the outer shelf. *The relative importance of eddies in the outer shelf should be determined.* Smith (pers. comm. 1996) has pointed out that the major source of current variance is not eddies but is wind-driven. He believes the eddies over the shelf are probably a result of instabilities in a coastal jet. Drifters have been used to make accurate determinations of the paths of the eddies. Davis (1985) gives some very good examples of the eddy phenomena off Northern California. *The specification of spatial and temporal changes of upwelling filaments, eddies, and jets should be a research topic both of PNCERS and GLOBEC.*

Columbia River Plume. Since the Columbia River provides a large amount of the freshwater entering the ocean from Washington and Oregon, its plume obviously plays a major role (Landry et al. 1989). The impact of the plume on salinity and density was shown in Figs. 4.6 and 4.7. Hickey (1989) believes a significant equatorward undercurrent may occur on the Washington inner shelf associated with the Columbia River plume. The construction of dams on the Columbia River has had the effect of increasing the amount of fresh water discharged into the northward flowing coastal current in winter (Ebbesmeyer and Tangborn 1992). This, in turn has given rise to an increase in fresh water intrusions into local bays and estuaries north of the Columbia River mouth and also into the Juan de Fuca Strait. Ebbesmeyer and Tangborn estimate that the new winter discharge to the north is the equivalent in magnitude of adding two rivers the size of the Fraser River. A comprehensive review of the situation in the post-dammed Columbia River is given by a set of papers edited by Small (1990).

Daily. The general effect of semi-diurnal and diurnal tides is twofold. They cause large changes in the volume of water at coasts twice a day and promote vertical mixing which breaks down the stratification of the coastal ocean water (Pickard and Emery 1990). Details on the different harmonic constituents of the tides may be found in Bowden (1983). The essence of the tidal response off the Washington and Oregon coasts is similar but the details depend upon exact bottom slope and water stratification (Hickey 1989). Tidal flows are naturally accelerated when constricted by topographic features such as estuaries. Ocean water movement can also be generated by internal waves formed through the interaction of tidal currents with bottom topography. Such movement may be focused by submarine canyons (Shanks 1995). When internal waves break they are manifested as tidal bores.

Possibly unrelated to tides is the fact that Breaker (1989) found a 40- to 50-day oscillation in the sea surface temperature off the California coast with an amplitude of as much as 1.5°C. *If it has not been performed already, a search for this oscillation should be undertaken for sea surface temperature off the Pacific Northwest coast.*

Other events such as "sneaker waves" and tsunamis occur but are relatively rare in the Pacific Northwest. The last major tsunami that affected the region was on March 17, 1964, when waves of between 3 and 6m (10 and 20 feet) high were reported. Flooding extended several miles up rivers. There is much evidence of past marsh burials in the Pacific Northwest region associated with tsunamis and previous tectonic events. The most recent extremely large tsunami in the Pacific Northwest occurred around 1700 AD (Jarman 1995).

Summary of Linkages between Ocean and Atmosphere

REVIEW AND EXTENSION OF MAIN LINKAGES FROM PREVIOUS SECTIONS

The foregoing discussion has revealed innumerable linkages between the atmosphere and the ocean in, and in the regions affecting, the PNCERS study area. The most predominant are first, the linkages between the basin-wide operation of the systems; second, the phenomenon of coastal upwelling; and third, the enhancement of coastal ocean El Niño effects by later atmospheric effects. The issue of atmosphere - ocean linkage particularly demands a scale-related treatment and is dominated by questions of identification of causal and resulting factors and the degree of temporal lead and lag.

Wind-driven ocean currents at the basin scale are critical across virtually every time scale. On the longer time scale, the cooling of sea surface temperatures in the central North Pacific is believed to be associated with the post-1976 eastward shift and deepening of the Aleutian Low (Trenberth and Hurrel 1994). In addition, Miller et al. (1994a) have demonstrated that the mid-latitude part of the 1976-77 regime shift in the ocean was driven by the atmosphere, although feedback effects are not ruled out. Indeed, they identify the research question *to what extent do ocean thermal anomalies, once initiated, act to modify the air-sea heat exchange and subsequently affect the atmospheric circulation?* The model, developed by Miller et al. (1994a) points up the important fact that the temperatures of the mixed layer of the ocean off the coast of California are controlled much more by heat-flux input anomalies than by advection. Further interesting associations on the decadal scale were found by Namias et al. (1988) in correlations between the persistence of sea surface temperature in the North Pacific during January, the amplitude of the first principal component of sea surface temperatures in the North Pacific, and Pacific North American Index and Southern Oscillation Index values.

We believe the feedback between sea surface temperatures and the atmosphere on interannual and lower scales is also important. Namias (1969) and his co-workers performed intensive work in the 1960s and 1970s in attempting to identify such feedbacks. They investigated a number of different situations including the possibility of cyclogenesis in the presence of anomalously warm sea surface temperatures (Pickard and Emery 1990). Davis (1976) however, made an in-depth study of the statistical relationship between atmospheric pressure and sea surface temperature and found only slight skill in forecasting atmospheric pressure from sea surface temperature anomalies. He concluded that the statistical connection between sea level pressure and sea surface temperature is more likely due to the driving of the ocean by the atmosphere. Davis did find that sea level pressure anomalies could be specified statistically from simultaneous sea surface temperature conditions. Walsh and Richman (1981) found significant correlations between North Pacific sea surface temperature anomalies and temperature fluctuations in the West Coast states. In more recent studies, Trenberth and Hurrell (1994) discovered that, on the monthly scale, in the North Pacific atmospheric changes lead sea surface temperatures by one to two months. They attribute this to changes in surface-sensible and latent heat fluxes combined with mixing in the ocean and entrainment (Trenberth 1995). At the same time, changes in the tropical Pacific sea surface temperatures lead those in the North Pacific by three months. Changes in the storm tracks in the North Pacific help to reinforce and maintain the anomalous circulation in the upper troposphere of the atmosphere.

The relationships between wind and upwelling have been treated above. However, as mentioned previously, there seems to be a need for a more comprehensive climatology of the upwelling phenomenon and one which also includes biologically-important wind and water velocities.

The ocean/atmosphere relations surrounding ENSO phenomena are some of the most closely integrated and difficult to unravel. Trenberth and Hurrell (1994) hypothesize that the deepened

Aleutian Low in ENSO events results in a characteristic sea surface temperature anomaly pattern that, on average, is enhanced through positive feedback effects from: 1) effects of the extratropical sea surface temperature itself; and 2) changes in momentum (and vorticity) fluxes associated with high frequency storm tracks. On the decadal time scale, changes in ocean currents reinforce the sea surface temperature changes. Changes in the ocean currents and Sverdrup circulation are slow and add persistence to the extratropical system which, together with heat storage in the upper 500m, helps to emphasize the decadal over the interannual scale relative to the tropics. *A research topic would be to flesh out this hypothesis and test it more thoroughly.* Emery and Hamilton (1985) support this idea. They found that the relationship between the North Pacific sea level pressure and the Southern Oscillation, together with the relationships between the North Pacific sea level pressure and oceanic conditions in the NE Pacific, could account for the observed general tendency for sea surface temperature and sea level high pressure along the west coast of North America to be anomalously high during tropical warm ENSO episodes, although not all ENSO events were accompanied by warming of the Northeast Pacific. On a more local scale we have mentioned that for 1982 -1983 El Niño initial ocean appearance of high sea surface temperature along the West Coast was later enhanced by the atmospheric manifestations of the warm ENSO event (Huyer and Smith 1985).

There are other important ocean/atmosphere links. One is the determination of ocean salinity as a result of variation in winter coastal and interior precipitation. This was considered in the development of the PNI. Interesting statistical relations exist in yet another arena. Dettinger et al. (1995), for example, find a 3.3 year periodicity in one of their principal components of US temperature variation. This periodicity is found mainly in the western US and coincides with an identical periodicity in North Pacific sea surface temperatures and boundary current flow. *Such statistical associations should be examined to see if a physical cause or relationship might be at work.* Indeed, Dettinger et al. explicitly say that *"connections of the 3.3- and 10 year oscillations (in US air temperature) to the oceanic sea surface temperatures and flow patterns in the North Pacific's double-gyre circulation ... are certainly worth pursuing."* Finally, one of the most intriguing ocean/atmosphere linkages is that related to the spring transition. *An important research task would be to investigate if there are interdecadal cycles and/or other kinds of long term variability in this transition. Also, what is the threshold that exists which leads to the onset of the transition?*

THE IMPORTANCE OF TIMING OF OCEAN/ATMOSPHERE EVENTS WITH RESPECT TO SELECTED BIOTIC ACTIVITIES

The importance of timing of ocean/atmosphere events with respect to biotic processes is discussed in Chapters 5 and 6. It needs to be emphasized here that oceanographers and climatologists should be sensitive to the fact that not all events of the atmosphere and ocean have equal importance to biota. Some events and phenomena can be quite critical to biota. Upwelling situations are one, and the ocean and atmospheric conditions when salmonids first leave the estuary and enter the marine environment are another. A review of some of these linkages and critical times has been provided by Greenland (1996). A critical point in this general context is that *the important times in the life cycles of biota should be recognized explicitly and these times and their related spatial and temporal scales, should be used to set priorities in PNCERS research in the ocean/atmosphere arena.*

TOWARDS MODEL DEVELOPMENT

The PNCERS program has started with a simple conceptual model focused on management decision-making with input from biophysical, and social and economic systems. The implicit underlying idea is that there are, or could be developed, more detailed sub-models of various parts of the biophysical and socioeconomic systems that can be used to extend the PNCERS conceptual model and make it more useful for ultimate management decision making. The whole approach leans towards being mechanistic and deterministic, which may be appropriate to a certain extent, but has some profound limitations. The limitations relate to the wide variety of existing or potentially new models that could be conceived, the difficulties of linking biophysical models together, the importance of recognizing the role of history and the larger context surrounding individual models, and also the very real difficulties of linking human and biophysical systems. The following discussion gives some idea of the different kinds of models already available and then expands upon the difficulties of linking human and biophysical systems.

Existing and Potentially New Models that Would Extend the PNCERS Conceptual Model

Existing models may be simplistically classified into conceptual models and deterministic numerical models. An example of the conceptual model is the "HWFS" model, an acronym for the interdecadal regime shift conceptual model developed by Hollowed, Wooster, Francis, and Sibley (Hollowed and Wooster 1991; Francis and Sibley 1991). It was discussed in earlier sections and diagrammed in Fig. 4.15. It is used in the present context as an example of the kind of conceptual model that brings together a number of cross-disciplinary features, has the potential for explaining a number of disparate observations, and can stimulate new research questions and data gathering programs. As such, it is a good example of a model lying between the extreme physical and mathematical complexities of the numerical models and overly simplistic conceptual models that are more descriptive than either diagnostic or prognostic.

There is a wide variety of deterministic numerical models. Numerical models are models that use equations of motion, hydrostatics, state, and radiative transfer in a three-dimension grid system space, and that use time-dependent, finite-difference computer solutions to model processes, particularly those of movement in both the atmosphere and the ocean. Usually there are separate models for the atmosphere and ocean but sometimes coupled models are used. Most commonly the models are employed on a global, coarse grid, but in many instances fine grid, or very fine mesh grid models are used separately or as nested models within a global grid. There are many versions of numerical models, the most well known being the global circulation models.

Physical models are best when they deal with relatively small, well specified parts of the physical system. A two-dimensional numerical model of coastal upwelling is a good example of this. The coupling together of different types of deterministic numerical models is no easy task. Nevertheless, GLOBEC (1995) planners have pointed out that many efforts to date have sought to incorporate basic ecological process formulations into regional scale transport models. They advocate the development of a series of multiscale nested models that will have a great deal of sophistication in their ecological parts and also be open to data assimilation techniques. It is conceivable that some future PNCERS models may be incorporated into this framework. Coupled ocean/atmosphere global circulation models will be the basis of large scale modeling for a long time to come. These global circulation models continue get better at bringing in realistic physical and biophysical processes but their spatial resolution will probably be coarse so as to necessitate nested, higher resolution models.

The Important Role of History in Models

Models are not very good at incorporating history and feedbacks into situations. When cyclic phenomena are being treated (as in the case of interdecadal variability in the Pacific Northwest) it is important to recognize that it is likely that when the time series returns to the point at which a new cycle begins, it is often the case that both biophysical and human-related situations have changed since the similar point was reached in the previous cycle. Consequently, the new cycle is operating on new background conditions and predictions of what will happen next cannot necessarily be made with confidence. Additionally, directional changes may also have taken place. For example, a century-long global climate-warming trend would mean that a cyclic phenomenon with a 20 year periodicity would start at different point every time the cycle repeated. This and analogous sets of events have caused severe problems in population ecology models (Kingsland 1995). Thus individual models must not be conceived as acting without a context. Francis and coworkers have argued this point eloquently with respect to biotic changes in the North and Northeast Pacific Ocean (Francis and Hare 1994; Francis 1996).

The role of the history of models is also instructive. Ecologists found in the 1960s that it was unwise to try to model everything into a large comprehensive model (e.g., an ecosystem). Problems of model-emergent properties and nonlinearity made the approach untenable. Huge, comprehensive models of individual ecosystems met with only very limited success with the result that it was found more effective to design smaller models of certain parts of the ecosystem and make sure these kinds of models worked well within the quite tightly prescribed limits that were set up for them. A later stage of development has seen increasing attempts to link the individual models but this procedure is performed cautiously and on a limited basis.

Currently it is generally found more effective to have a suite of individual efficient models than to aim for a large all-encompassing modeling system. It is likely that this kind of approach will work best for the PNCERS program as well.

Difficulties in Linking Biophysical and Social Science Models

Investigators in the natural sciences are not generally aware of the huge difficulties existing in attempts to link biophysical and social science models. The principal reason for these difficulties is that biophysical and social scientists generally work within totally different research paradigms. Biophysical scientists work mostly in the logical positivist paradigm where empirical observation, inductive and deductive processes are paramount. This framework is also used by social scientists, and to the extent that it is, then there is some possibility that natural and human-related systems can be linked. However, social scientists have found the logical positivist framework to be extremely limiting and have performed a great deal of their work under other paradigms. We will very briefly describe these paradigms and then re-state the difficulties that they represent for a program such as PNCERS.

Some of the more important social science paradigms that have found favor in the last four decades are as follows. Phenomenology is a philosophy that seeks to disclose the world as it shows itself *before* scientific inquiry, as that which is pre-given and pre-supposed by the natural sciences. Realism is the identification and abstraction of causal powers (as opposed to empirical regularities) acting under specific conditions, recognizing that all social science systems are open systems. Structuralism is a set of principles and procedures seeking to expose the basic structural logic underlying human actions and activities. Structuration is an approach concerned with the intersections between human agents and wider social systems and structures (agencies). More details of these can be found in many books (e.g., Johnston 1991). Post-Modernism is an approach assuming that “truth” and “explanation” has many equally possible, and often simultaneous, forms (e.g., Harvey 1989).

Most of these paradigms either present severe challenges to the logistical positivistic approach used in the sciences or are mutually exclusive of it. The only short-term pragmatic way to resolve this is to recognize that studies such as PNCERS, that seek to bring together biophysical and human systems, must be very carefully limited to specific subject areas where it is believed that some, albeit limited, progress can be made.

Use of Climate Forecasts in Decision-Making

In the 1960s, and following that time, there were many techniques developed for taking meteorological forecasts made in probability terms and using them within quantitative, operational, decision-making frameworks. The fact that a recent study has shown that salmon managers use only a very small part of the information available to them suggests that decision making methodology should be improved (Pulwarty and Redmond 1997).

The most suitable operations for applying decision-making theory, much of which is based on probability theory, are operations that are repetitive (such as deciding every year what salmon catch may be permitted). Once a solution or set of strategies has been established for a repetitive operation then they can be used repetitively. Classic early examples of techniques such as the cost/loss ratio were provided by Thompson (1950) and Thompson and Brier (1955). Naturally, advances have been made in this field since that time, particularly in the area of agricultural climatology. Thus a general research area for PNCERS would be *to review and apply current methods of operational decision making to the management problems of the Pacific Northwest given the availability of current weather and marine forecasting methods.*

DISCUSSION AND RESEARCH QUESTIONS

It is not easy to review the whole of the two very specialized fields of atmospheric science and oceanography even when consideration is limited to a particular region of the Earth. The Pacific Northwest region happens to be a very complex area because it is an interface between two of the world's great land and ocean masses. Consequently, there are severe limitations to this review. Many items have been omitted.

A little over a hundred years ago the first climate maps of the area were published (Secretary of War 1889) and they were based on less than a score of reporting stations. The complexity of the coastal ocean currents was discovered by noting the terminal points of the wreckage of ships and cargo lost at sea (Garfielde 1871). Just as there are trends in the biophysical time series, progress in the development of knowledge has been marked by trends and fashions in areas of research concentration. Early studies naturally tended to be descriptive. During the latter part of this century we have been reacting to *features* of the system. The 1982-83 El Niño was a wake-up call to the entire ENSO phenomena and was followed by intense study of that field, a study that is by no means complete. The late 1980s saw the discovery of the importance of interdecadal cycles/regime shifts and a great deal of effort has since been devoted to them. Similarly, oceanography has undergone a comparable pathway with concentrations, for example, on current flow and upwelling phenomena. Concentration on trends in study such as these are necessary and important. It is essential to thoroughly mine a research theme. But these focuses should not be permitted to take attention away from other important areas. In the Pacific Northwest region such items as paleoclimate and paleo-oceanography, the influence of extreme events, 40-70 year cycles, and techniques such as remote sensing and geographic information systems, all need further work and application.

Extent and Quality of Data Supporting the Conceptual Model

Available data on biophysical systems in the Pacific Northwest are abundant and many of them may be used to support the PNCERS conceptual model. The principal data shortages lie in the century and millennial time scales and in the ocean. Only new sources, and thorough re-examination of paleo-proxy data, can be used to redress the former need. Oceanography will continue to require large resources to be devoted to ship and other surface-based observation systems. The continuing and rapidly developing deployment of remote sensing systems will be of immense value in the larger spatial scale studies of both the atmosphere and the oceans. The Earth Observing System (EOS) will likely play a critical role in this development.

Research Questions

Research questions in the fields of atmospheric science and oceanography arising from this review may be categorized into ones dealing with general broad areas of study and research, specific questions of high priority, and other important specific questions. These questions are conceptually rather limited to the areas already studied. It is likely that there are whole suites of very important questions related to areas such as remote sensing which have not received attention in this review. Finally, five general discussion questions were provided for use at the PNCERS workshop.

GENERAL QUESTIONS AND RESEARCH AREAS

What is the degree to which the various sub-ecosystems such as upland and lowland terrestrial, freshwater, and marine, are coupled or decoupled at the interfaces with respect to abiotic and biotic fluxes?

To what extent are there cycles in the range 40 to 70 years periodicity in biophysical time series in the Pacific Northwest area and how important are these compared to other cycles?

It is necessary to learn more about climatic variability in the Pacific Northwest area on the century and on the millennial scale especially with regard to the oceans.

The specification of spatial and temporal changes of upwelling filaments, eddies, and jets is of great interest.

The important times in the life cycles of biota should be recognized explicitly and these times and their related spatial and temporal scales should be used to set priorities in PNCERS research in the ocean/atmosphere arena.

We need to review and apply current methods of operational decision making to the management problems of the Pacific Northwest given the availability of present weather and marine forecasting tools.

Discussion Questions

Five general questions are provided for this theme. They are:

1) What are the relationships existing between phenomena and processes occurring on all of the different scales considered in this theme?

2) How stationary (i.e., faithfully replicable over long periods of time) are the various cyclic and quasi-cyclic phenomena in the Pacific Northwest atmospheric and oceanic systems?

3) How best can information on our knowledge of the variability of climatic/oceanic regimes in the Pacific Northwest and their predictability be transmitted to ecosystem managers?

4) What are the most important research needs on scales of century and greater and annual and lesser?

5) What new and existing observing systems and data bases are required and exist for answering PNCERS-related questions and meeting its goals?

Specific Questions

Are forecasting models useful to managers? Specifically: 1) model forecasting studies should be reviewed with regard to their specific Pacific Northwest area forecast and their efficiency should be assessed; 2) the best methods for use of NWS Long-Lead forecasts by Pacific Northwest managers should be determined.

What are the most appropriate measures of both the atmospheric and the oceanic manifestations of ENSO in relation to the Pacific Northwest?

What causes the change between one part of an interdecadal scale cycle or modal type and another ? Specifically, has the HWFS model of West Coast to Alaskan flow regime switch also occurred in earlier decades. What causes the switch back from Alaskan to West Coast flow regimes?

What detailed set of events, such as the sea level pressure patterns found by Strub and James, determines the timing of the spring transition and how is the transition related to atmospheric conditions and atmospheric and oceanic cycles on a variety of scales especially the decadal?

To what extent can we use discontinuous historic coastal air and sea surface temperature data extending back to the early 1800s to assess the degree of 'stationarity' of decadal regime behavior?

In what ways can dendrochronological or other proxy data be best used to investigate interdecadal and century scale periodicity?

Can we determine whether the interdecadal scale changes are quasi-cyclic in form or quasi modal punctuated by step functions ?

Given the fact that interdecadal changes are statistical in nature (i.e. they show up best when the data are aggregated for the whole winter and in standardized anomalies rather than raw data) how can knowledge of them best be transferred to, and used by, decision makers?

What controls the position of the bifurcation point of the Alaskan and Californian ocean currents on scales from the annual to the decadal? To what extent can OWSP data and remote sensing be used to answer this question?

What mechanisms may be responsible for decadal scale shifts in the coastal ocean and how the effect spreads along the coast (i.e. how a sudden shift off southern California "diffuses" northward)?

Are long period tides with quasi 20 year cyclicity related to interdecadal regime change?

Can an observational framework be designed to gain information on the barotropic component of the ocean circulation in the NE Pacific?

What, if any, air-sea interactions are involved to give rise to changes of temperature in the order of 1.5 °C over a three to four year period in the interior mid latitude of the North Pacific Ocean?

What are the mean and fluctuating current dynamics of the inner continental slope flows ?

How do the dynamics and intensity of the Alaska current respond to a very large annual signal in wind and precipitation in the Gulf of Alaska ?

What is the frequency and what are the controlling factors of biologically optimal upwelling conditions (i.e, upwelling conditions with certain water velocity ranges)?

What is the role of mesoscale eddies in the Pacific Northwest area and what is their relative importance compared to other dynamic features in the outer shelf. In particular what is the relative importance of eddies in the outer shelf ?

Is there a 40 to 50 day oscillation in sea surface temperature off the Pacific Northwest coast ?

Expand and test the hypothesis that on the decadal time scale a deepened Aleutian low in ENSO events results in a characteristic sea surface temperature anomaly pattern which, on average, is enhanced through positive feedback effects from: 1) effects of the extratropical sea surface temperature itself; and 2) changes in momentum (and vorticity) fluxes associated with high frequency storm tracks.

What are the sizes of ENSO-related shifts in precipitation and temperature median values to climatic normal values in the Pacific Northwest?

To what extent do ocean thermal anomalies on the interdecadal scale, once initiated, act to modify the air-sea heat exchange and subsequently affect the atmospheric circulation?

Is there a physical causal relationship for the 3.3 and 10 year periodicity in a principal component of US temperature variation found mainly in the Western US and an identical periodicity in North Pacific sea surface temperatures and boundary current geometries ?

To what degree are the periodic and random components in the time series of biophysical data in the Pacific Northwest area not independent of each other and does this lead to non-linear interactions between the components? Is there evidence for linkage between processes occurring at shorter and longer time scales?

To what degree can models of fluctuations at different time scales be put together so as to know the state of any particular cycle at any given time and its quantitative relation to simultaneous cycles of other lengths ?

What is the role of extreme events such as floods and droughts on the ecosystem and what is the relation between extreme events and longer term cycles ?

More data sets like Brunengo's Storminess Index data set should be developed and analyzed for short and interdecadal variability.

More attention should be given to the La Niña- related climatic events in the Pacific Northwest and to answer such questions as are flood events more likely to occur in the Pacific Northwest during La Niña times?

WORKSHOP-GENERATED QUESTIONS

During the course of the workshop the following areas were identified as being important for climatic/oceanic research for the PNCERS program:

- Characterization of temporal/spatial environmental (climate and ocean) variability;
- Long-term climate history;
- Monitoring the salmon's physical environment;
- Linkages between the physical environment and biota; and
- Air - sea - land - dynamics.

More details of these questions are contained in Chapter 7. It was the view of many participants that an effective monitoring program was essential to begin to solve some of the problems which are the focus of the PNCERS. Participants believed the monitoring program should be integrated and comprehensive (see for example, Sharp and McClain 1992).

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APPENDICES

Appendix 4.1. Teleconnective/Circulation Indices

CNP Central North Pacific. The average sea level pressure over the region 35° to 55° N, 170° E - 150° W. The CNP measures the intensity and area of the Aleutian Low and is available from 1899. (Cayan and Peterson 1989).

NP North Pacific Index. Area-weighted mean sea level pressure (mean sea level pressure) over the region 30° - 60° N, 160°E - 140°W (Trenberth and Hurrell 1994). Measures the intensity of the Aleutian low pressure. See also Emery and Hamilton (1985).

PNA Pacific North American Index. ¼[z^* (20° N, 160° W) - z^* (45° N, 165°W)

z^* (55° N, 115° W) - z^* (30° N, 85° W)] where z^* is the 500 mb mean monthly geopotential height anomaly at the points identified (Wallace and Gutzler 1981). A three node PNA at 700 mb was also designed by Yarnal and Diaz (1986) and Leathers and Palecki (1992). This index effectively measures the degree to which the general circulation over the Pacific and North America is meridional and adopts a pattern with a well developed Aleutian low and a low over eastern North America together with a high pressure ridge over western North America. These pressure patterns collectively make up what is called the PNA pattern. Ebbesmeyer et al. (1989) conceive a negative PNA value as representing the Aleutian Low being located more to the west and *vice versa*.

SOI Southern Oscillation Index. The standardized sea level pressure difference between Tahiti and Darwin, Australia. Low values of the index tend to indicate El Niño conditions while high values suggest La Niña events.

Appendix 4.2. Data Sets

CRITERIA FOR INCLUSION

There are a large number of data sets already collected and maintained that are useful for studies related to the PNCERS. Although there is need for more, particularly with regard to the ocean, it is useful to list and partially review some of the data sets that already exist. Such is the purpose of this section. Criteria for inclusion in this report are: 1) the data have been used previously in a Pacific Northwest coastal ecosystems-related study; and 2) the data have a clear potential for future use in the PNCERS program. Some of the data sets listed below are also included in the other data sets. There has only been enough time and resources to do a cursory examination of these data sources. PNCERS workshop members were invited to add to and improve upon this list.

RELEVANT DATA SETS

NATIONAL WEATHER SERVICE LAND SURFACE CLIMATE DIVISIONAL DATA

The US National Weather Service, the prime atmospheric data collecting agency in the US, collects a wide variety of data. Particularly useful for PNCERS are the Climate Divisional data. Each state is divided into up to about 10 or 12 Climate Divisions and data on temperature and precipitation values from stations within the division are averaged to form the divisional data sets. Climatic data from the individual stations are also available. Climate Divisional data and data from some individual sites are easily accessible from the World WeatherDisc (1994). The data sets of other national meteorological services may also be useful. Canadian data are available from Atmospheric Environment Canada which is located at Downsview, Ontario, Canada. The Hadley Centre for Climate Prediction and Research of the United Kingdom Meteorological Office has produced time series of monthly mean hemispheric-mean surface air temperature and sea surface temperature anomalies for the years 1890 to 1993 (Wallace et al. 1996).

NOAA CLIMATE DIAGNOSTICS CENTER PRODUCTS

The NOAA Climate Diagnostics Center (CDC) produces a large array of data sets and products that concentrate on climatological summaries of raw data and derived variables. They are also responsible for issuing the Long- Lead Forecasts which give forecasts for several months ahead. CDC products are disseminated in both hard copy and electronic form and include values of teleconnective indices and sea surface temperature data. The NCEP/CDC has a useful monthly averaged climatology of sea surface temperature (Reynolds 1982 quoted by Graham and Barnett 1995). The electronic address for the CDC is http://www.cdc.noaa.gov/.

COADS

The development of the Comprehensive Ocean/Atmosphere Data Set (COADS) is described by Woodruff et al. (1987). Elms et al. (1993) have reported aspects of the digitization of the data set. The COADS data are discussed comprehensively in the COADS web site at http://www.cdc.noaa.gov/coads. The COADS project collected global weather observations since 1854 taken near the Earth's surface primarily by merchant ships. Statistical summaries for each month were made using a 2° latitude by 2° longitude grid from 70 million original observations up to 1979. Monthly summary products give 14 statistics for each of 8 observed variables (air and sea surface temperatures, scalar and vector wind, pressure, humidity, and cloudiness) and 11 derived variables. Periodic updates of the data sets are made. Several subsequent data sets have been prepared from the COADS. An often used one is that of Pan and Oort (1990) which has a 1° latitude by 1° longitude spatial resolution and a temporal span of 119 years from 1870 to 1988.

COASTAL AND OCEANIC UPWELLING (BAKUN INDICES)

There is a lack of direct measurements of coastal upwelling. Because of this Bakun developed a series of upwelling index data based on the derivation of northerly wind stress along the West Coast obtained from meteorological data. The Bakun indices, sometimes called PFEG indices, are regularly updated and are often used. They are available in electronic form from The Pacific Fisheries Environmental Group, Southwest Fisheries Center, National Marine Fisheries Service, NOAA, P.O. Box 831, Monterey, CA.

PACIFIC CLIMATE WORKSHOPS (PACLIM) DATA SET

This data set was established out of the first years of operation of the PACLIM workshops. A key reference to it is Cayan et al. 1991. The data take the form of standardized monthly anomaly time series for several climatic variables for locations in the eastern Pacific Ocean and the western Americas. Variables include air temperature, barometric pressure, precipitation, streamflow, sunshine, sea level height, sea surface temperature, sea surface salinity, atmospheric teleconnective/circulation indices and biological variables, and miscellaneous ocean subsurface temperature and salinity factors. The data are available in an electronic form. The set and documentation can be obtained by writing for the Cayan et al. 1991 reference, USGS, Books and Open File Reports Section, Federal Center, Building 810, Box 25425, Denver, CO 80225.

SPECIFIC DATA SETS OF INDIVIDUAL INVESTIGATORS AND INSTITUTIONS

Specific data sets exist of individual investigators and institutions such as state Department of Fish and Wildlife in Oregon and the state Department of Ecology in Washington, the School of Fisheries at the University of Washington and the Scripps Institution of Oceanography (SIO).

Mr. Daniel Bottom at the state Department of Fish and Wildlife in Oregon and co-workers have assembled a Pacific Basin-wide data base of information related to salmonids. This data base is in a GIS framework. Ms. Patricia Dell'Arciprete and coworkers at the School of Fisheries at the University of Washington are working on an integrated assessment of the dynamics of climate variability, impacts and policy response strategies for the Pacific Northwest, and in doing so have assembled a very useful multidisciplinary data set for the Pacific Northwest that concentrates on the Puget Sound but which also addresses Pacific Basin wide issues (Dell'Arciprete et al. 1996). SIO has used COADS data to provide a set of monthly sea surface temperatures for the global ocean between 1950 and 1979 (Barbour 1986; Graham and Barnett 1995). SIO possesses many large atmospheric and oceanographic data sets.

Two other potentially useful data CDs are available: 1) the "US Navy Marine Climatic Atlas of the World" version 1.0 released in March 1992 from the Naval Oceanography Command Detachment, Ashville, N.C.; and 2) "A Daily Stream Discharge Data Set for the Continental US" version 1.0, released in February 1991 by J.R. Wallis, IBM Thomas J. Watson Research Laboratory, D.P. Lettenmaier, Department of Civil Engineering, University of Washington, and E.F. Wood, Department of Civil Engineering and Operations Research, Princeton University.

SELECTED SATELLITE DATA SETS

Heavily under-represented in this review is the potential for the use of satellite-derived data for the PNCERS study. It is likely that many themes of the study can benefit from such data. Up to the present the most commonly used data type for PNCERS-related studies has been Advanced Very High Resolution Radiometer (AVHRR) data for oceanic use. The frequency of use is because of the daily availability and relative high resolution of this data source. LANDSAT and Satellite Pour l'Observation de la Terre (SPOT) data have some potential for use but suffer from the approximate 16 day interval return overpass. In the future, Earth Observing System (EOS) program platforms and sensors will be of immense use for both oceanic and terrestrial parts of the PNCE area. The use of satellite-derived data for land surface climatology has been reviewed in detail by Greenland (1994b). There are a number of remotely-sensed precipitation data sets for the North Pacific which have used microwave and other technologies.

HISTORICAL GRIDDED SURFACE PRESSURE AND CLIMATE NETWORK SETS

The Department of Energy (DOE) houses and distributes a wide range of climatological data sets from the Oak Ridge National Laboratory in Tennessee. At least two of these are of potential use for the PNCERS. A first is the historical gridded-surface pressure data set for the North American continent. This set provides monthly mean surface pressure on an approximately 250 km grid back to 1858. The area also covers parts of the NE Pacific Ocean. The data are available in hard copy and electronic form (Jones et al. 1987). A second data set distributed by DOE is the Historical Climate Network (HCN) data set (Karl et al. 1988). This is composed of temperature and precipitation data from a large number of individual recording stations. The data have been processed so as to remove errors due to such things as time of observer bias, and are especially useful for analysis of long-term climate variability. There are approximately 80 HCN stations in Washington, Oregon and Northern California. A new version of the US HCN was recently released and information concerning it can be found at the following URL: http://cdiac.esd.ornl.gov/ndps/ndp019r3.html.

NCEP GRIDDED PRESSURE SET

NOAA through its National Centers for Environmental Prediction (NCEP) provides a useful CD ROM entitled "National Meteorological Center Grid Point Data (Version II)" (1990) containing gridded surface and upper air atmospheric pressure data sets for the northern hemisphere. These have been widely used in synoptic climatological studies and are potentially of great value to future PNCERS investigations. The CD is available from the National Center for Atmospheric Research (NCAR) Data Support Section (303-497-1215) or Atmospheric Sciences at the University of Washington (206-543-0448). NCEP (along with the European Centre for Medium Range Weather and the Fleet Numerical Meteorology and Oceanography Center) also provide model "initial condition" wind fields over the North Pacific.

MOODS SUBSURFACE DATA SET

GLOBEC (1994) planners also have drawn attention to the Master Oceanographic Observations Data Set (MOODS), from the Fleet Numerical Meteorology and Oceanography Center (FNMOC), Naval Research Laboratory, which consists of sub-surface ship data from conductivity/temperature/depth (CTD) observing instruments, bathythermographs (BTs), and expendable bathythermographs (XBTs) which extends back into the 19th century. Sharp and McLain (1993) have made excellent use of these data to provide mean monthly depths of the 14°C isotherm from 60°N to 60°S along the coast of the W Americas from 1943-1991.

PHYSICAL PARTS OF CALCOFI DATA SET

The California Cooperative Oceanic Fisheries Investigations (CalCOFI) sampling program occurs along the California coast. It was initiated in 1950 and is still being continued. There were some data gaps in the 1970s. Stations in the sampling grid are typically 30 to 60 km apart and sampling is performed down to 500 m. Variables sampled include temperature and steric height (Roemmich 1992).

WASHINGTON DEPARTMENT OF ECOLOGY MARINE WATERS DATA BASE

Dr. Jan Newton of the state Department of Ecology in Washington has assembled a large collection of data related to the Puget Sound area. The data include 21 variables of physical, chemical, and biological significance (Newton et al. 1995).

NEWPORT HYDROGRAPHIC (NH) LINE

Temperature and salinity with depth observations taken at stations off Newport, Oregon, originally to 25 nautical miles offshore, and later to 165 nautical miles. The observations were started in 1959 by Oregon State University investigators. Quite good coverage exists for all seasons for the years 1960 to 1970. Partial coverage is available from 1971 to 1975 after which time the coverage is sporadic. These data are described by Huyer (1977) and have been used in several papers (e.g., Huyer and Smith 1985).

HYDROLOGY DATA SETS

Comprehensive hydrologic data are represented by the US Geological Survey stream flow/gage records and the US Department of Agriculture Soil Conservation Service (and Canadian) snow course and snow sensor records.

CHAPTER 5

VARIABILITY OF PACIFIC NORTHWEST MARINE ECOSYSTEMS AND RELATION TO SALMON PRODUCTION

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INTRODUCTION

Resource Status and Need for an Ecosystem Approach

In the last few decades, the Pacific Northwest has experienced a rapid decline of native species and economic resources including the widespread degradation of fisheries, forests, and watersheds (FEMAT 1993; Henjum et al. 1994). President Clinton's forest plan (FEMAT 1993) drew national attention to the management of forests in western Oregon and Washington because of their central role in the economic and ecological health of the region. Concerns about native forests and old growth-dependent species have expanded with the realization that much of the regional landscape has been degraded by forest practices and by intensive land use and development activities. Cumulative, catchment-wide loss of habitat has been identified as a major threat to native species and entire aquatic faunas of major drainage basins throughout the Pacific Northwest (Nehlsen et al. 1991; Minckley and Douglas 1991; Frissell 1993). These effects are amplified by large-scale climatic changes that alter habitat conditions and biological productivity across the entire Pacific Northwest.

Conservation and data-collection efforts in this region are in large part driven by the spatial boundaries and management interests of the many institutions that regulate the use of natural resources. Management jurisdictions rarely coincide with ecosystem boundaries, and monitoring and evaluation programs rarely account for the cumulative factors that affect the condition of whole watersheds, estuaries, or ocean ecosystems. Furthermore, conservation programs in fisheries and wildlife, forestry, and other applied sciences are traditionally based on concepts and models for maximizing production and yield of economic resources (e.g., Bottom 1997). These approaches often assume a stable equilibrium among populations and environments and provide little or no insight about the response of coastal ecosystems to changing conditions.

Salmon as an Indicator of Ecosystem Response to Change

To improve understanding of the linkages among terrestrial and aquatic subsystems, Pacific salmon are proposed as an indicator of response of the coastal ecosystem to environmental and anthropogenic change. Salmon are a potentially useful indicator because their life cycles integrate changes across the continuum of coastal environments from watershed to estuary and ocean. At the same time, the variety of responses and life-histories among local populations within salmon species reflects distinct combinations of environmental change across the geographic mosaic of different watersheds, estuaries, and ocean environments.

Other species or groups of species may afford a more comprehensive understanding of variability than is possible from evaluations of salmon alone. For example, salmon may not be sensitive indicators of the processes that affect marine demersal communities. Similarly, ocean recruitment factors may differ between salmon and other marine species. Survival of marine fishes with pelagic larval stages, for example, may be regulated by physical processes experienced very early in their life-histories. In contrast, juvenile salmon enter the ocean at a much larger size, and therefore, may be subject to different environmental limitations. The basic question of whether salmon are, in fact, useful indicators offers a valuable approach for understanding variability in the ecosystems of the Pacific Northwest. Answers to this question require comparisons among species to determine the scales and processes of variation that are most generally applicable across the coastal ecosystem.

The objective of this chapter is to evaluate the influence of ocean variability on the capacity of Pacific Northwest coastal ecosystems to produce Pacific salmon. This review is not intended to be an exhaustive survey of all information about the ocean ecosystem or Pacific salmonids of the region. For the purpose of this review, the Pacific Northwest is defined as generally within the coastal region of Washington, Oregon, and northern California (to Cape Mendocino). But migrations of salmon stocks from Oregon and Washington can extend long distances into the Gulf of Alaska. Predators and prey of salmon from the Pacific Northwest also include species that exhibit (or historically exhibited) migrations extending the length of the California Current region from southern California to the coast of Oregon and Washington. Furthermore, salmon and the California Current are embedded within a larger oceanic and atmospheric system that extends to a global scale and profoundly influences the productivity of these ecosystems. For these reasons, processes at the scale of the entire Pacific Ocean Basin as they relate to regional salmon production are considered.

There are two measures of the capacity of the ocean to produce salmon. The first involves variations in salmon abundance as influenced by the flow of energy supporting salmon production and the survival of individuals in the marine environment. Important factors that may regulate salmon abundance and survival include changes in the productivity of coastal waters; the distribution and structure of marine assemblages, including predator and prey species; and coastal currents or other physical variables that may directly influence salmon mortality.

The second measure of ocean capacity relative to salmon production concerns the temporal and geographic patterns of life-history organization among salmon populations. Over the course of their evolutionary history, salmon have evolved a variety of genetically-controlled traits between species and among populations (stocks or "races") within species to function in spatially and temporally variable environments (Ricker 1972). In addition to genetic traits, many salmon species and stocks have evolved diverse phenotypic or "tactical" responses (Healey 1991) that further enhance survival in a variable environment. Examples of variable life-history traits that may affect ocean survival are: the period of juvenile and adult migration, time of ocean entry, age of seaward migration, rate of juvenile growth and size at ocean entry; and age at maturity and return to natal streams (e.g., Reimers 1973; Nicholas and Hankin 1988; Taylor 1990a, 1990b; Clarke et al. 1992). Through natural selection, the survival of salmon in the ocean is directly tied to their riverine and estuarine survival. For example, each year selective forces in rivers and estuaries determine the range of sizes, physiological condition, and time of ocean entry of the population of migrants leaving each river system. Slightly different migration times, in turn, may be advantageous in different years depending on the onset of the spring transition, the specific timing and location of upwelling events, or the distribution of predators along the coast. In this way, the diversity of life-history characteristics within and among populations influence the capacity of salmon species to adapt to changing conditions. We will briefly examine the geographic distribution of salmon life-histories relative to environmental variability with emphasis on life-history linkages between freshwater and marine environments.

OCEAN PRODUCTION OF SALMON IN THE CONCEPTUAL FRAMEWORK FOR PNCERS

Until recently, changes in salmon abundance were attributed primarily to conditions in freshwater. These ideas were formalized in theoretical population models, which emphasized mortality during egg and early juvenile stages, and in hatchery programs, which assumed that annual production would be increased by eliminating the causes of fresh-water mortality (Bottom 1997; Lichatowich et al. 1996). The unexpected collapse of Oregon coho salmon (*Oncorhynchus kisutch*) in 1976, despite continued increases in the production of hatchery smolts, provided the first convincing evidence that factors in the ocean environment might regulate salmon abundance (Bottom et al. 1986). Successful prediction of adult returns from the previous year's run of precocious males (jacks) indicated that survival of juvenile coho salmon sometime within their first six months in the ocean could determine production of adults for an entire year class (Gunsolus 1978). Considerable variation in climatic and oceanographic conditions that may regulate marine salmon production contradicts traditional management approaches that are based on equilibrium models of populations. An alternative conceptual framework is needed to account for the heterogeneity of environments of the Pacific Northwest as reflected in the diversity of salmon populations and variability in salmon production. Such a framework must incorporate: 1) the full sequence of environments (including oceanic habitats) affecting salmon populations throughout their life cycle; and 2) the diversity of life-histories within and among populations across the wide geographic range of salmon species.

One useful conceptual approach that meets these criteria is Sinclair's (1988) "member/vagrant" hypothesis, which describes possible mechanisms to account for the number (richness) of populations, absolute abundance, and variability in marine species. Sinclair describes how marine populations become adapted to geographic sequences of habitats that allow them to maintain the continuity of their life cycles. From this perspective, the number or richness of populations within a species is a function of the availability of specific physical oceanographic or geographic features (e.g., rivers, estuaries, ocean gyres, currents, etc.) at specific times that allow populations to bring their life cycles to closure. Sinclair notes that losses from a population can result from advection or other "spatial" processes that displace individuals from the area/time necessary to achieve closure of their life cycle. Losses can also result from "energetics" processes related to biological effects such as predation, competition, or disease. However, for many marine species with pelagic larvae, Sinclair emphasizes the importance of spatial losses that displace individuals from the appropriate geographic area thus creating "vagrants" unable to contribute to the population.

Both spatial and energetics processes may also cause losses from salmon populations throughout their entire sequence of riverine, estuarine, and oceanic habitats (Figure 5.1). We might hypothesize a longitudinal gradient in the relative importance of each process, for example, a proportionally greater role for spatial processes when adults home to their natal streams to spawn, or the predominance of energetics effects (e.g., competition or predation) during freshwater rearing by juveniles. Yet the relative importance of either process may quickly change. For example, extreme flow conditions or loss of habitat structure in fresh water may sweep juveniles downstream. The role of spatial losses during the marine life-history of salmon has received little if any research, but may be particularly relevant to the California Current, which is considered a physically controlled system (e.g., McGowan and Walker 1993). Sinclair's hypothesis is also discussed relative to the the geographic structure of salmon life-histories.

The richness of life-history types within and among salmon populations has been described as a strategy for spreading risks across a variety of habitats to avoid brood failure (Healey 1991). As implied by Sinclair's (1988) hypothesis, it may also be an important factor in explaining variability in salmon production. Salmon production in the Pacific Northwest, for example, may vary each year depending on how many life-history types can be supported under a particular sequence of

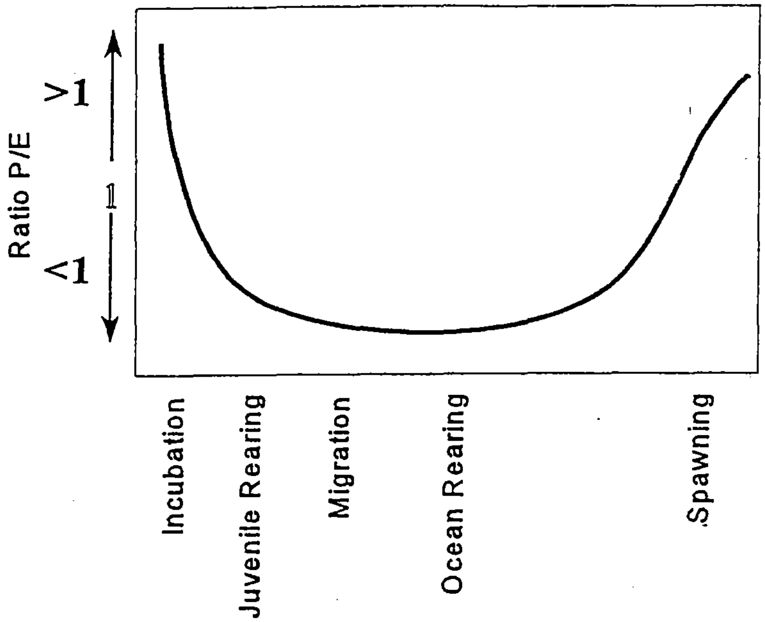

Figure 5.1. Hypothetical gradient in the relative proportion of spatial to energetics (P/E) losses at each stage of the life cycle of salmon. This suggests that spatial processes may be more important in early incubation and juvenile stages, while energetics may be more important during ocean rearing.

freshwater, estuarine, and marine conditions (Figure 5.2). Under extreme conditions, only a small number of life-histories may fully come to closure, although these few types may be critical in sustaining at least some production. During more favorable environmental conditions, a greater number of life-history types and populations may be "captured," producing a stronger year class for the species as a whole. Sinclair (1988) notes that absolute abundance of marine species is influenced by the spatial extent of areas in which life cycle closure is possible. Similarly, the spatial (and temporal) expansion and contraction of suitable environmental conditions may be particularly important in coastal ecosystems in the Pacific Northwest, which encompasses the southern edge of the range for several salmon species.

ECOSYSTEM SPATIAL AND TEMPORAL VARIABILITY AS RELATES TO SALMON

Background

In the last several decades, oceanographers have described dramatic changes in marine fish assemblages and food chains that have important implications for salmon and ecosystem

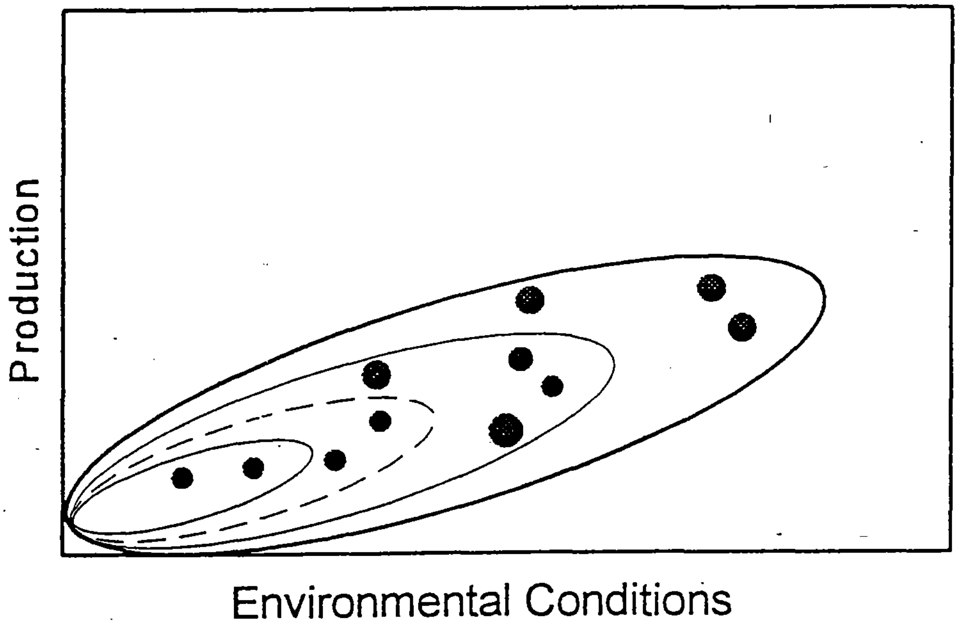

Figure 5.2. Hypothetical salmon production as a function of the number of different salmon life-histories (as indicated by the solid dots) that are "captured" under different environmental conditions. The environment experienced by each life-history type depends on the particular spatial and temporal sequence of habitats used throughout the life cycle of each type.

conservation. From analysis of fish scales deposited in anaerobic marine sediments off Southern California, researchers documented large fluctuations in abundance and shifts in the dominance of pelagic species that occurred well before intensive fisheries had any impact on fish stocks (Soutar and Isaacs 1969, 1974; Smith 1978). Regional fluctuations in fish populations have been linked to large-scale climatic changes. For example, strong El Niño conditions in the tropics have been associated with changes in marine fauna throughout the Northeast Pacific including northern range extensions for marine, fishes, birds, and plankton (McClain and Thomas 1983; Pearcy et al. 1985; Mysak 1986); reduced reproductive success of Oregon seabirds (Graybill and Hodder 1985); changes in the migration routes of adult sockeye salmon (*O. nerka)* returning to the Fraser River in British Columbia (Wickett 1967; McClain and Thomas 1983); and reduced size,fecundity, and survival of adult coho salmon off Oregon (Johnson 1988). Shifts in abundance of dominant species may reverberate throughout marine food chains with unpredictable effects on the abundance of associated species. For example, Sherman (1991) reported that overfishing on the northeast continental margin of the United States was responsible for sudden flips in the biomass of dominant pelagic species with cascading effects on marine birds, mammals, and zooplankton. Coincidental declines in the abundance of several bird and marine mammal populations has raised similar concerns about the potential effects of intensive harvest of walleye pollock (*Theragra chalcogramma*) on pelagic food chains of the Bering Sea and Gulf of Alaska (e.g., Springer 1992). Although poorly understood, the risks of harvest-mediated effects on many marine ecosystems may be increasing. Pauly and Christensen (1995) estimate from 24 to 35% of the primary production of fresh water, upwelling, and continental shelf ecosystems of the world is required just to sustain present levels of fishery harvest.

Unlike the well-defined and relatively restricted boundaries of streams and watersheds, ocean habitats continually shift with changes in the location of winds and currents and the horizontal and vertical gradients of temperature, salinity, and nutrients. Oceans are highly "open" systems in which physical and biological properties are linked across vast distances. Short (days to years) and long-period (decades to centuries) signals propagate through the ocean and atmosphere and change (e.g., become amplified or dampened) through their interaction. Resulting shifts in the distribution of predators or in the structure of entire food chains are important factors in the dynamics of salmon populations, whose ocean distributions, physical environments, and biotic interactions are at least partially predetermined by the migratory route they must follow to and from their home streams.

The scope of variability influencing salmon production in the ocean involves a nested hierarchy of spatial scales (see also Chapter 4). Geographic variations in salmon production reflect latitudinal gradients in the availability of protected embayment and estuarine habitat, the intensity of local upwelling, and the southward advection of nutrients in the California Current (Nickelson and Lichatowich 1984; Bottom et al. 1986; Chelton et al. 1982). These habitats and processes, in turn, are embedded within a larger oceanic and atmospheric system that regulates regional wind and current conditions and shifts the locations of high and low productivity around the Pacific Ocean Basin (Barber 1988; Sharp 1992). Large-scale atmospheric and oceanic changes have been correlated with interannual to interdecadal variations in salmon production (Beamish 1993; Beamish and Bouillion 1993; Francis et al. 1996). The effects of longer periods of climate change are implicated by the centennial to millennial cycles recorded in the scales of pelagic fishes deposited in anaerobic sediments of the Santa Barbara Basin (Baumgartner et al. 1992; Sharp 1992).

Ecosystem Spatial and Temporal Variability

ECOSYSTEM GEOGRAPHY

Geographic features of the North Pacific Ocean that directly affect biological production have been mapped or classified using a variety of criteria. Dodimead et al. (1963) with later refinements by Favorite et al. (1976) classified major ocean "domains" based on water masses of similar chemical and physical properties (Figure 5.3). They identified a subarctic boundary by the 34 parts per thousand (ppt) isohaline, which was chosen to represent the southern extent of the subarctic water mass where rates of precipitation equal those of evaporation. Important physiographic features of the coastal region of the Pacific Northwest relative to salmon production include a narrow continental shelf and, along the coastline, relatively little estuarine or protected inlet habitat. Deimling (1990) classified regions of the continental margin and shoreline of the northeast Pacific based on large-scale patterns of geomorphology, width, and topographic features of the continental shelf and shoreline of the North American coast. Three areas that were classified for the Oregon-Washington region, Cape Mendocino north to Cape Blanco, Cape Blanco to Tillamook Head, and Tillamook Head to Cape Flattery, correspond to the same regions identified by Bottom et al. (1989) based on patterns of winds, currents, bathymetry, and upwelling.

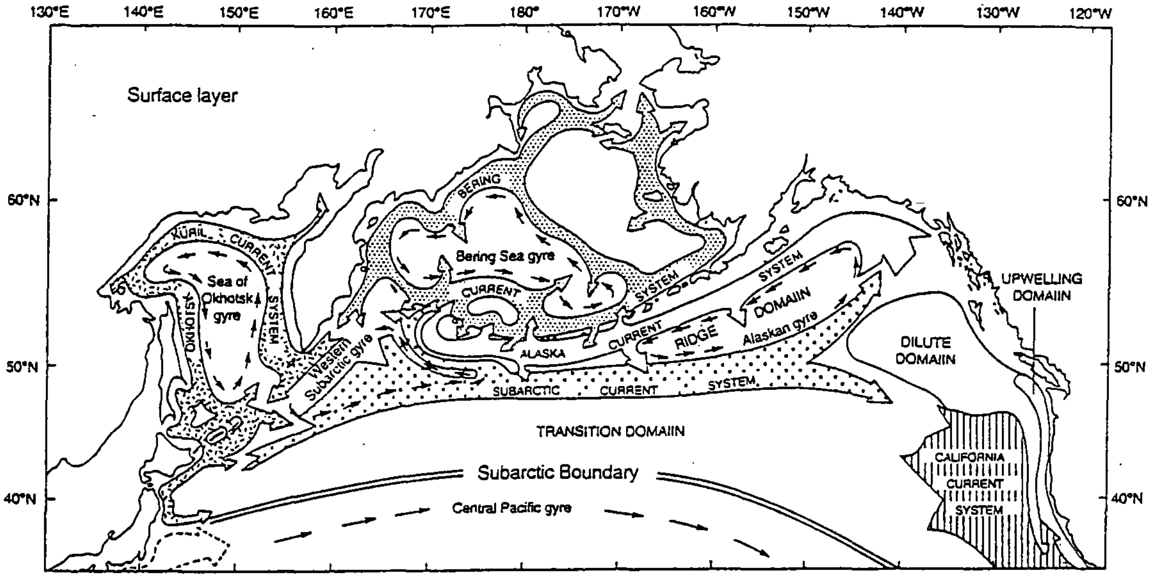

Figure 5.3. Generalized ocean currents and domains of the North Pacific Ocean as redrawn from Favorite et al. 1976. (Source: Groot, C., and L. Margolis. 1991. *Pacific Salmon Life-histories*. Vancouver: UBC Press. Reprinted with permission, courtesy of UBC Press.)

A discontinuity in winds and currents at Cape Blanco is particularly noteworthy. South of Cape Blanco, the zone of upwelling and increased nutrients is wider than along the central and northern Oregon coast, the influence of the Columbia River plume is reduced, and summer winds and upwelling are stronger and more variable than in regions to the north. Furthermore, strong offshore flow much greater than is explained by typical upwelling processes may have an important influence on the transport of phytoplankton biomass and could explain large-scale patterns of zooplankton in areas of the California Current (Abbott and Zion 1987). Deimling (1990) notes that the region between Cape Blanco and Cape Mendocino is a physical transition zone because, like areas to the south, it is characterized by strong upwelling in the summer and, like regions to the north, it experiences weak downwelling in the winter. It is interesting that the ocean migration patterns of coastal chinook (*O. tshawytscha*) stocks also show a discontinuity at

Cape Blanco: stocks from Elk River (located on the south side of Cape Blanco) and northward appear to rear in waters from Oregon to Alaska; stocks south of Elk River generally rear off southern Oregon and northern California (Nicholas and Hankin 1988).

PELAGIC BIOGEOGRAPHY

Biotic Provinces. In the 1960s, biogeographers discovered a close association between the major water masses of the Pacific Ocean as characterized by temperature and salinity profiles (Sverdrup et al. 1942) and the boundaries of large biotic provinces of the pelagic ocean as defined by the distributions of planktonic and nektonic species. North of the equator, Johnson and Brinton (1962) identified three major biotic provinces of the Pacific Ocean: a Subarctic assemblage associated with the nutrient-rich waters north of roughly 40 degrees north latitude; a Central Pacific faunal group corresponding to the oligotrophic waters of the central Pacific gyre; and a group of Transition Zone species occupying the boundary between these two groups along the east-west path of the Subarctic Current and West Wind Drift. Because these biological provinces correspond generally with the boundaries of large semi-enclosed ocean gyres, McGowan (1971, 1974) suggested that they represent discrete, functional ecosystems. Ware and McFarland (1989) defined three fisheries production domains in the northeast Pacific also based on large-scale circulation features and the distribution of commercial marine fish species: a Central Subarctic Domain; a Coastal Upwelling Domain; and a Coastal Downwelling Domain (Figure 5.4). They reported substantial differences in species composition, annual harvest, and catch/biomass ratios among these areas.

Unlike the large semi-enclosed gyres that circulate in the Central and North Pacific, the California Current forms an ecotone between adjacent water masses and the rivers that enter along its landward boundary. Here a small number of coastal species endemic to the region co-occurs with a larger mixture of subarctic, subtropical, and equatorial species, many of which are near the peripheries of their distributional ranges (Johnson and Brinton 1962; McGowan 1971, 1974). Researchers have inferred from these patterns that remote physical factors controlling the input of water and species from other regions may be more important determinants of species composition and abundance in the California Current than biological interactions such as competition and predation (Bernal 1981; Bernal and McGowan 1981).

The northern California Current region from Cape Mendocino to Puget Sound is described by Ekman (1967) as a zoogeographic transition between the Californian and Aleutian biological provinces to the south and north, respectively. However, based on distributions of coastal marine fishes, Horn and Allen (1978) place the southern boundary of this transition (Montereyan Province) at Cape Blanco (Figure 5.5). Most physical and biological classifications agree on a distinct northern coastal boundary near 48° N (near Puget Sound), which represents a discontinuity in the relative availability of protected inlet habitat used as nursery areas for many species including salmon. Zoogeographers have associated distributional boundaries of many marine groups with changes in sea-surface temperatures, which, in turn, are related to the temperature of water masses carried by current systems (Hubbs 1948; Lehner 1979 cited in Brown and Gibson 1983).

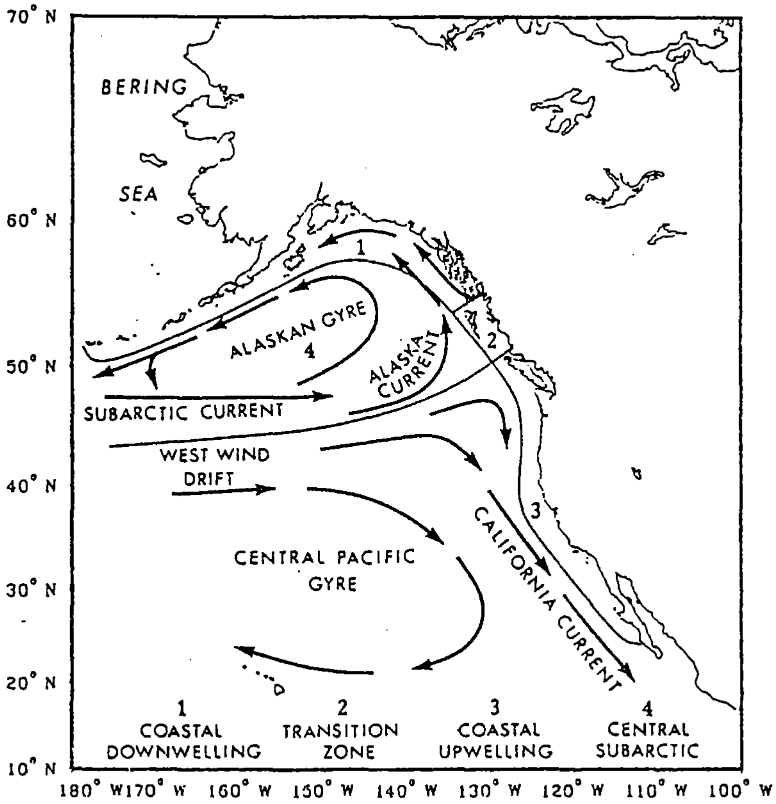

Figure 5.4. Generalized ocean currents and fisheries production domains. (Source: Ware, D.M, and G.A. McFarlane. 1989. Fisheries production domains in the Northeast Pacific Ocean. In *Effects of ocean variability on recruitment and an evaluation of parameters used in stock assessment models*, eds. R. J. Beamish and G. A. McFarlane, 359-379. *Canadian Special Publication in Fisheries and Aquatic Sciences* 108. Reprinted with permission, courtesy of National Research Council of Canada.)

Salmon Distribution and Migrations. The five most abundant species of Pacific salmon (pink, chum, sockeye, coho, and chinook) are distributed widely across the North Pacific Ocean and Pacific Rim with their southern marine distribution generally extending basinwide to the southern limit of the Transition Domain (see Fig. 5.3). Distributions differ among species, and stocks from Asia and North America intermingle in the northern North Pacific Ocean (Figure 5.6; Beamish and Bouillon 1993). Modern patterns of coastal distribution and within-species variability of salmon may be greatly influenced by the location of glacial refugia and available dispersal routes (McPhail and Lindsey 1986; Taylor 1990a). Chinook salmon, for example, probably survived the last glaciation in two refuges: Beringia (lower Yukon River and exposed portions of the Bering Sea and Siberia) and in the southern two-thirds of the Columbia River system and further south on the North American coast (McPhail and Lindsey 1986; Taylor 1990a; Healey 1991). Spawning populations of chinook salmon occur in the eastern Pacific as far south as the Ventura River (34° N) in California to Point Hope, Alaska, and perhaps east to the Mackenzie and Coppermine rivers, which drain into the Arctic Ocean (Taylor 1990a).

Despite considerable information available from commercial fisheries, understanding of the ocean migrations influencing the distribution of different stocks and species of salmon is very sketchy.

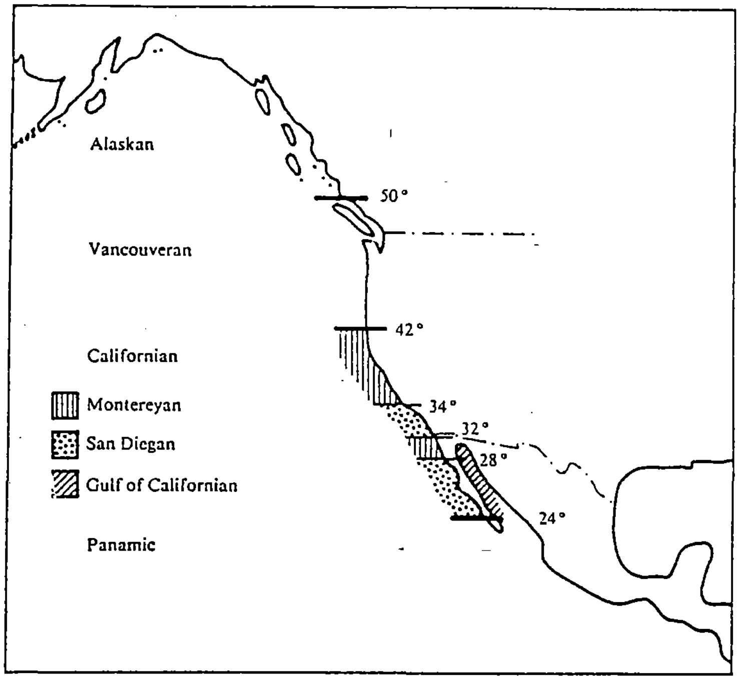

Figure 5.5. Biogeographic provinces and latitudinal boundaries for coastal marine species of western North America as defined by Horn and Allen (1978). (Source: Brown, J.H., and A.C. Gibson. 1983. *Biogeography*. St. Louis: C. V. Mosby Company. Reprinted with permission, courtesy of The McGraw-Hill Companies.)

Information on the distribution of mature salmon is derived from sampling of commercial troll fisheries, sampling of Japanese mothership and land-based gillnet fisheries, research cruises, and tag and recovery studies for selected stocks or groups of stocks (Healey 1991). Distribution of adults may be influenced strongly by temperature, oceanographic conditions, and food availability, but Pearcy (1992) notes that oceanic features have not been consistently associated with salmon migrations and distributions. Relationships between salmon and temperature apparently change with seasonal warming of surface waters and aging of salmon. Welch (1996) recently reported a strong pattern of temperature-related migration by salmon species characterized by a long northward movement in winter to locate cold (<7° C) water, and a southward expansion into warmer areas during spring and summer.

Perhaps the best documented example of oceanographic influences on salmon migrations involves sockeye salmon returning to the Fraser River (Figure 5.7; Groot and Quinn 1987). Most sockeye return to the river via Juan de Fuca Strait at the southern end of Vancouver Island. But in some years, a higher than average proportion enter from the north end of the island through Johnstone Strait, 500 km to the north. Hamilton (1987) reports that from 1906-1977 the typical rate of diversion to Johnstone Strait was 10 to 15 percent except for occasional large diversion years. Five of the eight exceptional years prior to 1977, and a remarkable 85% diversion in 1983, all followed El Niño occurrences in the tropics. The specific mechanisms are not clear. Correlations have been found with onshore Ekman transport off northern California (positive correlation; McClain and Thomas 1983), coastal temperatures in the summer off British Columbia (positive correlation), and coastal temperature 18 months preceding the spawning run (negative correlation; Hamilton 1987). Furthermore, a shift to much higher diversion rates since 1977 is coincident with the timing of the latest interdecadal shift in climatic regime, which has affected oceanic conditions throughout the North Pacific (Francis et al. 1996; see section below).

Juvenile salmonids were sampled by purse seine from 1956-1970 in the eastern north Pacific (north of the Strait of Juan de Fuca) and Bering Sea. Those data were summarized by Hartt (1980). Since sockeye, chum, and pink salmon were rare in offshore areas during their first summer at sea, Hartt (1980) concluded those species remained in coastal waters. In contrast, some chinook and coho salmon moved offshore, although substantial numbers remained in nearshore waters. The majority of steelhead appear to migrate rapidly from the coastal area to the open sea (Hartt 1980). Juvenile coho, chinook, and steelhead captured, tagged, and released in

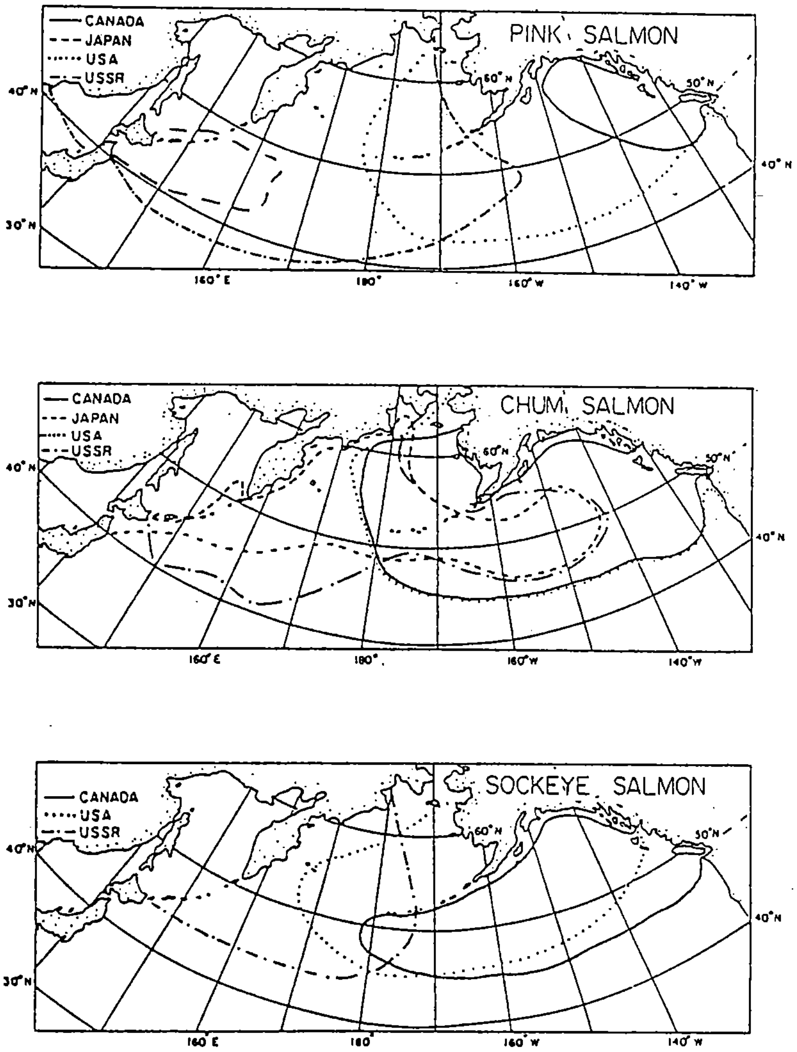

Figure 5.6. Known limits of ocean distribution of pink, chum, and sockeye salmon based on tag recovery data. (Source: Beamish, R., and D.R. Bouillon. 1993. Pacific salmon production trends in relation to climate. *Canadian Journal of Fisheries and Aquatic Sciences* 50:1002-1016. Reprinted with permission, courtesy of National Research Council of Canada.)

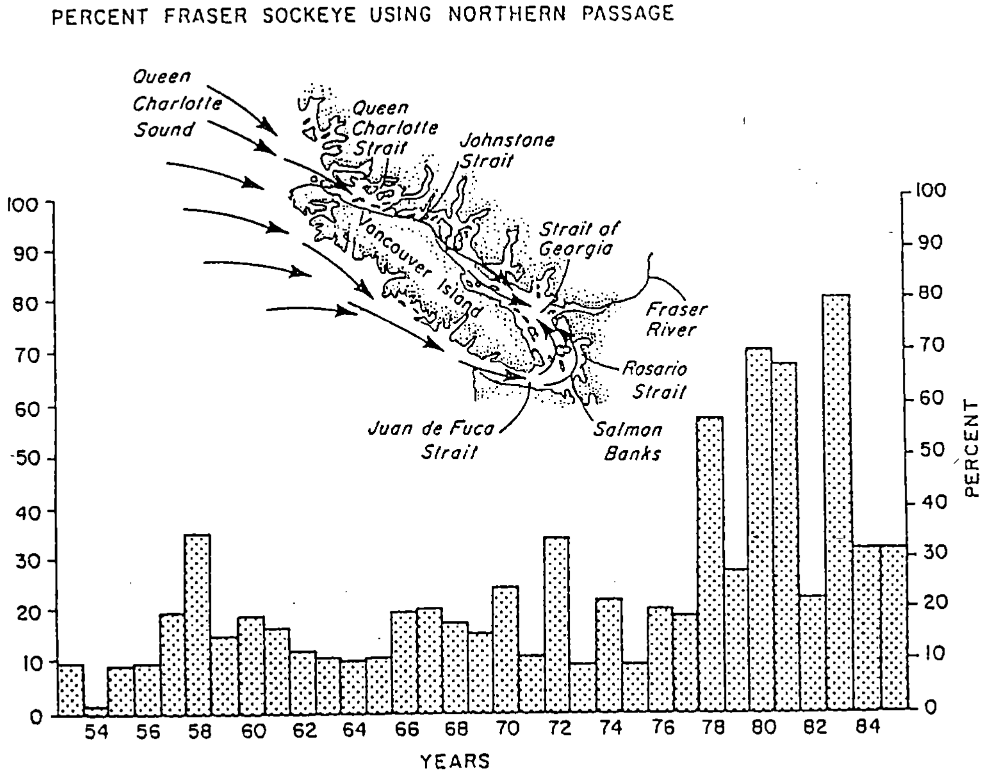

Figure 5.7. Proportion of the total run of adult sockeye salmon that used the northern route (Johnstone Strait) around Vancouver Island on their return to the Fraser River, 1953-1985. (After: Groot, C., and T.P. Quinn. 1987. Homing migration of sockeye salmon to the Fraser River. *Fisheries Bulletin* 85:455-469.)

the northeastern Gulf of Alaska were recovered in coastal streams of Oregon and California and the Columbia River. Based on limited tag returns (54 coho, 3 chinook, and 1 steelhead), Hartt (1980) suggested that a large proportion of the coho from that region migrate north during their first summer of ocean residence. However, based on his sampling of those stocks in the early 1980s, Pearcy (1992) concluded that many juvenile salmon in the Oregon Production Index (OPI) area remain in the coastal waters off Oregon and Washington during their first summer at sea. The different conclusions of Hartt (1980) and Pearcy (1992) could have resulted from different oceanographic conditions (Pearcy 1992).

Little is known about the migratory behaviors of individual populations of salmon or how these may influence marine survival and production. Lack of information about population-specific migrations limits present understanding of habitat use, production, and mortality factors influencing salmon at sea. Data generated from tagged hatchery stocks may or may not be representative of historic or present ocean distributions in naturally reproducing salmonids.

Some recent studies offer indirect evidence that different stocks of sockeye salmon may occupy geographically distinct areas within the Gulf of Alaska. Blackbourn (1987) hypothesizes that differences in the centers of distribution of sockeye stocks could account for interannual variations in return times to the Fraser River. This hypothesis is supported by correlations between sea surface temperatures in particular regions of the Gulf with variations in salmon return times. Welch and Parsons (1993) provide circumstantial evidence of stock-specific differences in salmon distributions based on variations in the concentrations of stable isotopes (δ^{15} N) in salmon tissue. Such differences may reflect the particular sources of organic material found in different oceanic areas where salmon feed.

PHYSICAL PROCESSES IN PELAGIC PRODUCTION

Among the scales of physical processes that play an important role in regulating ocean survival of salmon are: local upwelling events, which bring nutrient-rich water to the surface during the spring and summer months and involve periods of 1-10 days and distances of 5-200 kilometers (Barber and Smith 1981); currents that transport water seasonally along the entire Washington, Oregon, and California coast and determine the character of the water mass affecting salmon along a north-south gradient; and global oceanic and atmospheric changes that regulate both local and regional processes from interannual to interdecadal scales.

Upwelling. The upwelling system of the California Current, which extends along the West Coast of the United States, has been the subject of extensive physical and biological research. Since 1949, large-scale systematic surveys have been conducted off California, primarily south of San Francisco, as part of the California Cooperative Fisheries Investigations (CalCOFI; Huyer 1983). Detailed small-scale studies of the coastal upwelling system were completed off central Oregon in the 1960s and early 1970s (Peterson et al. 1979; Small and Menzies 1981; Smith 1983). The shorter time frames and local scales of most research off Washington and Oregon are not directly comparable to the larger interannual scales of information collected off California. Several reviewers (Huyer 1983; Strub et al. 1987a, 1987b; Landry et al. 1989) have synthesized a variety of data sets to understand the broad-scale features of the Washington and Oregon coastal ocean.

Nickelson (1986) found a positive correlation between the percent survival of hatchery coho salmon released in the Oregon Production Area and average upwelling conditions in the spring and summer. These results further suggested a "threshold" response to upwelling levels: in years of "strong" upwelling (greater than 625 units) survival of hatchery coho averaged 8% compared with only 3.4% during "weak" upwelling years. Nickelson (1986) also noted a possible negative correlation between surface temperature and survival independent of upwelling. The specific mechanisms of these correlations are uncertain. Furthermore, following the 1976 collapse in coho production off Oregon, the correlation between survival and upwelling has changed and, for the last ten years has been negative (Jamir et al. 1994), suggesting that upwelling alone is not sufficient to explain variation in coho salmon production.

Geographic variations in coastal currents and upwelling affect spatial patterns of biological production off Washington and Oregon. Such variations may be important to the survival and adaptations of salmon populations originating from different river systems and following different migratory paths. The gradient in atmospheric pressure that produces southward winds along the coast varies with location and with seasonal and daily changes, creating geographic and temporal variation in winds, currents, and the strength of coastal upwelling. South of about 40° N (approximately Cape Mendocino, California), winds are southward throughout the year, while north of this location, winds are northward, and therefore, unfavorable for upwelling during the winter months. Upwelling occurs year-round from San Francisco south (Figure 5.8). Yet upwelling in this region has little influence on temperature distributions much of the year and, therefore, may be ineffective in overcoming the strong California Undercurrent and the downward sloping density gradient associated with it (Huyer 1983). The average intensity of upwelling is relatively weak northward from the central Oregon coast. Upwelling off the narrow Oregon continental shelf is generally stronger than off Washington and more evenly distributed throughout the summer (Landry et al. 1989). Maximum upwelling off Washington occurs in June, one or two months earlier than along the Oregon coast. South of Coos Bay, coastal currents show considerable short-term variability, while a smoother seasonal cycle is apparent in currents from the central Oregon coast northward (Strub et al. 1987a). Complex bathymetry and the orientation of the shoreline also result in considerable local variation in the intensity of upwelling (Huyer 1983).

The coastal ocean off Washington and Oregon exhibits distinct winter and summer regimes. The shift to the summer upwelling regime occurs suddenly and the specific timing varies between years. While areas of coastal upwelling involve local scale events, the transition to a coastal upwelling regime is regulated by large-scale atmospheric conditions. The annual northward migration and strengthening of the North Pacific High pressure system (also termed the Sub-Tropical High pressure system in Chapter 4) causes a shift in wind direction that produces the transition from a winter to a spring/summer regime in the coastal ocean off Washington and Oregon (Huyer 1983). In the winter, coastal currents over the shelf are northward, sea levels are high, and downwelling occurs. Summer conditions are characterized by reduced sea-levels, southward mean surface currents over a northward undercurrent, and a strong density gradient across the continental shelf (Strub et al. 1987b). Southward winds and the resulting offshore flow raises cold, nutrient-rich water at the surface along the West Coast of the United States. The zone of active upwelling is generally restricted to a narrow coastal band (about 10-25 km) but the affected region can be much broader. The response of the coastal system to southward winds is very rapid. A single upwelling event of a few days' duration, typically in March or April, may be sufficient to cause the shift to the spring/summer regime (Huyer 1983). Thus, timing of the onset of the transition relative to the period of smolt migration may be important to the survival of juvenile coho salmon (Pearcy 1992). Small and Menzies (1981) reported differences in the distribution of chlorophyll biomass and its productivity under different upwelling conditions off Oregon. During weak or intermittent periods of upwelling, the band of maximum chlorophyll was located against the coast and had very high concentrations. Productivity of chlorophyll bands during periods of relaxation between upwelling events could be twice that of the strong upwelling state and often 20 times that in the surrounding water. Peterson et al. (1979) found that very high concentrations of zooplankton off Oregon occurred shoreward of the upwelling front

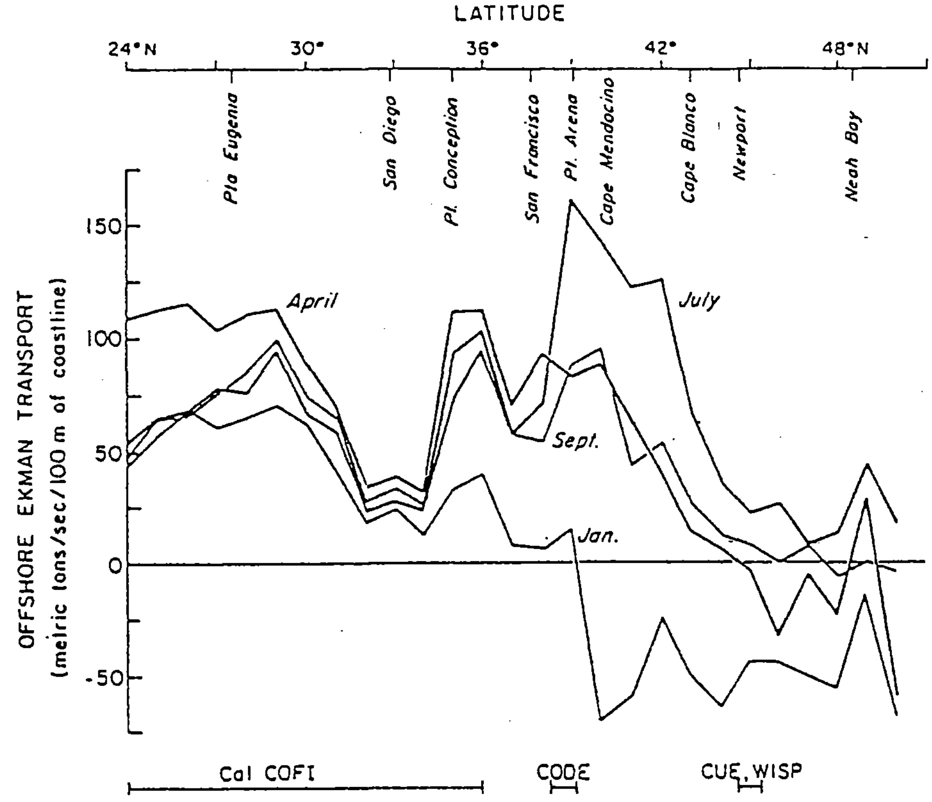

Figure 5.8. Calculated offshore Ekman transport based on long-term mean wind stress data for one-degree areas along the coast for January, April, July, and September. Alongshore distance of major upwelling studies is shown by bars at bottom: CalCOFI is California Cooperative Fisheries Investigations; CODE is Coastal Ocean Dynamics Experiment; CUE is Coastal Upwelling Experiment; and WISP is WInter-SPring (transition experiment). (After: Huyer, A. 1983. Coastal upwelling in the California Current system. *Progress in Oceanography* 12:259-284.)

(the sharp interface between upwelled water and the warmer ocean water displaced offshore) and were carried below the pycnocline (density gradient) when upwelling relaxed. However, patterns of abundance of zooplankton populations varied by species.

The most favorable upwelling conditions for fish production also likely vary by species. Lasker (1978) found that physical factors associated with upwelling affected the survival of anchovy (*Engraulis mordax*) larvae and explained variations in year-class strength. Successful year classes were associated with calm periods between upwelling events that supported the production of favored prey species. Cury and Roy (1989) found evidence that successful recruitment of pelagic fishes depended on winds that were strong enough to promote upwelling but sufficiently calm to prevent turbulent mixing that disperses concentrations of food required for larval survival. They proposed upwelling driven by wind speeds of 5-6 m sec^{-1} as an optimal level. Cushing (1995) further notes that northern anchovy and sardine (*Sardinops sagax*) may have developed different survival strategies for upwelling systems: anchovy grow more slowly and can tolerate periods of low food availability and intermittent periods of stronger upwelling; sardine seem to grow more rapidly and favor a weaker but more persistent upwelling state. But both species appear to avoid spawning locations of the strongest upwelling. Such nonlinear relationships raise questions about the apparent threshold level of upwelling associated with juvenile coho salmon survival in the 1960s and 1970s (e.g., Nickelson 1986) or the shift to a negative relationship over the last decade (Jamir et al. 1994).

The Columbia River plume influences the distribution of nutrients, salinity, and the upwelling front off Washington and Oregon. Changes in the river hydrograph associated with flow regulation (i.e., dams) may significantly impact coastal ecosystems. Discharge from the Columbia River is the dominant source of freshwater runoff to the Washington and Oregon coast, particularly during the late spring and early summer. Both the Columbia and Fraser rivers are point sources of high nitrate, phosphate, and silicate near shore in winter and summer (Landry et al. 1989). The low salinity surface water of the plume represents an offshore extension of the estuary that varies seasonally in its location along the coast. During winter when surface currents are predominantly northward, the Columbia River plume forms a low-salinity tongue of cold water near the Washington coastline to the north (Landry et al. 1989). During the spring/summer regime, low salinity water from the Columbia River is located offshore and to the south off Oregon (Figure 5.9). The plume can extend beyond Cape Mendocino, California and its effects are even visible past San Francisco. Measurements in July 1961 reported the maximum depth of the plume as 2 meters off the Columbia River mouth and 0.5 meters off of Cape Blanco (Huyer 1983). As a result of the influence of the Columbia River plume, variability in surface salinity is much greater in the Pacific Northwest than off California or in the Subarctic region (Landry et al. 1989).

The Columbia River plume influences surface density gradients and the cross-shelf properties of coastal waters which may affect patterns of biological production and biomass. Specifically, the plume can retard offshore transport during upwelling, particularly when river flow is maximum (e.g., June). The zone of upwelling influence can be most narrow off northern Oregon where the Columbia River plume forms a partial barrier to the offshore movement of surface water (Huyer 1983). Interaction between upwelling intensity and the volume of flow from the Columbia River affects the location of the upwelling front and, therefore, the distribution of chlorophyll and zooplankton biomass. During strong upwelling the Columbia River plume is advected far offshore. Changes in the distribution of the upwelling front may not only influence environmental conditions for outmigrating juveniles, but may be important to the movements of adult salmon. Coho salmon, for example, prefer temperatures between 11 and 14° C, which are intermediate between the offshore ocean water (15 to 17° C) and upwelled water at the coast (8 to 10° C; Smith 1983). Short-term changes in temperature and feeding conditions that concentrate or disperse fish, in turn, create significant variations in salmon catch rates and landings (Nickelson et al. 1992).

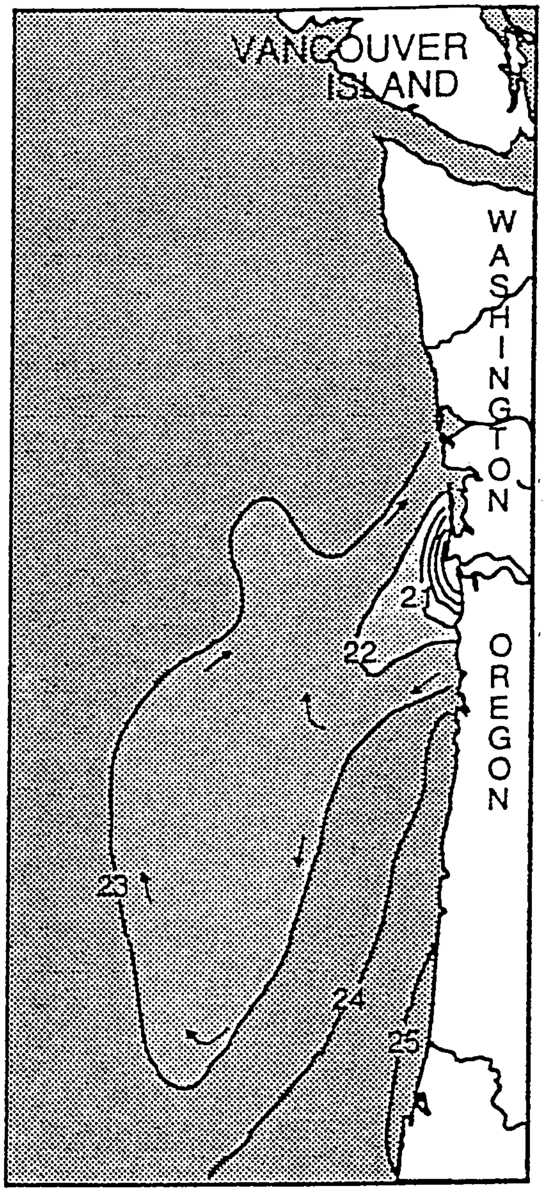

Figure 5.9. Surface density of water (sigma-t) in the summer off Washington and Oregon. Note southward tongue of low density water from Columbia River plume. Arrows indicate direction of expected circulation based on horizontal density gradients. (Source: Landry, M.R., J.R. Postel, W.K. Peterson, and J. Newman. 1989. Broad-scale distributional patterns of hydrographic variables on the Washington / Oregon shelf. In *Coastal Oceanography of Washington and Oregon*, eds. M.R. Landry and B.M. Hickey, 1-40. New York: Elsevier. Reprinted with permission, courtesy of Michael Landry.)

The region of the Columbia River plume is a summertime spawning area for an endemic subpopulation of northern anchovy (Bakun 1993). Local stability of the water column and circulation characteristics associated with the plume during the summer may provide the conditions needed to support larval production. A local minimum in wind velocity and upwelling intensity (< 500 m^3 s^{-1} [cubic meters per second]) minimizes offshore transport while the low salinity lens of the plume maintains vertical stability and reduces turbulence. Furthermore, the density gradient at the interface of the plume and higher salinity surface waters may provide a counterclockwise circulation (Fig. 5.9) that would benefit retention of larvae and other organisms (Bakun 1993). Because such convergence zones tend to concentrate larvae and food particles, they are often important areas of secondary production.

Ebbesmeyer and Tangborn (1992) conclude that impoundment of summer flows and releases during the winter by Columbia River dams have altered sea surface salinities from California to Alaska. In terms of the seasonal transition in coastal currents, this shift in the hydrograph results in a decrease in the volume of Columbia River water transported off the Oregon coast during the summer and an increase off Washington in the winter. In the last 60 years, salinity has decreased approximately 1.0 ppt over a distance of 500 km to the north and increased 0.6 ppt over the same distance to the south (Ebbesmeyer and Tangborn 1992). The influence of the plume on other physical and biological properties (e.g., temperature, nutrients, density gradients and circulation, the upwelling front) suggests that regulation of Columbia River flows may significantly affect coastal ecosystems of the California Current and Subarctic region. Such effects could extend to coho salmon smolts entering the ocean in the spring and early summer (Pearcy 1992).

The California Current. After traversing eastward across the North Pacific, the Subarctic Current splits into the northward flowing and counterclockwise Alaskan Gyre and the southward flowing California Current (see Fig. 5.3). During the upwelling season, the California Current carries cold nutrient-rich water from the subarctic Pacific along the West Coast. When upwelling subsides in the fall and the downwelling season returns, the northward-flowing California Undercurrent (Davidson Current) appears at the surface and carries warm equatorial water inshore (Favorite et al. 1976; see Fig. 4.30).

The "classical view" of the eastern boundary regions of the world's oceans has generally assumed that local upwelling is the major factor controlling pelagic production (Bernal and McGowan 1981). But over the last two decades, researchers have found that the productivity of the California Current is not entirely regulated by internal processes, but may be substantially influenced by input from outside the system. Both zoogeographic patterns and fluctuations of plankton biomass in the California Current point to large-scale processes that are not fully explained by upwelling.

Patterns of zooplankton biomass provide evidence that outside forces may regulate biological productivity within the California Current system. Wickett (1967) first reported that annual concentrations of zooplankton off southern California vary directly, and concentrations in the western Bering Sea vary inversely, with the southward transport of water at the divergence of the California Current and the Alaskan gyre. The influence of advection in the California Current was further supported by Bernal (1980) and Bernal and McGowan (1981) who correlated zooplankton abundance with the transport of low salinity water from the north. Chelton et al. (1982) concluded that interannual variations in zooplankton biomass off California are not correlated with wind-induced upwelling but are explained by variations in the flow of the California Current itself. Zooplankton biomass may respond to changes in the amount of nutrients transported southward in the California Current and the depth of the thermocline, which influences the capacity of upwelling to enrich surface waters (Chelton 1981; McClain and Thomas 1983). Furthermore, fluctuations in the current are indicated by changes in coastal sea-level and are often, but not always, related to El Niño occurrences in the eastern tropical Pacific (Chelton et al. 1982). Thus, physical and biological properties are dominated by a large-scale, interannual signal generated outside the California Current system.

Local upwelling may play a somewhat greater role in interannual variability off the Washington and Oregon coasts than off California. Unlike California (Chelton et al. 1982), monthly anomalies of temperature and salinity off Washington and Oregon in the summer are negatively correlated (Landry et al. 1989), which is an indicator of the upward advection of cold, high-salinity water during upwelling (as opposed to lower salinity water transported from the north). Monthly nutrient (nitrate) anomalies along the mid-shelf of Washington are also positively correlated with temperature and with upwelling. Landry et al. (1989) conclude that interannual scales of variability off Washington and Oregon are probably influenced by both regional and global scale processes. A global influence is suggested by a consistent pattern of temperature anomalies throughout the California Current and subarctic regions and by the influence of El Niño events in the eastern tropical Pacific. Again, however, a gradient of factors may regulate biological production in the California Current as evidenced by: the north-south pattern in the variability of winds, currents, and upwelling (see Fig. 5.8); the latitudinal cline in the relative proportions of subarctic, transitional, and equatorial species (Chelton et al. 1982); the north-south gradient in the amount of Columbia River water found along the Oregon coast during the summer (see Fig. 5.9); and the southward decline in the relative proportion of protected inland bay and estuarine habitat from British Columbia to California (Nickelson and Lichatowich 1984; Bottom et al. 1986).

Interannual variations along the California Current ecotone create special challenges for southern coho salmon stocks, which are generally less productive in Washington and Oregon compared with areas located nearer the center of their range (see Fredin 1980). Fulton and LeBrasseur (1985) defined a subarctic boundary based on interannual variations in the distribution of mean zooplankton biomass (Figure 5.10). They reported a large area between Cape Mendocino and the Queen Charlotte Islands where the transition between high and low biomass varied widely between extreme "cold" and "warm" years (e.g., during strong El Niño events). They hypothesized that in years of strong southward advection of cold water, the larger zooplankton characteristic of the subarctic water mass may provide a better source of food for juvenile pink salmon (*O. gorbuscha*) than the smaller species otherwise typical of the California Current. As noted above, the strength of southward advection changes not only during El Niño events. Interannual variations in the subarctic boundary, the location of the divergence of the California Current, and associated changes in temperature, zooplankton, or other conditions may be particularly important to the survival of the southernmost stocks of subarctic salmon.

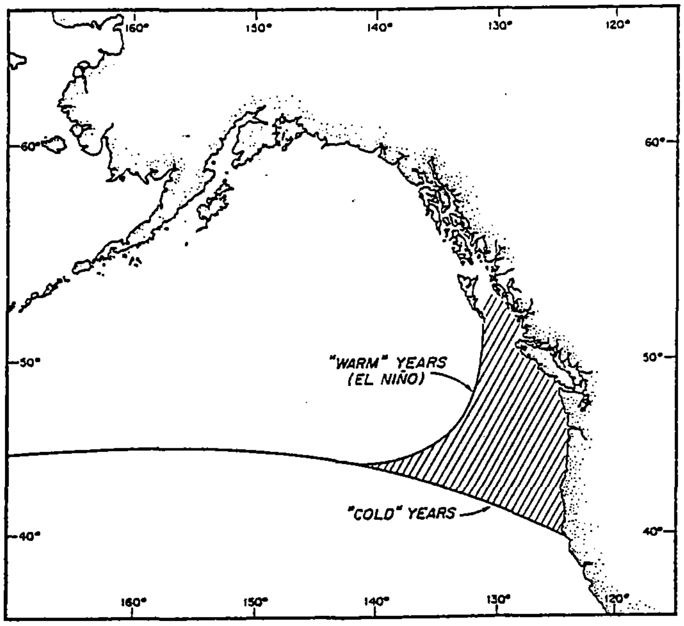

Figure 5.10. Area influenced by shifting of the subarctic boundary. (Source: Fulton, J.D., and R.J. LeBrasseur. 1985. Interannual shifting of the subarctic boundary and some of the biotic effects on juvenile salmonids. In *El Niño North: Nino effects in the eastern subarctic Pacific Ocean*, eds. W. S. Wooster and D. L. Fluharty, 237-247. Seattle: Washington Sea Grant Program. Reprinted with permission, courtesy Washington Sea Grant Progam.)

Attempts to explain variations in the year-class strength of marine fishes have often emphasized effects of food availability on larval survival (e.g., Lasker 1978; Cushing 1995). However, advective processes may also exert a direct physical influence on survival and interannual variability of some pelagic fishes. For example, survival rates to age 1 of Pacific mackerel (*Scomber japonicus*) increase during years of low southward transport (as indicated by high coastal sea level) and relatively low zooplankton biomass, which, in turn, are related to El Niño events in the eastern tropical Pacific (Sinclair et al. 1985). Conversely, poor survival is associated with strong southward flow of the California Current when zooplankton biomasses are generally higher. In this case, Sinclair et al. (1985) proposed that survival rates of Pacific mackerel during early life-history may be influenced directly by interannual changes in hydrographic processes rather than by biological interactions. This hypothesis emphasizes that displacement of larvae from the appropriate location to complete their life cycles (whether or not displacement causes direct mortality) may be as critical to recruitment success as the condition of their feeding environment.

The influence of advective processes on year-to-year salmon survival is unclear. Unlike larval fishes, salmon are free-swimming when they enter the ocean, but at small sizes their distribution may be affected by the strength of surface currents. Pearcy (1992) found that juvenile salmon from Oregon and Washington generally swim northward against the current. However, during May and June, soon after they entered the ocean, juvenile coho off Oregon were captured south of the area of ocean entrance, suggesting a southward advection of the smallest fish during their first few weeks in the ocean. Later in the summer, when currents were weaker and fish were larger, most young salmon were caught north of their point of ocean entry. The fact that year-class strength of coho salmon may be decided sometime within the first few weeks in the ocean (Fisher and Pearcy 1988) suggests that early survival conditions perhaps not far from the point of ocean entry may be critical. It is conceivable that advective processes could have a direct physical influence on early migrant salmon by determining whether the geographic distributions of local stocks are appropriate to prevent "spatial" losses (Sinclair 1988) from populations.

El Niño. Until 30 years ago, El Niño was believed to be the result of local changes in the winds that produced upwelling along the coasts of Peru and Ecuador (Mann and Lazier 1991). Oceanographers later discovered that this upwelling system was part of a higher level of organization involving global winds and ocean dynamics across the entire Pacific Ocean basin. They concluded that the upwelling system is a component of the global heat budget such that the physical and biological characteristics of coastal systems change as the thermal budget of the ocean and atmosphere is disturbed (Barber 1988). While local upwelling may operate somewhat independently, it is also an integral part of the larger thermal structure of the ocean, which determines whether or not upwelling is able to enrich surface waters with nutrients (Barber and Chavez 1983). Barber (1988) describes this single interconnected system, which is structured by the El Niño/Southern Oscillation (ENSO) cycle in the tropical Pacific, as the "basin wide ocean ecosystem." Within this large ecosystem, habitats continually shift, producing opposing regions of abundance and scarcity with the displacement of entire water masses and changes in the thermal structure of particular locales (Sharp 1991). Although not all changes in the North Pacific can be traced to El Niño, the oscillations in the equatorial Pacific provide important clues about the basin-wide processes that shape the biotic structure and productivity of salmonid ecosystems.

Through its connections to the equatorial Pacific, the upwelling system, thermal structure, and biotic assemblage of the California Current may be directly affected by El Niño. At the height of El Niño, warm water drains toward both poles, reducing the warm pool in the eastern basin and influencing conditions in the northeast Pacific and the Southern Ocean. The California Undercurrent, which carries warm water northward along the West Coast of the United States, thus may serve as a "release valve" for the build-up of heat in the tropical Pacific, and may be involved in the resetting of the ENSO cycle to the cold (La Niña) phase (Barber 1988). Following the mature phase of El Niño in the winter and spring, southward flow of the California Current is reduced (Chelton et al. 1982) and the strength of northward flow in the California Undercurrent is increased (McClain and Thomas 1983; Mysak 1986). Responses to El Niño along the West Coast of the United States may include elevated sea levels and sea surface temperatures, increased thermocline depths, and the northward expansion of the ranges of southern species (McClain and Thomas 1983).

The frequency and intensity of El Niño events also exhibit patterns of variation. Through a reconstruction of El Niño occurrences over the last 450 years, Quinn et al. (1987) note that intervals between strong and very strong events have averaged close to 10 years, but may range from 4 or 5-year intervals to as high as 14 to 20 years. El Niños classified as "very strong" such as the 1982-83 event are rare, and have occurred with a frequency of 14 to 63 years. Decadal or longer climatic changes are indicated by extended periods of unusually strong El Niño activity. Examples include the periods 1701-1728, 1812-1832, 1864-1891, and 1925-1932 (Quinn et al. 1987). Recent El Niño activity is also associated with an extended period of climatic change over the last 15 years. For example, three major El Niño events have been recorded since 1981 with only one major intervening cold (La Niña) event (Kumar et al. 1994). Furthermore, warm ocean conditions have persisted in the tropical Pacific since 1990. By comparison the only similar episode of sustained warming this century lasted only three years (1939-1941).

Recent changes in the tropical Pacific are raising questions about whether the general warming trend since 1976 might have influenced the frequency of ENSO cycles, and whether the increased heat itself could be an early sign of global warming from greenhouse gases (Kerr 1994; Kumar et al. 1994). Such concerns are heightened by observations off southern California where, since 1950, the upper 100 meters of the ocean has shown a uniform 0.8° C increase and associated mean sea level has increased by 0.9 mm/year (Roemmich 1992). This warming has occurred despite an apparent increase in the intensity of upwelling favorable winds off southern California over the same period (Bakun 1990). Roemmich and McGowan (1995) speculate that increased stratification from ocean warming has made upwelling less effective in raising nutrients to the surface and may account for an approximately 70% decline in zooplankton volume documented since 1951. While the causes of this general warming are not clear, the results illustrate how even moderate increases in temperature and adjustments in the ocean thermal structure might override the benefits of local upwelling to pelagic food chains.

The 1982-83 El Niño was described as the strongest this century at the time of writing. Johnson (1988) summarized the direct effects of this event on Oregon coastal and Columbia River stocks of salmon. The 1982-83 El Niño increased mortality of both adult and juvenile salmon. Evidence of increased mortality was shown by returns of adult coho salmon to the Oregon Production Area, and tule fall chinook, a stock specific to the lower Columbia-Bonneville pool area, that were much lower than the preseason predictions. Mean sizes of chinook and coho salmon that survived El Niño were much smaller than average, and fecundity of female coho salmon also was reduced. The direct mortality of adults under strong El Niño conditions suggests a different scale, habitat, and mechanism of population regulation, which occurs soon after smolts enter the coastal ocean, than those that control juvenile survival in non-El Niño years (Nickelson 1986; Pearcy 1992). In September of 1983, Pearcy and Fisher (1988) found juvenile salmon distributed further north off Washington than in other years surveyed, suggesting either an increased northward migration of fish during El Niño or a proportionally greater mortality of those fish remaining in the southern portions of the study area. The migration behavior of individual populations may determine their relative vulnerability to changes in oceanographic conditions. For example, unlike chinook stocks off southern Oregon and locally distributed stocks from the Columbia River, northerly migrating populations from the Columbia River showed little or no decline in abundance during the 1982-83 El Niño (Johnson 1988).

A strong El Niño in 1957-58 also affected coho salmon production in Oregon (McGie 1984: Pearcy 1992). The mean weight of returning adults was low in 1959 (Johnson 1988), and total ocean landings in 1960 from smolts that entered the ocean the previous year declined to their lowest level since 1917. Anomalously high water temperatures in the northeastern Pacific from 1957 to 1960 probably indicate that the relatively strong upwelling during this period was not effective in raising cold, nutrient-rich water above a deepened thermocline (Pearcy 1992).

Interdecadal Regimes. While El Niño events usually occur with a frequency of 3 to 7 years, climatologists and oceanographers have also described abrupt shifts in the predominant patterns of atmospheric circulation, oceanic currents, and thermal regimes that may persist for several decades. These interdecadal shifts, which may be linked by teleconnections to conditions in the tropical Pacific and often follow strong El Niño events, involve extended periods of eastward migration and intensification of the Aleutian Low pressure system during the winter half of the year (Trenberth 1990). The most recent shift occurred in 1976-77, when a strengthened Aleutian Low caused a southward migration of storm tracks, anomalous southerly winds and warming along the west coast of North America and Alaska, and anomalous northerly winds and cold temperatures in the Central North Pacific region between Japan and 160° N (Trenberth 1990; Ebbesmeyer et al. 1991). In the Northeast Pacific, the pattern of strong Aleutian Low is associated with a rise in sea level and ocean surface temperature; reduced flow of the California Current (Mann and Lazier 1991); and reduced precipitation, increased river temperatures, and low streamflow conditions in Oregon (Greenland 1994a).

The relationship between El Niño and atmospheric and oceanic conditions in the North Pacific is not a simple one-to-one correspondence. For example, ENSO events can occur without causing a change in the Aleutian Low pressure system, and warm water conditions in the North Pacific may be present in the absence of El Niño (Mysak 1986). A 1972-73 warming off California occurred without a change in the atmospheric circulation, suggesting a direct oceanic connection to a strong El Niño event (Norton et al. 1985), while the moderate El Niño of 1976 produced the strongest Aleutian Low in a 36-year period of record (Mysak 1986). The climatic effects of large pressure anomalies that often form in response to strong El Niños also may vary. The degree of warming and the effects on precipitation depend on the particular latitude of storm tracks and the position of the low pressure system relative to the coast (Roden 1989). The climatic response to El Niño in the Pacific Northwest, for example, may vary with the strength of the teleconnections. Thus the Northwest may fall inside or on the southern edge of a region of lower rainfall following a particular ENSO event (Melack et al. in press).

In recent years interdecadal variations in fish populations have been traced to large-scale climatic changes influencing oceanic regimes. Perhaps most dramatic are the analyses indicating synchronous trends in sardine (*Sardinops* spp.) abundance (as indicated by harvest) from three widely separated regions of the Pacific Ocean basin: California, Japan, and Chile (Figure 5.11) (Kawasaki 1983). The specific relationships explaining the 40-year cycle in abundance are not clear, but all three stocks appear to track variations in mean surface air temperatures in the northern hemisphere. These relationships may be a proxy for changes associated with basin-wide winds and conditions in upwelling systems that somehow influence sardine recruitment. In the eastern Pacific, sardine appear to favor shifts from a cool, upwelling-dominated regime to periods of reduced wind strength (Sharp 1992; Cushing 1995). Ware and Thomson (1991) identified a 40 to 60-year cycle in wind and upwelling conditions that may influence long period fluctuations in pelagic fish biomass off southern California. Both the period of peak sardine production this century and the recent recovery off California beginning in the late 1970s coincide with periods of relaxation of upwelling (Bakun 1990; Lluch-Belda et al. 1992). Although the region of sardines off Japan is not generally considered an upwelling system, the same large-scale changes in wind stress may influence the frontal system shoreward of the Kuroshio Current to the benefit of sardine (Cushing 1995). A rapid increase in Japan sardine from a very strong 1970 year class was related to a shift in the Kuroshio Current, which created an expanded sardine spawning area, increased egg abundance, a broad area favoring copepod production, and increased survival of sardine post-larvae (Lluch-Belda et al. 1992). Basin-wide regime shifts are not only reflected in patterns of sardine abundance, but involve coherent changes in the organization of entire pelagic assemblages. Anchovies (*Engraulis* spp.) and their associated predators—hake (Merlucidae), mackerel (*Scomber scomber*), bonito (*Sarda* spp.), and seabirds—are abundant during the opposing, cooler upwelling periods. On the other hand, Jack mackerels (*Trachurus* spp.), chub mackerels (other *Scomber* spp.), and other Transition Zone predators are associated with the warmer periods favored by sardine (Sharp 1992).

Climate changes across the Pacific Basin also may explain interdecadal cycles in salmon production. Beamish and Bouillon (1993) document synchronous trends in pink, chum, and sockeye salmon abundance estimated from the combined annual harvests in US, Canadian, Japanese, and Russian fisheries. These trends, as well as abundance of copepods sampled at Ocean Station P (50^{o}N, 145^{o}W), were associated with an Aleutian Low Pressure Index (Figure 5.12). A profound shift in climatic regime of the North Pacific in 1976-77 (Ebbesmeyer et al. 1991) was associated with the strongest Aleutian Low since 1940-41. In addition to corresponding increases in salmon abundance, this shift is implicated in the almost doubling of

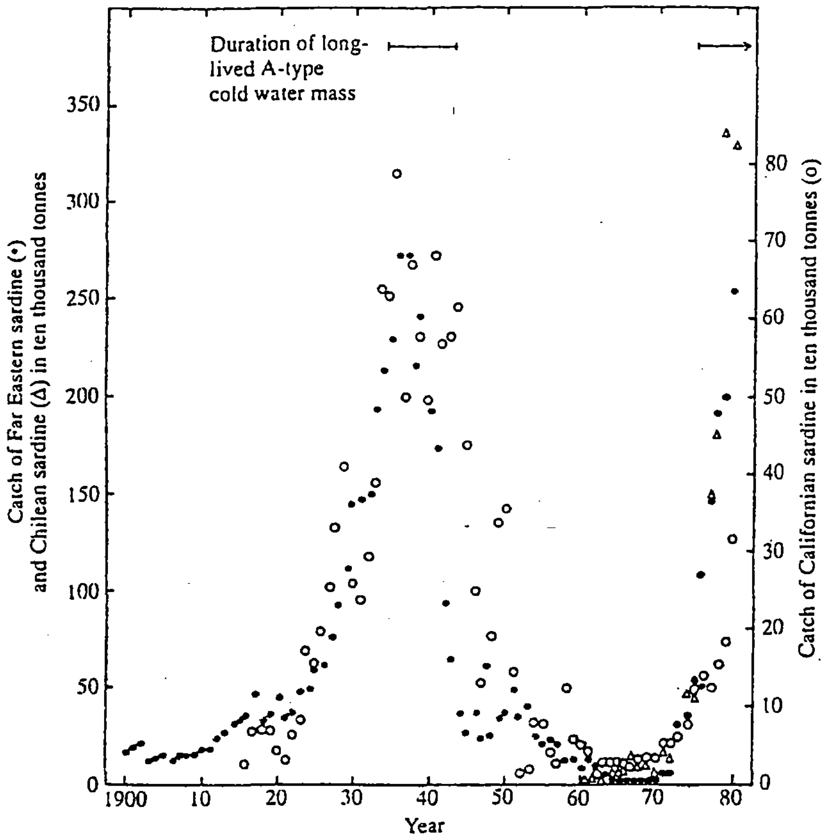

Figure 5.11. Comparison of catches of Far Eastern, Californian, and Chilean sardine between 1900 and 1981 (from Kawasaki 1983). Catches increased during warm temperature anomalies and decreased with declining temperatures. (Source: Cushing, D. 1995. *Population production and regulation in the sea: A fisheries perspective.* Cambridge: Cambridge University Press. Reprinted with permission, courtesy Cambridge University Press.)

chlorophyll *a* in the central north Pacific north of Hawaii (Venrick et al. 1987), a doubling of summer zooplankton abundance in the Alaskan Gyre between 1956 to 1962 and 1980 to 1989 (Broedeur and Ware 1992), simultaneous increases in the abundance of a variety of nonsalmonid fishes in various regions of the North Pacific (Beamish 1993), and increases in prey availability for marine birds and mammals (Francis et al. 1996). Through time series analysis, Francis and Hare (1994) and Francis et al. (1996) describe multidecadal variations in salmon production associated with sudden changes in atmospheric conditions of the North Pacific. Their results show a close correlation between physical and biological conditions of the North Pacific spanning four major oceanic/atmospheric regimes this century: 1900 to 1924, 1925 to 1946, 1947 to 1976, and 1977 to the present. The regimes beginning in 1925 and in 1977 were associated with periods of high salmon abundance in the Gulf of Alaska. Variations in the harvest of coho and chinook salmon from Washington and Oregon also show interdecadal patterns, but these fluctuate out of phase with the more northerly stocks of pink, chum, and sockeye salmon in the Gulf of Alaska (Figure 5.13; Francis 1993).

The influence of large-scale atmospheric changes on the ocean environment and, in turn, Oregon salmon, are further indicated by an inverse relationship between salmon harvest and annual mean temperatures in western Oregon (Figure 5.14; Greenland 1994b). This contrasts with a positive relationship between pink salmon harvest, winter air temperatures, and winter sea surface

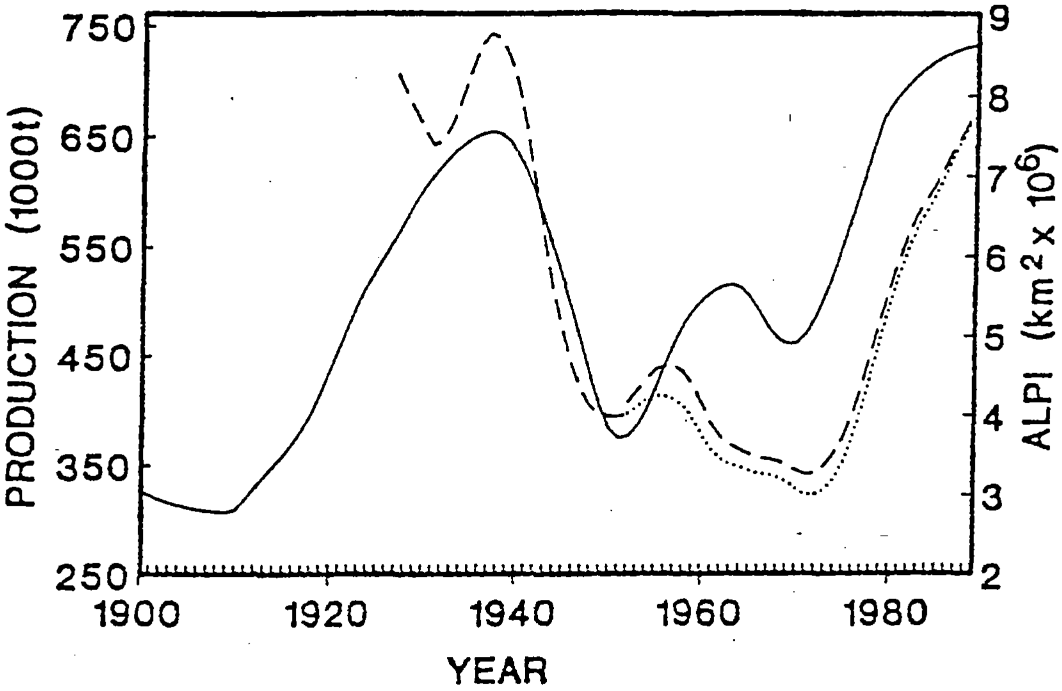

Figure 5.12. Total all-nation catch of pink, chum, and sockeye salmon (combined), both adjusted (broken line) and unadjusted (dotted line) for lost production from the high-seas salmon fisheries. Solid line represents smoothed Aleutian Low Pressure Index (ALPI). (Source: Beamish, R., and D.R. Bouillon. 1993. Pacific salmon production trends in relation to climate. *Canadian Journal of Fisheries and Aquatic Sciences* 50:1002-1016. Reprinted with permission, courtesy of National Research Council of Canada.)

temperatures in the Gulf of Alaska (Francis and Sibley 1991). These opposing patterns are consistent with the hypothesis that atmospheric forcing influences the position of the subarctic divergence and relative flows into the Alaska and California Currents: periods of a strong Aleutian Low and increased northward flows into the Alaska Current may reduce southward flows into the California Current and vice versa, with inverse effects on the productivities of each region (Wickett 1967). To explain these regional differences, Francis and Sibley (1991) and Francis (1993) use a model by Hollowed and Wooster (1991) which proposes two average conditions in the North Pacific designated as Type A and Type B (see Fig. 4.15). Type B conditions are represented by a strong Aleutian Low centered in the east, increased southwesterly winds and increased downwelling, greater northward advection into the Alaska Current, decreased southward flow of the California Current, and above average temperatures in the northeast Pacific. Type A conditions are characterized by the opposite trends. Francis (1993) proposes that salmon production tracks abrupt shifts in these sets of conditions (Francis 1993; Francis et al. 1996) with periods of high productivity in the Gulf of Alaska generally associated

Figure 5.13. Comparison between harvest of pink salmon in the Gulf of Alaska (GOA) and coho salmon catch in the region off Washington, Oregon, and California (WOC). (Source: Francis, R.C. 1993. Climate change and salmonid production in the North Pacific Ocean. In Proceedings of the Ninth Annual Pacific Climate (PACLIM) Workshop, April 21-24, 1992, eds. T. Redmond and V. L. Tharp, 33-43. California Department of Water Resources, Interagency Ecological Studies Program. Technical Report 34. Reprinted with permission, courtesy of California Department of Water Resources.)

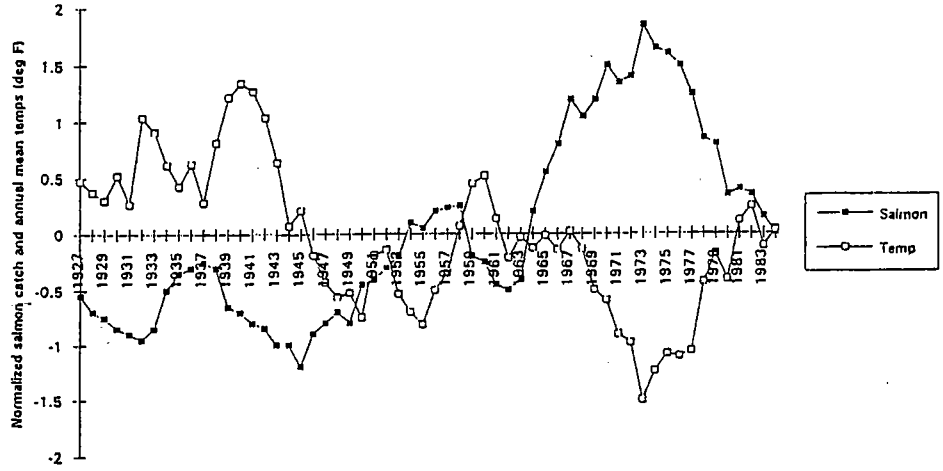

Figure 5.14. Comparison of annual mean temperatures at the H. J. Andrews Experimental Forest (5-year filter) and catch of coho salmon off Washington and Oregon (7-year filter) between 1927 and 1983. (After: Greenland, D. 1994b. Salmon populations and large scale atmospheric events. In *Salmon Ecosystem Restoration: Myth and Reality. Proceedings of the 1994 Northeast Pacific Chinook and Coho Salmon Workshop*, ed. M. Keefe, 103-114. Corvallis: Oregon Chapter American Fisheries Society.)

with the type B state. Interestingly, the shift from Type A to Type B conditions over the last 60 years has always coincided with significant El Niño events in the tropical Pacific (Francis 1993).

The climatic conditions that influence the ocean environment of salmon also affect the quality of their freshwater habitats. For example, in a review of the climate on the H.J. Andrews (HJA) Experimental Forest in western Oregon, Greenland (1994a) found correlations between various indices of atmospheric circulation with temperature and precipitation. The results indicate that during periods of a strong Aleutian Low (as suggested by correlations with the Pacific North America and Central North Pacific teleconnective indices), storms are pushed north of Oregon, causing relatively dry weather during the winter and raising January air temperatures due to the southwesterly flow of warm air into the region. These patterns are also associated with El Niño events. During many El Niño years, winter precipitation on the HJA Forest is low, and annual mean temperatures are high, while in La Niña years, winter precipitation increases, particularly a year later, and annual temperatures are below average. The influence of both low precipitation and high temperatures in much of the Pacific Northwest may cause a reduced snowpack during El Niño years (Greenland 1994a).

While interdecadal regimes affect vast areas, the degree of independence between freshwater and ocean conditions of various regions may be important to salmon resilience. In western Oregon, stream and ocean conditions affecting salmon survival tend to oscillate in phase. That is, during periods of warm ocean conditions and reduced flow of the California Current, freshwater habitat conditions may also decline due to reduced streamflows and increasing river temperatures in western Oregon (Greenland 1994a). These effects suggest a kind of "double jeopardy" for salmon stocks caused by a synchrony of mortality factors that involve more than one stage of life-history. It is also possible that in other regions or among diverse watersheds within large basins like the Columbia River, ocean and river conditions for salmon survival are not in phase so that the effects of large-scale climatic change may be dampened. For example, since 1980, during a favorable regime for salmon survival in the Gulf of Alaska, annual precipitation on the coast of British Columbia has been above average. On the other hand, discharge of the large Fraser River declined during the same period due to reduced snowpack in the interior of British Columbia (Beamish 1993). Varying degrees of "connectedness" between the environments supporting each life-stage of salmon may have an important influence on the capacity of populations to adapt to shifts in climate. Stock diversity and habitat heterogeneity may serve to dampen otherwise synchronous effects of large-scale climatic change.

Regime shifts reset ecological conditions within different oceanic regions by changing the composition of marine assemblages and altering the physical environment. Thus, local salmon populations may encounter different combinations of conditions each year they enter the coastal ocean as determined by the basin-wide climatic regime and its interactions with regional and local scales of variation. Such changes alter the carrying capacity "rules" by changing the interrelationships that govern how much of the ocean's productive capacity may be realized by salmon or other species. New interactions might explain, for example, why coho salmon survival was positively correlated with upwelling under one oceanic regime in the 1960s and early 1970s, and negatively correlated under a different regime during the last decade (Jamir et al. 1994). A similar shift in environmental relationships is described by Skud (1982), who concluded that correlations between a species and environmental factors may shift from positive to negative with changes in the dominance hierarchy. In this case, Atlantic herring (*Clupea harengus*) abundance was positively correlated with temperature when herring was the dominant species and negatively correlated when Atlantic mackerel (*Scomber scombrus*) assumed the dominant position (and visa versa). Skud (1982) proposed that abiotic factors determine the overall composition of assemblages but that absolute population density of the subordinate species is regulated by density-dependent interactions. This does not argue that the failure of correlations with physical parameters always involves a shift in dominance. Regardless of the specific mechanisms of control, oceanic regime shifts may introduce new sets of conditions that alter the relationships between a species and selected environmental indicators. Thus, forecasts based on short-term statistical analyses are likely to fail because the biological response patterns may vary under different environmental regimes (Sharp 1992).

The fact that salmon populations of the Pacific Northwest are near the southern range of salmon species and that they are very sensitive to changes in the coastal ocean raises concerns about the effects of global climate change on salmon production. Neitzel et al. (1991) discuss potential effects of global warming on fresh-water habitats of the Columbia River basin. Significant ecological changes in the ocean environment could also be critical to local salmon production. For example, Peterson et al. (1993) suggest that El Niño events in the eastern Pacific provide an indication of the kind of biogeographic shifts in the California Current that may accompany global warming. Although it is expected that upwelling-favorable winds would increase in the northern hemisphere due to differential heating of the land and ocean (Bakun 1990), depression of the nutricline could limit the capacity of upwelling to supply surface nutrients (Peterson et al. 1993). This mechanism has been suggested as one explanation for a decline in zooplankton abundance off southern California since 1951 (Roemmich and McGowan 1995). Increased upwelling would also increase offshore transport and thereby decrease the number of areas and time periods suitable for the spawning of pelagic fishes such as anchovy and sardine. Peterson et al. (1993) hypothesize a shift in the California Current from short food chains leading to anchovy and sardine production to longer food chains favoring large migratory species such as albacore tuna (*Thunnus alalunga*) and jack mackerel (*Trachurus symmetricus*). Alternative energy pathways may also increase the production of demersal species. While the specific effects may vary in the northern reaches of the California Current offshore Washington and Oregon, the results may be detrimental to local salmon stocks if El Niño is an appropriate model of the qualities of future change. These results underscore the importance of maintaining habitat complexity and stock diversity in fresh water to help buffer potential effects of global warming on salmon survival in coastal environments.

Trends and Variability in Pelagic Production

OVERVIEW OF AVAILABLE DATA SETS

Data sets that give a direct measure of marine production of Pacific salmon generally are not available; production has to be inferred from catch data which are usually aggregated over large areas containing many individual stocks. Surveys of spawning escapements, dam counts and individual studies also provide important data sets.

Catch Data. The intensive fishery for Pacific salmon has been in existence for about 130 years. Data sets which span that entire period with a reasonable degree of integrity are not available. For example, harvest records for the Columbia River salmon fishery extend back to 1866, however, after 1920, those data account for a decreasing percentage of the total harvest of Columbia River salmon. Growth of the troll fleet after 1920 meant that increasing numbers of salmon from the Columbia River were landed in distant ports and not included in the Columbia River database. The troll fleet has always harvested mixed stocks of salmon, which are not routinely disaggregated in the catch records. After the 1940s, the growth of the sport fishery made the commercial catch records less representative of total production.

Historical harvest data are available by river (for selected rivers) in Oregon and California (e.g., Clark 1929; Cleaver 1951; Mullen 1981). Historical catch data for the Columbia River are reported by Beiningen (1976). More recent aggregated catch data are available in annual reports from the International North Pacific Fisheries Commission and the Pacific Fishery Management Council. Individual states also publish catch information.

The Oregon Production Index (OPI) is the only data set that approximates an actual measurement of total production. The OPI is an index of the total adult production of coho salmon from southwestern Washington to, and including, California. The OPI includes sport and commercial marine harvest, in-river sport harvest, escapement to natural spawning areas and returns to hatchery racks. The OPI is available from 1960, and is reported annually by the Pacific Fishery Management Council.

Spawning Surveys. State fish and wildlife agencies monitor the abundance of salmon that escape the fisheries and spawn in the coastal and inland basins of the Northwest. Some spawning surveys are continuous from the late 1940s in Oregon's coastal streams, and the 1950s in the upper tributaries to the Columbia River. Sporadic spawning surveys were conducted in Puget Sound until the 1970s. Since then, continuous surveys are available for many streams. Spawning escapements are compiled and published by state agencies (e. g., Egan 1978; Cooney and Jacobs 1995; ODFW and WDFW 1995).

Dam Counts. Many rivers of the Pacific Northwest have been dammed, and in some cases the dams have been fitted with ladders for passing adult salmon. The ladders are ideal places to obtain complete counts of salmon at that point in their migration. The US Army Corps of Engineers maintains counting stations at the Columbia River dams and publishes the annual counts of salmon. Counts at other dams are generally available from the appropriate state fish and wildlife agency or the organization that owns or operates the dam.

Individual Studies. Few studies have undertaken direct monitoring of salmon in the ocean and for those that have, the data sets cover only a few years. In the early 1980s, Bill Pearcy from Oregon State University and his colleagues sampled juvenile salmon off the coasts of Oregon and southern Washington. Annual cruise reports contain those data sets. In addition, several papers based on that project have been published in peer-reviewed journals. From 1956 to 1970, the Fisheries Research Institute (College of Fisheries, University of Washington) sampled juvenile salmon from the Strait of Juan de Fuca north to the Bering Sea. The results of that sampling effort are reported in several bulletins of the International North Pacific Fisheries Commission (e.g., Hartt 1966). The National Marine Fisheries Service conducted limited sampling of juvenile salmon off the mouth of the Columbia River in 1980 (Dawley et al. 1981).

Adult salmon were captured off Vancouver Island, tagged and released from 1925 to 1930 and 1949 to 1951. The distribution of those tagged fish were monitored on spawning grounds over a wide geographical area (Milne 1957). The International North Pacific Fisheries Commission has published the results of research on the distribution and origin of adult salmon in the North Pacific Ocean (e.g., Takagi et al. 1981).

Other Species. Other important data sets are those that pertain to the distribution and abundance of potential predators or prey of Pacific salmon. Probably the best data sets of various components of the marine community off California are those collected by the California Cooperative Oceanic Fisheries Investigations. Harvest records compiled by state agencies provide additional data sets. Acoustic surveys conducted by National Marine Fisheries Service provide periodic point estimates of pelagic fishes off the coasts of Oregon, Washington and California.

MARINE SALMON PRODUCTION

Coastwide Reviews of Salmon Abundance and Status. Hewes (1947) estimated total Indian harvest and harvest by individual tribal units in the Pacific Northwest region prior to contact with Euroamericans. Harvest was calculated from estimates of the annual per capita consumption of salmon. Rostlund (1952) surveyed all North American fisheries by Indians in the precontact period and also estimated the maximum sustainable harvest of anadromous fishes in the Pacific region of North America. Chatters et al. (1995) used a variety of techniques to estimate the relative abundance of salmon in the Columbia River for the past 8,000 years.

Throughout the history of the Pacific salmon fishery there have been periodic reviews of its status. The earliest status reports were included irregularly in the annual reports of the U. S. Commission of Fish and Fisheries. In addition, Jordan and Gilbert (1887) reviewed the Pacific salmon fishery up to 1880. Cobb (1911, 1916, 1921, 1930) published statistical surveys of the fishery. By the mid-1950s the International North Pacific Fisheries Commission (INPFC) was documenting the harvest of Pacific salmon in the eastern and western Pacific in several monographs on the distribution and life-history of salmon. In 1963, the United States and Canada established the Informal Committee on Chinook and Coho (ICCC) to identify existing information on stocks of coho and chinook salmon and identify future research needs. The committee's report (ICCC 1969) described the status and outlook for stocks of coho and chinook salmon from British Columbia, Washington, Oregon, Idaho and California. This was one of the first attempts at a regional assessment of the status of salmon stocks. Fredin (1980) reviewed the history and condition of the commercial and sport harvests of salmon in both the eastern and western Pacific. Pearcy (1992) surveyed the life-history and production of salmonids in the marine environments of the North Pacific.

Konkel and McIntyre (1987) analyzed the escapement records for the period 1964-1984 for 886 salmon and steelhead populations in the northeast Pacific region. Significant population trends were found in about 30% of the 886 populations. Chum and coho salmon escapement trends were predominantly decreasing throughout the range. Trends in escapement of chinook, pink, and sockeye predominantly increased in Alaska and either lacked evidence of a trend or decreased in the other areas.

Nehlsen et al. (1991) reviewed the status of individual stocks of Pacific salmon in Washington, Idaho, Oregon and California, and identified 101 stocks of salmon at high risk of extinction, 58 stocks at moderate risk of extinction and 54 stocks of special concern. In addition, they identified at least 106 previous extinctions. More recent reviews of stock status include the Washington Department of Fisheries et al. (1993) and Nickelson et al. (1992). The National Marine Fisheries Service status reviews relative to the Endangered Species Act are useful summaries of existing information (e.g., Weitkamp et al. 1995).

Coastwide Production Trends. Table 5.1 summarizes periodic estimates of salmon production (largely inferred from harvest) from precontact to the present. Hewes (1947) estimated Indian harvest of salmon from the Fraser River south to and including California at 77 million pounds annually. Rostlund (1952) estimated the precontact production of salmon in the Pacific Northwest through an index of productivity per unit of land area. His estimate expressed as the maximum sustainable harvest of anadromous fishes in an area including the Fraser River in British Columbia south to and including California was 240 million pounds (Table 5.1).

Indices of postcontact production (Table 5.1) were derived from harvest records by the following method: three time intervals were selected at 1864-1922, 1923-1960, and 1961-1979. The first period covers the beginning of the non-Indian fishery to the initial development of efficient offshore salmon fishing vessels. The second period ends at about the time hatchery technology became effective in contributing to the fisheries (Lichatowich and Nicholas in press). After 1979, interception fisheries caused a major redistribution in commercial harvest among regions as well as a shift from commercial to sport fisheries.

In each period, the peak commercial harvest in each area or specific river basin was summed over all regions. Regional variation in climate and market factors caused harvests to peak in different years throughout the region. A comparison of peak harvest between periods gives a qualitative picture of the trend in production. The comparison of harvest as an index of production between periods is influenced by changes in regulations, fishing gear, and methods and markets as well as climatic factors that drive long-term productivity cycles. Combining the peak harvests gives a rough estimate of the magnitude of the resource being harvested; however, harvest rates, especially during the early years, were probably not sustainable. After 1960, the catch was comprised of increasing numbers of hatchery fish, which masked declines in natural production.

Commercial salmon harvest in the individual areas generally peaked in the first decade or two of the Twentieth Century. Exceptions are the Columbia and Sacramento Rivers which peaked before 1900. It is interesting to note that the index of peak production for the early years of the commercial fishery (1864 to 1922) approximates the maximum sustainable harvest of Rostlund (1952; Table 5.1). However, peak catches since have been declining, and in the last period shown

Table 5.1. Summary of historical estimates of production of Pacific salmon in the Northwest.

Species	*Region*	*Measure of Production*	*Pre-Contact Production or Harvest (pounds)*	*Post-Contact Harvest (pounds)*	*Source and Notes*
All	Oregon Washington Northern California So. B. Columbia	Precontact harvest and consumption by Native Americans	~77 million pounds		**Hewes (1947)** Estimate based on population size and per capita consumption of salmon.
All	Oregon Washington California B.C. (Fraser River)	Precontact sustainable harvest based on productivity/unit area of land mass (580 pounds/sq. mi.)	~240 million pounds		**Rostlund (1952)** Estimate of sustained annual yield of anadromous fish in the Pacific region.
All	Oregon Washington California B.C. (Fraser River)	Peak Cannery Pack (1864-1922) Klamath (1912) Sacramento (1882) Coastal Oregon (1911) Columbia (1895) Willapa Harbor (1902) Grays Harbor (1911) Coastal Washington (1915) Puget Sound (1913) Fraser River (1901) Total		 864,000 9,600,000 6,631,008 30,432,000 1,895,616 3,645,312 1,523,280 124,006,224 47,947,824 226,545,264	**Cobb (1930)** Mild cured salmon could add as much as 20 million pounds to the total.
All	Oregon Washington California B.C. (Fraser River)	Peak Commercial Harvests (1922-1960)* California (1946) Oregon (1925) Washington (1929) B.C. (Fraser R.) (1953) Total		 13,629,000 34,287,000 116,503,200 23,408,000 187,827,200	INPFC (1979) (Data for Fraser area of British Columbia 1922-1951 not available).
All	Oregon Washington California B.C. (Fraser River)	Peak Commercial Harvests (1961-1979)* California (1965) Oregon (1970) Washington (1973) B.C. Fraser R. area 1971 Total		 11,176,000 19,399,600 58,487,000 14,027,200 103,089,800	**INPFC (1979) and Forrester (1978, 1979, 1981a, 1981b, 1982)**

* Includes hatchery and wild production (see Table 5.2).

in Table 5.1, amounted to less than half of the harvest achieved during the early exploitation of the resource.

Coho salmon in the OPI illustrate changes that were taking place following the development of improved hatchery technology around 1960. Prior to 1960, the OPI was comprised almost entirely of wild salmon. By 1969, hatchery fish made up 54% of the catch, and in more recent years, 67-91%, of the catch was comprised of hatchery fish (Figure 5.15).

Table 5.2 summarizes comparisons between historical and contemporary estimates of salmon harvest or production. The catches of wild coho and chinook salmon have declined by 43% and 61% respectively, in Puget Sound, Washington. In the Columbia Basin total production has declined by 75-85%. Only 20% of contemporary production is comprised of naturally produced fish. Total contemporary production (hatchery and wild) of coho salmon was less than 25% of the historic production in eight of the ten Oregon coastal basins surveyed. However, recent studies by Jacobs and Cooney (1991) suggest contemporary coho production shown in Table 5.2 for Oregon coastal streams is an overestimate (i.e., contemporary production is a smaller fraction of the historic). In two of Oregon's coastal streams, contemporary production of chinook salmon is greater than production circa 1900. Overall, contemporary production of chinook salmon was 77% of historic. Lichatowich (1989) suggested that chinook salmon production circa 1900 in Oregon coastal streams was already severely degraded due to splash dams and streamside logging. Contemporary production reflects recovery from those early devastating practices.

Production of Salmon in Relation to Other Marine Species. Soutar and Isaacs (1974) estimated the abundance of pelagic fishes in the California Current from scales found in cores of anaerobic marine sediments. Their data permitted estimates of biomass for an extended time series from 1785 to 1970 (Smith 1978). Baumgartner et al. (1992) recently used the core samples to extend estimates of sardine biomass to a 1,700 year period. The pelagic fish community in the upwelling zone has been dominated by three species (California sardine, hake, and anchovy) for the past 200 years (Smith 1978; Figure 5.16). The time series of combined biomasses for those species show three important features: 1) the years from 1895 to 1915 were a period of exceptional productivity unequaled in the 200 year period; 2) exceptional productivity near the turn of the century was followed by a precipitous decline;[1] and 3) the decline after 1925 was deeper than any of the troughs in the previous 150 years. The latter decline appeared to coincide with intensified exploitation of marine fisheries and a strong relaxation of wind induced upwelling between 1916 and 1942 (Ware and Thomson 1991). Overall the biomass in the California Current declined from about 25 million tons in 1905 to 4.5 million tons by 1950, and has remained well below historic levels (Ware and Thomson 1991).

As discussed earlier, commercial salmon harvest also peaked between 1890 and 1915 in most areas of the Northwest (Cobb 1930). When the commercial harvests of coho and chinook salmon are superimposed on the 200 year record of biomass of marine pelagic fishes (Figs. 5.16 and 5.17), the trend in salmon catches appears to follow a pattern of abundance similar to hake,

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[1] Baumgartner et al. (1992) show nine collapses and recoveries of the California sardine over the past 1,700 years.

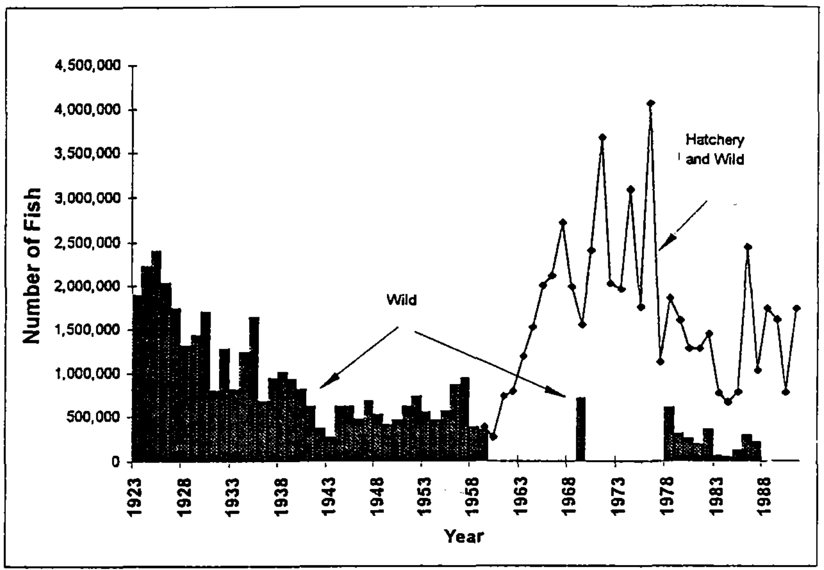

Figure 5.15. Harvest of coho salmon in the Oregon Production Index partitioned into wild and hatchery fish. Solid bars are catch of wild coho salmon. All coho salmon are assumed to be wild before 1960. (Source: OPI Harvest 1923-1970, unpublished data from Oregon Department of Fish and Wildlife (1982); 1971-1991, Pacific Fishery Management Council (1992); Harvest of wild coho salmon 1959 and 1969 Oregon Department of Fish and Wildlife (1982); 1978-1987 from Borgerson, Oregon Department of Fish and Wildlife, December 1992.)

anchovy, and California sardine. Nickelson (1986) also showed a correspondence between anchovy and coho abundance for more recent years. The information presented in Figs. 5.16 and 5.17 suggests that the physical and ecological processes driving the decline of pelagic fisheries through the first half of this century also had a strong influence on the production of coho and chinook salmon. The similarity in the patterns of decline after 1900 suggests that the species represented in Figs. 5.16 and 5.17 shared similar environmental constraints on production. However, life-history patterns of three of those species (coho, hake and sardine) also suggest a possible biological interaction which is discussed below.

VARIABILITY IN FOOD WEB PATHWAYS

Predator-Prey Interactions in Coho Salmon. A positive correlation between coho salmon jacks and the number of adults from the same brood that returns the following year implies that most of the variability in marine survival of coho salmon occurs within the first four to six months at sea (Gunsolus 1978). Fisher and Pearcy (1988) found a relationship between an index of jack survival and their catch of juvenile coho in the ocean in June. Since the outmigration of coho smolts from the Columbia River peaks in May, their data narrowed the critical survival period to the first

Table 5.2. Reported comparisons between historical and contemporary salmon production in specific areas of the Northwest.

Species	*Region/River*	*Historical*	*Contemporary*	*Source and Notes*
Wild Coho Salmon	Puget Sound	Average catch 1896-1905 1.13 million fish	Average catch 1966-1975 0.648 million wild fish	Bledsoe, et al. (1989) This represents a decline of 43%
Wild Chinook Salmon	Puget Sound	Average catch 1896-1905 0.344 million fish	Average catch 1966-1975 0.132 million wild fish	Bledsoe, et al. (1989) This represents a decline of 61%
All Native Species	Columbia River Basin	Total predevelopment production 10-16 million fish[1]	Total contemporary production 2.5 million fish (hatchery and wild fish)	Northwest Power Planning Council (1986) This represents an overall decline of 75-85% (hatchery + Wild) and a 95% decline in wild production.
Coho Salmon	Oregon coastal streams	Total natural production Thousands of fish Circa 1890	Total production hatchery & wild parentheses are % of historical	Lichatowich & Nicholas (in press) Coho production strongly supported by hatcheries.
	Alsea	123	45 (37)	
	Tillamook	181	15 (8)	
	Siletz	96	12 (13)	
	Nehalem	188	18 (10)	
	Nestucca	85	5 (6)	
	Yaquina	51	10 (20)	
	Siuslaw	438	27 (6)	
	Umpqua	159	56 (35)	
	Coos	129	31 (24)	
	Coquille	273	25 (9)	
Chinook Salmon	Oregon coastal streams	Total natural production Thousands of fish Circa 1890	Total production hatchery & wild parentheses are % of historical	Lichatowich & Nicholas (in press) Chinook salmon slightly supported by hatchery fish.
	Alsea	30	21.0 (70)	
	Tillamook	56	109.0 (195)	
	Siletz	27.5	12.8 (47)	
	Nehalem	36	10.4 (29)	
	Nestucca	27.5	33.1 (120)	
	Yaquina	13	6.7 (52)	
	Siuslaw	19	9.4 (49)	
	Umpqua	40	20.3 (51)	
	Coos	45	10.0 (22)	
	Coquille	23	11.4 (50)	

[1] Chapman (1986) estimated production in Columbia River circa 1900 was 8.9 - 7.5 million fish.

month at sea (Pearcy 1992). As indicated above, Pearcy (1992) concluded that juvenile coho remained in local coastal areas during their first summer at sea. This means that the coastal upwelling zone of Oregon and Washington is the critical habitat: the place where coho year class strength is determined. Although both coho survival and zooplankton abundance have been positively correlated with upwelling, Pearcy (1992) noted little evidence for food limitation of juvenile coho in the nearshore marine habitats of Oregon and Washington. He based his conclusion on a review of the literature and his own work. The two principal observations are described below.

First, the biomass of prey consumed by coho is small compared to the biomass of prey potentially available. Walters et al. (1978) also concluded that ocean limitation on production was unlikely unless the biomass of zooplankton is largely unavailable to the salmon. Honkalehto (1984) reached a similar conclusion. A possible exception to these observations occurs during periods of low upwelling when prey abundance is reduced and additional competitors such as mackerels move north with the warmer water. Pearcy (1992) did note that coho have a large number of competitors for the same prey organisms.

Second, if the relationship between marine survival of coho salmon and upwelling (Nickelson 1986) is a function of prey abundance (that is, low upwelling reduces prey abundance leading to reduced growth and starvation of coho), we should expect a positive relationship between upwelling and coho growth during their first month at sea. However, growth of juvenile coho salmon from Oregon coastal streams estimated from the spacing of scale circuli laid down after ocean entrance did not show a positive relationship with upwelling (Bottom 1985; Pearcy 1992). Variation in annual survival of coho is greater than the variation in growth determined from scales of surviving adults (Bottom 1985).

Pearcy (1992) also evaluated the hypothesis that upwelling influenced smolt transport in marine waters, making the juvenile coho more or less available to predators. He presented evidence from the literature that adult salmon preyed on juvenile salmon as well as evidence of predation by other species including marine birds. However, in his own sampling Pearcy (1992) did not obtain direct evidence of heavy predation on juvenile salmonids by adult salmonids and other predators. Pearcy (1992) suggested that survival of coho during the critical first month at sea is determined by functional responses of predators to coho smolts and alternative prey. The abundance of alternative prey and the dispersal of coho is mediated by upwelling. In high upwelling years more alternative prey is available to predators of juvenile salmon and the coho are more dispersed. Pearcy (1992) also discussed evidence that Pacific herring buffered predation on juvenile coho salmon. Smolt-to-adult survival rates of coho from Carnation Creek, British Columbia, increased during years when herring were abundant (Holtby 1988, cited in Pearcy 1992). Pearcy (1992) concluded that the cause of mortality of juvenile coho salmon during the first critical month at sea is still speculative.

Pearcy (1992) evaluated the food limitation and predation hypotheses as though they were independent events. There is support for combining the two hypotheses. Based on a model of minimum sustainable biomasses of marine ecological groups along the northwest coast, Laevastu and Favorite (1977) concluded that predation rates in the nearshore habitat are high. They concluded that ecosystem internal consumption was much higher than the catch, that is, the

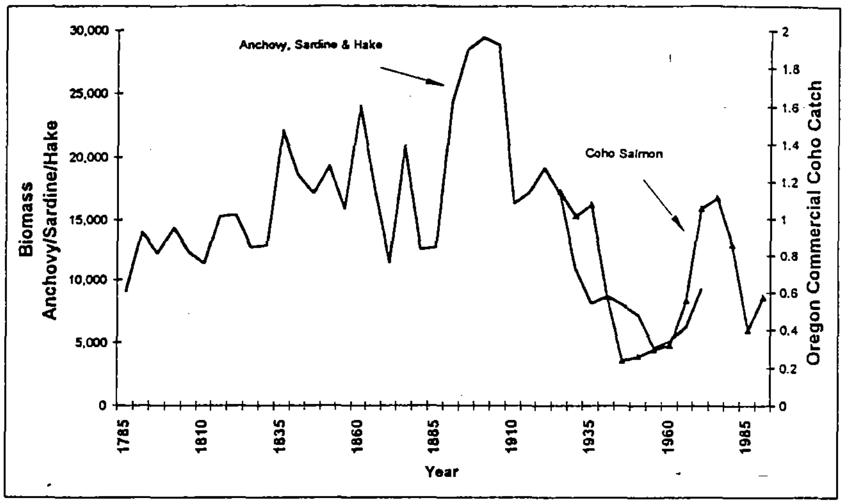

Figure 5.16. Total biomass of anchovy, sardine and hake in the California Current in thousands of metric tons. Standing stock inferred from contemporary stock size and scale deposition rates in 18th and 19th centuries (after Smith 1978). Commercial catch of coho salmon in millions of fish. Annual coho data averaged by 5 year intervals (after Lichatowich 1993).

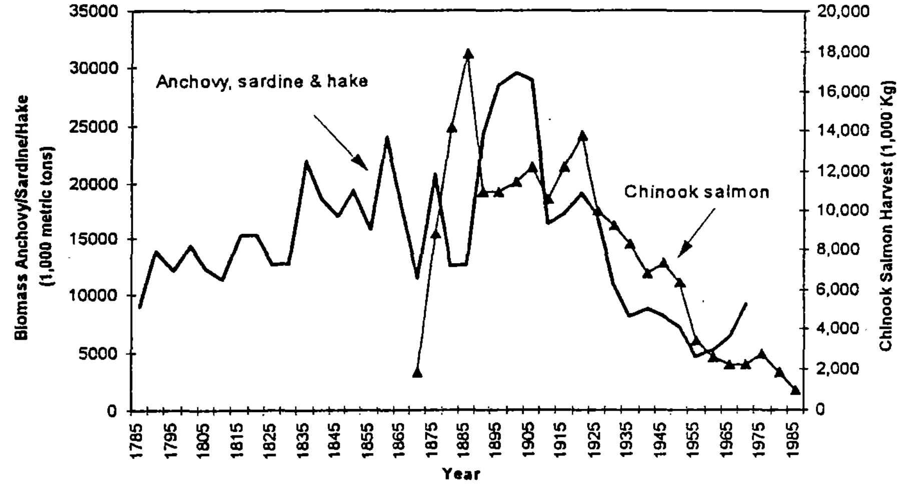

Figure 5.17. Total biomass of anchovy, sardine and hake in the California Current in thousands of metric tons. Standing stock inferred from contemporary stock size and scale deposition rates in 18th and 19th centuries (after Smith 1978). Commercial catch of Columbia chinook salmon in millions of fish (after Beiningen 1976; ODFW and WDFW 1995).

marine ecosystem itself was consuming at rates much higher than those of the commercial and sport harvest.

Laevastu and Favorite (1977) suggested that the high turnover rates indicate partial starvation might be common at sea. Partial starvation combined with high predation pressure could explain the relationship between upwelling and survival of juvenile coho during the critical first month at sea. This explanation is supported by Iles (1980) who proposed a hypothesis of preprogrammed growth rate that he summarized this way:

> The high zygote production by teleosts results in intense density dependent mortality at the larval - post larval stage. The mortality agency is "programmed growth", the need to maintain a minimum genetically determined growth rate. The motto for teleost larva is "grow, or die!"

The failure to show growth differences in juvenile coho between low and high upwelling years (Bottom 1985; Pearcy 1992) could be interpreted as support for Iles' (1980) hypothesis rather than rejection of the hypothesis of food limitation and starvation. There was no evident difference in growth of coho between high and low upwelling years because the juveniles that failed to grow at the minimum rate during years of high upwelling were consumed by the intense predation; and in low upwelling years, the juveniles that failed to grow were a higher proportion of the population. Bottom (1985) did show better than average growth for the one brood of coho that entered the sea during the El Niño event of 1983. That year class exhibited poor survival (Johnson 1988). Improved growth in years of poor survival also supports Iles' hypothesis in that Iles' predicted better than average growth when the habitat was not fully seeded because of a brood failure.

We suggest that Iles' hypothesis can be extended to the Pacific salmon during the first critical month at sea. This implies that there is a high degree of interaction between Pearcy's productivity growth and predation hypotheses. If growth is slow during the first month at sea, the high predation rates in the sea will overtake and consume the slower growers. Growth might be influenced by reduced food availability, poor physiological condition (specifically in hatchery reared fish), and stress from poor passage conditions at mainstem dams.

Hatchery-Predator Interactions in Coho and Chinook Salmon. Marine survival rates of coho and chinook salmon reared and released in coastal hatcheries have decreased significantly over the last decade (Johnson 1996). Data also suggest that marine survival of wild salmon smolts in Oregon (Bottom et al. 1986; Nickelson 1986) and in British Columbia (Beamish et al. 1992) is significantly higher than for hatchery-reared stocks. If this is generally true, then it raises an important management concern because, over the last 40 years, naturally produced salmon have been steadily replaced by increasing proportions of hatchery fish (Bottom et al. 1986).

Beamish et al. (1992) provided evidence that predation on hatchery smolts, in this case by spiny dogfish (*Squalus acanthias*), may be the cause of declining survival of hatchery fish in the Strait of Georgia. Although a small percentage of spiny dogfish preyed on the smolts, large numbers of the predators seemed to account for the relatively low rate of survival among hatchery salmon.

Research has shown that the behavior of artificially-reared salmon may be altered by crowding or other conditions that cause salmon to be less wary or otherwise less capable of eluding predators (citations in Beamish et al. 1992). Through this mechanism, other predator species in other locations could similarly account for low rates of survival among hatchery salmon. It is also possible that predation rates may be intensified if the narrow release schedules and limited stock diversity of most hatcheries cause an adaptive response by the ecosystem. As noted by Beamish et al. (1992), an adaptive response by predators may limit the increase in adult returns that are possible beyond some optimum release levels:

> Increasing freshwater survival of coho and chinook salmon through hatchery rearing was expected to increase total survival, but it was not expected that the marine environment would impose a maximum on the relationship between number of released smolts and survival to adults. The occurrence of a dome-shaped survival curve for hatchery-reared salmon indicates that survival decreases as releases increase beyond an optimum threshold, resulting in fewer adult returns.

The mortality rate for hatchery fish may change with shifts in the structure of coastal assemblages. During El Niño conditions or a shift to the Type A climatic regime discussed above, the presence of new predator or competitor species might have an important influence on marine survival rates of salmon. At the very least, a "dome-shaped survival curve" and the low rates of survival of hatchery fish over the last decade suggest a need to examine current hatchery release levels. The same levels of artificial propagation established under optimum ocean conditions may not be appropriate following a shift to a low productivity state (Beamish and Bouillon 1993).

Life-history Interaction Between Predators or Prey of Coho Salmon. Figures 5.18, 5.19, and 5.20 illustrate the migration patterns of Pacific hake, California sardine, and coho salmon, respectively. Pacific hake migrate north from winter spawning grounds off California and northern Mexico reaching the northwest coast in July and August (Fig. 5.18). The Pacific hake supports the largest single-species fishery on the West Coast, and it is an important trophic link in the California Current (Francis et al. 1984). Pearcy (1992) examined the stomach contents of 290 Pacific hake and found no juvenile salmon.

Before its collapse, the large northern subpopulation of the California sardine migrated north from spawning areas off Southern California reaching Oregon, Washington and the west coast of Vancouver Island in July and August (Fig. 5.19). In addition to the large California fishery, the large migrating schools of sardines supported significant fisheries in the Pacific Northwest peaking at 26,000 tons per year in Oregon and Washington and 88,000 tons per year in British Columbia. The northwest sardine fishery collapsed after 1948.

Coho salmon appear to migrate northward in their last summer at sea as evidenced by the timing of peak catches in the ocean fishery off California (June) and Oregon (July; Fig. 5.20). The timing of coho, sardine and hake movement along the West Coast suggests a trophic connection: the possibility that coho and hake were feeding on sardines. Chapman (1936) examined the food habits of ocean-caught chinook and coho salmon from Westport and Neah Bay, Washington.

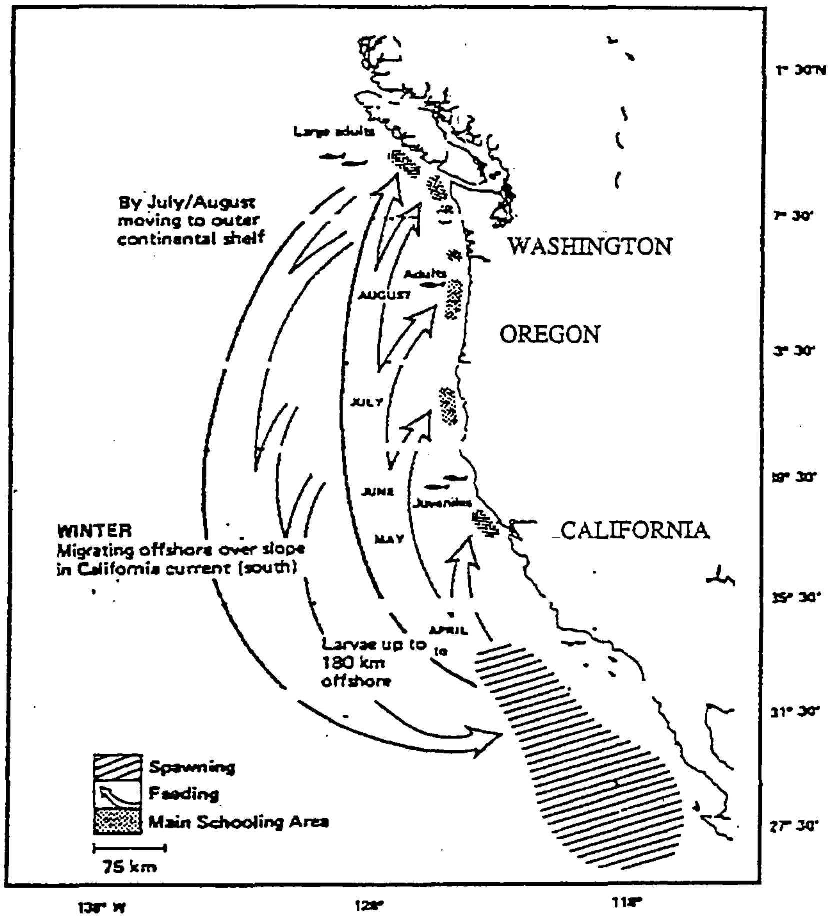

Figure 5.18. Life-history and migration of Pacific hake off the West Coast. (Source: Francis, R.C., G.A. McFarlane, A.B. Hollowed, G.L. Swartzman, and W.M. Getz. 1984. Status and management of the Pacific hake (*Merluccius productus*) resource and fishery off the west coast of the United Sates and Canada. Northwest and Alaska Fisheries Center, National Marine Fisheries Service, NWAFC Processed Report 84-18, Seattle, Washington.)

Prey preference shifted with the length of the chinook salmon. Fish between 11 and 20 inches fed almost entirely on euphausiids; between 21 and 30 inches the chinook salmon shifted to sardines and herring with sardines being more important; and about 80% of the stomach contents of fish 31 to 50 inches in length were sardines. Sardines were also important prey of coho sampled at Westport in July and Neah Bay in August.

This review does not verify the importance of sardines in the diet of adult salmon but it does suggest that sardines and salmon were trophically linked. Sardines may have been an exceptionally rich source of calories for salmon especially in the final months before entering rivers to spawn. While feeding off the northwest coast during the summer months, the oil content of the sardine increases dramatically from a low of about 14 gallons of oil per ton of fish in late July to 54 gallons of oil per ton of fish in early September (Chapman 1936). Sardines were a rich source of energy just before salmon began their migration to their spawning areas. Sardines may have had another trophic linkage to salmon: the large schools of sardines may have served as a buffer against predation of juvenile salmon during their critical first summer at sea. The buffer may have acted in much the same way as the herring buffered predation of Carnation Creek coho discussed earlier.

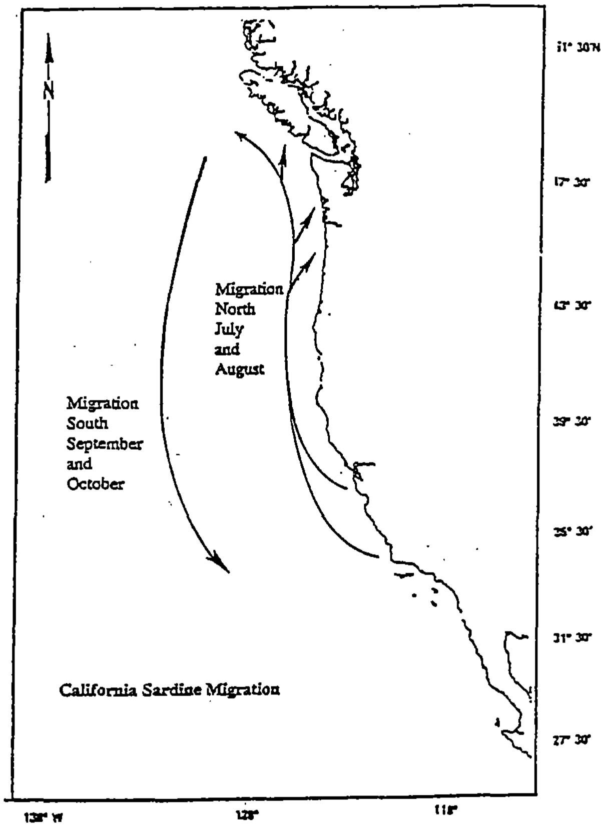

Figure 5.19. Migration of California sardine on the West Coast. (Source: Murphy, G.L. 1966. Population biology of the Pacific sardine (*Sardinops caerulea*). *Proceedings of the California Academy of Sciences*, Fourth Series, XXXIV:1 1-84. Reprinted with permission, courtesy California Academy of Sciences.)

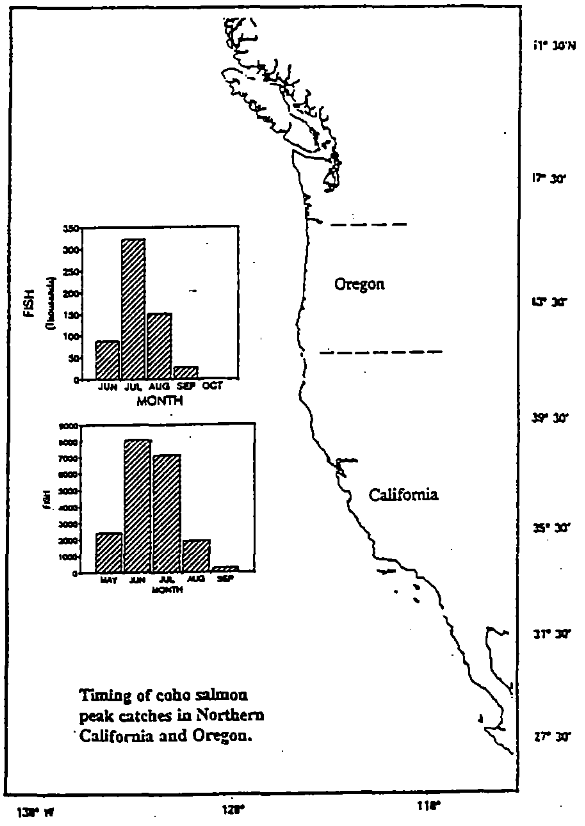

Figure 5.20. Timing of coho harvest in northern California and Oregon. Harvest peaks in California in June and in Oregon in July. Data are averaged harvest for the years 1952-1990. (Source: Oregon Department of Fish and Wildlife unpublished data.)

The Geographic Structure of Salmon Populations and Patterns of Life-History

BACKGROUND

The change in the capacity of coastal ecosystems in the Pacific Northwest to produce salmon cannot be explained by changes in the physical or biological environment alone. The response of salmon to interacting scales of environmental and anthropogenic change is itself highly variable. The multitude of individual salmon populations and life-histories across the geographic range of each species can be viewed as a regional time-space fabric or living textile that intimately links terrestrial landscapes; riverine, lacustrine, and estuarine habitats; and near-shore and open ocean environments. The net production of salmon in the Pacific Northwest is a result of the many separate population responses to unique sets of riverine-estuarine-marine conditions (e.g., see Fig. 5.2). Over the past century, the regional time-space fabric of salmon has become threadbare as increasing numbers of populations have been depleted and fragmented and the productivity of the Pacific Northwest has declined (Walters and Cahoon 1985; McEvoy 1986; Nehlsen et al. 1991; Frissell 1993). This deterioration is associated with pervasive environmental effects, including the loss of human fishery resource and the decline of many other species that directly or indirectly depend on salmon (Wilson and Halupka 1995). This section provides a theoretical overview of the functional significance of the distribution of salmon species, populations, and life-history types across space, with emphasis on the linkages between freshwater and marine environments.

The geography of populations and life-histories and its role in the productivity of salmon ecosystems has been conspicuously neglected in coastal resource management (Frissell et al. 1997). Future progress in salmon and ecosystem conservation not only requires additional empirical data, but, more fundamentally, an alternative conceptual foundation to account for the complex spatial structure of salmon populations and life-histories within species. Although the following ideas have received little attention in coastal management, they are well grounded in scientific theory and largely consistent with available empirical information. They are presented here to help frame a rationale for redefining coastal research and management programs. However, the theoretical ideas themselves are neither unequivocal nor universally accepted, and therefore require further scientific scrutiny, testing, and refinement.

NATURE AND POTENTIAL CONSEQUENCES OF GEOGRAPHICAL DIVERSITY

In the past, ecological theory has not adequately explained the occurrence of geographic diversity within species, except in the crude sense that the range of occurrence of a species is broadly constrained by its inherited physiological and ecological capabilities. Based on observations and logical arguments that first appeared early in the development of the stock concept of fisheries science, Sinclair (1988) suggested a new perspective on the problem of geographic distribution and within-species population diversity (which he terms population richness of the species). As discussed in an earlier section, Sinclair proposed that geographic distribution and population subdivision of a species reflect the geographic distribution and complexity of habitats that facilitate life-cycle closure. In particular, the specific requirements of early life-history phases, which are typically the most vulnerable life stages to passive environmental damage or displacement, determine which of the available universe of habitat patches are suitable starting points for rearing and subsequent homing of mature individuals to the natal spawning area. Local adaptation of life-histories to specific suitable habitats evolves, in Sinclair's view, to allow mates with similar heritage and local adaptive capacity to locate each other and reproduce.

Especially for species whose complex life cycles span large oceanic and perhaps terrestrial domains (e.g., the Pacific salmon), fidelity of life cycles to specific sequences of spatial locations at specific times becomes critical to the persistence of populations, and by extension, to the species they comprise (and the fisheries they support; Sinclair 1988). As a result, many habitat patches that appear otherwise suitable to support a salmon species, for example, remain unoccupied because the patch lacks sufficient connectivity to other habitats needed to ensure life-cycle closure. Sinclair concluded that this model of spatial constraints on the continuity of life cycles should apply to most sexually reproducing marine organisms. It is clearly applicable to Atlantic and Pacific salmon.

Sinclair argued that the forces that shape geographic distribution and subdivision of species (and also control absolute abundance and a large share of recruitment variation) are not necessarily density dependent, nor may they involve interspecific competition or predation. The operative mechanisms may largely stem from the spatial arrangement and connectivity of habitats and the physical loss (not necessarily direct mortality, but effective geographic displacement) of individuals as organisms traverse the environment from the habitat of one life stage to the next. Thus, certain physical discontinuities in space and time may provide important benchmarks, pathways, or critical points for the navigation of organisms in search of their critical habitats. Temporal variation or unpredictability in these environmental discontinuities can displace individuals and disrupt life-history cycles, with critical consequences for the persistence and abundance of local populations. As described elsewhere in this chapter, variation in oceanic discontinuities (e.g., nearshore changes associated with ENSO events) can have serious consequences for salmon survival and production, particularly during the freshwater and early marine juvenile life stages. The effect of environmental change on the abundance of a species can be greatly exaggerated as the geographic and intra-population diversity of the species declines (Walters and Cahoon 1985; Frissell et al. 1997). In a sense, diversity among salmon populations buffers the regional species-level response to environmental fluctuations, while within-population variations in life-history patterns may serve to buffer the response of individual stocks to such fluctuations.

Because populations of diverse local origin encounter different environmental discontinuities, and thus may respond independently to temporal discontinuities at sea or elsewhere in the environment, geographic diversity can be vitally important for the persistence and abundance of a species. For example, the wide distribution of Pacific salmon as a result of diversification of locally adapted populations presumably allows species to persist and eventually recolonize in the face of regional scale and catastrophic disturbances. Such disturbances, which periodically strike the Pacific Rim and transform land- and riverscapes, include subduction zone earthquakes, landslides, and volcanic eruptions (Waples 1991; Frissell 1993).

GEOGRAPHIC DIVERSITY AND LIFE-HISTORY PATTERNS

Legett and Carscadden (1978) documented latitudinal and river-specific variations in life-history patterns of the anadromous American shad that appeared to be locally adaptive. They suggested that the "fine tuning of reproductive strategies to local environmental conditions may be widespread among fish and may be the ultimate basis for the evolution of homing." MacLean and Evans (1981) pointed out that subdivision of species into local populations has genetic benefits including local adaptation through natural selection, increased genetic variation by partitioning genotypes among locations, and promoting new gene combinations through epistasis and local genetic drift. Moreover, each spawning and rearing area in freshwater has a unique and fixed spatial relationship to the marine environment. As discussed below, salmon populations may experience strong, river-specific natural selection for life-history patterns that allows them to successfully traverse the freshwater-marine interface.

POTENTIAL SIGNIFICANCE OF METAPOPULATION DYNAMICS

In addition to recolonization and genetic functions, there may be demographic advantages for maintaining a constellation of geographically separate breeding populations. If there is opportunity for successful immigration from one population to another, even if this opportunity is infrequent, small populations may be "rescued" from local extinction that might otherwise result from demographic limitations (e.g., a skewed sex ratio in a small population; Brown and Kodric-Brown 1977). Particularly when straying results from density dependent processes (e.g., crowding on spawning habitats), and local populations experience uncorrelated (or offsetting) fluctuations in survival, such exchanges of individuals among local populations can dampen the effects of population fluctuations (den Boer 1968; Harrison and Quinn 1989). Today such processes are generally described under the mantle of metapopulation theory (Hanski 1991).

Although what we do know about the biology of salmonids suggests that they are likely to operate as metapopulations across at least some scales of space and time (Waples 1991; Frissell et al. 1993; Li et al. 1995; Stanford et al. 1996; Rieman and McIntyre 1996), there is a need to test this concept and more carefully define the scales and environmental conditions for which metapopulation processes may be important to salmon persistence and production. Both genetic evaluations and observations of the movement and reproduction of salmon within and between spawning populations are needed. For salmonids generally we have little information about volitional movements of individuals between populations, dispersal during catastrophic events that can infrequently displace entire populations, and the reproductive success of such immigrants within receiving populations (Rieman et al. 1993; Gowan et al. 1994).

GEOGRAPHIC VARIATION IN LIFE-HISTORIES AND RELATIONSHIP TO MARINE, ESTUARINE AND FRESHWATER VARIABILITY

Pacific salmon are known to exhibit strong geographic patterns in life-history variation. Many of the life-history parameters that vary among populations have been demonstrated experimentally to be under some degree of genetic control. Life-history traits that are known to vary among salmon populations include age at maturity (Ricker 1981; Hankin et al. 1993), timing of spawning and rate of egg and larval development (Beacham and Murray 1987), and swimming performance (Taylor and McPhail 1985). Geographic variation of life-history patterns, however, can be manifest at different spatial scales (Taylor 1991), and can be viewed as a reflection of a patchwork of local habitat templates. Each template selects for a subset of the potential range of life-histories that a species can exhibit. Therefore, the life-history diversity within a population is a fraction of the possible variation in the species. The proportion of diversity expressed in a population reflects the complexity and diversity of the habitat template across the entire sequence of riverine, estuarine, and marine environments (Frissell et al. 1997).

There is an increasing, but limited, number of studies that assesses large-scale geographic distribution of variation in life-history features of salmon. Most of these are based on a limited number of rivers, as few studies have provided the relevant life-history data. Groot and Margolis (1991) provide an excellent international review of existing information on this subject for Pacific salmon, organized by species. Nicholas and Hankin (1988) compiled a comprehensive, river-by-river compendium of variation in life-history features and trends in abundance of chinook salmon of Oregon coastal streams. Much of the information included in their excellent report was previously unpublished. Roni and Quinn (1995) summarized much of the existing information on size and age at maturity of chinook salmon populations for the Pacific and Arctic coasts of North America. Taylor (1990b) did the same for juvenile chinook salmon. No such geographically comprehensive syntheses exist for other species and regions within the PNCERS area. In Washington, recent state-wide assessments (e.g., SASSI; WDF 1993) focus on stock abundance, harvest, and habitat management issues; life-history information remains neglected and its significance largely unappreciated by managers. Across the Pacific Northwest, significant local knowledge of life-history variation resides among local biologists, fishers, Native peoples, and nonfishing residents who closely interact with salmon runs, but this information is often discounted by management institutions (Frissell et al. 1997).

FUNCTIONAL SIGNIFICANCE OF LIFE-HISTORY VARIATION AND ITS ALTERATION

The possible functional significance of life-history variation among or within populations for long-term survival and production is an old question in biology (Darwin 1859; Mayr 1963; denBoer 1968). Its potential significance for salmon management has been suggested for decades (e.g., Thompson 1959; Ricker 1963; Everest 1973). However, to date, relatively few empirical studies have directly addressed this issue in Pacific salmon. While numerous published works demonstrate such variation in salmon and speculate about its importance (Taylor 1991), relatively few have experimentally or analytically evaluated its functional significance.

Perhaps the best examples of empirical studies on this subject are from the Pacific coast of Canada. Healey (1983) showed that the length of freshwater residence of chinook salmon coast-wide was correlated with distribution in the marine environment. Stream-type chinook (i.e., those with extended freshwater residence) tended to be caught disproportionately in high-seas fisheries, while ocean-type chinook (short freshwater residence) more strongly dominated catches from nearshore waters, regardless of latitude (Figure 5.21). This correlation implies a strong connection between freshwater life-history and ocean life-history, with divergence of two distinct life-history strategies that Healey (1983) suggested could be considered races within the species.

Variation in the reproductive life-histories of chum salmon populations among rivers and regions of British Columbia has been associated with local adaptations to natal habitats, especially the thermal regime (Beacham and Murray 1987). This spatial diversity in freshwater life-histories results in a nearly synchronous timing of ocean entry for a multitude of chum salmon populations. This phenomenon may be an important ecological strategy for optimizing ocean growth and saturating predator assemblages during the first few weeks at sea, when salmon are typically most vulnerable to predation (Holtby and Scrivener 1989; Holtby et al. 1989, 1990; Pearcy 1992).

Similar life-history strategies at the interface of freshwater-estuarine and ocean environments in other salmon species and regions have not been widely investigated. Holtby et al. (1989) and others have suggested that selection regimes ("windows of opportunity" for successful transition to ocean life) and the resulting evolutionary strategies differ among salmon species owing to differences in their freshwater habitats and life-histories. Thermal regimes within the local freshwater habitats occupied by salmon may be among the most critical environmental signals around which life-history strategies evolve (Holtby et al. 1989; Holtby and Scrivener 1989). Most studies lack data on survival to adult stages over a period of years, which are necessary to directly gauge the success of life-history strategies. But a relatively long time series of appropriate data is available for Carnation Creek, Vancouver Island (Holtby and Scrivener 1989; Holtby et al. 1989, 1990). For coho salmon in Carnation Creek, which reside in freshwater or the small estuary for 1-2 years before ocean entrance, intrinsic variation among habitats of thermal regimes (or other environmental factors affecting rates of growth and development) apparently conferred a sufficient degree of compensatory capacity to buffer the population from many of the effects of habitat alteration caused by logging, although over the long term, or under persistently poor ocean conditions, declines in coho populations in response to logging effects may become more evident (Holtby and Scrivener 1989). By contrast, increased stream temperatures from logging more clearly affected chum salmon populations in Carnation Creek, as the freshwater life-history of this species (e.g., spatial distribution of spawning and rearing, duration of stream residence) was more restricted than coho salmon (Holtby and Scrivener 1989).

In Oregon, the classic work by Reimers (1973) illustrated the extent of life-history diversity within the fall chinook salmon run of Sixes River. From field data on distribution and growth and analysis of scale circuli, Reimers defined six life-history types within the population based on the duration of riverine and estuarine life of juveniles and their time of ocean entry. Figure 5.22 collapses this diversity to two dimensions (size at ocean entrance and time of ocean entrance) to illustrate variation in representation of these life-history types in juvenile populations and in returning adult salmon in Sixes River. The difference between the proportion of outmigrants and

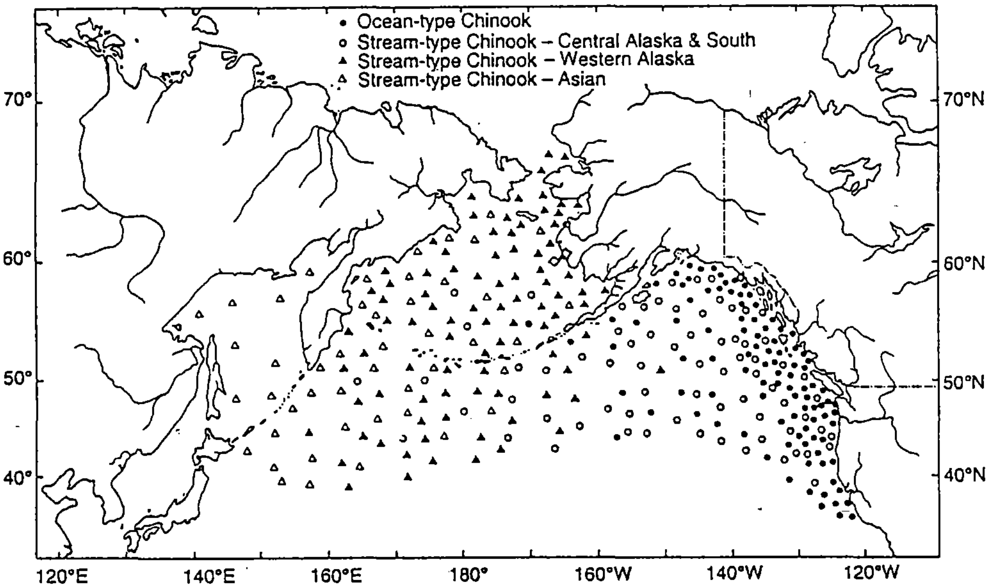

Figure 5.21. Probable ocean distributions and relative abundance of ocean- and stream-type chinook salmon from different regions of North America and Asia from Healey (1991). Healey (1991) discusses the difficulties of analysis, for example, due to estimates of fish from different origins landed by different fisheries sampling bias of the fisheries. Nonetheless, the broad patterns suggest distinct patterns of ocean migration directly linked to freshwater life-histories.

returning adults displaying these life-history features can be used to infer the relative marine survival of different life-history types, which based on Reimers' analysis, may vary by as much as 2-3 orders of magnitude. The dashed line in Fig. 5.22 delineates a domain of early-migrating, rapidly-growing juveniles that appeared to be absent in Sixes River, but which are known from other coastal rivers. Based on subsequent research (Frissell 1992), it appears likely that, under historical conditions, when cool water habitat during June and July was more prevalent in the mainstem and major tributaries, such an early, large juvenile life-history was present in the river. If present, this life-history type might have very high marine survival rates in many years. This suggests an hypothesis that freshwater habitat changes leading to the loss of mainstem-rearing, early-smolting juveniles caused disproportionately large declines in the abundance of returning adults in the Sixes River, and reduced the level of harvest that the population can sustain. Due to apparently limited marine survival of other life-history types, recovery of habitat conditions that allow the redevelopment of this "early-large" life-history might be necessary before substantial increases in salmon production can be realized in the Sixes River or similar watersheds.

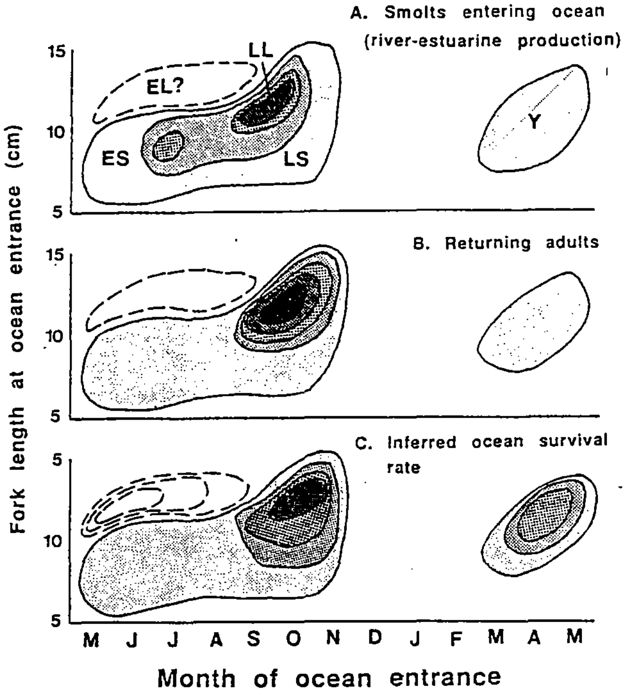

Figure 5.22. Hypothetical depiction of life-history variation in riverine and estuarine habitats and its effect on ocean survival, based on Reimers' (1973) study of fall chinook salmon in the Sixes River, southern Oregon. Intensity of shading reflects relative abundance of life-history types, characterized by the time of ocean entrance and the size of juvenile salmon at the time of ocean entrance, in A) the population of juvenile salmon that enter the ocean and B) the population of adult fish returning in a single brood year (Reimers 1973). Shading intensity in C) reflects relative survival rate of the different life-history types, inferred from the topologic difference between graphs A and B. *ES* denotes a region of life-histories that can be classified as early (spring-early summer) and small (<10 cm F.Fl.) smolts, *LS* a region of late (late summer-fall) and small smolts, *LL* late and large (>10 cm F.L.) smolts, *Y* indicates fish that overwinter in the river and enter the ocean as yearlings. *LS* group includes two life-history types identified by Reimers—fish that spend all summer in the river and leave the estuary rapidly in fall, and fish that spend summer in the estuary but head to sea (perhaps due to estuary crowding) before they grow to large size. *EL?* refers to a region of early, large (rapid-growing) life-histories not found in Sixes River by Reimers when he did his work, but which if present could potentially contribute to adult production. The *EL* life-history is known from other coastal rivers with high-quality habitats and low rearing densities.

SPATIAL DISCONTINUITIES IN THE PACIFIC COASTAL ECOSYSTEM AS CENTERS OF ORGANIZATION FOR SALMON POPULATIONS

A number of regional studies has suggested that major oceanographic discontinuities along the Pacific Coast of North America form critical boundaries for the diversification of salmon life-histories. As mentioned previously, differences in the marine environment may also selectively force many differences in the freshwater portion of the life-history, depending on the species and diversity of habitats available.

Nicholas and Hankin (1988) suggested, based on recovery of tagged fish in the ocean catch, that the general direction of ocean migration paths differed between northern and southern coastal populations of chinook salmon in Oregon. In general, chinook salmon from the Rogue River southward appear to migrate southward or remain nearshore along the Oregon and California coasts during their ocean life, while populations to the north migrate north to British Columbia and the Gulf of Alaska. Chinook from the Umpqua basin appear to include both south- and north-turning life-histories. The pattern in ocean migration could be evolutionarily selected by the spatial association of particular natal streams to oceanic features and patterns in marine currents; over many generations, north- or south-migrating fish may be more successful at a given latitude, although there may be considerable interannual variation.

Spence (1995) compared the mean and variance around the date of ocean entrance by coho salmon smolts along the Pacific coast. There was a clear pattern of later and shorter duration (less variable) migration timing in northern rivers (Alaska and British Columbia) as compared with central populations (Washington); still earlier and more variable migration times were evident among most southern (Oregon and California) populations. Spence (1995) hypothesizes that these differences, which were rather consistent among rivers within each region, reflect strong selection for timing relative to "windows of opportunity" for high smolt survival during early ocean life.

Since ocean conditions are strongly related to atmospheric circulation and weather across the Pacific Basin, it appears likely there are teleconnections between oceanic and terrestrial or riverine environments driven by common atmospheric patterns (Greenland 1994a; see also Chapter 4). From the central Oregon coast northward through the Columbia River basin, for example, El Niño-Southern Oscillation (ENSO) events are typically associated with low winter precipitation, summer drought, and low streamflows (Redmond and Koch 1991; Greenland 1994a). However, in the southwestern states and the California coast, most ENSO events are associated with winters of prolonged or high-intensity rainfall and flooding (Redmond and Koch 1991). Preliminary analysis of hydrographic records of Oregon coast rivers indicates that interannual variation of flood events in southern Oregon is closely aligned with that of California and the southwest, and thus contrasts with rivers to the north (Frissell unpublished). Additionally, very preliminary analysis hints at a second major discontinuity in interannual patterns of winter precipitation near the Olympic Peninsula and far northern Puget Sound. Therefore, salmon populations across the PNCERS area may experience dramatically different patterns of variation in freshwater and marine conditions over time. Moreover, variations in productivity of salmon populations across the area could be partly explained by covariance of freshwater and oceanic conditions that have synergistic or compensatory effects depending on the prevailing atmospheric regime and its differential effects among areas. Research on this subject could greatly benefit understanding of the causes of salmon decline and is probably critical for forecasting future responses of salmon populations to environmental change.

LOSS OF LIFE-HISTORY AND SPECIES DIVERSITY

There are few studies that describe changes in the diversity of life-history types within populations over time, or in response to management actions except Ricker (1981) and other above-cited papers on the effects of selective harvest on age, size, or growth rates. Numerous historical records suggest that declines in salmon abundance are associated with the complete disappearance of life-history types. Although theoretical treatments (e.g., Lichatowich et al. 1995; Spence 1995; Frissell et al. 1997) hypothesize that attrition of life-history diversity may be a cause, as well as a consequence, of declining population productivity and abundance, this remains a key unresolved research question. Lichatowich et al. (1995) have proposed a logical framework described as "patient-template" analysis. In this approach, existing data and informed biological judgment are used to reconstruct historical habitat templates and the hypothetical spectra of life-history types that likely used them. The historical template is compared to present patterns to identify opportunities for incremental return of productive habitats and life-histories that have been lost. This approach is a promising tool to inform restoration efforts. Presumably, it should be possible to identify certain common habitats and life-histories that are, or were, particularly productive and important to the persistence of salmon populations (Frissell et al. 1993).

Spatial analysis of regional patterns of fish population extinction and endangerment along the US Pacific coast shows clear latitudinal and longitudinal clines in deterioration of freshwater fish assemblages, and in the status of individual salmon species (Frissell 1993; see also The Wilderness Society 1993). Decline and loss of spatially marginal populations at southern latitudes and in interior drainages might reflect disproportionate loss of populations dominated by a small subset of life-histories adapted to ecologically marginal conditions near the edge of the species' range. For example, recent loss of early-spawning fall chinook salmon in southern Oregon coastal rivers could be partly responsible for the persistently diminished productivity of remaining populations and their increased vulnerability to extinction (Frissell et al. 1997). At the same time, loss of populations at the edge of the range could presumably result in loss of some life-history types that are rare or absent elsewhere in the range of the species (Allendorf et al. 1997; Frissell et al. 1997). Aside from the direct consequences of reduced distribution and diversity, the topic of consequences of edge-of-range extinctions and progressive range collapse for life-history diversity within species of salmon is ripe for research.

Within a river basin or region, the progressive loss of life-history types eventually gives rise to local extinction of species. The ecological consequences of loss of salmon life-history and species diversity are poorly known, but the consequences for species directly dependent on salmon resources could be great, and are probably underappreciated in regions where salmon have already experienced major declines from historical abundance (Wilson and Halupka 1995). Such extinctions may be very difficult to reverse, particularly where adjacent populations are also extinct, depressed, or highly fragmented (Frissell et al. 1993). In terms of salmon diversity across the northeast Pacific Basin, each local extinction or range contraction may represent long-term, perhaps permanent, elimination of a point source of salmon to the ocean; as the diversity and distribution of such point sources along the coast declines, increased temporal fluctuations of ocean populations and harvest are probably inevitable (Walters and Cahoon 1985; Frissell et al. 1997).

RECOVERY OF LIFE-HISTORY DIVERSITY

Little is known about the processes and rates of development of new life-history patterns within populations. We have very little documented experience with successful restoration of native salmon populations. From a few case studies, we can infer that salmon populations have the capacity to evolve life-history variation over time scales spanning several reproductive cycles. For example, chinook salmon introduced to New Zealand circa 1905 from a single stock in California have colonized several adjacent South Island rivers and evolved stream-specific, life-history variations that appear to have a genetic basis. Known differences among these populations today include time of ocean entrance, time spent at sea, and ocean growth pattern (i.e., weight gain relative to body length; Quinn and Unwin 1993).

Unfortunately, many of the best-documented cases of life-history evolution result from introduction of salmon to novel habitats outside their native range. It is uncertain whether depressed populations within the native range have the same capacity for relatively rapid development of life-history variation (e.g., owing to suppression or countervalent selection from indigenous, co-evolved competitors, predators or pathogens). Clearly, in some cases, healthy salmon populations within their native range have shown the ability to colonize new habitats after barriers are removed, or as water quality limitations are relaxed. However, there appear to be many comparable cases where salmon have not recolonized after creation or re-establishment of apparently suitable habitat.

Holtby et al. (1989) discussed the possibility that chum salmon had been directionally selected within a single generation to partly compensate for adverse shifts in time of ocean entrance that had been caused by logging-related alteration of the thermal regime on Carnation Creek. If this occurred, it is consistent with the notion that salmon populations continually track local variations in their habitat through microevolution of life-history patterns, with some predictable lag time determined by the consistency, duration and magnitude, and reproductive consequences of the environmental change, as well as the generation time and intrinsic genetic diversity of the population. However, the data available were insufficient for Holtby et al. (1989) to test this hypothesis, and the Carnation Creek project has been curtailed. Continuation or initiation of new long-term case studies such as the Carnation Creek research will be necessary, and perhaps the only effective means, to better understand the capacity of salmon populations for behavioral and evolutionary compensation in life-history patterns. Such understanding is critical for accurately predicting the response of salmon to virtually any kind of environmental change.

DISCUSSION

Extent and Quality of Data Supporting Conceptual Framework

Understanding the capacity of coastal ecosystems in the Pacific Northwest to support salmon is hampered by long-standing inattention to the oceanic phase of the salmon life cycle. Traditionally, management programs have emphasized year-to-year variations in adult abundance and, in studies of environmental factors, the spatial scales of freshwater habitats, stream reaches, or river systems (meters to tens of kilometers). Consequently, understanding of salmon variability in the ocean is frequently based on indirect statistical correlations between coastwide trends in survival or production and selected indices of environmental conditions (e.g., Nickelson 1986). Fewer data are available regarding the effects of smaller or larger scale processes on salmon production. For example, other than the general surveys conducted in the early 1980s (Pearcy and Fisher 1988, 1990), relatively little is known about the stock-specific migrations of juvenile salmon from Washington and Oregon streams, conditions that might alter these movements, or the mechanisms that cause the loss of individuals from a population. The surveys of salmon distribution off the Washington and Oregon coast in the early 1980s may or may not be representative of the movements of local salmon stocks under variable ocean conditions. Furthermore, much of the understanding of ocean life-history in the Pacific Northwest is based on information for hatchery stocks which may or may not provide useful indicators of the distribution and ecology of locally adapted populations. Reported estimates of survival for freshwater and marine life-history stages of salmon species were recently reviewed by Bradford (1995). However, difficulties in accounting for smolt abundance, fishing mortality, and total escapement generally limit our understanding of ocean survival of wild populations, and, therefore the specific mechanisms that might account for any local differences. At the other end of the spectrum, processes at scales much larger than the size of individual management jurisdictions have only recently been considered with regard to salmon production, and much of this research emphasizes stocks in the Gulf of Alaska (Beamish and Bouillon 1993; Francis et al. 1996).

Added to this lack of information are the practical difficulties of conducting ocean research and developing knowledge about a system that is continually changing through the interaction of environmental processes at many scales. Two overriding questions for the PNCERS program to consider are:

> Given the significant uncertainty regarding mechanisms of salmon production in the ocean, the logistical difficulty in sampling in marine waters, and the changing state of the ocean and the salmon, what is the best way to incorporate new knowledge into management programs?
>
> If the traditional management goals of environmental prediction and control are unattainable, then what alternative conservation approach is more appropriate and what information is needed to support it?

Research Questions

ENERGETICS PROCESSES

The pertinent literature on the trophic structure and predator-prey interactions during the salmon's first critical month at sea was not exhausted in the above review. Other changes in community structure may be important to salmon production. But the general observations are sufficient to frame new questions or hypotheses regarding predator interactions, changes in those interactions, and the influence of those changes on salmon. For example:

> Did the most recent collapse of the California sardine trigger a trophic cascade in the California Current characterized by standing stocks at depressed levels over the last 40 to 50 years?
>
> Has a change in community structure been an important factor in the failure of recovery programs for Pacific salmon?
>
> What are the critical components and interactions within the pelagic community that need further research before we can advance our understanding of salmon production in the marine environment?

SPATIAL PROCESSES AND CLIMATIC EFFECTS

The California Current is described as a highly variable system controlled by external climatic forces that regulate the transport of water and species from adjacent biogeographic provinces. Plankton species are apparently replenished from outside so that the assemblage remains highly resilient despite large climatic disturbances and the reordering of dominant species at all scales (McGowan and Walker 1993). Recruitment of at least some pelagic marine fishes may also be regulated by spatial processes that may determine whether larvae remain in suitable geographic areas for completing their life cycle (e.g., Sinclair et al. 1985). The importance of physical processes in shaping the California Current ecosystem raises a number of questions about the influence of physics and geography on salmon production:

> By what mechanism(s) do climatic variations such as El Niño or interdecadal regime shifts regulate ocean production of salmon within the Pacific Northwest? Do spatial (advective) processes influence salmon production directly (for example, through transport effects on early migrants) or indirectly (for example, through climate-mediated changes on community structure)?
>
> Are climatic influences on salmon production "coupled" or "decoupled" among riverine, estuarine, and marine life stages of salmon? That is, do large-scale atmospheric patterns have similar effects on salmon survival during all life stages or are negative climatic influences at one stage offset by positive effects at another? Do the positive and negative effects at different life stages vary geographically?

How are the processes that regulate ocean production of salmon in the Pacific Northwest likely to be affected by global climate change?

LIFE-HISTORY-HABITAT LINKAGES

Resource managers are being encouraged to incorporate a watershed perspective in their programs when dealing with production problems and conflicts in resource use (see for example, Naiman 1992). However, for salmon, the watershed defined as a catchment basin is not adequate. The salmon's watershed includes oceanic rivers such as the California Current. Thompson (1959) defined the home stream of salmon as a "chain of favorable environments connected within a definite season in time and place." He went on to speculate that the chain extends to the sea. Thompson (1959) suggested that people attach more importance to what they can see. That is why traditional solutions to salmon decline, for example, hatcheries, harvest quotas based on spawning escapements and stream habitat improvements, emphasize the freshwater phase of salmon life cycles. The following questions suggest a need to devote more effort to evaluating the entire chain of life-history-habitat linkages including those at sea:

> Are there distinct ocean migration patterns within or among local populations? What other life-history traits and habitats are linked with these migration patterns? Can we identify characteristic linkages between freshwater, estuarine, and marine environments that account for much of the geographic variation in salmon life-history and productivity across the Pacific Northwest? At what scales are these linkages most evident?
>
> How do geographic distribution and spatial diversity of salmon species affect their overall productivity, persistence, and ecosystem function? Do metapopulation dynamics play a role in population persistence and recovery? At what scales do metapopulation processes operate?
>
> At what rates and under what conditions can salmon populations change life-history patterns? How rapidly can new life-histories evolve within populations? Under what conditions do salmon colonize or re-colonize new or restored habitats?

ANTHROPOGENIC EFFECTS ON SALMON PRODUCTION AND LIFE-HISTORY

Two classes of anthropogenic change have affected salmon production and life-history diversity in the Pacific Northwest: habitat alteration, which changes the physical template for biological organization in the region; and hatchery and harvest effects, which directly alter the gene pool and population structure of salmon. Table 5.3 hypothesizes some of the effects of such change on the energetics and spatial processes that may cause losses from a salmon population. We include examples of effects at one life stage/environment that may be linked to another. A few of the questions raised by these examples include:

> How do anthropogenic changes affect spatial and energetics losses from salmon populations?

Table 5.3. Some hypothesized increases in spatial and energetics losses from salmon populations associated with fishery management activities, riverine/estuarine habitat loss, and regulation of river flows (hydropower development). Spatial losses include direct losses from the geographic area appropriate for continued membership in a population (e.g., advective losses or inability to return and find a mate within the population; Sinclair 1988). Energetics losses include effects of predation, disease, starvation, physiological stress, or reduced fecundity. Examples emphasize linkages between river, estuary, and ocean.

Habitat Loss	Hatcheries	Harvest	Hydropower
	Energetics Losses		
Decreased juvenile growth, increased marine predation	Increased marine predation on hatchery fish	Size selection fecundity decreased	Physiological stress and injury
	Increased stress, disease from crowding (hatchery fish)	Decrease in ocean nutrients and carbon delivered to streams (adult carcasses)	
	Competition, inter-breeding with wild fish		
	Spatial Losses		
Reduced diversity of routes and times of ocean migration	Narrowing of routes and times of ocean migration (hatchery selection)	Narrowing time of return and associated distribution of spawning sites	Narrowing times of migration according to flow and bypass schedules
Decreased freshwater refuges at high flows, increased vagrants to estuary/ocean			
Smaller size at ocean migration increasing advective losses			
Loss of spawning areas for returning adults			

> Has the growing reliance on artificial propagation, which uses fewer stocks and life-histories of salmon, changed the relationship between oceanic conditions and salmon production?
>
> How do human activities change the potential development of riverine, estuarine, and marine life-histories, and what are the consequences of such changes for the freshwater-marine interface that appears to be so critical for salmon survival and recruitment?
>
> Can we identify a general syndrome of changes in specific habitat conditions and life-history types that have a common, disproportionate influence on the productivity of many salmon populations? If so, do such general syndromes vary among regions within the Pacific Northwest?

If the California Current has undergone a "change in state" that influences salmon production, then it follows that the state of the freshwater links in the chain may become more important. Healthy freshwater habitats may become more critical when oceanic productivities are lower and marine mortality higher. Degradation of freshwater habitat combined with cyclic changes in ocean productivity and high harvest rates may have had the effect of "burning the candle at both ends."

> To what extent does the degradation of freshwater habitat influence the depth of the troughs and height of the peaks in the natural fluctuations in ocean productivity?

Cycles of ocean productivity can at the very least mask the effects of improvement in freshwater habitat or hatchery production or cause resource managers to falsely attribute increased marine survival to restoration effects in freshwater. However, there may also be important additive or multiplicative consequences of freshwater habitat degradation during the troughs of ocean productivity cycles.

The above research questions emphasize the need for a better understanding of variability to support management efforts in coastal ecosystems. While many indicators may be necessary to fully provide this understanding, Pacific salmon offer important advantages for ecosystem-level investigations: they are distributed over a wide geographic area and diversity of habitat types; their life cycles integrate conditions across the entire continuum of freshwater, estuarine, and marine environments; harvest data provide an index of trends in abundance over a relatively long period of record; and differences in the performance of stocks with different life-histories can offer clues about the principle factors of ecosystem change. These attributes argue for a fundamental reassessment in fisheries research to consider the role of salmon as an ecological indicator rather than simply as an economic commodity.

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CHAPTER 6

VARIABILITY OF RIVERINE AND ESTUARINE ECOSYSTEM PRODUCTIVITY FOR SUPPORTING PACIFIC SALMON

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INTRODUCTION

This chapter summarizes the key characteristics of riverine and estuarine habitats in the coastal ecosystems of Washington, Oregon, and northern California, relative to their utilization by Pacific salmon. The objectives are to characterize the structural and functional variability in riverine and estuarine physical processes and biological production that could influence juvenile Pacific salmon; and to identify important research questions. In the context of this chapter, a river drainage is viewed as the mainstem river channel and its network of tributary watersheds and a river and its estuary as a coastal ecosystem.

Because Pacific salmon populations depend on riverine, estuarine and ocean ecosystems throughout their life-histories, salmon life-history patterns are reviewed in the context of the influences of both environmental conditions and human actions. The complex anadromous life-histories of the five species of salmon within the region integrate ecosystem change across a multitude of spatial and temporal scales. The resiliency (i.e., ability to adapt and recover; National Research Council 1992) of populations of juvenile salmon within riverine and estuarine ecosystems indicates the influences of human actions (Chapters 2 and 3) as well as their dependence on climatic/oceanic regimes (Chapters 4 and 5).

The first section focuses on the concepts of variability and scale in ecosystems in the context of the biological processes and physiographic factors that influence the growth and survival of juvenile salmon. The next section provides summaries of the diverse anadromous life-histories of the five species of salmon within the region and describes salmon genetic diversity variation at local and regional geographic scales. In the third section, research directions are suggested: 1) by examining the variability of physical processes (e.g., variations of maximum and minimum flow events of different river drainages), geomorphic characteristics (e.g., habitat quality and landscape structure and their potential influences on the survival of different salmon life-history stages in riverine ecosystems); and 2) by examining the variability of estuarine production, food web structures supporting salmon, and the importance of riverine inputs of organic matter and nutrients.

VARIABILITY OF RIVERINE AND ESTUARINE ECOSYSTEM PRODUCTIVITY TO SUPPORT PACIFIC SALMON

The productivity or the "capacity" of riverine and estuarine ecosystems to sustain juvenile Pacific salmon populations can be broadly described by variations in structural or physical characteristics, and "trophic" processes. Traditionally, biological production has been defined as an increase in biomass during any time interval (Δt; Chapman 1971). Trophic processes describe the flow of organic matter from primary producers (autotrophs such as phytoplankton or bacteria) to primary (such as salmon prey) and secondary consumers (such as salmon). Physical characteristics of riverine and estuarine ecosystems that influence salmon production include small scale microhabitats in the gravel of spawning areas in rivers to larger scale estuarine currents and tidal fronts. Other important ecological factors include: influences of habitat conditions, predators and competitors on the survival of individual fish; and fish population characteristics that maximize the long-term conservation of diverse species and life-history traits (i.e., genetic fitness and the opportunity to express diverse life-history traits). Influences of most physical and biological processes, as well as human actions, on salmon populations are poorly understood and will require considerable research attention.

Riverine Ecosystems and Salmon Production

Variations in salmon productivity in riverine drainages of the Pacific Northwest coast relate to different environmental conditions (e.g., climatic, hydrologic, and geomorphic), fish life-history and genetic diversities, and natural and anthropogenic disturbances (Stearns 1989; Waples 1991; National Research Council 1996). As stated above, drainages are defined here as the mainstem river channel and the network of tributary watersheds.

RIVER DRAINAGE PHYSIOGRAPHIC CHARACTER AND VARIABILITY

River drainages along the Pacific Northwest coast exhibit a range of channel morphology, from shallow to deeply entrenched, depending on geologic and geomorphic formations (e.g., bedrock to glacial alluvium). Along with highly variable geology (e.g., hardness and permeability), fluvial processes of erosion and deposition also contribute to many large-scale morphological characteristics of the drainage basins. Lithology determines bedrock channels in deep, narrow valleys, while erosion and deposition produce semi-confined and unconfined channels in alluvial valleys and broad floodplains. Geologic and geomorphic features of headwater tributary watersheds usually control modes of delivery of debris (e.g., streambank failures, landslides from hill-slopes) to stream and riparian habitats, and influence the type and size of sediment supplied to downstream valleys (Montgomery and Dietrich 1994). Factors such as hill-slope relief, stream channel drainage density, climatic conditions, and high and low flow events can influence cumulative effects of sediment regimes.

Variations of climate and hydrology are important to the unique productivity of individual riverine ecosystems and salmon runs along the Pacific Northwest coast. The hydrological variability sets the stage for possible high and low discharge periods that could coincide with salmon entry to rivers, spawning, egg incubation, and juvenile rearing. Such flow periods can have important ramifications in terms of anthropogenic modifications of hydrologic conditions (e.g., flow regulation).

The Pacific Northwest can be stratified into major hydrologic regimes based on precipitation as rain and snow and average winter temperatures. Major topographic features of mountain ranges and marine influences (e.g., oceanic currents) create climates that yield distinct hydrologic regimes and patterns of vegetation. In mountainous regions, elevation and orographic effects result in unique precipitation and snow accumulation patterns. Once the water reaches the earth's surface, the hydrologic regimes are influenced by topography, relief, stream length and gradient, vegetation, and soils. These factors have considerable influence on the source and timing of streamflow and the productivity of riverine ecosystems. The coastal river drainages of warm maritime-subclimatic zones on the Pacific Northwest coast. (i.e., Olympic Peninsula, British Columbia, Southeast Alaska) have flow patterns characterized by rainfall-induced floods in fall and winter. Many of these river drainages are short in length, originating in mountainous coastal regions. These river drainages can have distinct subclimates because of interactions between atmospheric circulation patterns and abrupt coastal mountain terrains. High mountains serve as barriers to the movement of air masses and enhance the formation of dense clouds that cause high precipitation and flashy discharge regimes in rivers that drain these west-facing mountains.

The warm maritime-subclimates in the Pacific Northwest region are the result of macro-scale atmospheric processes (Melone 1985). The usual circulation pattern during the winter is produced by a strong temperature gradient between tropical and polar latitudes. Winter low pressures over the Gulf of Alaska and high pressures on the continent combine to produce strong pressure gradients on the North Pacific coast with southerly surface winds. As a result, numerous storms develop rapidly over the Pacific Ocean with smaller-scale frontal systems that break away from storm centers and move onto the coast. These fronts bring strong southwesterly flows of warm air that are responsible for coastal rainfalls. Summer atmospheric circulation patterns are controlled by the dominance of a large high pressure center over the North Pacific Ocean and coast that results in weaker pressure gradients, northwesterly winds, and low frequency and intensity of Pacific storms (see also Chapter 4, Fig. 4.8).

Because of the varied mountainous topography in the Pacific Northwest coastal region, flood-producing mechanisms vary within different river drainages (Melone 1985). River drainages west of the coastal and Cascades mountain ranges can have *rainfall-induced* flood regimes either as rainfall runoff only or as *rain-on-snow* runoff in fall and winter; some western drainages can have both *rainfall-induced* and *rain-on-snow* flood regimes. Other drainages, both west and east of the Cascades, have *snowmelt-induced* flood regimes in spring or summer. Drainages in the large

Columbia River basin can feature *snowmelt-induced* flood regimes (spring/summer) typical of cold interior or continental regions.

Historical flood records of western Washington can be used to establish ranges of extreme floods and low-flow periods (seven-day minimum flow), and to identify general trends and similarities between hydrologic regions. We examined flow characteristics by calculating unit discharge per unit drainage area for maximum and minimum instantaneous flows of record. These data permit the comparison of different-sized drainages and an assessment of the variability of rates of streamflow in different hydrologic regions. The general premise for identification of the hydrologic regions is based on Melone (1985), where maximum instantaneous discharge values <1.0 m^3 sec^{-1} km^{-2} (read as cubic meters per second per square kilometer) suggest *snowmelt-induced* floods, and values >1.0 m^3 sec^{-1} km^{-2} point to *rainfall-induced* flood regimes. Three general hydrologic regions occur in western Washington: *rainfall-induced*, *rain-on-snow*, and *snowmelt-induced* flood regimes. Comparisons of maximum instantaneous flows of record for different river drainage in coastal regions of western Washington indicate the Northern Puget Sound, the north coast of the Olympic Peninsula, Willapa Bay, and Grays River (lower Columbia River) regions (Figure 6.1) exhibit unit discharge values that commonly exceed 1.0 m^3 sec^{-1} km^{-2}. The values that exceed 1.0 m^3 sec^{-1} km^{-2} illustrate the flashy nature of floods that are most likely induced by *rainfall* and *rain-on-snow* events. Only a few river drainages (Fig. 6.1) appear to exhibit *snowmelt-induced* flood regimes.

Somewhat different patterns are apparent in comparisons of maximum instantaneous flows and river drainages of southern Puget Sound, Hood Canal, Strait of Juan De Fuca, and the Chehalis River (Figure 6.2). Most of the unit discharge values are <1.0 m^3 sec^{-1} km^{-2}(south Puget Sound and the Chehalis River) except for some higher values for Hood Canal and Strait of Juan De Fuca drainages. These values suggest variable orographic influences (e.g., rain-shadow effects of the Olympic Mountains, and snow field-glacial areas in the Olympics and Cascades) as well as the presence of some *rainfall -induced* flows in coastal lowlands and *rain-on-snow* flows in uplands. Orographic influences are common throughout the year, increasing during late summer to a maximum in November. Very high winter rain rates during December, January and February may negate the orographic effects of elevation, causing considerable variation in flood levels within hydrologic regions.

Comparisons of mean maximum and minimum instantaneous flows of record for the different sized drainages (Table 6.1) suggest how the high variability of rates of streamflow in different hydrologic regions could influence the productivity of riverine ecosystems and salmon runs. This synthesis (Figs. 6.1 and 6.2; Table 6.1) points to potentially high risk flow periods (e.g., high and low discharge periods) for salmon entry to river, spawning, egg incubation, and juvenile rearing. For example, the ranges for the mean unit discharge values for minimum instantaneous flows of record (0.001 to 0.007 m^3 sec^{-1} km^{-2}) and the most frequent months of occurrence within the different river drainages and hydrologic regions (Table 6.1), suggest low flow periods that could impact spawning salmon and incubating embryos. Further analyses of low flow periods (seven-day minimum flow) of various river drainages and freshwater life-history traits of different chum salmon stocks may suggest possible base-flow risk periods for different stocks.

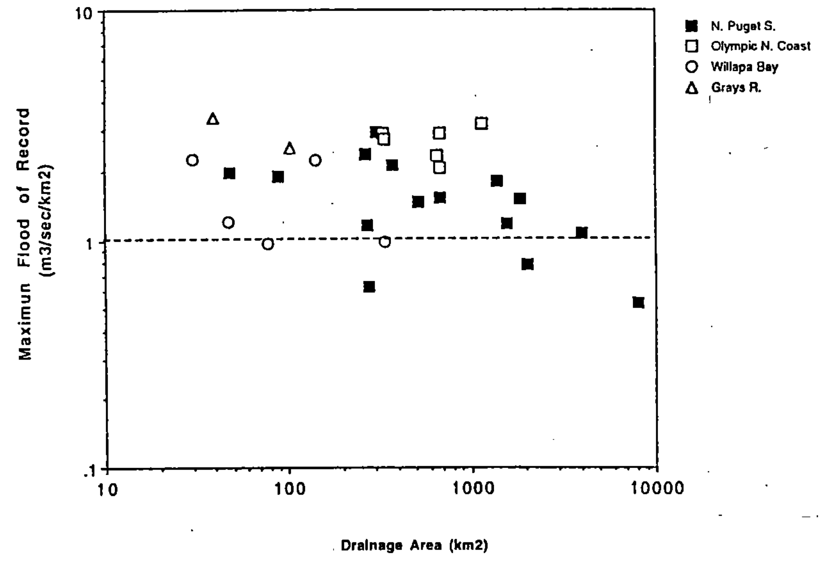


Figure 6.1. Maximum flood of record versus drainage areas of rivers in different regions (Northern Puget Sound, north coast of Olympic Peninsula, Willapa Bay, Grays River) of western Washington.

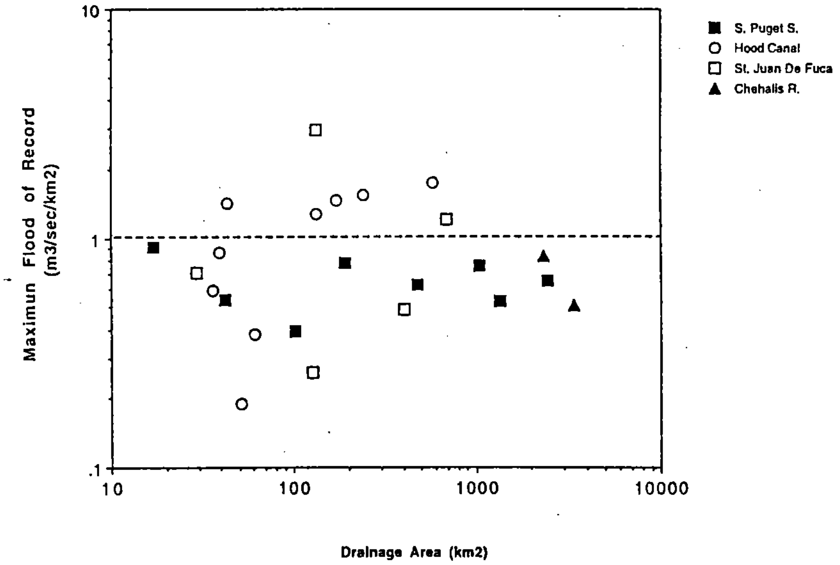


Figure 6.2. Maximum flood of record versus drainage areas of rivers in different regions (Southern Puget Sound, Hood Canal, Strait of Juan de Fuca, Chehalis River) of western Washington.

Table 6.1. Comparison of mean maximum and minimum instantaneous flows (m^3 sec^{-1} km^{-2}) of record for the different sized drainages of hydrologic regions within western Washington, where S.D. indicates percent standard deviation and n indicates the number of river drainages in the hydrologic region with flow recorders. Most frequent months of flood occurrences include November (N) through February (F). Most frequent months of minimum flows include July (J) through November (N)..

Hydrologic Region	**Instantaneous Discharge** (m^3 sec^{-1} km^{-2})						
		Maximum Flood			Seven Day Minimum		
	n	Mean Discharge	S.D. (%)		Mean Discharge	S.D. (%)	
S. Puget Sound	8	0.65	26	(N, D, **J**)	0.004	25	(J, A, S, O)
Hood Canal	9	1.05	53	(**N**, D, J, F)	0.006	50	(**A**, **O**)
St. Juan De Fuca	5	1.13	96	(**N**, D, **J**)	0.004	50	(**O**, N)
Chehalis R.	2	0.67	34	(**J**)	0.001		(**A**, **O**)
N. Puget Sound	15	1.52	44	(**N**, **D**, J, F)	0.006	33	(A, **O**)
Olympic N. Coast	6	2.68	15	(N, D, J)	0.007	43	(S, **O**)
Willapa Bay	5	1.53	43	(**N**, D, **J**)	0.003	67	(**A**, **O**)
Grays River	2	2.95	21	(**J**)	0.004	25	(A, O)

PRODUCTIVITY OF RIVER ECOSYSTEMS

The biological productivity of most rivers and streams that contain juvenile salmon along the Pacific Northwest Coast can be limited by nitrogen (N) and phosphorus (P). N and P limitation of primary producers becomes especially pronounced at high light levels (Gregory et al. 1987; Bilby and Bisson 1992). The literature review by Gregory et al. (1987) shows that P limitation of primary production tends to be more frequent in waters of drainages dominated by igneous bedrock than where volcanic geology allows P availability. Weathering reactions (Wissmar et al. 1997b) that interact with volcanic rocks may release inorganic phosphorus. Lack of nutrient inputs from river drainages to estuaries with high flushing rates also plays a significant role in reducing the levels of production (Triska et al. 1984; Wissmar 1991). P-limited freshwater ecosystems can exhibit dissolved nitrogen to phosphorus ratios (N:P) that exceed 16:1 (MacDonald et al. 1991). For example, N:P loading ratios approaching 20 for the Nanaimo (Vancouver Island, B. C.) and Columbia Rivers suggest P limitation in these drainages (Wissmar 1986). Lower ratios commonly occur in estuarine and marine waters, where N limitation is more pronounced. Comparative information for N:P ratios and about the nutrient cycling dynamics in riverine and estuarine ecosystems can be very important to managers and scientists who are interested in influences of nutrient availability, flow regulation and eutrophication on salmonid production.

The levels of riverine inputs of organic carbon to estuaries can be useful indicators of the productivity of river ecosystems. For example, inputs of carbon (dissolved and particulate carbon) from the Nanaimo and Columbia Rivers ranged from three to sixteen-fold greater than the total primary production (attached plants and phytoplankton) in the estuaries (Wissmar 1986). Dissolved and fine particulate terrestrial organic matter can provide valuable surfaces for heterotrophic organisms (e.g., bacteria) and activity in aquatic systems. In addition to releasing organic carbon and providing a substrate, large woody debris can affect both freshwater and estuarine systems by controlling the movement of sediments, water and organic matter, dissipating the energy of flow regimes, and providing habitat for fish and invertebrates (Maser and Sedell 1994). Because the capacity to biologically, chemically and physically process carbon and nutrients can vary greatly within different river and estuarine ecosystems, these processes need considerable research in order to understand and predict the influences that different sources of organic matter have on aquatic food webs and salmon production.

Historical records and studies of pristine stream conditions suggest how riverine and estuarine ecosystems once interacted with the productive forests in the Pacific Northwest (Maser and Sedell 1994). In freshwater ecosystems, organic matter from riparian forests dominates the energy base of the aquatic ecosystems by supplying detrital forage for insects and shading for waters. Shading by forest cover affects both water temperature and light availability for primary production. While aquatic primary production is low due to shading, inputs of terrestrial organic materials act to subsidize the energy available to decomposers and insect consumers (Wissmar et al. 1982). While the gross primary production (e.g., algae, moss) provides only 3 to 5 % of the total organic input, the heterotrophy in these ecosystems is supported by terrestrial inputs of fine detritus (29%), large woody debris (22%) and dissolved organic matter (43%). Thus, supplements of terrestrial organics determine the balance of autotrophy and heterotrophy in these aquatic ecosystems. However, organic carbon budgets for small pristine streams in western Oregon show a paucity of primary production in stream channels (Triska et al. 1982). Interestingly, these trophic pathways could represent the habitat conditions to which rearing juvenile salmonids have been adapted for eons.

Historically, the supply of nutrients in riverine ecosystems that produce salmon could have been closely coupled to the decay of spawned-out salmon carcasses. Historical information such as catch, early hatchery, and cannery records indicate that riverine and estuarine systems once supported large salmon runs that greatly exceeded present levels. Several studies of decaying salmon carcasses on spawning grounds suggest the release of considerable amounts of nutrients to streams (Richey et al. 1975; Kline et al. 1994; Bilby et al. 1996). Evidence from the abundance of natural stable isotopes of carbon and nitrogen in decaying fish tissues suggests considerable recycling of nutrients transported upstream by runs of Pacific salmon (Kline et al. 1994; Bilby et al. 1996). The declines in spawning salmon stocks suggest large losses in supplies of marine derived nutrients in riverine ecosystems

Numerous biological and abiotic processes support salmon production in riverine and estuarine ecosystems. Food supplies, habitat space, and surface and subsurface flow fluctuations (Stanford and Ward 1988) all act together to influence juvenile survival. For example, juvenile salmon are opportunistic predators that feed on a variety of aquatic invertebrates, vertebrates and terrestrial insects that drift in currents and occur in benthic environments. If food and cover are abundant, the carrying capacity increases and more fish can occupy a given area and establish territories. However, high mortalities of juvenile salmonids commonly occur during the first few months when fry populations attempt to adjust to the ecosystem's carrying capacity. Because the levels of food and habitat space depend on the season (temperature, nutrient supplies and hydrologic conditions), they can limit juvenile fish abundance through density-dependent mortality (Meehan 1991). Absence of habitat cover and refugia (Sedell et al. 1990) can also increase the exposure of juveniles to bird or fish predation. Human alteration of these processes in riverine ecosystems can also readily reduce salmon reproduction and rearing (Hartman and Scrivener 1990). Because these interactions can be easily altered by anthropogenic modifications, they need to be better understood in order to predict the influences of changing conditions.

Estuarine Ecosystems and Salmon Production

PHYSIOGRAPHIC CHARACTERISTICS OF ESTUARINE ECOSYSTEMS

Estuaries in the Pacific Northwest vary widely from glacially-formed fjords that dominate the coast of British Columbia to southeastern Alaska, to the drowned river valley estuaries of the coasts further south, and the bar-built and lagoonal estuaries of southern Oregon and northern California, where seasonal low river flow and strong along-shore currents can close off ocean entrances. Fluvial drainage areas range over four orders of magnitude, from 10 to 100 km^2 for many coastal estuaries of Oregon to 100,000 to 1,000,000 km^2 for Puget Sound (all sub-basins combined) and the Columbia River. Estuarine surface areas typically are less than 5% of that area except for estuaries such as Hood Canal, Netarts Bay and Humbolt Bay (Figure 6.3).

Estuarine circulation varies extensively as a function of river flow and seasonal cycle, tidal range, and estuarine bathymetry (tidal prism). Salinity can be completely mixed vertically through the water column (shallow systems), or completely stratified (fjords), or switch back and forth between these two states. Tidal prism volume of estuaries north of the Columbia River is considerably higher, by as much as two orders of magnitude, than most of the estuaries in Oregon.

This does not appear to reflect river flow (long-term average daily flow), but is probably due to the geologic history of the estuary (which accounts for the deep fjord systems of Puget Sound; Figure 6.4). The proportion of total estuarine surface area that is intertidal is typically greater than 40%, except in southern Oregon, and tends to reach maxima of >75% in central Oregon. The extent of tidal marsh is highest (>20%) at the northern and southern extremes of the Oregon coast, but negligible in central coastal Oregon estuaries (Figure 6.5). Within estuaries, the natural occurrence and distribution of habitats depends upon the combined interaction of bathymetry, salinity regime, sediment structure, and disturbance level (i.e., river and tidal current and wave energy). Intertidal habitats are colonized by emergent marsh vegetation in euryhaline and brackish salinity regimes and tidal shrub-scrub swamps and forests in tidal freshwater reaches.

Land-uses also affect the physiographic characteristics of estuaries in the Pacific Northwest. Contemporary land-use is predominantly forest land (managed and preserved forest lands are not distinguished) throughout the region until agriculture becomes more important in San Francisco Bay. "Barren" (urbanized) land is most notable in Puget Sound watersheds, and is prominent south from Humbolt Bay (Figure 6.6).

PRODUCTIVITY OF ESTUARINE ECOSYSTEMS

Estuarine production that supports Pacific salmon is extremely pulsed; the quantity, composition, timing and rate of primary and secondary production processes supporting juvenile salmon vary extensively over space and time (Simenstad 1997). Estuaries can experience high frequency events (daily, monthly), intermediate or mesofrequency events (seasonal, interannual, quintennial), and low frequency (decadal events, climatic regime, century, millennial). Variability in estuaries can be: 1) predictable, as in tidal cycles; 2) subtle, as in delayed warming of estuarine waters coincident with a cold, wet spring season; or 3) stochastic, such as imposed by large-scale flood and storm disturbances. To all degrees, salmon productivity and the diversity of life-history strategies, as well as the structure of estuaries, reflects these various scales of variability. Even exceedingly destructive, mega- to macroscale events, such as the subduction zone earthquakes that occur every 300-500 years along the Pacific Northwest (Atwater 1987; Atwater and Yamaguchi 1991; Atwater and Hemphill-Haley 1996), are within the scope of natural adaptation of Pacific salmon populations.

Juvenile salmon themselves pulse through the systems, although perhaps at different frequencies than in pre-hatchery eras. Because many factors regulating the dynamics of juvenile salmon migrations through estuaries are relatively independent, as are the production of prey organisms and associated food web processes, the coincidence of salmon with the primary consumers may be random and uncoupled.

Food webs of Pacific Northwest estuaries are based predominantly on detritus, and juvenile salmon, in large part, are supported by detritus-based trophic pathways. But the composition of organic matter contributing to the estuarine detritus pool may vary significantly depending upon location (ecoregion), extent and type of watershed and estuary, climate, geology, and oceanic energy regime, among many factors, including anthropogenic effects. Comprehensive, estuary-scale accounting of organic matter production and consumption has not been attempted for many

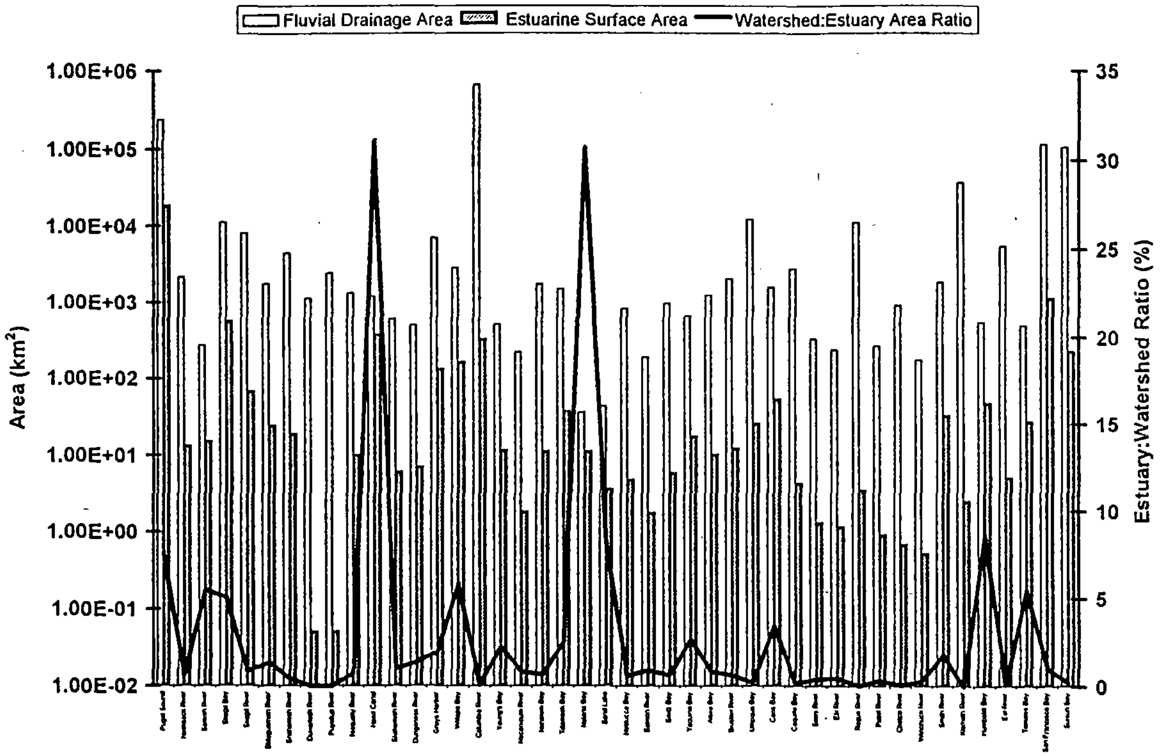


Figure 6.3. Fluvial drainage and estuarine surface areas and watershed:estuary area ratios of Pacific Northwest estuaries where data were available.

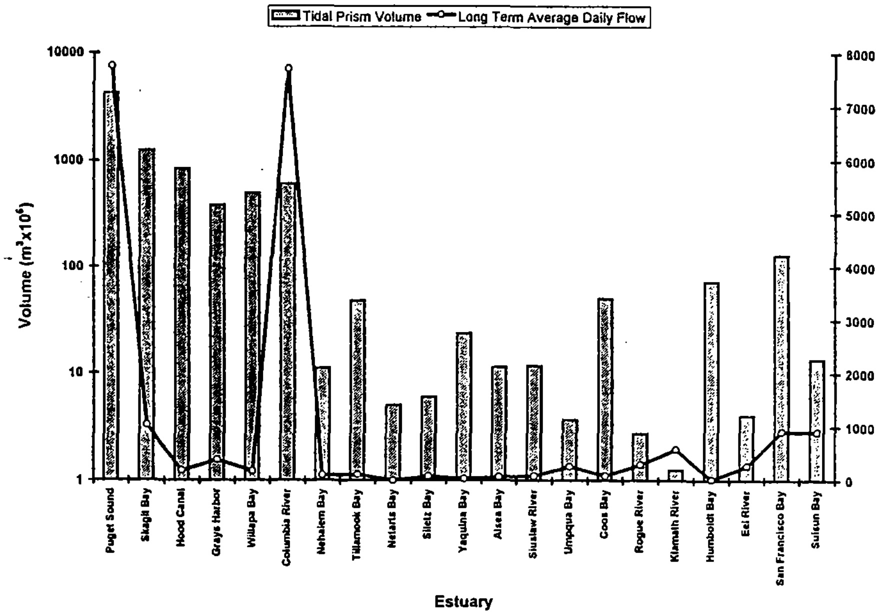


Figure 6.4. Tidal prism and long-term average daily flow of Pacific Northwest estuaries where data were available.

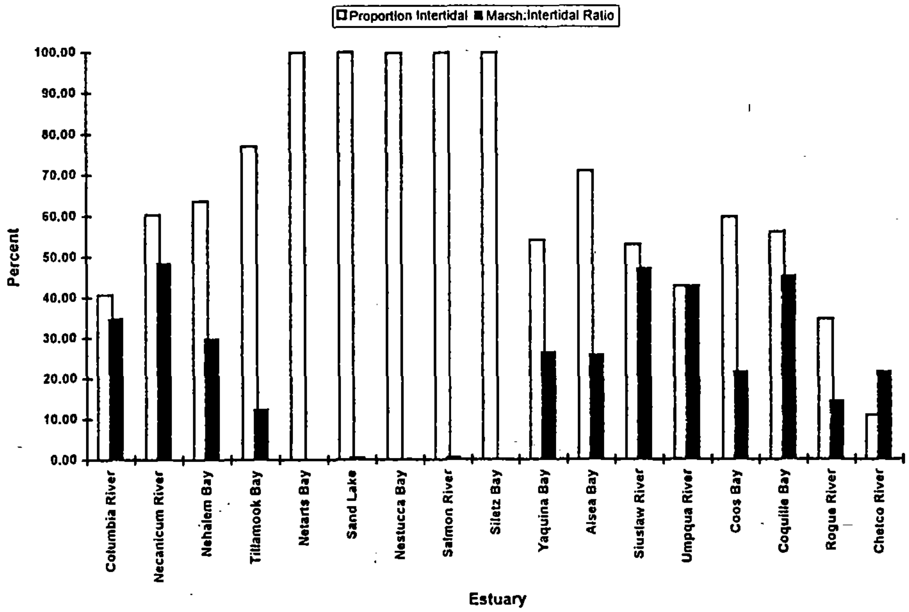


Figure 6.5. Proportion of estuarine surface area that is intertidal and the marsh:intertidal ratio of Pacific Northwest estuaries where data were available.

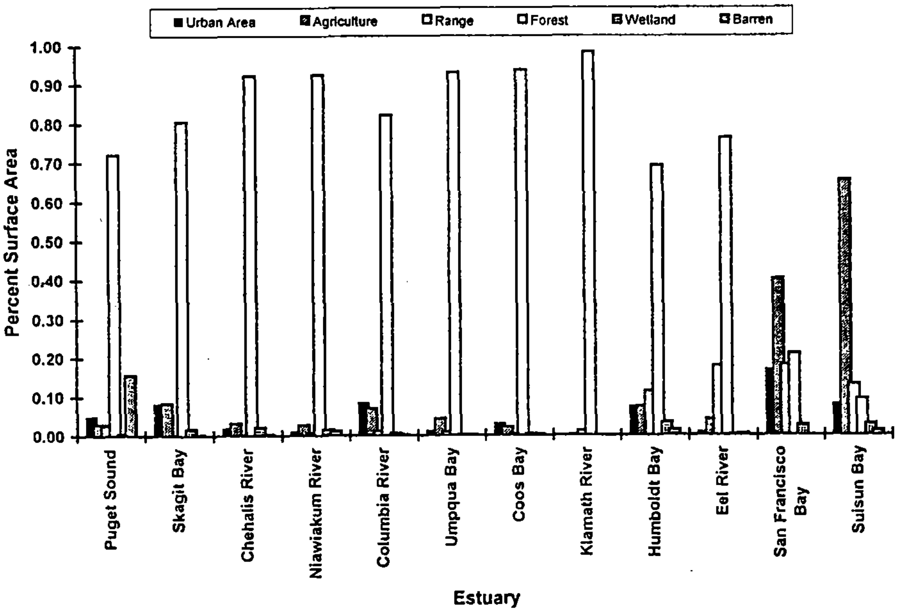


Figure 6.6. Land-use of watersheds of Pacific Northwest estuaries where data were available.

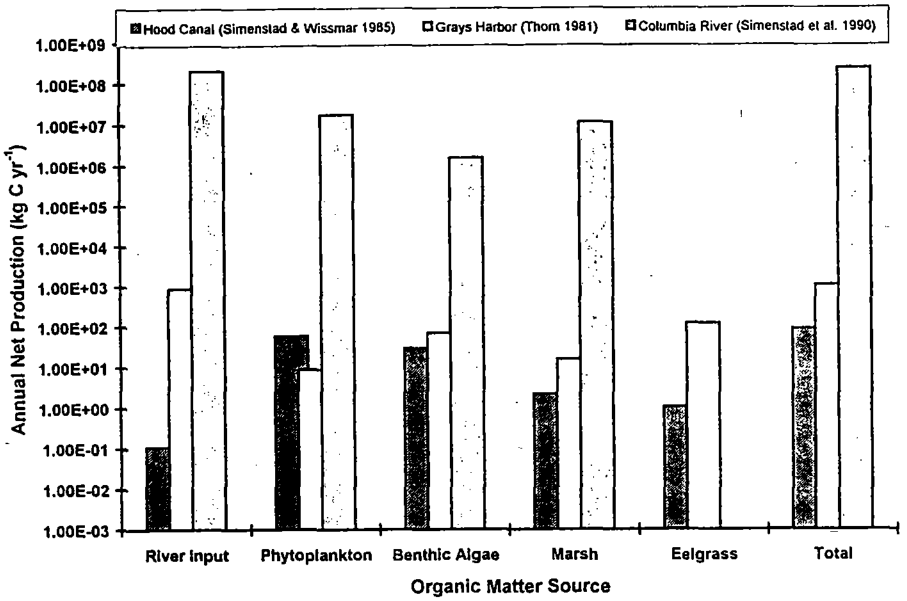


Figure 6.7. Variability in annual net production of three Pacific Northwest estuaries.

estuaries in the region, but annual carbon input budgets have been calculated for at least three contrasting estuaries: Hood Canal (Simenstad and Wissmar 1985); Grays Harbor (Thom 1981, 1984); and the Columbia River estuary (Simenstad et al. 1990). Not surprisingly, given the considerably greater extent of the Columbia River watershed, the total annual loading of organic carbon to that estuary is about five orders of magnitude greater than that in either Hood Canal or Grays Harbor (Figure 6.7). While import of fluvial organic matter dominates carbon budgets in both the Columbia River estuary (87.2%) and Grays Harbor (80.1%), phytoplankton (59.7%) and benthic algae (29.7%) contribute much more to the Hood Canal budget, and eelgrass production is of significance (11.3%) primarily in Grays Harbor. Emergent marsh production is comparatively insignificant (1.4-4.8%) in all three systems (Figure 6.8).

Timing of delivery of these different organic matter constituents to the estuarine food web is neither proportional to the sources, nor coincident. Riverine input tends to correspond to river discharge, peaking with winter storms and spring snowmelt, while organic matter generated within the estuary is available at different times; eelgrass production enters the estuary in late winter, benthic algae and phytoplankton in mid-summer and emergent marsh in the fall (Figure 6.9; Thom 1987).

The quality of organic matter is fundamentally more important than the quantity of organic contribution to the estuary, implying that the sources of organic matter in the estuarine detritus pool may be more important than the bulk delivery. Terrestrial and marsh detritus tend to be much more refractory, and less efficiently incorporated into the estuarine food web, than phytoplankton and benthic algae. Some food web pathways may be almost immediate, as

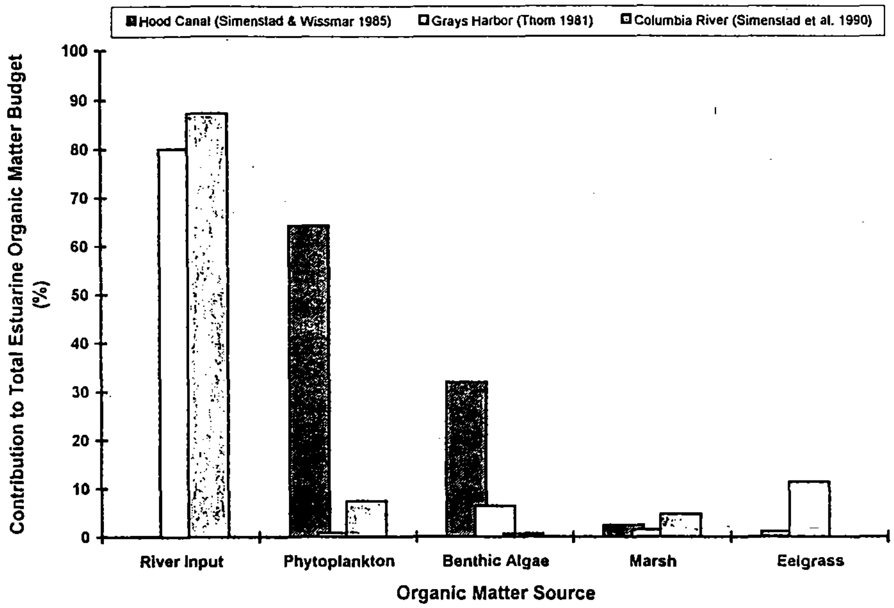


Figure 6.8. Contribution to total estuarine organic matter budget of dominant organic matter sources from watershed and estuary for three Pacific Northwest estuaries.

suggested for the incorporation of estuarine foam into littoral flat consumers (Wissmar and Simenstad 1984).

In comparison to simple accounting for organic matter budgets, a more powerful tool for identifying components of estuarine food web variability is the use of stable natural isotopes, particularly multiple isotopes (e.g., carbon $\delta^{13}C$, nitrogen $\delta^{15}N$, and sulfur $\delta^{34}S$) because significant overlap can occur among isotopic signatures of different organic sources for any one isotope. For instance, differentiating terrestrial inputs from brackish marsh would be impossible without coupling $\delta^{34}S$ with $\delta^{13}C$; addition of $\delta^{15}N$ further distinguishes trophic level shifts. While $\delta^{13}C$ analyses of food web sources and pathways have been used to investigate a variety of estuarine systems (e.g., Hood Canal, Simenstad and Wissmar 1985; Padilla Bay, Puget Sound, Simenstad and Wissmar unpublished; Fraser River estuary, Levings 1994; Willapa Bay and Columbia River estuary, Simenstad unpublished), $\delta^{15}N$ has been used only for Padilla Bay and the Fraser River, and $\delta^{34}S$ for only Willapa Bay and the Columbia River estuary.

As more data from stable isotope studies in these different estuaries emerges, it is becoming apparent that organic matter production and the food web processes supporting juvenile salmon differ among estuaries, often irrespective of seemingly deterministic food web pathways. For instance, the $\delta^{13}C$ signature of epibenthic harpacticoid copepods and amphipods may vary by as much as $11^{0}/_{00}$ (read as "parts per thousand"; $-9^{0}/_{00}$ to $-20^{0}/_{00}$), and signatures for a single species, *Corophium salmonis,* can differ by as much as $5.5^{0}/_{00}$ in adjacent estuaries (Willapa Bay,

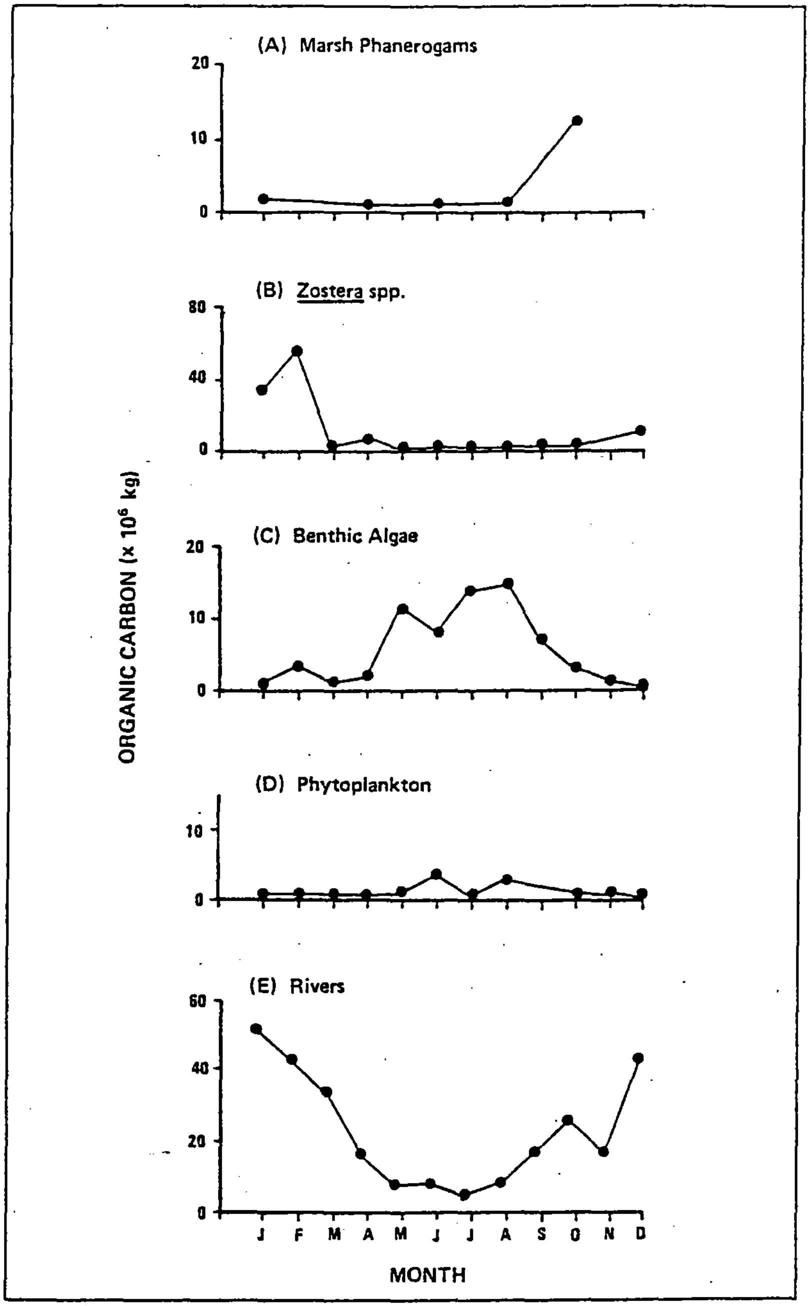


Figure 6.9. Seasonal variation in input of organic matter from primary organic matter sources of Grays Harbor (after Thom 1987).

-18.9$^{0}/_{0}$ $_{0}$ versus Columbia River estuary, -24.4$^{0}/_{0}$ $_{0}$). Spatial variation within the same estuary is also evident, as indicated by a wide range for chinook fry (~-20$^{0}/_{0}$ $_{0}$ to -30$^{0}/_{0}$ $_{0}$) and a narrow range (~-34$^{0}/_{0}$ $_{0}$ to -36$^{0}/_{0}$ $_{0}$) for coho presmolts found in the lower Fraser River (Levings 1994). Similarly, the δ^{13}C signature for the calanoid copepod, *Eurytemora affinis*, in the brackish channels of the Columbia River estuary was -19.8$^{0}/_{0}$ $_{0}$ versus -29.9$^{0}/_{0}$ $_{0}$ from the estuarine turbidity maxima in the euryhaline portion of the same estuary (Simenstad unpublished; where the signature, 7.4$^{0}/_{0}$ $_{0}$, did not differ at all between these samples). These preliminary indicators of food web pathway variability suggest that both differential pulses of organic matter and heterogeneous distributions of living and detrital food sources across estuarine habitats, may account for dramatically different trophic support of secondary consumers such as salmon, especially when salmon localize their rearing and migrations in a specific estuarine region or habitat.

Irrespective of the variation in quantity, quality, and timing of organic matter contributing to the food web, evidence indicates that certain species and life-history stages of juvenile salmon focus their foraging in estuaries on certain types of prey, which in some cases may be an important factor determining estuarine residence time and growth (Wissmar and Simenstad 1990). Results from ongoing studies of juvenile salmon use of estuarine wetlands in Puget Sound and coastal Washington sustain earlier interpretations that certain salmon species and life-history types (e.g., chum, *Oncorhynchus keta*, and sub-yearling chinook, *O. tshawytscha*) prey selectively on specific benthic or epibenthic organisms, such as tubicolous amphipods (*Corophium* spp.) and harpacticoid copepods (*Harpacticus uniremis*, *Tisbe* sp.; C. Simenstad and J. Cordell, University of Washington; K. Fresh, WDFW; and D. Stouder, Ohio Cooperative Fish & Wildlife Unit unpublished). It appears too, that in tidal freshwater and brackish wetlands, juvenile salmon (sub-yearling chinook and coho) concentrate feeding on emergent marsh and riparian insects (e.g., chironomids, aphids; Shreffler et al. 1992; Miller 1993; Miller and Simenstad 1997; G. Hood, Univ. Wash. unpublished).

Earlier workshops on estuarine and coastal carrying capacity for Pacific salmon (e.g., Levings 1984; Levy 1984; Simenstad and Wissmar 1984), have described the issue of estuarine carrying capacity limitations for juvenile salmon as an untested enigma. Few studies have attempted to describe juvenile salmon production, much less survival, relative to temporal and spatial variability in estuarine conditions, and most of these were prior to 1983. The descriptive comparisons of juvenile fall chinook relative abundance and size in eleven Oregon estuaries in 1977-1982 by Herring and Nicholas (1983) remain one of the few comparisons between salmon use and estuary structure. That study examined the distribution of estuary area (at MLLW), from 6,180 hectares (ha) for Coos Bay to 90 ha for the Chetco River estuary (Oregon Division of State Lands 1973; Figure 6.10). They found trends in increasing catch-per-unit-effort (CPUE) and decreasing mean fish size with decreasing estuary area (Figure 6.11), although considerable variability in these trends was also evident. Interannual variation was also apparent within the inverse estuary area-fish length relationship. A density-dependent limitation on fish growth and production, as

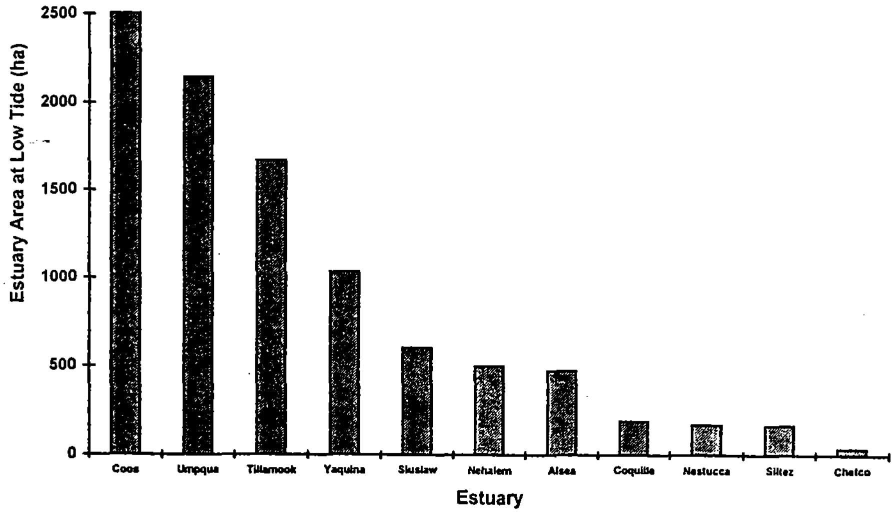


Figure 6.10. Estuarine surface areas (at mean lower low water) for eleven Oregon estuaries (after Herring and Nicholas 1983).

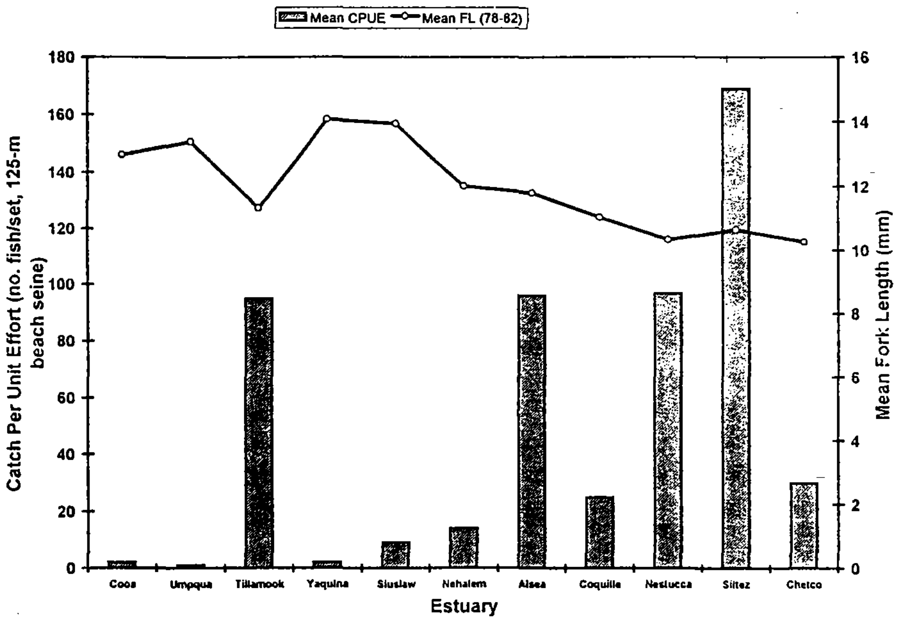
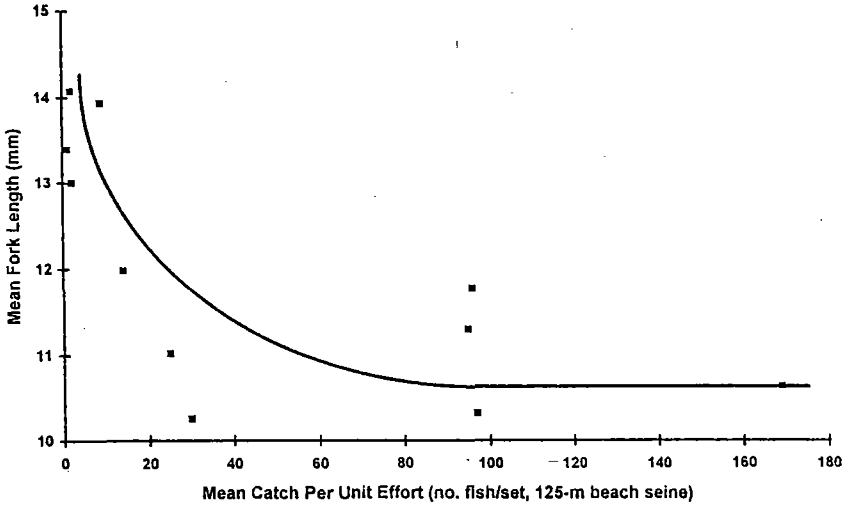


Figure 6.11. Mean catch-per-unit-effort (CPUE) from beach seining and mean size (fork length, FL) of juvenile fall chinook salmon in eleven Oregon estuaries (after Herring and Nicholas 1983).

indicated by fish length (assuming equal emigration and immigration rates), was suggested beyond a CPUE threshold of ~10-20 fish per set (Figure 6.12). This may coincide with observations from sixteen British Columbia estuaries between 1970 and 1982 (Levings 1984), and our own comprehensive estuarine catch data (Simenstad unpublished), that it is rare to find juvenile chinook densities higher than ~1.0 fish m^{-2}. The implications of an estuarine carrying capacity, as modulated by salmon life-history type and timing of estuarine entry, are still sustained principally by Reimers' (1973) seemingly ageless study of the survival of chinook life-history types in the Sixes River estuary, which has yet to be repeated or expanded upon for any other estuaries.

There is also some evidence that the abundance and availability of prey in estuaries may play a large role in determining juvenile salmon life-histories, at least the tactical responses such as migration rate and residence time (e.g., Simenstad et al. 1982; Simenstad and Salo 1982). The population abundance of some prey, like *Corophium* spp. amphipods that appear to be preferred prey, may be extremely variable over space and time, as illustrated for Grays Harbor by Albright and Armstrong (1982; Figure 6.13). In some smaller estuaries, where decreased river flows may concentrate prey and foraging salmon, the scarcity of prey may actually become limiting. Reimers et al. (1979) indicated that the densities of adult *Corophium* spp. declined precipitously after the abundance and density of juvenile fall chinook salmon increased in early July in the Sixes River estuary (Figure 6.14). It is important to remember that Reimers' (1973) data for the 1965 brood

Figure 6.12. Relationship between density of fish, as assessed by mean catch-per-unit-effort and mean size (fork length) of juvenile fall chinook salmon in eleven Oregon estuaries (after Herring and Nicholas 1983).



year indicated that the fish that remained in the estuary under lower densities (of both salmon and *Corophium* spp.) actually had the highest fitness in terms of returning to spawn as adults.

Thus, while the paradigm of detritus-based estuarine food webs may still be generally applicable across salmonid ecosystems, the actual food web processes supporting specific salmonid prey may not be as indicative of broad-based detritus inputs. Factors regulating the production of primary consumers may not necessarily depend on the availability of food resources. While there appear to be certain sequences of benthic/epibenthic prey community structure and production, considerable temporal and spatial variability prevail. Production of key prey species that are distributed across estuarine salinity gradients, such as insects (chironomids in tidal freshwater-brackish reaches of estuaries), amphipods (*Corophium* spp., in brackish-mesohaline), and harpacticoid copepods (*Harpacticus uniremis, Tisbe* sp.; in mesohaline-euryhaline) may not be coincident, and not necessarily linked to processes (natural, or anthropogenically "managed" by salmon hatcheries) that regulate juvenile salmon entry, residence and survival in the estuary. Alternatively, both the physical (e.g., inflow, temperature) and biological (e.g., primary production, predation) factors that affect juvenile salmon and their prey may be "optimal" during the estuarine residence period of the salmon, but may not coincide with the timing of subsequent ocean conditions that are advantageous to juvenile salmon. In fact, diversity of Pacific salmon species populations, and tactical life-history strategies that have declined under historic exploitation and management may offer a clue to the salmon's evolutionary solution to such variability in estuarine conditions.

Ultimately, increased knowledge about the influence of dynamic ecosystems, such as estuaries, on salmon is more likely to elucidate the constraints of salmon management strategies rather than predictable relationships that can be used to "take advantage" of estuaries. As pointed out by

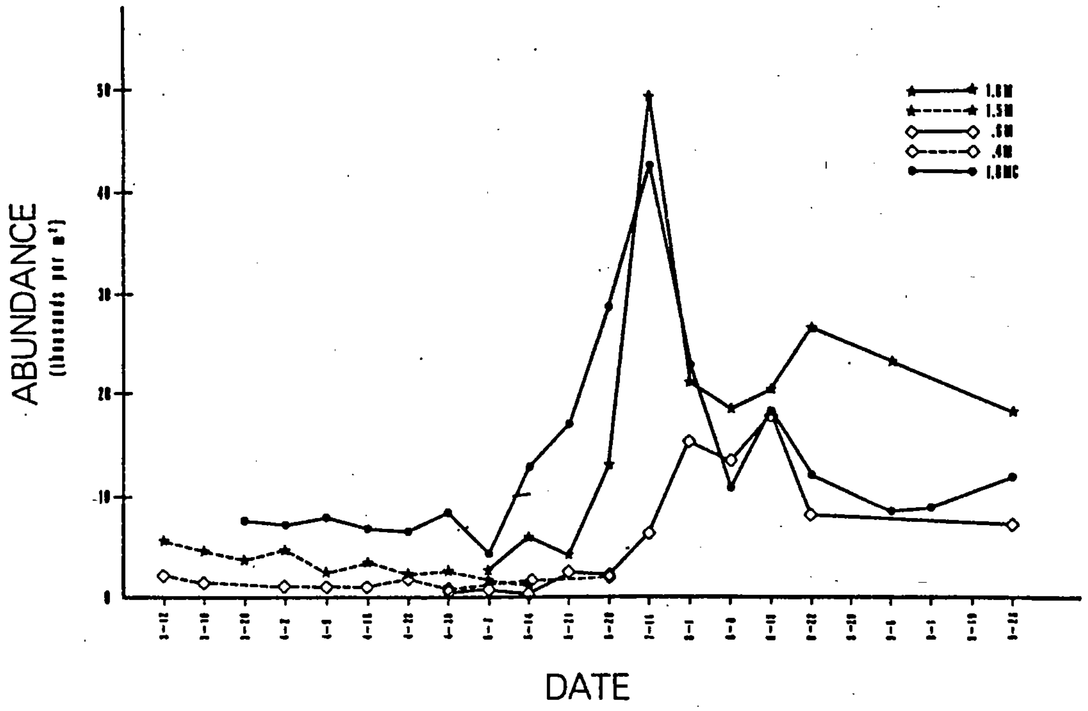


Figure 6.13. Mean population densities of *Corophium* spp. by date for sample stations in Grays Harbor, Washington, 1980 (after Albright and Armstrong 1982).

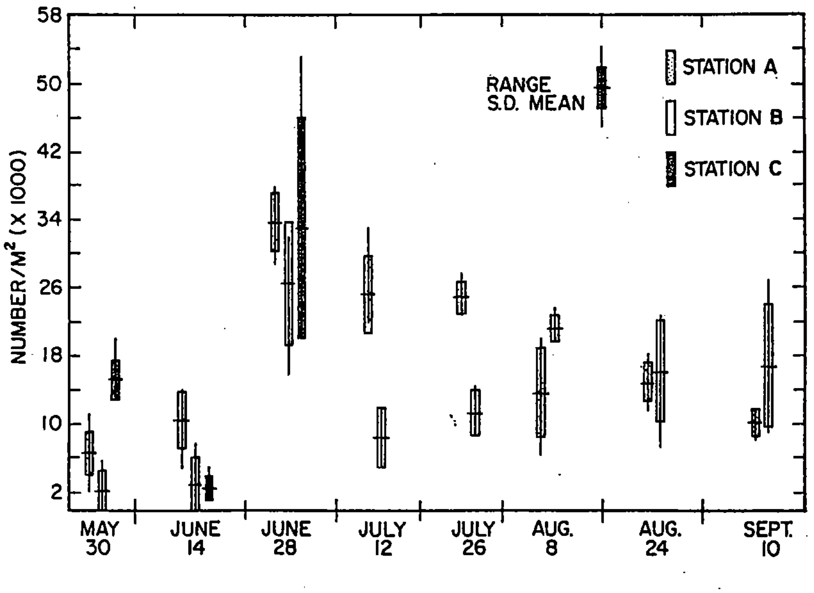


Figure 6.14. Mean number of adult *Corophium* spp. in five replicate samples take at three different locations in the Sixes River estuary, 1979. (Source: Reimers, P.E., J.W. Nicholas, D.L. Bottom, T.W. Downey, K.M. Maciolek, J.D. Rodgers, and B.A. Miller. 1979. Coastal salmon ecology project. Annual Progress Report, Fishery Research Project AFC-76-3, Oregon Department of Fish Wildlife.)

Levings (1984), it may be entirely unrealistic to use production at lower trophic levels as indicators of estuarine production potential for juvenile salmon given the variability in fish "dependence" on specific prey or the spatial distribution of prey.

Understanding the scope of salmon population responses to estuarine variability will require considerably more focused and intense research into questions such as: 1) the links between variation in estuarine organic matter production and consumer population dynamics; 2) whether pulses of salmon prey resources are interlinked with salmon utilization; 3) the relationships between organic matter quality (sources) and consumer (salmon prey) production; 4) the variation in juvenile salmon estuarine entry, residence time, growth and mortality, and relationship to primary and secondary food web pulses; 5) the effects of life-history diversity on estuarine-ocean variability; and, 6) the presence or lack of interdependence between estuarine survival and ocean survival.

Human Actions and the Degradation of Riverine and Estuarine Ecosystems

The high rate of exploitation of anadromous fish resources and expanding human land-use activities throughout the 20th Century has caused many Pacific salmon populations to be depleted in Washington, Oregon and northern California (Nehlsen et al. 1991). Agricultural use, urban growth and timber harvesting in river drainages have displaced or destroyed some of the habitat used by fish populations. In general, the decline in the environmental quality of riverine and estuarine ecosystems in the United States is evident in the dramatic reduction in fish and wildlife population levels and diversity (Benke 1994; Karr 1994), losses of aquatic, riparian and wetland habitats (Simenstad et al. 1992; Wissmar and Beschta in press), and the lack of habitat connectivity within and between ecosystems (Ward and Stanford 1995).

Most riverine and estuarine ecosystems in the Pacific Northwest coastal region have changed significantly over the past 150 years (Maser and Sedell 1994). Rivers have been channelized and cleared of woody debris for flood control and navigation. Floodplain and valley forests have been removed for agricultural and timber harvest. Channelization has isolated river channels and tributary watersheds from floodplains by blocking side channels, and draining backwaters and oxbow lakes. Flood control by levees and revetments has also greatly reduced river interactions with historical floodplains (Gore and Shields 1995; Dahm et al. 1995; Wissmar 1997a). Habitat benefits provided by interactions between riverine and terrestrial ecosystems (e.g., large woody debris that form pool habitats, and lower inputs of detrital food sources) have been lost.

In-stream salmon habitats have been degraded or destroyed by excessive substrate deposition, channel erosion, removal of large woody debris, and lower streamflows. The combined effects of burial of large rocks due to the excessive sediment input, accumulation of finer sediments, and removal of large trees from channels, have greatly reduced the complexity of channels, in some cases eliminated pool and refuge habitats, and altered temperature regimes (Hartman and Scrivner 1990; Sedell et al. 1990; Meehan 1991).

These degraded habitat conditions are confounded by land-use practices (e.g., timber harvest) that have caused snowmelt and peak flows to shift to earlier in the year. The removal of vegetative cover in watersheds can reduce streamflows in the summer, resulting in fish entrapment and high temperatures that lead to high fish mortalities (Hicks et al. 1991). Hydrologic studies of clear-cut forests in western Oregon and Washington show that snowfall accumulations will melt earlier because of increased exposure to solar radiation (Harr 1983; Coffin 1991). The earlier snowmelt and peakflows reduce water storage in surface and subsurface soils during the summer. These water losses lead to lower discharge rates and habitat holding capacities for fish during summer and base flow periods.

An important research question is to determine how these human-induced changes have impacted the different riverine habitats used by salmon. For example, impacts such as sedimentation and low flows can reduce the quality and function of pool and riffle habitats in streams, habitat complexes of channels and riparian zones of large river channels, and the connectivity of channel networks within floodplain river reaches. The loss of connectivity has broad ramifications at both local (within a river drainage) and regional geographic scales (e.g., several coastal river drainages). Reduced connectivity increases fragmentation that alters the diversity of habitats at all landscape scales (Frissell et al. 1993; Gore and Shields 1995). All of these habitat changes can reduce salmon rearing and migration options.

Many of these human-induced changes have occurred at frequencies and magnitudes that transcend natural disturbances (Reice et al. 1990; Wissmar and Swanson 1990). The variety, complexity and high frequency of human-induced modifications could be causing permanent alterations to the connectivity of habitats and ecosystems that have taken millennia to form (e.g., ~1 to 10 thousand years; Benda et al. 1992). If so, interactions between human-induced alterations (termed "press disturbances") and natural disturbance regimes (termed "pulse disturbances") may negate the possibility of future conservation and habitat restoration efforts. The maintenance, protection and improvement of salmon stocks and habitats is a very significant issue with the public, different state and Federal resource managers and the numerous Native American Tribes of the region. Chinook, coho, pink, chum, and sockeye salmon are extensively managed because they are significant sport/commercial, subsistence and cultural species, and because their viability is sensitive to environmental change. A 1991 American Fisheries Society report (Nehlsen et al. 1991) indicates that distinct salmonid stocks could be at risk and could qualify as candidates for federal listing as threatened or endangered species. During the 1990s, most management agencies in the region have emphasized restoring and increasing anadromous fish populations that are at risk of extinction.

Presently, river drainages and estuarine ecosystems of states along the North Pacific coast are at a critical point. These naturally fragile ecosystems, now significantly degraded, are increasingly vulnerable to climatic and other natural disturbance events. For example, clearing of vegetation and construction of roads in geologically unstable areas of the Cascades and Olympic mountain ranges, when combined with storms and flooding events, create high-risk conditions resulting in increased soil instabilities and frequency of landslides. These altered drainage conditions commonly affect landscapes from headwaters to downstream floodplains and estuaries (e.g., Simenstad et al. 1992). Thus, land-uses that maintain ecological, physical and societal functions in one portion of a large drainage may have unanticipated consequences in another, contributing to far greater losses of biological diversity and sustainability.

The effects of land-uses and other human modifications have forced local and federal resource managers to regulate salmon harvest and conduct habitat enhancement and hatchery programs for salmon to insure the viability of these economically, culturally and biologically important species. Numerous fish hatcheries have been built during the past century to mitigate loss and augment the natural production of anadromous and resident fish. For example, the State of Washington operates the largest state hatchery system in the nation. More recent fish enhancement activities include the construction of riverine spawning channels and rearing ponds to mimic natural habitat functions. However, many of these habitat enhancement projects (e.g., connecting abandoned river side-channels to the main river) have had varying levels of success. The lack of a basin-wide or ecosystem perspective in management programs for anadromous fish species most likely retards the recovery of many salmon populations from the cumulative impacts of natural disturbances and human modifications across a multitude of spatial and temporal scales. In summary, many current management practices, as well as the lack of ecosystem-based initiatives, could increase the long-term costs of these resources to the public.

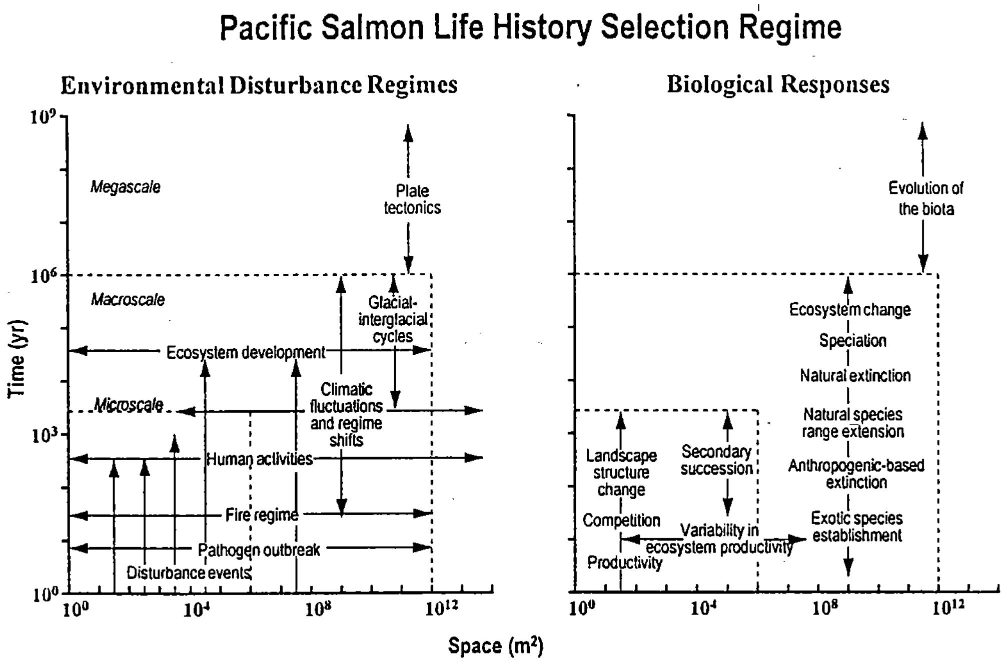
PACIFIC SALMON ADAPTATION, POPULATION RESILIENCE, AND LIFE-HISTORY DIVERSITY

Because of their diverse and often complex anadromous development from egg to adult, Pacific salmon integrate environmental processes and conditions across the breadth of Pacific Northwest coastal ecosystems. The life-histories of Pacific salmon encompass increasing scales of time and space between freshwater spawning and hatching and oceanic rearing. For example, the early life-history stages of Pacific salmon have shorter residence times in freshwater and estuarine habitats than mature stages in the ocean (e.g., chinook can spend two years in freshwater and up to eight years in the ocean; Healey 1991).

An overarching hypothesis that can be addressed by the PNCERS research framework is that different species of Pacific salmon have evolved diverse life-histories (i.e., life-history "types") to take optimal advantage of the environmental variability of the landscapes and seascapes they occupy (see also Chapter 5). The variations in life-history characteristics (e.g., residence time and survival rates) of the different species of Pacific salmon are assumed to be the result of evolution across large oceanic and coastal geographic regions for perhaps several million years (Neave 1958; Smith 1975; Thomas et al. 1986). As a result they have evolved complex life-history patterns that sustain viable populations over a broad spectrum of ecosystem change at varying temporal and spatial scales (see Fig. 6.23).

The hypothesis can be expanded to include evolutionary responses by fish to variations in past environmental conditions at a variety of temporal and spatial scales. Specifically, Pacific salmon populations are hypothesized to have adapted to low frequency, large magnitude events and large spatial scale changes, and that, as a result, different salmon populations have either been destroyed or have survived and adapted to past climatic fluctuations and other natural disturbances (Figure 6.15).

In addition, salmon appear to possess phenotypic traits (e.g., physiological and behavioral adaptations) that enable them to respond as individuals to rapidly changing conditions. For


Pacific Salmon Life History Selection Regime

Environmental Disturbance Regimes

Biological Responses

Figure 6.15. Environmental disturbance regimes and biological responses affecting the selection of Pacific salmon life-histories (modified from Delcourt et al. 1983).

example, while natural selection promotes "optimum traits", a certain plasticity of behavior enables the fish to survive and return to spawn. These characteristics do not occur in only one particular stage in the salmons' life-histories, but in all stages across the continuum of habitats within riverine, estuarine and ocean ecosystems.

It follows that present day extinctions of some salmon populations may be attributable to short-term temporal and spatial variations in environmental conditions that are outside the historical ranges of conditions in response to which salmon have adapted. Furthermore, because environmental conditions are not optimum, fish with "suboptimal traits" may be contributing to population persistence by becoming the "only" survivors in the face of numerous and more frequent stressful conditions, and could be adapting to conditions outside the historical range of environmental conditions. Concurrently, the few remaining fish with optimum traits may becoming less able to survive.

Salmon Populations of the Pacific Northwest Coast

Salmon populations have historically inhabited most river systems within the geographic areas of the British Columbia, Washington, Oregon and California coasts. River drainages originating in the coastal and Cascades mountain ranges are highly significant to the early life-history stages of salmon that ultimately use Puget Sound, the Strait of Georgia, or migrate directly into ocean waters. Almost all the drainages of the region provide spawning and rearing habitats as well as a source of high water quality for downstream fishery resource areas. Production of anadromous and resident fish within river drainages include fish that spawn naturally, as well as hatchery fry that are out-planted to suitable areas to imprint and rear. Within several drainages (e.g., Skagit and Hoh Rivers) exist some of the last remaining miles of "natural" anadromous fish habitat capable of producing and sustaining wild populations of chinook, coho, pink, and chum. Such natural habitats are in short supply in many river drainages of the Cascade Mountains and even sparser along the West Coast.

Principal salmon-supporting river systems in southern British Columbia include the Fraser River, a major source of freshwater input to the Strait of Georgia and nearshore ocean, as well as streams draining Vancouver Island. In Washington, there are a number of principal river systems with headwaters in the northern Cascade Mountains that drain into Puget Sound, including the Nooksack, Skagit, Stillaguamish, Snohomish, Green, Puyallup-White, and Nisqually Rivers. Two other systems draining into Puget Sound are the Elwha and Skokomish. Streams that discharge to the "outer coast" of Washington include the Hoh, Queets, and Quinault Rivers on the Olympic coast; the Chehalis River of Grays Harbor; the Willapa and Naselle Rivers of Willapa Bay; and the Cowlitz River, which drains into the lower Columbia River. Each of these river drainages supports populations of more than two species of salmon.

The Columbia River is the largest river system in the Pacific Northwest, draining some 671,000 square kilometers. It has historically supported vast numbers of Pacific salmon, including chinook, coho, sockeye and chum, in five US states and British Columbia. Estimates of predevelopment annual salmon runs on the Columbia have ranged from 7.5 to 16 million (National Research Council 1995).

The Oregon coast has a large number of coastal river systems that have supported one or more salmon species. Two of these systems, the Umpqua and Rogue, drain from the Cascade Mountains and interior of the Klamath Mountains, respectively. The remaining Oregon coastal rivers are relatively small in size, and have headwaters in the Coast Range mountains. Of these latter systems, the largest is the Coquille River system. Others include the Nehalem, Nestucca, Trask and Wilson, all of which drain to Tillamook Bay, and the Salmon, Siletz, Yaquina, Alsea, Siuslaw, Coos, Elk, Sixes, Pistol and Chetco. Still other smaller steams such as Big Creek and Floras Creek have also been significant salmon supporting streams.

In northern California, the principal systems north of Cape Mendocino include the Smith and Klamath Rivers, that also drain parts of interior Oregon, and the Eel and Trinity Rivers. Other major salmon supporting streams draining central California discharge into San Francisco Bay, south of Cape Mendocino and the PNCERS area of interest.

Five species of Pacific salmon have historically occupied these coastal steam systems: pink, chum, coho, chinook and sockeye. Other important anadromous salmonid species include the sea-run cutthroat trout and steelhead. Some river systems, such as the Skagit River in northern Washington, contain populations of all five species. Other systems have supported three or four species, but most have two, coho and chinook. Within each species within each river system are a number of "runs" of fish (e.g., tule spring chinook) subpopulations that have adapted to and exploited the habitat diversity and opportunities presented by each stream network.

Diversity of Pacific Salmon Life-histories

The diversity of salmon life-histories can be more readily understood by characterizing the continuum of their life cycles as at least eight life-history "stanzas" along the succession of habitats within riverine, estuarine and ocean ecosystems. These eight stanzas are: 1) *emergence* which entails the processes of post-spawning egg development through to the emigration of alevin salmon out of the gravel; 2) *freshwater residence* which involves prolonged occupation of a freshwater environment, although it is not necessarily restricted to the vicinity of the spawning habitat; 3) *downstream migration* which is defined as directed movement toward the estuary and ocean; 4) *freshwater-estuary transition* which involves the period when salmon must undergo osmoregulatory, behavioral and other changes across the initial estuarine gradient, from tidal freshwater to brackish salinity 5) *estuarine residence* which includes the period during which the juvenile salmon move across the entire estuarine gradient, irrespective of the type of estuary; 6) *estuary-ocean transition* which is the stage at which the juvenile salmon move from the relative protection of estuarine waters to nearshore-shallow coastal ocean environments and open ocean waters; 7) *ocean residence* which includes that period of maturation in the North Pacific, including the Gulf of Alaska and Bering Sea; and 8) *return migration to spawn* which takes the fish from the ocean through the estuary and back to the natal stream, the location of the first stanza.

Within each of these stanzas, there is considerable potential for variability among different stocks and diverse life-history traits (genetic and phenotypic; Table 6.2). The potential diversity in alternative life-history pathways of Pacific salmon is very evident during development in fresh water and migration to ocean (Figures 6.16 to 6.22 adapted from Simenstad and Fresh, in preparation; and comprehensive species syntheses in Groot and Margolis 1991). These potential pathways are not all represented by any individual stock, but rather are an aggregate of potential expressions of alternatives available to each species across all life-history stanzas. For example, alternative pathways from emergence could represent two different stocks with different spawning times, rather than different life-histories from the same genetic pool of fish. In some cases, however, differential "tactical" (Healey 1991) responses to environmental conditions may result in alternative pathways from the same genetic stock (e.g., see the example for chinook, Figs. 6.21 and 6.22).

Table 6.2. Life-history traits of pacific salmon that are genetically and environmentally determined.

Emergence	Freshwater Residence	Downstrean Migration	Freshwater-Estuary Transition	Estuarine Residence	Estuary-Ocean Transition	Ocean Residence	Return Migration to Spawning
				Genetic			
*temperature-dependent development rate of eggs & alevins * threshold response to environmental cue(s) * size & robustness of fry	* depth & other habitat distributions * territorial behavior	* rate & time of active migration * robustness	* smoltification schedule & tolerance	* size-specific depth & habitat distribution * size- & age-specific growth rate	* rate & time of active migration * depth & habitat distribution	* ocean distribution & migration route * size- & age-specific growth rate	* size at ocean maturity * return & spawning timing * sex-specific size at spawning * fecundity * egg size
				Environmental			
* emergence cues * intragravel water temperature & quality (dissolved oxygen) * intragravel prey availability?	* freshwater flow * water temperature & turbidity * prey production & availability	* freshwater flow * water temperature & turbidity	* fresh-water flow * water temperature & turbidity	* current speeds and patterns * prey production and availability	* current speeds & patterns * freshwater flow * prey production & availability	* current speeds & patterns (ocean regime state) * prey production & availability	* current speeds & patterns (ocean regime state) * freshwater flow * water temperature & turbidity

PINK SALMON

Pink salmon (Figure 6.16) have the most simple or specialized life-history, with little variability except perhaps at the stage of transition from the estuary to the ocean, which can be protracted for some stocks. The most genetically-fixed and evolutionarily interesting aspect of pink salmon is their unvarying two year (18-month) maturity schedule, which results in extremely dominant and genetically separate year classes, that is, strong runs in either odd years (Washington and southern British Columbia) or even years (most of Alaska and northern British Columbia) but negligible or no returns in the opposite years.

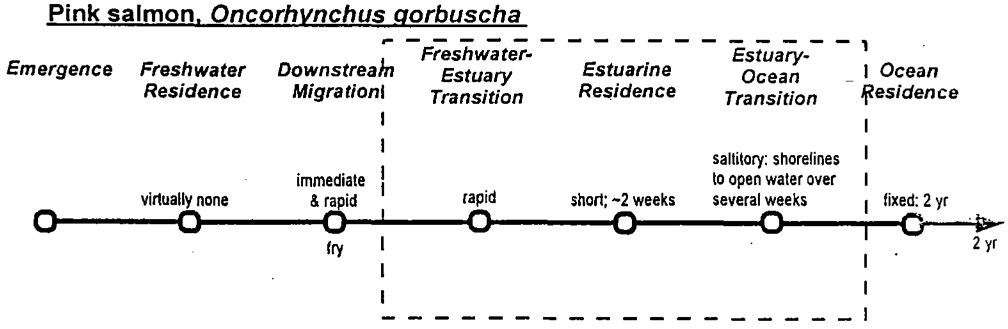


Figure 6.16. Life-history pathways of pink salmon (from Simenstad and Fresh in prep.).

CHUM SALMON

Chum salmon (Figure 6.17) display the second most simple set of life-history pathways between the freshwater and estuarine stanzas, but their ocean residence can range between one and five years, resulting in ten potential alternative life-history pathways. The dominant pathway involves rapid downstream movement after emergence to estuaries and moderately rapid passage through estuaries to the ocean, although some stocks illustrate slower migrations downstream with the initiation of in-stream feeding (Salo 1991). Chum salmon often have multiple, genetically-distinct populations in one watershed, especially in regions of Puget Sound and Hood Canal, Washington, where sometimes as many as three discrete and morphologically different (Koski 1975) spawning populations occur in the same river system between late summer (September) and mid-winter (as late as March). The consequence of discrete genetic populations passing from fresh water to the ocean at different times of the year, along with the potential for different tactical responses to varying environmental conditions, may ultimately be reflected in variations in the length of ocean residence. For instance, recently emerged juveniles of early and late spawning chum from Big Beef Creek, Hood Canal, Washington, move rapidly into Hood Canal at different times of the late winter and spring, may reside for shorter or longer periods in the estuary, respectively, and rear in

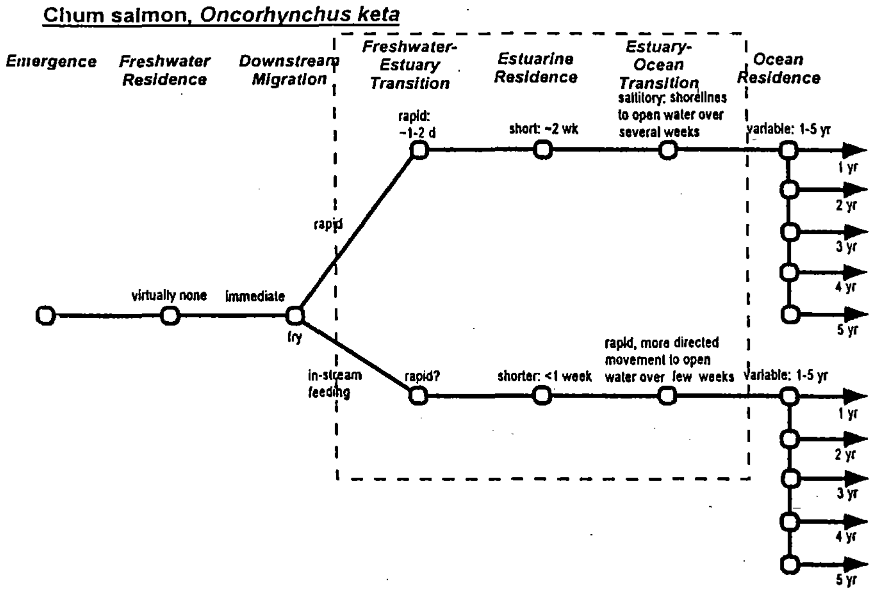


Figure 6.17. Life-history pathways of chum salmon (from Simenstad and Fresh in prep.).

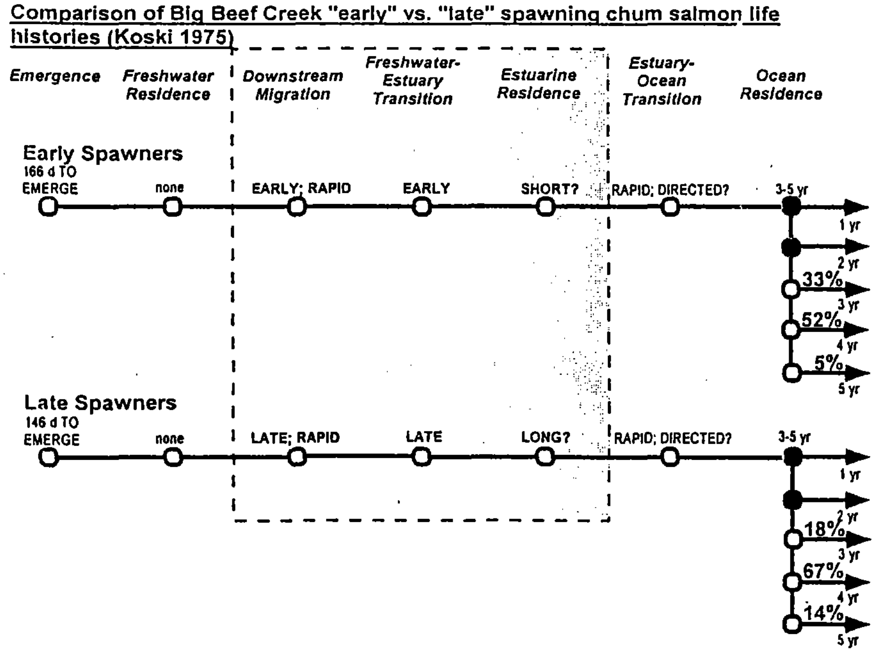


Figure 6.18. Comparison of Big Beef Creek "early" vs. "late" spawning chum salmon life-histories (based on Koski 1975).

the ocean for significantly different periods (e.g., 57% as 4-5 year ocean fish compared to 81% 4-5 year fish, respectively; Figure 6.18; Koski 1975). Similar life-histories of different species may impose a higher potential for interspecific interactions among the different salmon species. Chum salmon in Washington and southern British Columbia tend to have stronger year classes and different age structures during even years when they do not co-occur extensively with pink salmon in estuarine and coastal waters, suggesting competitive interactions occur between the two species in odd years (Gallagher 1979; Smoker 1984).

COHO SALMON

Coho salmon (Figure 6.19) present additional life-history complexity, with up to four years of freshwater residence, displaying a potential of eleven alternative life-history pathways. With extensive freshwater rearing, and seaward migration as large smolts, the estuarine residence of juvenile coho tends to be very brief. However, the estuary-ocean transition may be more prolonged. Some coho never leave proximal coastal waters, returning to spawn as small, immature "jacks" after less than one year. There is also an "ocean-type" of coho that demonstrates essentially no freshwater residence; these fish migrate as fry to tidal freshwater and brackish regions of estuaries where they are presumed to rear for extensive periods and are especially prominent in tidal sloughs, such as the estuarine-influenced floodplain of the Chehalis River (Simenstad et al. 1992, 1993; Miller 1993). Pritchard (1940) conducted a comprehensive analysis of British Columbia coho age structures (e.g., 0.3, where the first numeral represents freshwater age and the second numeral the ocean age in years), and found that only the 1.1 age class (i.e., one year freshwater and one year ocean residence) tends to dominate the composition of most returning adult populations.

SOCKEYE SALMON

Sockeye salmon (Figure 6.20) are unique in utilizing lakes for freshwater rearing. They are comparable to coho in that nine of the potential ten life-history pathways include varying permutations of freshwater and ocean residence years, with very rapid movement from freshwater to the ocean and essentially no estuarine residence. One sockeye life-history, however, includes relatively rapid immigration to estuaries from fresh water and extensive estuarine rearing, a pathway that is common though not necessarily prominent in the Fraser (Sandercock 1991) and Stikine Rivers (Wood et al. 1988). Levy and Northcote (1981) document sockeye rearing with pink, chum, and chinook fry in Fraser River marshes.

CHINOOK SALMON

Chinook salmon (Figures 6.21 and 6.22) have the most complex suite of diverse life-history types among the salmon (Healey 1991), including 13 potential life-history pathways under the "stream-type" chinook (Fig. 6.21) that rear extensively in fresh water, and another 35 permutations of life-history pathways could be theoretically feasible for "ocean-type" chinook (Fig. 6.22). Stream-

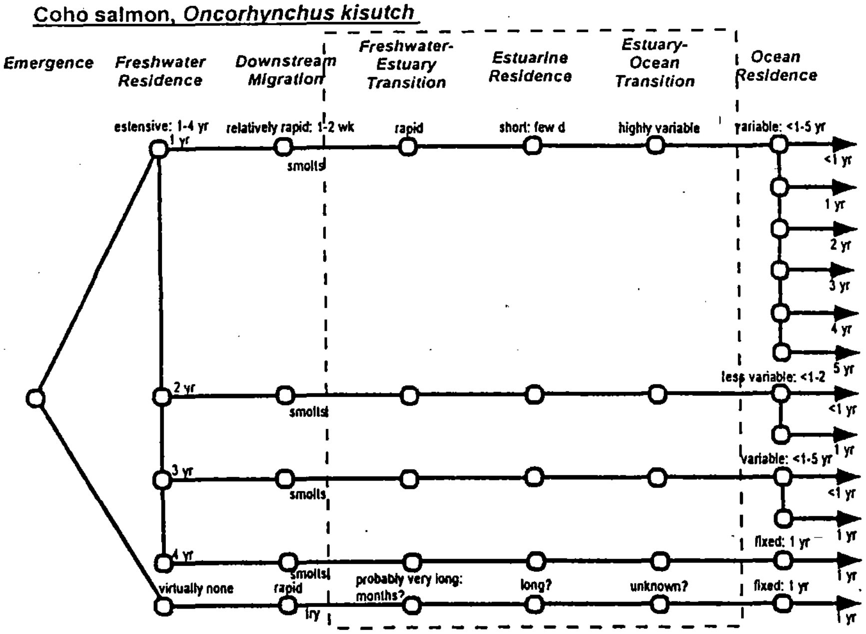


Figure 6.19. Life-history pathways of coho salmon (from Simenstad and Fresh in prep.).

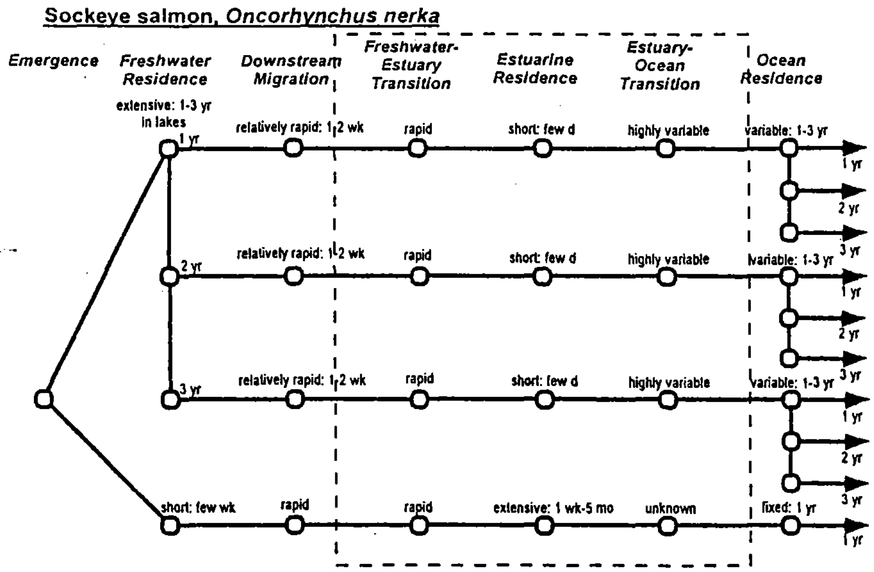


Figure 6.20. Life-history pathways of sockeye salmon (from Simenstad and Fresh in prep.).

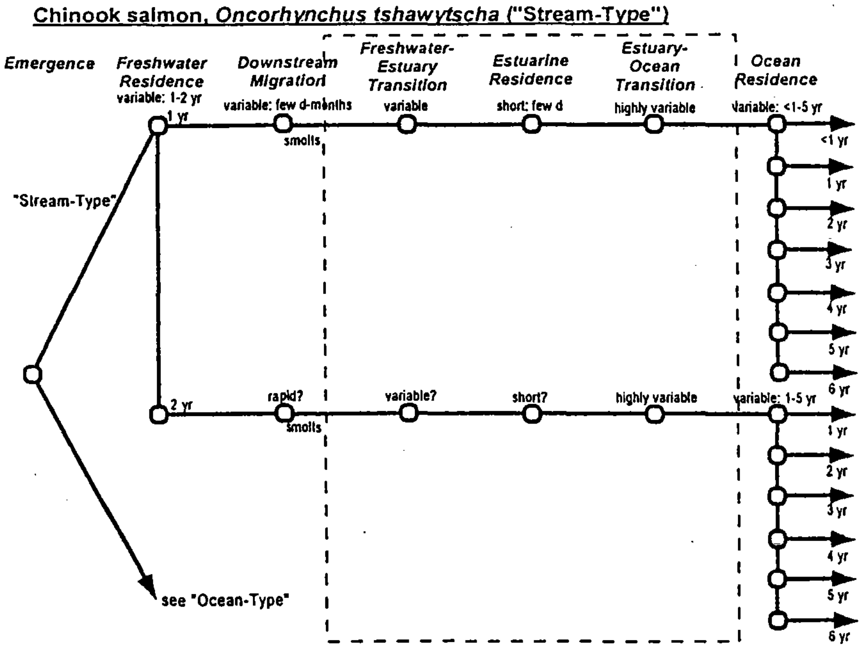


Figure 6.21. Life-history pathways of stream-type chinook salmon (from Simenstad and Fresh in prep.).

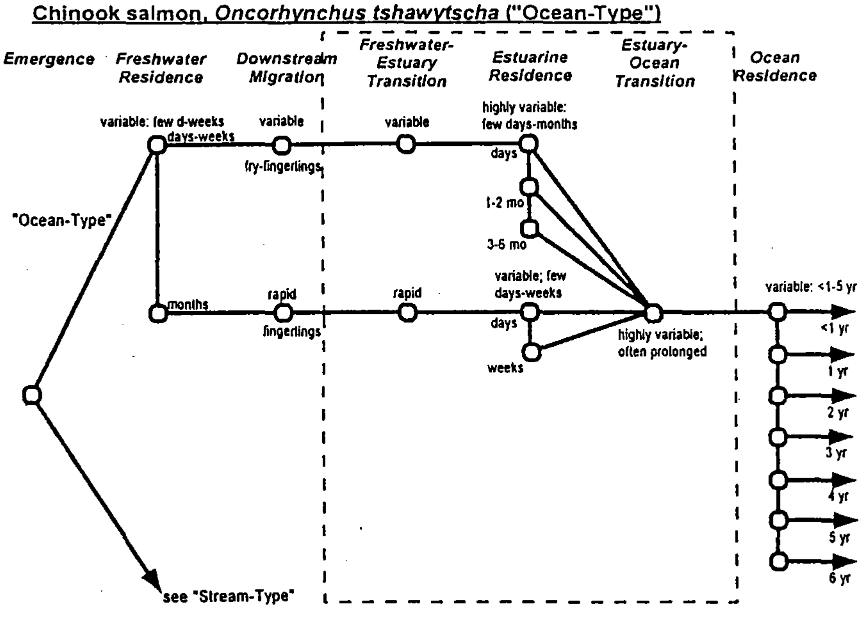


Figure 6.22. Life-history pathways of ocean-type chinook salmon (from Simenstad and Fresh in prep.).

type chinook occupy fresh water for only one or two years, but may reside in the ocean for up to six years before returning to spawn; their use of estuarine rearing habitats is generally minimal although some stocks may remain nearshore during a short ocean residence (Healey 1991). Ocean-type chinook are quite the opposite; their freshwater residence is generally brief, only as much as a few months, but their estuarine residence may be exceedingly long and variable, followed by similarly diverse ocean residence up to six years. Estuarine residence appears to be a function of the time when juveniles enter the estuary as well as estuarine conditions. The various freshwater and estuarine pathways do not seem necessarily associated with particular ocean residence periods. For instance, Reimers (1973) identified five life-history types of fall chinook passing through the Sixes River estuary, Oregon. Only one type (type 3: freshwater rearing, early summer, extensive rearing in the estuary, and ocean entry in autumn) contributed significantly (average 90.6%) to the adult spawners returning from one brood year (1965). However, the fish returned equally as two-, three-, four- and five-year ocean fish.

Salmon Genetic Diversity and Geographic Scales

Chum salmon provide an excellent example of the genetic diversity of stocks of different species of Pacific salmon (Phelps et al. 1994). A strong homing instinct, like that of all Pacific salmon, combined with the diverse geography of the region, offers the potential for a large variation of genetic structuring in chum salmon populations. These variations are expressed in such phenotypic traits as age and size at maturity, run and spawning timing, fecundity, and egg size (Beacham and Murray 1987). Chum salmon spawn in summer, fall, and winter, a temporal separation among stocks (even in the same watershed) that contributes to isolation among breeding populations and, hence, the maintenance of distinct genetic stocks. Breeding isolation also occurs simply as a result of geographic separation throughout the Pacific Northwest coast in river drainages that vary substantially in size and in drainage densities (e.g., stream miles).

Genetic diversity among and within populations in the Pacific Northwest Coastal region has been characterized using electrophoresis (Phelps et al. 1994). This technique showed that significant differences in heterogeneity occur among geographically clustered populations as well as among stocks with different run timing (Phelps et al. 1994). For instance, summer-run Hood Canal and Strait of Juan de Fuca chum stocks, which have decreased to critical levels in recent years, perhaps from loss of gene flow or from environmental influences, are distantly isolated from all other the Pacific Northwest Coastal stocks. This genetic analysis also shows that fall-run stocks in the Strait of Juan de Fuca and coastal Washington and Oregon are more similar to west coast Vancouver Island and Strait of Georgia fall-run stocks, than those in Puget Sound (Phelps et al. 1994). Stocks within larger river systems are often genetically distinct from one another. Stocks that were atypical of their location and run-timing were often influenced by hatchery production and/or stock transfers, many from Hood Canal in Washington.

LOCAL GEOGRAPHIC SCALES

The distinct variations in genetic diversity, as well as life-history characteristics as shown by Phelps et al. (1994) for chum salmon, suggest that different local breeding populations of salmon species could vary in their susceptibility to anthropogenic modifications that affect only a particular locale. At the local scale, the local breeding populations (demes) appear to be the primary demographic and genetic units that operate on relatively short evolutionary scales. The partial isolation of local breeding populations allows the evolution of adaptations to local environmental conditions (Allendorf 1983). For example, the Skagit River, a very large north Puget Sound river system, has multiple demes of chum, coho, and chinook salmon that display unique run timing characteristics in discrete geographic regions of the river drainage. The rate of genetic exchange among these demes likely is low, but the overall genetic composition of the entire group and its set of unique traits makes the Skagit River system an indispensible source of genetic variation. Disruption of the evolutionary responses of salmon populations at local scales by anthropogenic actions could alter the diversity of life-history patterns which tend to develop and be expressed under different natural conditions (e.g., hydrologic, climatic, habitat, and physiographic). Similarly, anthropogenic modifications could alter how populations are structured at regional geographic scales.

REGIONAL GEOGRAPHIC SCALES

The findings of Phelps et al. (1994) and others (National Research Council 1995) suggest that the potential exchange of genetic material between salmon populations at regional geographic scales could play an important role in the differences in vulnerabilities of fish stocks to anthropogenic modifications. The concept of "metapopulation" suggests that the infrequent exchange of individuals among stocks in different parts of a stream network or between entire stream systems (e.g., straying of spawning fish) ensures that all the characteristics within the metapopulation are available to each local population (Allendorf 1983). Such a hierarchy of levels of genetic diversity over a large area could provide a basis for maintaining diversity in salmon gene pools and population structure on evolutionary time scales longer than several generations (Riddell 1993).

Disruption of the processes of salmon metapopulations from human actions could cause a loss in the balance between local adaptation and the evolutionary advantages that result from the exchange of genetic information among local populations. Such disruption can alter and possibly reduce the geographical distribution of discrete spawning populations that are adapted to particular environmental conditions. Such changes could reduce the diversity of life-history patterns needed to sustain salmon productivity at both the local and regional geographic scales.

Case Study: Chum Salmon Life-History Diversity

The life-history variations of chum salmon offer a useful case study in highlighting some of the differences in life-history patterns of salmon stocks, and related problems with managing and conserving stocks. The chum salmon is a biologically diverse species that ranges from northern

California to Alaska, the Northwest Territories of Canada, and along the northern rim of the Pacific Ocean to Asia (Salo 1991). Chum salmon of the Pacific coastal region of Oregon, Washington, and British Columbia occur in physiographically different rivers and stream environments, from large river drainages, such as the Fraser, to small streams, such as Big Beef Creek, Washington. This species can use a wide variety of habitats because the fry migrate directly to salt water after emerging from the gravel. Thus, like pink salmon, their marine dependence is greater than their freshwater dependence relative to other species. However, unlike pink salmon, which have a fixed age at maturity (2 years), chum salmon age at maturity varies from 3 to 7 years.

Chum salmon stocks in the Pacific Northwest coastal region spawn over three distinct time periods; summer, fall, and winter. Summer and fall or winter populations often are found in the same river system (Beacham and Murray 1987; Salo 1991), although the use of different spawning areas and morphological differences among these breeding populations is common. In British Columbia, Beacham and Murray (1987) found that summer-run stocks tended to have a larger body size, older age at maturity, and higher fecundity than fall-run stocks. Larger, older summer-run chum spawned in mainstem channels with deeper, faster water, while smaller, younger chum salmon spawned in tributaries with slower, shallower water. Where spawn timing is not distinct within a river drainage, salmon stock segregation may nevertheless occur in larger geographically diverse river systems (e.g., Skagit River, Washington), than in small coastal or island rivers.

Some of the problems associated with management of chum stocks can be demonstrated by reviewing the status of anadromous fish and select chum salmon stocks within western Washington. Review of the status of *summer, fall, late fall, and winter* stocks (WDF 1993) indicates *summer* stocks are in poor condition. One *summer* stock in southern Puget Sound (Chamber Creek) is rated extinct (WDF 1993). The WDF (1993) inventory indicates that of the 72 stocks, 48 are healthy (67%), three are depressed (4%), two are critical (3%), 18 are unknown (25%), and one is extinct (1%). However, inclusion of the extinct Washougal *fall* stock of the Lower Columbia (Nehlsen et al. 1991), results in an extinction rate of 3%.

Because the WDF (1993) inventory did not identify past extinctions, no adequate estimate exists of the historical and present effectiveness of stock management practices. The *extinct* rating is based on escapement and other management data bases and applies to a stock exterminated within its native range. The one stock rated as *extinct*, the Chambers Creek Summer-run chum (South Puget Sound), has been absent since the early 1980s. This extinction is of interest because the other viable seven summer stocks (three in South Puget Sound, two in Hood canal, and two in the Strait of Juan de Fuca) were either rated as *depressed* or *critical*. This report (WDF 1993) indicates that considerable research and management should focus on defining management practices, environmental and genetic factors influencing the survival of chum and other stocks of salmon along the Pacific coast.

The review of the *variability of climate and hydrology* (Figs. 6.1 and 6.2; Table 6.1) and chum salmon stocks (WDF 1993) suggests that variations in flow conditions could be important factors influencing the health of several stocks (Table 6.3). Prolonged low-flow periods combined with the cumulative effects of flow regulation, flood control levees, and channelization of rivers and estuaries (Dahm et al. 1995; Gore and Shields 1995; Ward and Stanford 1995) undoubtedly causes considerable loss of habitat complexity and capacity in numerous river drainages. An analysis of low flow periods (seven-day minimum flow) of various river drainages and freshwater life-history traits of different chum salmon stocks suggests the possibility of high risk periods for different stocks (Table 6.3).

A review of chum stocks (WDF 1993) indicates the presence of four stocks (summer, fall, late fall and winter) within several river drainages of Puget Sound and the Strait of Juan de Fuca (Table 6.3). These stocks occur in four geographical regions: North Puget Sound, South Puget Sound, Hood Canal, and the Strait of Juan de Fuca. The potential for the co-occurrence of chum salmon timing of river entry and spawning with the most frequent low-flow periods appears highest for summer stocks (Table 6.3). These patterns suggest that past extinctions and the present and future health of these summer stocks may relate to the loss of habitat areas during low flow periods.

In summary, the differences in Pacific salmon homing instincts, run timing and use of spawning habitats have led to the formation of the stock concept (Simon and Larkin 1972). Genetic differences among stocks are related not only to distance, but appear to have specific differences that display a hierarchical structure. This hierarchical structure suggests influences of past colonization by fish, the geographic dispersion of fish, and length of time that populations have been isolated. Research is needed to better understand these patterns of genetic diversity as well as stock origins and other important factors like phylogenetic characteristics. Future research could improve the effectiveness of the stock concept (Hanski and Gilpin 1991; Riddell 1993; Utter and Ryman 1993; National Research Council 1995) and perhaps provide new paradigms for managing and conserving salmon populations.

Historical Salmon Management and Ecosystems

The history of fisheries science provides few perspectives for managing salmon at the ecosystem level. Historically, salmon management has been based on a concept of fixed and stable "carrying capacity" of fish populations, a view that still permeates contemporary fisheries management in the principles associated with the concept of maximum sustainable yield (MSY). MSY models commonly determine the amount of "excess" harvestable fish that can be harvested and are based on statistical relationships between the abundance of spawning fish and the number of progeny that in turn, return to spawn in return (Ricker 1948). This interpretation, which is based on the logistic growth curve, suggests that populations developing under constant food and environmental conditions can provide a constant harvestable surplus of fish. The historical applications of these management paradigms are now viewed as contrary to the dynamic ecosystem processes that regulate the production of anadromous fishes (Barber 1988; Botkin 1990; Bottom 1997). Latter modifications such as "optimum sustained yield" (OSY, or the ability of the population and environment to sustain maximum productivity), remain technically flawed because of assumptions that continue to follow the logistic growth curve and fixed carrying capacity (Botkin 1990). For example, management actions that continue to maintain and enhance

Table 6.3. Monthly co-occurrence of river entry (--->) and spawning (***) times of four stocks of chum salmon adult salmon with the most frequent low flow periods (●●●).

STOCK	Region	A	S	O	N	D	J	F	M
SUMMER									
Snow Cr.	St. Juan De Fuca		------------->						
			**********						
				(●●●●●●)					
Union R.	Hood Canal	---------->							
			*********						
		(●●●●●●)		(●●●●●●)					
Chambers Cr.	S. Puget Sound			------------>					
				*********					
			(●●●●●●)						
FALL									
Nooksack R.	N. Puget Sound				--------------------->				
						***************			
				(●●●●●●)					
Skagit R.	N. Puget Sound			---------------------->					
					***********				
				(●●●●●●●●●●●●)					
Big Beef Cr.	Hood Canal				---------->				
					*******				
		(●●●●●●)		(●●●●●●)					
Humptulips R.	Grays Harbor			------------>					
					*******				
				(●●●●●●)					
LATE FALL									
Skokomish R.	Hood Canal				----------->				
						*************			
				(●●●●●●)					
Hamma Hamma R.	Hood Canal					------------------>			
						**************			
				(●●●●●●)					
Big Beef Cr.	Hood Canal					-------->			
						*******			
		(●●●●●●)		(●●●●●●)					
WINTER									
Nisqually R.	S. Puget Sound						---------------------->		
								************	
			(●●●●●●)						
Chambers Cr.	S. Puget Sound						----------------->		
							*************		
			(●●●●●●)						

population levels in changing environments (e.g., setting harvesting goals, hatchery supplementation, and manipulation of critical habitats) could actually be reducing the resiliency of many fish populations.

The inherent limitation in the MSY and OSY management approach is the assumption that the sole source of salmon variability can be accounted for by the maximum ratio of recruits per spawner, where excess pairs of spawning fish are surplus. This approach implies that management of the freshwater portion of the life cycle (e.g., hatcheries), from spawning-to-egg-to-alevin stages, could maintain and increase potential yield. The lack of significant increases, and the occurrence of declines in salmon runs in rivers under heavy hatchery production, has proven the error of this implication (Bottom 1997). Since salmon hatcheries were embraced at the turn of the century, these management concepts have stimulated numerous efforts to maximize salmon production (e.g., fishways, passage facilities, spawning channels, and barging), and have sustained the inherent belief, to this day, in the idea that a single life-history "bottleneck" regulates salmon carrying capacity throughout their life cycle. Simenstad (1997) suggests that given the naturally complex and ecosystem-specific life-histories of Pacific salmon, the populations are most likely limited by multiple so-called "bottlenecks".

Contrary to the long-term time frames and wide spatial scales involved in the development of the evolutionary fitness of salmon, management of salmon occurs on short time frames (weeks to a few years) and small spatial scales (small streams, river reaches, river drainages) as shown in Figure 6.23. Other than a few long-term research endeavors (Hall et al. 1987; Hartman and Scrivener 1990), minimal information is available for evaluating salmon responses to environmental variability at the scales encompassing the entire salmon life-history.

In summary, if the variability of the whole system is less than the sum of the variability of the parts (Weiss 1969; O'Neill et al. 1986), management of resources at the ecosystem scale requires empirical knowledge of the behavior of the system as a whole (e.g., sediment budgets of river drainages), rather than of individual components. Ecosystem management also requires managing man's activities at the appropriate scales.

A PERSPECTIVE ON FUTURE RESEARCH

Research on the Variability of Riverine and Estuarine Ecosystems

Research is needed to better understand the range of variability of riverine and estuarine ecosystems as well as the scales of their physical and biological processes. Such perspectives are especially important to ecosystem managers who desire to restore and sustain Pacific salmon populations, habitats, and the connectivity of rivers, estuaries, and oceanic waters (Wissmar and Beschta in press).

Research should consider and evaluate procedures like the "Hydrogeomorphic Approach to the Functional Assessment of Wetlands" or HGM approach (Brinson et al. 1995; Brinson and Rheinhardt 1996). This approach, which was developed for riparian and wetland systems,

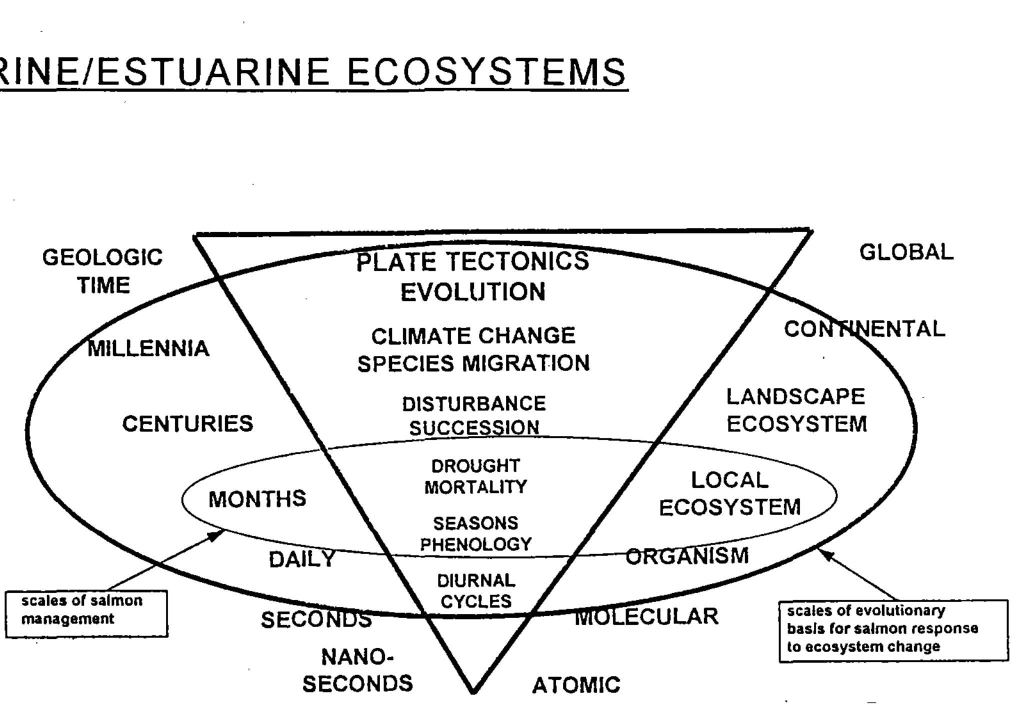


Figure 6.23. Temporal (left) and spatial (right) scales of variation and examples of ecosystem change (inside triangle) that influence the evolution of Pacific salmon and their management.

requires the establishment of reference ecosystems that capture the "natural" range of variation as a basis for describing functions within the systems.

The spatial and temporal scales of various ecosystem structures and functions need investigation. Ecosystems can be viewed as hierarchical in structure (O'Neill et al. 1986). For example, a river drainage contains different sized spatial scales nested within one another (Newbury and Gaboury 1993). This perspective can be expanded to include temporal scales. The largest temporal and spatial scales include the river drainage (10^1 to 10^6 years; km^2) and the smallest, the particle scale (<10 years, <0.10 cm^2; Sear 1994). Riverine and estuarine ecosystem-wide analyses and retrospective studies at different scales will help define functions such as interactions between channel hydraulics, geomorphology, and habitat requirements of fish, riparian and wetland vegetation.

Studies of environmental histories should document the effects of past natural events (e.g., disturbances such as flood and fire) and human actions on ecosystem structures and functions. Research on natural disturbances and ecosystem responses should better define physical processes (e.g., the formation of floodplain terraces) and biological responses (e.g., succession of riparian forests and wetlands habitats) and their interactions. Companion studies of the influences of human modifications should include land and water uses, management practices, and other developments (e.g., agriculture and urbanization; Wissmar et al. 1994).

Studies of the scales of changing ecosystem and habitat conditions and human modifications are needed to gain insights on how to conserve and restore natural resources (Wissmar 1997a). Such knowledge can be useful in developing informed predictions about future conditions, and the ability to make predictions as well as to ask pertinent questions provides a basis for defining objectives of management programs like pollution abatement and habitat restoration. Most importantly, future research needs to define the resilience or the physical and biological capacity and times required for recovery of different ecosystems and fish populations (National Research Council 1992).

Future Research and the Recovery of Salmon Populations

Future research should focus on several key factors that influence the production of Pacific salmon. These factors include: 1) the variability of climate and hydrology; 2) ecosystem productivity and biological integrity; 3) predation; 4) anthropogenic disturbances; and 5) the genetic diversity of local breeding populations and metapopulations. Priority research areas include genetic and ecological evaluations at different geographical scales. Genetic evaluations should consider the conservation of genetic diversity and organization of fish populations (local and metapopulation) at different geographical scales. Considerable attention should also be given to defining the genetic and evolutionary risks of hatcheries.

Ecological research is needed on the linkages between tributary, river and estuarine ecosystem areas that are most ecologically intact and contain the relatively unimpacted habitats (Frissell et al. 1993; Ward and Stanford 1995). Numerous management and research agencies need information for developing strategies for defining and conserving ecosystems and populations of endangered and threatened species (e.g., Federal Endangered Species Act of 1973). Little is known about what ecosystem scales, in terms of size, spacing and function of reserve areas, will benefit the behavior and dispersal of different salmon species. Such information would help explain how Evolutionary Significant Units (ESUs) for salmon operate across large geographical areas in terms of species, populations, and their ecosystems. Important questions include how fish habitats can be maintained and restored across different ecosystems (Lichatowich et al. 1995), and what roles natural disturbances play in the formation of habitats (Benda et al. 1992; Reeves et al. 1995).

Considerable ecological research should be focused on understanding the evolutionary significance of fish metapopulations and the role of metapopulations in defining ESUs and reserve systems (Li et al. 1995; Reeves et al. 1995). Li et al. (1995) have pointed out the difficulty of matching reserve and refuge areas with salmon ESUs. For example, few populations inhabit high quality habitats because many of the areas tend to occur at the extremes of species' ranges. A possible approach for addressing this problem might be to define the occurrence of metapopulations (interbreeding populations that have equal evolutionary weight) versus core or distinct fish population segments relative to the designation of reserve areas. Li et al. (1995) point to the need to identify congruent patterns between biogeography and phylogeny of different species among fish assemblages. In summary, all of these studies, as well as the evaluation of numerous other scientific, management, and institutional issues (National Research Council 1995), need to be integrated by research and long-term monitoring programs designed to conserve and restore Pacific salmon populations, life-history diversities, and habitat connectivity at the riverine, estuarine and oceanic ecosystem scales.

Salmon Life-History Research Opportunities

Future research should consider how the differences in life-history and genetic diversities of various salmon species and local breeding populations become uniquely adapted to the environmental variability of diverse freshwater, estuarine and oceanic ecosystems. For example, does the heterogeneity of habitats within each ecosystem influence the diversity of life-histories of different salmon populations? Furthermore, how do the diverse life-history types relate to the resilience (i.e., adaptation and recovery time) of the salmon populations under varying environmental conditions?

Little is known about which ecosystem scales, in terms of size and spacing of ecosystems and habitat areas, benefit the behavior and dispersal of different fish species. Research is needed to help explain how evolutionary significant units (ESUs, in terms of species, populations, and their ecosystems; Waples 1991) for different species of salmon operate across large geographical areas. For example, the findings of Phelps et al. (1994) and others (National Research Council 1995) suggest that the degree of genetic exchange between salmon populations at regional geographic scales could play an important role in the differences in vulnerabilities of fish stocks to anthropogenic modifications. Such networks, or the metapopulation, could connect local breeding populations, and therefore the diversity of life-history patterns, needed to sustain salmon productivity at both the local and regional geographic scales (Hanski and Gilpin 1991; Riddell 1993).

Predation on Salmon: Research Issues

The rates of survival of salmon in spawning and rearing habitats are significant issues. Past research indicates predator-prey interactions have strong linkages to habitat complexity, carrying capacity and fish distribution and production (Hackney 1979; Fresh and Schroder 1987; Power 1990; Wissmar 1992). Considerable research is needed to better define salmon survival (fry and juvenile fish) in natural and artificially created spawning and rearing habitats. Such research is very important because most salmon mortalities (natural and land-use impacted) occur during the fishes' early life-history stages (Cederholm et al. 1982). Information about fish survival and the success of habitat improvement projects would benefit fish managers. No known estimates are available for egg-to-fry survival in created spawning habitats. Future research to assess the survival of the populations in the spawning habitats should simultaneously consider the role of several physical factors (e.g., inadequate flows and dissolved oxygen supplies, fluctuating temperature and accumulation of fine sediments) and biotic factors (e.g., predation by cutthroat trout and various birds). Low survival rates in ponds may relate to both abiotic constraints and biotic factors such as an inadequate food supply per fish and predation (Meehan 1991).

A major concept that could be researched is the balance between predator, prey, and habitat carrying capacity; that is, the density, size, and depth distributions of prey fish relative to habitat use by piscivorous fishes (depth distribution) and other predators. This information could be significant to the planning of many management programs that strive to protect and restore threatened and endangered salmon stocks and their habitats.

Also, minimal information is available about predator-prey interactions during salmon residence in, and migration between, spawning and rearing habitats. Juvenile fish commonly migrate because different age classes ("sizes") of salmon require seasonal rearing habitats (e.g., summer and winter) that are distributed throughout river basins. Both carrying capacity of the streams and mortality constraints during the late summer-fall could force the juveniles to shift to downstream-winter habitats. However, during fish migrations between summer and winter habitats, predation could occur. Predation by birds might occur in shallow side-channels and by fish (e.g., large trout) in deep pools (Alexander 1979; Power 1990; Lonzarich and Quinn 1995). Habitat preferences of specific size classes and influences of numerous biotic and physical factors (e.g., food availability, predators, habitat space, stream flows and temperatures) need to be investigated seasonally and over longer periods of time. Additionally, both the alteration and destruction of habitats in river and stream ecosystems could increase fish susceptibility to predation. For example, alteration of rearing habitats by land-use practices and flow regulation could affect fish survival during the late summer and early fall by decreasing habitat carrying capacity (e.g., loss of habitat volume by dewatering, crowding of fish, and less forage).

Future research should examine the survival of juvenile salmon through avoidance of predators. Consideration should be given to fish size and depth distributions in different habitats and fish movements between habitats. These studies, while providing information about prey susceptibilities to different predators, could also reveal seasonal uses of habitats by predators. Burgess (1985) provides an excellent example of how mink took more prey in streams than in riparian habitats during summer months. Mink predation on fish and crayfish was attributed to mink denning and rearing of young and availability of prey. In the fall, mink predation pressure shifted to riparian habitats because of the apparent low water levels and lack of forage in streams.

Select Research Questions

- Do riverine and estuarine production (e.g., food webs of salmon) have any relationship to the fitness of Pacific Salmon?
- What life-history characteristics of salmon are most appropriate for predicting the fitness of salmon?
- What are the appropriate spatial and temporal scales for considering the variability in salmon survival of different life-history stages?
- What life-history characteristics are most appropriate for assessing responses of salmon populations to changing carrying capacity conditions at both local breeding population and metapopulation scales?
- How do anthropogenic actions disrupt the network of local populations and metapopulation organization that operate across different spatial and temporal scales (local and regional geographic)?
- What are the most appropriate spatial and temporal scales for considering the variability of riverine and estuarine ecosystems?

- How do losses in connectivity between habitats within and among ecosystems influence salmon production at both local and regional geographic scales?
- Do multiple and high frequency human-induced modifications cause permanent alterations to the connectivity within and between riverine and estuarine ecosystems?

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CHAPTER 7

RESULTS OF THE 1996 PNCERS WORKSHOP

BACKGROUND AND PROCESS

The PNCERS workshop was conducted in Troutdale, Oregon, on August 13 and 14, 1996, with 85 participants (see Appendix A). The goals of the workshop were to bring together and synthesize available information for the PNCERS Program Management Team (PMT) to further define the program conceptual model and develop a research plan, and to generate a stand-alone synthesis of coastal environmental change in Pacific Northwest Coastal Ecosystems (i.e., this volume).

The PNCERS workshop was designed to reflect the program's conceptual model (see Chapter 1). The PMT identified five discipline-related themes to synthesize the ecosystem and socioeconomic components of the model. It was assumed that the management/policy component would eventually flow from the ecosystem and socioeconomic components, but for simplicity's sake, detailed assessment of coastal resources management and policy was delayed until a later stage in the PNCERS program. The five themes, as discussed in detail in Chapters 2-6, were:

1. The Variability and Stability of Climatic/Oceanic Regimes in the Northeast Pacific Ocean;
2. The Variability of Marine Ecosystems and Relation to Salmon Survival;
3. The Variability of Estuarine and Riverine Ecosystem Productivity;
4. Human Intervention in the Coastal Ecosystem; and
5. The Socioeconomic Causes and Consequences of Ecosystem Change.

Each theme author or team of co-authors was directed to include in the theme synthesis five or more major, researchable questions within the theme. For the workshop, a dozen researchers in complementing disciplines within each theme were invited and given the opportunity to review the theme-specific draft syntheses before attending. During the workshop, facilitators posed questions (shown below) designed to elicit: 1) feedback on the draft syntheses; 2) additional key research areas; and 3) other information, in each of five theme-specific working groups.

Theme-Specific Working Group Questions:

1. Considering the strategic approach to PNCERS (i.e., salmon as the integrating organism), is the theme paper a good overall discussion of the topic? How might you strengthen it?
2. What are the important, researchable questions in this theme area and how should they be approached?
3. How do the research questions and approaches you have identified within this theme interrelate? How should they be sequenced?
4. How might the research you've identified contribute to the sustainable management of ocean and coastal ecosystems?
5. (optional) If PNCERS cannot address all the questions, what are the top research priorities and why?

During the second day of the two-day workshop, integrative, interdisciplinary working groups were formed by mixing participants from various disciplines. The facilitators then posed questions designed to further define major research topics, concentrating on the integrative aspects linking the themes.

Integrative Working Group Questions:

1. What are the critical relationships, linkages or gaps (specify) between this theme area and each of the others?
2. What are the overarching research questions that integrate two or more themes?
3. How might the research you've identified contribute to the sustainable management of ocean and coastal ecosystems?
4. (optional) If PNCERS cannot address all the questions, what are the top research priorities and why?

The information developed at the workshop sessions was recorded on flip charts and audio taped, and in addition, the plenary sessions were videotaped. Participants identified additional research topics, but did not generate substantial, specific information on technical details related to research needs. The results of the theme-specific sessions below are generally reported in the form of lists of research questions. The results of the integrative sessions are presented by way of brief discussions of the key, recurring discussion themes.

THEME-SPECIFIC WORKSHOP RESULTS

The reaction of the theme-specific working groups to the draft syntheses was generally very positive. The facilitators attempted to maximize the opportunity for discussion resulting in the identification of refined, related or additional research questions. Some groups chose to prioritize the resultant lists; some did not. Some groups also chose to provide a hierarchical or thematic framework to the research lists.

Variability And Stability Of Climatic/Oceanic Regimes

Participants: David Greenland (Chair), Nicholas Bond, Daniel Cayan, Curt Ebbesmeyer, Barbara Hickey, Beverly Law, Nathan Mantua, Douglas McLain, Tom Murphree, Kelly Redmond, Robert Smith and George Taylor. (See Appendix A for affiliations.)

The nonprioritized, key research areas identified by the author in Chapter 2 are the following:

1. What are the relationships existing between phenomena and processes occurring on all of the different scales considered in this theme?
2. How stationary (i.e., faithfully replicable over long periods of time) are the various cyclic and quasi-cyclic phenomena in the Pacific Northwest atmospheric and oceanic systems?
3. How best can information on our knowledge of the variability of climatic/oceanic regimes in the Pacific Northwest and their predictability be transmitted to ecosystem managers?
4. What are the most important research needs on timescales of century and greater and annual and lesser?
5. What new and existing observing systems and data bases are required and exist for answering PNCERS-related questions and meetings its goal?

Participants in the Theme 1 working group categorized an additional 20 research priorities under five general, nonprioritized headings.

1. Characterization of temporal/spatial climatic variability
    - Identify key time and space scales and key times and places (related to salmon life history) and develop a monitoring program for these.
    - Comprehensively specify the ocean-atmosphere variability over annual to decadal scales.
    - Characterize the spatial/temporal variability of the Pacific Northwest/Northeast Pacific Ocean region.
    - Identify key cause and effect processes operating at key time and space scales and at key times and places.
2. Long-term climate history
    - Reconstruction of long-term climate history in marine and terrestrial locations.
    - Develop longer time series from proxy records to evaluate instrumental record history.
    - Develop long-term historical data sets for climate to compare with biotic time series.

3. Monitoring the salmon's physical environment
    - Monitoring the salmon's ocean.
    - Identify the critical measurements for monitoring the coastal ecosystem and its biota.
    - Establish an ocean monitoring program with standardized methods and real-time reports.
4. Linkages between the physical environment and biota
    - Identification of key forcing functions for predicting coastal ecosystem conditions.
    - Identification of key ocean-atmosphere/salmon interaction processes.
    - Identifying and understanding the critical biological - environmental interactions.
    - Establish the key transfer functions between the physical environment to biota.
5. Air-sea-land dynamics
    - Physical forcing for decadal changes and modeling of the physics of decadal changes.
    - Dynamics of intraseasonal to interdecadal climate variability in the Pacific Northwest.
    - Causes and effects of ocean-atmosphere teleconnections.
    - Understanding long-term variations in air-sea interaction in the North Pacific with a focus on factors important to salmon.
    - Development of a regional model of oceanic circulation.
    - Estuary-ocean coupling processes.

The Theme 1 working group endorsed the use of time and space scales as an effective organizing element for this theme. Since there is an extensive data record, many retrospective analysis opportunities exist in this theme, especially in the larger scales. The use of evolving technologies, including satellite and other remote sensors, will also enhance the ability to perform future studies. The recurring themes of retrospective analyses, monitoring, the lack of information on inner shelf processes (<30m bottom depth), connectivity and linkages, and how to provide valuable forecasting information to managers were also discussed in this group.

The Theme 1 working group identified a number of potentially valuable data sets in addition to those named in the draft synthesis. These data sets include: Canadian streamflow (stream gauge) records available from the US Geological Survey (through Daniel Cayan at Scripps Institution of Oceanography); Canadian snow course and snow sensor records available from the Natural Resources Conservation Service; model "initial condition" wind fields over the North Pacific available from the European Centre for Medium Range Forecasts or the U.S. Navy Fleet Numerical Meteorology Oceanography Center (FNMOC); and remotely-sensed precipitation records over the North Pacific (no source identified).

Variability Of Marine Ecosystems

Participants: Daniel Bottom (Chair), Hal Batchelder, Richard Beamish, Ric Brodeur, Christopher Frissell, Steven Ignell, John McGowan, Jeffrey Rodgers, Alan Shanks, Kenneth Sherman, Lawrence Small and Alan Springer. (See Appendix A for affiliations.)

The overall research objective identified by the authors in Chapter 3 is: "Given the uncertainty regarding mechanisms of salmon production in the ocean, the logistical difficulty in sampling marine waters, and the changing state of the ocean and salmon, what is the best way to incorporate new knowledge into management programs?" This was followed by the following unprioritized key research areas:

1. What are the critical components and interactions within the pelagic community that need further research before we can advance our understanding of salmon production in the marine environment?
2. By what mechanism(s) do climatic variations such as El Nino or interdecadal regime shifts regulate ocean production of salmon within the Pacific Northwest Coastal Ecosystem?
3. Are climatic influences on salmon production "coupled" or "decoupled" among riverine, estuarine, and marine life stages of salmon? That is, do large-scale atmospheric patterns have similar effects on salmon survival during all life stages or are negative climatic influences at one stage offset by positive effects at another?
4. Can we identify characteristic linkages between freshwater, estuarine, and marine environments that account for much of the geographic variation in salmon life history and productivity cross Pacific Northwest Coastal Ecosystems?
5. How do human activities change the potential development of riverine, estuarine and marine life histories, and what are the consequences of such changes for the freshwater-marine interface that appears to be so critical for salmon survival and recruitment?
6. To what extent does the degradation of freshwater habitat influence the depth of the troughs and height of peaks in the natural fluctuations in ocean productivity?

The Theme 2 working group spent a considerable amount of time addressing the question of whether or not Pacific salmon are good indicators of ecosystem integrity and health, as intended by PNCERS. While it is clear that salmon are integrating environmental stress from the watersheds to the oceans and back again, it may be very difficult to isolate the various sources of stress. The applicability of the metapopulation concept was also discussed in this context. Overall, the group agreed that salmon do make appropriate indicators with some limitations, but they recommended that longer-lived fishes such as some of the rockfish, which have life spans over 100 years, may be of additional value in examining the marine components. Pacific lamprey, which spawn in freshwater, prey upon salmon, and are thought to be in decline, are also of potential value as a complementary indicator species.

Two major areas of research were discussed at length by the Theme 2 working group: 1) basic information on salmon biology and ecology; and 2) retrospective analyses and monitoring. The sources of mortality and food during the early phase of ocean life history and the overall lack of information about the nearshore marine habitat, especially that shallower than 50 feet, are important gaps in our understanding of basic salmon biology and ecology. They are made more critical by the fact that year class strength of coho salmon appears to be determined within the first month in the ocean. There is an extensive body of data from the fisheries to support retrospective analyses, including the opportunity to look for correlations between fish productivity (that of salmon and other fish species, as well) and long-term records of ecological parameters such as salinity, temperature, chlorophyll concentrations and zooplankton biomass. The recurring themes of monitoring, ecological indictors, and managing for uncertainty were also discussed at length in this group.

Variability Of Estuarine And Riverine Ecosystems

Participants: Charles Simenstad and Robert Wissmar (Co-chairs), David Armstrong, Peter Bisson, Robert Emmett, Kurt Fresh, David Hankin, Greg Hood, David Jay, Colin Levings, Jan Newton, Fred Prahl, Stephen Ralph, Gordon Reeves and Steven Rumrill. (See Appendix A for affiliations.)

The key, nonprioritized research areas identified by the authors in Chapter 4 are the following:

1. Does riverine and estuarine production (e.g., food webs of salmon) have any relationship to the fitness of Pacific salmon?
2. What life history characteristics of salmon are most appropriate for predicting the fitness of salmon?
3. What are the appropriate spatial and temporal scales for considering the variability in salmon survival of different life history stages?
4. What life history characteristics are most appropriate for assessing responses of salmon populations to changing carrying capacity conditions at both local breeding population and metapopulation scales?
5. How do anthropogenic actions disrupt the network of local populations and metapopulation organization that operate across different spatial and temporal scales (local and regional geographic)?
6. What are the most appropriate spatial and temporal scales for considering the variability of riverine and estuarine ecosystems?

7. How do losses in connectivity between habitats within and among ecosystems influence salmon production at both local and regional geographic scales?
8. Does the complexity and high frequency of human-induced modifications cause permanent alterations to the connectivity of ecosystems?

Eleven additional research questions were posted and prioritized by the Theme 3 working group. They are, in order of priority:

1. What is the scope of variability in watershed-estuary ecosystems across the Pacific Northwest and how does it relate to species/life history composition and status of Pacific salmon?
2. How do disturbance processes (both natural and anthropogenic) in watersheds affect estuarine ecosystems?
3. How do the structural and trophic characteristics and processes of Pacific Northwest watershed-estuary ecosystems vary on long-term temporal and large spatial scales?
4. How do anthropogenic stressors affect natural processes and landscape structure?
5. How do both natural and anthropogenic changes in landscape connectivity alter the complexity of habitats that support Pacific salmon?
6. Does the variability in estuarine residency and production influence the survivability of Pacific salmon through principally density-dependent or independent processes in the river, estuary and ocean?
7. What are the patterns and rates of change in restored riverine and estuarine habitats that are important to Pacific salmon production and life history diversity?
8. Does the metapopulation structure of Pacific salmon vary with species and watershed-estuary size and complexity?
9. How have salmon harvest and hatchery management modified metapopulation and life history structure?
10. How do natural watershed-estuary ecosystem processes maintain diversity of habitat structure?
11. How is salmon life history maintained?

The Theme 3 working group concurred that a new physical classification system or typology is needed for the estuarine ecosystems in the Pacific Northwest. In biological terms, the estuary extends offshore and the magnitude of offshore influence is largely related to freshwater flow volume. Since the estuaries link the watersheds and the ocean, linkages and connectivity were discussed in some detail in this group. The basic linkages of between the ocean and the estuary are not well understood in the context of varying ocean regimes and their effects in the estuary. Similarly, the role of connectivity in estuarine ecosystems is a large unknown with respect to the effect of human disturbances on the smaller scales versus natural disturbance regimes on the larger scales. In the context of discussing research priorities, the concepts of "pulse" versus "press" disturbances were applied to natural variability and anthropogenic impacts, respectively. Additional discussion themes common to the other groups included those of performance measures, the communication of scientific information to managers, the metapopulation concept, and monitoring.

Human Intervention

Participants: Ronald Thom (Chair), Steven Berkeley, Douglas Canning, Eric Crecelius, James Lichatowich, Tom Mumford, Bruce McCain, Roger Pulwarty, John Williams, L. Dorsey Worthy and David Young. (See Appendix A for affiliations.)

The key research areas identified, but not prioritized, by the authors in Chapter 5 are the following:

1. Development of methods to assess cumulative effects of multiple stressors on coastal ecosystems (i.e., natural variability, climatic variability, human intervention).
2. Assessment of the ecological role, and development of methods for control, of undesirable introduced species.
3. Further refinement of GIS technologies coupled with numerical models for assessing damaged areas and for planning restoration actions.
4. Assessment of the vulnerability of ecosystems and components of ecosystems to natural variability.
5. Quantification of the ecological and resource response to restoration activities, and costs and benefits of various restoration strategies.
6. Development of a systematic, highly objective, adaptive management system.

Additional research topics discussed by the Theme 4 working group, but not prioritized, included various approaches to retrospective studies, studies of the effects of turbidity and contaminants, comparative studies of the effects of habitat loss versus chemical contaminants, trophic interaction studies, and comparative case studies. The group summarized its work with 10 general recommendations:

1. Use retrospective studies of long-term losses or degradation to plan restoration activities.
2. Determine the interaction of sediment dynamics and turbidity on the ability of habitats to support salmon.
3. Evaluate the effects of contaminants on the behavior of fisheries resource species.
4. Provide managers with a better assessment of habitat versus chemical effects on coastal ecosystem processes.
5. Evaluate how long restoration activities take to meet stated performance goals.
6. Understand the uncertainties associated with each restoration scenario.

7. Develop more case studies of restoration conducted in the region.
8. Determine shifts in trophic interactions due to human intervention.
9. Prevention versus intervention: do we understand the system baseline well enough to focus on restoration and/or to balance restoration with further research?
10. Rank the importance of relative impacts. (Restoration for salmon equals ecosystem restoration, that is, it is different than restoring a species in one habitat.)

Discussion of the difficulty in separating natural from anthropogenic impacts and further, separating out the many anthropogenic effects, is a fundamental problem and occupied much discussion. The working group also spent a significant amount of time discussing the issues involved in the overall topic of restoration. Principal among those issues were prevention versus restoration, uncertainty about future conditions (as they apply to restoration), determining baselines, and performance measures. Other topics aired in this group were common to those discussed in the other groups, including connectivity/linkage of physical habitat and processes with biological/ecological functions, and the dearth of nearshore information.

Socioeconomic Consequences

Participants: Daniel Huppert (Chair), Jan Auyong, Stephen Freese, Susan Hanna, Marc Hershman, Daryll Johnson, Annette Olson, Hans Radtke, Peter Schoonmaker, Courtland Smith and Miranda Wecker. (See Appendix A for affiliations.)

The key, unprioritized research questions listed by the authors in Chapter 6 are the following:

1. How can we assess the relative importance of salmon and salmon habitats to coastal communities and to the broader national community (including but not limited to economic values)?
2. What baseline socioeconomic and demographic information is needed to facilitate assessment of socioeconomic consequences of ecosystem management measures?
3. How can we develop a better understanding of coastal recreational and tourism activities and assess the degree to which they are tied to salmon and salmon habitats?
4. How can we incorporate response to "exogenous" changes, like increase or decrease in human populations or economic development, in coastal ecosystem management?
5. What data and research methods are needed to assess legal, institutional, and organization requirements for improved coastal ecosystem management?
6. How can coastal ecosystems research contribute to the development of management objectives and decision criteria?

The Theme 5 working group identified an additional six unprioritized research areas. They are listed below:

1. Develop baseline social, economic and demographic data with a focus on the following:
    - demographic trends in coastal communities;
    - economic input-output studies;
    - trends over recent decades;
    - examine sub-county and multi-county scales; and
    - social trends.
2. What are appropriate (useful and cost-effective) performance indicators (social, economic and institutional) for salmon ecosystem management?
    - How do they link to ecological performance indicators?
    - Are different indicators required for the marine and land-based components?
    - How can the indicators be used as design principles for better ecosystem management?
3. When looking at ecoregions where salmon occur, the following institutional questions arise:
    - What changes are occurring in the formal and informal institutional framework for decision making which impact ecosystem change and salmon habitat?
    - What are the historical mandates and operational pressures which affect responses of institutions?
    - Are institutions integrating decision making among Federal, state and local levels, and, if so, how is this being done?
4. What is the distribution of social values that are relevant to ecosystem management among diverse stakeholder groups (e.g., relative importance of salmon and salmon habitats to coastal communities and others)?
5. Is the watershed management paradigm an effective organizational structure for managing ecosystems (socioeconomic/biogeochemical) in which salmon are a component? Can performance indicators answer this question?
6. Perform economic trade-off analyses of different alternatives to improve salmon survivability. Such analyses should include focus in the following:
    - hatchery policies, production costs, survival into fisheries, etc.;
    - cost of alternative watershed use;
    - value of natural salmon to the fisheries (direct and indirect harvest); and

- measurement strategies to compare watershed programs in terms of costs and benefits (who receives benefits and who pays costs?).

The Theme 5 participants pointed out that while there was a separation of disciplines within the ecosystem components of the workshop, all of the social sciences were integrated into a single theme, and this resulted in more limited discussion and exposure for the various social science disciplines. The group also noted that there are many opportunities for comparative social studies within the Pacific Northwest region, for example, the differences in government between Oregon and Washington.

INTEGRATIVE WORKSHOP RESULTS - PRINCIPAL ISSUES

Whereas the theme-specific working groups tended towards defining or identifying important research topics and questions, the integrative groups tended to discuss in some detail the germane research and management issues. The following summary of integrative results discusses these principal issues, many of which originally surfaced during the theme-specific discussions and recurred during the cross-cutting discussions of the interdisciplinary groups. The general message from the workshop participants to the PNCERS Program Management Team was that these are many of the issues and themes that need to be carefully considered in designing a multi-year, integrated science program. The list is not prioritized.

Retrospective Analyses

Retrospective analysis techniques were discussed in all of the workshop sessions as a preferable way to address questions on the larger time scales. Because retrospective studies use existing data, they are preferable because they are inexpensive and yield relatively quick results. Extensive data sets exist related to weather, climate, fisheries and human intervention in the environment. One simple approach to retrospective studies is to analyze for correlations between salmon production and other ecological or human-related variables of record. Longer timescales may also be addressed through paleoecological means, such as tree rings or fish scales.

Monitoring

All groups discussed in some detail the tension between need for monitoring data and the lack of funding availability for this kind of data collection (i.e., monitoring is not "hypothesis-driven"). Participants frequently noted that almost no long-term data are presently being collected in Pacific Northwest Coastal Ecosystems. There was general concurrence at the PNCERS workshop on the importance of regular oceanographic time-series data collection to document change at many time and space scales, but especially in the ocean over the larger scales. Participants stressed that the PNCERS Program, in conjunction with US GLOBEC and CoOP (both scheduled to begin concurrently with PNCERS), presented an opportunity to acquire data with which to compare to earlier data from the Pacific obtained during the 1960s and 70s (for example, to re-establish the

"Newport Line" offshore of Yaquina Bay, Oregon). The significance of the CalCOFI time series, initiated in response to the California sardine crash of the 1940s, was repeatedly recognized as the sole, systematic, integrated long-term data record in the northeastern Pacific Ocean.

Evolving Technology

The PNCERS workshop repeatedly received advice to utilize evolving technologies where possible. The technologies specifically mentioned included genetic markers and other means of describing and defining metapopulations (see below), and a wide variety of remote-sensing capabilities, from greatly improved satellite-based sensors planned for deployment over the next few years, to very new capabilities such as land-based coastal current monitors. New technologies in fish tags should soon offer the opportunity to track smaller fish for greater distances offshore and fill this important data gap. (See also Geographic Information Systems, below.)

Metapopulation Concept

The concept of metapopulations as it applies to Pacific salmon is still evolving and thus, is loosely defined. Generally, the metapopulation concept holds that locally-reproducing populations (for instance, within one watershed or stream system) may be lost during extreme events but are repopulated by individuals from nearby populations. As it applies to salmon, an important aspect of the metapopulation is that genetic breadth in the local populations is maintained by a very low frequency of reproduction by "strays." This genetic breadth is essential to the maintenance of life-histories (see Chapter 3). An operational definition of metapopulation is provided by the Endangered Species Act terminology of Evolutionarily Significant Units (ESUs) utilized by the National Marine Fisheries Service and US Fish & Wildlife Service.

Lack of Nearshore Ocean Information

All of the integrative working groups mentioned or discussed the dearth of scientific information on the inner continental shelf, especially between the shoreline and about 30 meters depth. Data are lacking largely because it is too shallow for oceanographic ships and a very rough area for small craft operations. Yet studies indicate that some species of salmon remain within this area for a significant amount of time after moving out of the estuaries and that year-class strength for coho may be determined during this time. Very little is known about physical circulation or about salmon food or predators in this habitat, especially in relation to the level of knowledge about the other habitats utilized by salmon.

Variability - Space and Time Scales

This topic derives from the need, given the PNCERS conceptual model, to reconcile various scales of natural variability versus anthropogenic change. Thus, the topic of describing and quantifying variability was one of the important recurring themes. The need to characterize and understand natural variability in both physical and biological systems (at all scales) is a limiting factor in the ability to quantify and understand human impacts, and is thus an essential component of the PNCERS program. The working groups noted that the range of human impacts tends to be press disturbances at the smaller scales, while natural variability tends to be pulse disturbances at all scales.

Connectivity and Linkages

PNCERS workshop participants repeatedly expressed the need for a better understanding of the linkages between all of the ecosystem components, especially linkages between the physical and biological components, which are poorly understood. Specific examples include how the estuaries connect to the riverine habitats on the one side, and to the nearshore marine habitats on the other. A better understanding of the linkages between the ecosystem and the human "system" of institutions and management is also needed.

Basic Biology And Ecology Of Salmon

An observation repeatedly heard in the cross-cutting workshop session was that there is a fundamental lack of basic knowledge about the biology and ecology of Pacific salmon. Several large, important holes in the present understanding that could be addressed by PNCERS include the relative importance of predators and prey in estuaries and in the nearshore ocean, and overall habitat utilization in the nearshore ocean. The importance of salmon metapopulations (see above) is also an important factor in this context.

Institutional Versus Natural Time and Space Scales

A significant amount of cross-cutting discussion revolved around the mismatches between natural and institutional scales. Natural resource management has been made much more complicated by the fact that natural events occur on timescales, long or short, that are generally out of phase when compared to the life span or reaction time of human institutions, and on spatial scales that cross many jurisdictional boundaries. The lack of a central authority for managing Columbia River salmon is a good example of the spatial mismatch. On the positive side, there was considerable discussion of the potential for success with the recent implementation of the watershed management approach.

Use of Geographic Information Systems (GIS) layers

There was strong concurrence among the workshop participants that one of the best technical tools and practical approaches to integrating scientific information into management lies with the use of geographic information systems (GIS). The use of GIS layers allows environmental data to be overlain with management information (e.g., land-use patterns), which allows both assessment of existing impacts and planing for future management activities. Thus, the participants generally supported the collection of data amenable to GIS layers, when feasible, as well as conversion of existing data to GIS layers.

Extent and Definition of Estuary

The estuary has traditionally been viewed (from the land) as an extension of the ocean into freshwater, with a landward extent usually defined by salt wedge intrusion or head of tide. By changing perspectives the estuary can be viewed as an extension of freshwater into the ocean. This nearshore ocean component of an estuary is more difficult to define in comparison to a substrate-confined channel or basin, but could be no less important as a variable but distinctive habitat. Thus, there was discussion of the "extended" estuary and how it may be influenced by natural variability.

Ecological Indicators

Much discussion at the workshop related to ecological indicator species. The choice of the PNCERS PMT to orient the workshop synthesis themes toward Pacific salmon was controversial and led to debates of the merits of salmon as integrators and indicators of ecosystem integrity. There was substantial agreement that since salmon utilize so many Pacific Northwest coastal ecosystem habitats, habitat-specific indicator species are also needed. A strong point was made that ecological indicator species need to be sensitive enough to human disturbance to exhibit measurable stress before the most important components of the ecosystem (such as the fisheries) begin to decline.

Columbia River Plume

The influence of the Columbia River Plume on the offshore Pacific Ocean was an important subject. This feature dominates the surface of the nearshore ocean off Washington during fall and winter and a much larger area offshore of Oregon during the spring and summer months. The emplacement and operation of the Columbia River dams over the past 50 years have resulted in a major shift in the timing and volume of peak river flows and have altered the sediment supply regime, especially to the north of the river's mouth. The plume has not been extensively studied since the 1960s and little or nothing is known about the changes in offshore pelagic ecology that may have been brought about by the changes in flow.

Public Education - Transfer of Technical Information to Public

Public education was repeatedly cited as a critical tool in the context of the PNCERS conceptual model and program. The social changes that will support better natural resource management are ultimately tied to public education. A major challenge in this area is to get technical information available to the public in an understandable way. There were many suggestions for PNCERS outreach to the public, including the use of a World Wide Web site and a newsletter. Public education was also seen as an important factor in obtaining the political support for funding for needed scientific studies.

Uncertainty Applied To Management

A clear message at the workshop was that part of the breakdown between scientists and managers lies with the problem of managing for "uncertainty". Managers generally do not know how, or are administratively or politically unable, to manage for uncertainty, and most management systems are tied to steady-state views (i.e., deterministic) of the world. This topic applies to hatchery and harvest management as well as habitat management. The problem is exacerbated by the disjunct in natural versus institutional scales (see above).

Information Transfer to Managers

A topic closely related to that of uncertainty was the quality and mechanism of the transfer of technical information to managers. A considerable amount of discussion was directed towards the fundamental question of how much understanding to try to impart to managers versus using very simplified approaches and "watered down" information. There was universal agreement at the workshop that managers must participate in the development of approaches for information transfer (and ultimately, adaptive ecosystem management) in order to have acceptance of the implementation phase.

Restoration

There was significant, often heated discussion on the issue of the value of ecological restoration. Much of the controversy revolves not around the lack of success of most restoration, which is generally acknowledged, but around the competition for limited funds between restoration and prevention approaches. A closely related issue is the problematic concept of the "baseline" as a target for restoration.

Performance Indicators

The lack of useful and reliable indicators for measuring the success of human management activities was noted in all of the integrative groups. The combined effects of natural variability and the time-lag required to see results makes it very difficult to assess, and, if necessary, correct for the effects of management activities. For example, while the ultimate performance indicator of a salmon restoration program will be the salmon populations themselves, ecologically relevant indicators are needed to measure progress in specific activities (e.g., improvements in water quality parameters) over shorter time scales. General indicators of ecological health and integrity are also needed for many habitats, as are indicators of salmon fitness and productivity.

Other Existing Programs

Participants in the PNCERS workshop were aware of many existing research programs with which they thought the PNCERS Program should communicate, cooperate, and collaborate. The general philosophy of, and advice from, the participants was that past efforts at collaboration between programs was not aggressive enough and that increasing funding constraints over time have made this an even more important issue. The PNCERS program will have the opportunity to collaborate with a number of programs starting up in the Northeastern Pacific, having immediate prospects with the US GLOBEC and CoOP combined West Coast studies. The list of programs that follows is compiled from all of the workshop sessions (program acronyms and funding institutions are parenthesized).

- US/Canadian Global Ocean Ecosystems Dynamics programs, California Current System Study (GLOBEC; National Science Foundation/National Oceanic and Atmospheric Administration),
- Coastal Ocean Processes Program (CoOP, National Science Foundation),
- Land Margin Ecosystem Research (LMER, National Science Foundation),
- National Estuary Programs, including those for Puget Sound, Tillamook Bay and the Columbia River (NEP; US Environmental Protection Agency),
- Long Term Ecological Research Program (LTER; National Science Foundation)
- The Ecology and Oceanography of Harmful Algal Blooms (ECOHAB; US Environmental Protection Agency, National Oceanic and Atmospheric Administration, National Science Foundation, Office of Naval Research)
- Southeast Bering Sea Carrying Capacity and Fisheries Oceanography Coordinated Investigations (SEBSCC, FOCI; National Oceanic and Atmospheric Administration)
- Regional Marine Research Programs (RMRP; National Oceanic and Atmospheric Administration, research agendas exist but research program funds were redirected)
- Economics and Human Dimensions of Climate Fluctuation (National Oceanic and Atmospheric Administration)
- Governor's Coastal Salmon Restoration Initiative (CSRI; Oregon Governor's Office)

LIST OF ACRONYMS AND ABBREVIATIONS

AL	Aleutian Low Pressure system
ASP	Amnesic shellfish poisoning
AVHRR	Advanced Very High Resolution Radiometer
BMP	Best Management Practice
BOD	Biochemical Oxygen Demand
BP	Before present (1950 AD)
BT	Bathythermograph
CAC	Climate Analysis Center (NOAA)
CalCOFI	California Cooperative Oceanic Fisheries Investigations
CCS	California Current System
CDC	Climate Diagnostic Center (NOAA)
CLIMAP	Climate Mapping and Analysis Project
COADS	Comprehensive Ocean/Atmosphere Data Set
COHMAP	Comparative Holocene Mapping Project.
CoOP	Coastal Ocean Processes Program (NSF and NOAA)
COP	Coastal Ocean Program, NOAA
CTD	Conductivity/temperature/depth
CWA	Clean Water Act (Federal; 1972)
CWT	Coded wire tag
CZMA	Coastal Zone Management Act (Federal)
CZMRA	Coastal Zone Management Reauthorization Act (Federal)
DDD	1,1-dichloro-2,2-*bis*-(p-chlorophenyl) ethane; persistent breakdown product of DDT

DDE	1,1-dichloro-2,2-*bis*-(p-chlorophenyl) ethylene; persistent breakdown product of DDT
DDT	1,1,1-trichloro-2,2-*bis*-(p-chlorophenyl) ethane; persistent pesticide
DEQ	(Oregon) Department of Environmental Quality
DOE	(Washington) Department of Ecology
ECOHAB	The Ecology and Oceanography of Harmful Algal Blooms (study)
ESHB	Engrossed Substitute House Bill (state of Washington)
EMTF	Ecosystem Management Task Force
ENSO	El Niño-Southern Oscillation
EOF	Empirical orthogonal function (same as principal component)
EOS	Earth Observing System
EPA	U.S. Environmental Protection Agency
ESA	Endangered Species Act (Federal)
ESU	Evolutionary Significant Unit
FEMAT	Forest Ecosystem Management Assessment Team
FNMOC	Fleet Numerical Meteorology Oceanography Center (formerly FNOC)
GCM	General Circulation Model
GIS	Geographic information system
GMA	Growth Management Act (state of Washington)
HCN	Historical Climate Network
HCP	Habitat Conservation Plan
HGM	Hydrogeomorphic approach to the functional assessment of wetlands
HWFS	Acronym for the interdecadal regime shift model developed by Hollowed, Wooster, Francis and Sibley
ICCC	Informal Committee on Chinook and Coho
INPFC	International North Pacific Fisheries Commission
JISAO	Joint Institute for the Study of the Atmosphere and Oceans (University of Washington and NOAA Pacific Marine Environmental Laboratories)
LMER	Land Margin Ecosystem Research Program (NSF)
LTER	Long Term Ecological Research Program

LWD	Large woody debris
MLLW	Mean lower low water
MOODS	Master Oceanographic Observations Data Set data set from the FNMOC
MRFSS	Marine Recreational Fisheries Statistics Survey
MSL	Mean sea level
MSLP	Mean sea level pressure
MSY	Maximum sustained (or sustainable) yield
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction
NCRI	National Coastal Resources Research and Development Institute
NEP	National Estuary Program (EPA)
NEPA	National Environmental Policy Act (1969)
NGO	Non-governmental organization
NP	North Pacific Index
NPDES	National Pollutant Discharge Elimination System
NMFS	National Marine Fisheries Service, NOAA
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council
NRDA	Natural Resource Damage Assessment
NSF	National Science Foundation
NWS	National Weather Service (NOAA)
ODFE	Oregon Department of Fish and Wildlife
ONR	Office of Naval Research
OPI	Oregon Production Index, for Coho salmon
OSY	Optimum sustained yield
OWSP	Ocean Weather Ship P (or Papa)
PAHs	Polyaromatic hydrocarbons
PACLIM	Pacific Climate Workshop
PCA	Principal components analysis
PCBs	Polychlorinated biphenyls

PC	Principal component
PDO	Pacific Decadal Oscillation
PFEG	Pacific Fisheries Environmental Group; NOAA NMFS
PFJ	Polar Front Jet Stream
PMT	Program Management Team (i.e., of PNCERS)
PNA	Pacific North American Index
PNCERS	Pacific Northwest Coastal Ecosystems Regional Study
PNCE	Pacific Northwest Coastal Ecosystems
PNWI	Pacific Northwest Index, which is similar to the later PNI
PPT	Parts per thousand
PSAMP	Puget Sound Ambient Monitoring Program
PSP	Paralytic shellfish poisoning
PSWQA	Puget Sound Water Quality Authority
QBO	Quasi Biennial Oscillation
RCW	Revised Code of Washington
RHA	Rivers and Harbors Act (Federal)
SAMP	Special Area Management Plan
SEPA	State Environmental Policy Act (Washington)
SI	Storminess Index
SIA	Social Impact Assessment
SIC	Standard Industrial Classification
SLH	Sea level height
SLP	Sea level pressure
SMA	Shorelines Management Act (state of Washington)
SMP	Shoreline Management Plan
SO	Southern Oscillation
SOI	Southern Oscillation Index
SPOT	Système Probatoire d'Observation de la Terre
SSS	Sea surface salinity
SST	Sea surface temperature

STHP	Sub-tropical high pressure system
SWM	Storm water management
TBNEP	Tillamook Bay National Estuary Program
USDA	US Department of Agriculture
US GLOBEC	US Global Ocean Ecosystem Dynamics Program
USGS	US Geological Survey
WAC	Washington Administrative Code
WDCTED	Washington Department of Community, Trade, and Economic Development
WDFW	Washington Department of Fish and Wildlife
WDOE	Washington Department of Ecology
WTA	Willingness to accept
WTP	Willingness to pay
XBT	Expendable bathythermograph

GLOSSARY

Note: The definitions contained herein are intended only to address the use of the words in the context of their appearance in this report.

Abiotic Factor	in ecology, a physical or chemical process or parameter (such as temperature or salinity) affecting a biological population
Acoustic	pertaining to sound; a method of fish surveying employing an active sound source
Adaptive Management	an approach to natural resource management that involves evaluating the results of management actions and modifying subsequent actions
Advection	generally indicating large-scale movement of a fluid in the horizontal or vertical direction
Aggregate Variable	in economics, variables such as costs that are not assigned to sectors, but are rather aggregated across all sectors
Alevin	a larval salmon that has hatched from the egg, but is still living off the attached yolk sac, usually still in the gravel of the redd (nest)
Allelic	pertaining to genetic heterogeneity; allelic distance within a population is a proxy for genetic drift
Allochthonous	produced outside a system; imported (a opposed to autochthonous)
Alluvium	sediment deposited by a river, as in a floodplain
Amenity	in economics, something of value that is not considered a good or a service; for example, something of aesthetic value
Amphipod	a small benthic or planktonic crustacean; may be an important food source for outmigrating juvenile salmon
Anadromous	animals that mature as adults in seawater, but that migrate into freshwater to reproduce
Anticyclonic	rotating clockwise in the northern hemisphere; high pressure systems are anticyclonic
Anomaly	a deviation from the long-term average state or value
Anoxic	without oxygen; the deep waters of some ocean basins can be anoxic and can therefore preserve fish scales for long periods of time
Aquatic	related to water; for example, organisms living in water during one or more life stages

Anthropogenic	of human origin or cause; in the context of this report, anthropogenic stressors are contrasted to "naturally occurring" stressors
Autochthonous	produced within a system; "in situ" production
Autotroph	primary producer; plants or protists that perform photosynthesis (or chemosynthesis), providing food for higher trophic levels
Axial	pertaining to circular motion in fluids
Baroclinic Wave	a form of internal Kelvin wave (see Kelvin wave) where pressure and temperature surfaces intersect
Barotropic	air or water flow in a simplified model considering only pressure gradient and Coriolis acceleration (pressure and temperature surfaces do not generally intersect in this situation)
Basin-wide	a phenomenon affecting or observable through the entire basin, used herein to mean the entire Pacific basin
Bathymetry	the depth contours of the bottom of a body of water
Benefit/Cost Analysis	an analysis in which the net economic benefits are balanced against the costs
Benthic	living on or in the substrate at the bottom of the water column
Biennial	having a periodicity of two years
Biomass	a measure of a population or community based on mass as opposed to numbers
Biophysical	referring to a system or model with both physical and biological components
Biota	plants, animals or other living things
Biotic Factor	in ecology, a biological process or parameter affecting a population, such as predation or competition
Brackish	water of low salinity, found where freshwater and seawater first meet
Carrying Capacity	the level at which an ecosystem can support a given species under a given set of conditions
Cell	a horizontal or vertical flow in a fluid having a return flow within a specified area; for example, an atmospheric convection cell has upward, downward and lateral flows
Channelization	the practice of straightening rivers and estuarine channels, and simplifying their channel morphologies; has profound hydrologic and biologic impacts
Chironomid	insect (midge) having aquatic larvae
Chlorophyll	the major photosynthetic pigment in most plants; often used as a proxy for biomass or primary production
Circuli	annual rings in fish scales that may be used as indicators of age and growth
Competition	in ecology, the struggle between or among organisms for a limited resource, such as space or food; competition may be interspecific (between species) or intraspecific (within a species)

Consumer	in ecology, an organism that is not a primary producer, but is at the higher trophic level in a food web or chain; also, a predator or grazer; in economics, a consumer is a person who purchases market goods and services or who enjoys the use of publicly-supplied goods and services
Consumer Surplus	the maximum amount that consumers are willing to pay for a given quantity of good or service minus the amount that they actually have to pay, roughly equal to the area under a demand curve above the price
Continental Margin	the seaward extent of the edge of the continent, which includes the continental shelf and slope
Contractarian Ethics	in this ethical system an outcome is judged to be good if it respects the rights of all affected parties; a condition that could be reached by consent among parties with enforceable rights (or moral claims) as in a contract
Convergence	a location in a body of water where surface currents converge; this results in a downwards transfer of surface water which generally yields low primary productivity (the concept may also be applied to the atmosphere)
Crustacean	a group of aquatic invertebrate animals with external skeletons and jointed legs (i.e., arthropods), including crabs, shrimp, crayfish and many smaller, related organisms, such as copepods, amphipods and mysids, which are important prey of salmon and of other fishes
Cyclic	occurring in cycles, on a regular, periodic basis
Cyclogenesis	the development or generation of cyclones (low pressure areas) in the atmosphere
Cyclonic	rotating counterclockwise in the northern hemisphere; low pressure systems are cyclonic
Decadal	occurring in periods of decades, or tens of years
Detritus	dead organic matter, such as phytoplankton cells, leaves and bark, that is broken down by bacteria and other consumers; forms primary basis of estuarine food webs
Demersal	large organisms, such as fishes and crabs, that live near or on the sea floor
Deme	locally breeding population
Demand	the relationship between price and quantity purchased, normally downward-sloping which indicates quantity demanded declines with higher price
Demographic	related to the descriptive characteristics, such as age structure, birth and death rate, of populations
Dendrochronology	the study of tree rings to date past events
Density	in water, largely a function of salinity and temperature; usually expressed as grams per cubic centimeter (g cm^{-3})
Density Dependent	a concept in ecology that predicts that different population densities prescribe different results, for example, from predation

Density Independent	a concept in ecology that holds that an environmental process affects populations the same no matter what the density, for example, the effects of temperature
Dependent Variable	in statistics and modeling, a factor whose value is influenced by another factor; an output variable
Deterministic	an approach to modeling that ignores stochastic processes (i.e., ignores probabilities)
Disturbance Regime	the net backdrop of cyclic, periodic and episodic disturbances against which local floras and faunas have evolved
Diurnal	occurring on a daily basis; usually referring to daytime (as opposed to nocturnal)
Divergence	a location where surface currents diverge; this results in the transport of deeper water to the surface, often nutrient-rich, generally yielding high primary productivity (the concept also applies to the atmosphere)
Diversity	heterogeneity; in genetics, a measure of genetic breadth in a population; involves both richness and evenness
Domoic Acid	a toxic chemical produced by a species of phytoplankton and newly discovered in the Pacific Northwest marine environment
Downwelling	the process by which surface waters are forced downwards
Ecosystem	an ecological community (biotic) and its physical environment (abiotic) approached as a unit of study
Ecosystem Management	an approach to natural resource management entailing an attempt to take into account processes that encompass or account for the conditions of entire ecosystems, such as watersheds
Ecotone	a transitional habitat zone, exhibiting a continuum in community characteristics, at the interface of different ecological communities
Eddy	in physical oceanography, a movement of water contrary to the major flow in a current, often in a circular motion
Ekman Transport	in physical oceanography, the process by which the net transport of water is 90 degrees to the right of the direction of the wind stress (in the Northern Hemisphere); this transport is the basis of the coastal upwelling in the Pacific Northwest
El Niño	literally Spanish for "boy child" (Christ child); refers to the El Niño-Southern Oscillation Equatorial (ENSO) conditions that generally lead to reduced upwelling, low biological productivity and the collapse of the rich anchovetta fishery offshore Peru and Ecuador; so named because the warm water normally appears around Christmas; also leads to warming in the North Pacific
Empirical	Based on direct observation (as opposed to theoretical)
Endemic	in ecology, a population confined to a specific region or area
Endogenous	originating or acting from within a system
Epibenthic	living in association with the substrate surface in aquatic habitats; generally applied to invertebrates

Episodic	pertaining to events that are characterized by unpredictable episodes, such as subduction zone earthquakes
Epistasis	in genetics, a situation in which one combination of nonallelic genes has a dominant effect over other combinations
Equilibrium Model	a simplistic fisheries model
Escapement	the number of fish in a given population or subpopulation surviving to spawn
Estuary	an enclosed body of water where a river interacts with the ocean, generally characterized by a range of salinity from oceanic values (33 ppt) to freshwater; estuaries are unique and essential habitats for early life-history stages of many species
Euphausiid	a group of planktonic or epibenthic marine crustaceans that are major forage food for certain fishes
Euryhaline	estuarine waters having a wide range of salinity; also refers to organisms adapted to this wide range of salinity
Exogenous	acting from without (i.e., outside of) a system
Exotic Species	a species of animal or plant that has been introduced by man or natural events, and is not indigenous to the region
Fauna	animals
Fecundity	the mean capacity of the females of a given population to produce young
Feedback	the capacity in systems for the output of one or more components of the system to affect the input to the system
Filament	in physical oceanography, a long and narrow tongue from one water mass extending into another
Finite Difference	in modeling, a digital computational approach to calculus
Fjord	an estuary formed by glacial action, having characteristic physical circulation patterns; Puget Sound is a fjord
Flora	plants
Fluvial	of riverine origin; a riverine process
Flux	a flow of matter or energy
Forage	food; "foraging" is the process of obtaining food
Forecast	output of a model predicting future conditions
Front	in meteorology and physical oceanography, the location where two water or air masses meet, characterized by abrupt changes in characteristics like temperature and salinity over relatively short distances
Fry	very young salmon that have just emerged from the gravel; for some salmon species, the life-history stage that migrates directly to the ocean
Genetic Drift	a natural process by which genetic diversity in a population increases

Geomorphic	in geology and physical geography, surficial physical characteristics or structure related to the underlying causal geologic processes
Greenhouse Gases	gases that inhibit the loss of heat (long wave electromagnetic radiation) reflected from the earth; the principal greenhouse gases associated with anthropogenic activities are carbon dioxide and methane
Gyre	basin-wide horizontal ocean circulation, generally circular
Harpacticoid Copepod	a small benthic or epibenthic crustacean, an often-preferred food for outmigrating salmon fry
Heterotroph	a plant or animal that does not perform photo- or chemosynthesis, thus, a consumer
Hierarchy	a system that is comprised of an increasing diversity of subsystems, the subsystems themselves being comprised of yet smaller subsystems, and so on; a way of conceptualizing natural systems
Holistic	a conceptual approach that attempts to consider all factors
Holocene	the present-day geological epoch; beginning at the end of the Pleistocene epoch, about 11,000 years before present (BP)
Hydrograph	the volume of river runoff per unit time over a period of weeks or months
Hydrography	in oceanography, the vertical and horizontal structure of a body of water in terms of salinity, temperature, and density
Hydrologic	referring to the processes involved in the water cycle
Hyporheic	referring to the flow of water through the surficial sediment along the sides of a streambed
Independent Variable	in statistics and modeling, a factor the value of which is not influenced by another factor; an input variable
Indigenous	native to the region
Input-Output Model	a linear multi-industry model in which transactions between industries reflect inputs to the buying industry and outputs of the selling industry
Interannual	a phenomenon that is observable across a few years
Intertidal	an area that is exposed during low tides and submerged during high tides
Interspecific	between species
Intraspecific	within a species
Isohaline	a line or surface of equal salinity
Isopycnal	a line or surface of equal density
Isostatic	motion or processes resulting from forces within the earth that move to establish balance (i.e., equilibrium) between elevating and sinking land masses
Isotherm	a line or surface of equal temperature
Isotopes	the multiple atomic configurations of a given element; both radioactive (unstable) and stable isotopes are used to study ecological processes

Jack	a precocious male salmon that returns to spawn a year or more before the rest of his cohort or year class
Jet	a high velocity stream within a slower moving fluid; applies to both the ocean and the atmosphere
Jet Stream	a persistent high altitude wind with speeds often exceeding 250 miles per hour; its dynamics have a strong effect on weather in the Pacific Northwest
Juvenile	young animal; in the case of salmon, in the age range from fry through smolt
Kelvin Waves	coastally trapped waves that transmit the ENSO signal through the ocean to the Pacific Northwest
Laminar	pertaining to the nonturbulent flow of a liquid or gas
Langmuir Cell	a three-dimensional surficial circulation cell in water driven by wind stress; adjacent cells create zones of surface convergence and divergence
La Niña	literally Spanish for "girl child", refers to the set of conditions in the El Niño-Southern Oscillation Equatorial (ENSO) that leads to cooler temperatures in the North Pacific
Larva	developmental stage of an animal prior to metamorphosis from a different form to an adult-like stage; most marine and estuarine organisms have larval life stages
Latent Heat	the heat energy absorbed during the process of evaporation
Limitation	in ecology, the law of the minimum, holding that production is limited by a single limiting resource in the shortest supply; aquatic primary production is generally limited by light or nutrients, and nutrient limitation is generally by nitrogen or phosphorus in coastal ecosystems
Linear Model	a simplified numerical model that assumes linear relationships between independent and dependent variables
Lithology	the structure of bedrock in a given area
Littoral	the area between mean low and high tides; synonymous with intertidal
Macroinvertebrate	an invertebrate animal large enough to be seen with the naked eye; generally refers to benthic or epibenthic fauna retained on a 0.5 mm sieve
Marginal Cost	in economics, the extra cost incurred as one additional unit of anything is produced; can be much lower than average cost as lump-sum set-up costs are unaffected by number of units produced
Market Price	the price for a good or service at which quantity demanded and quantity supplied are equal (i.e., where the demand and supply curves intersect); also known as the market equilibrium price
Meander	a deviation from the main direction of flow in a current or a riverbed
Mediation	a process by which proponents of opposing sides of an issue are aided in finding common ground by a trained third party called a mediator
Meiofauna	a benthic or epibenthic invertebrate generally small enough to pass through a 0.5 mm sieve

Meroplankton	planktonic animals that spend only an early part of their life history as plankton; most benthic invertebrates and many fishes have planktonic larvae
Mesoscale	on a spatial scale of tens to hundreds of kilometers
Metapopulation	an evolving concept in population biology that relates the maintenance of genetic breadth in populations to periodic genetic exposure to a larger, more diverse "metapopulation"
Mitigation	an action taken to eliminate, lessen the severity of, or compensate for, an environmental impact or impacts
Model	a simplified representation of reality; models may be conceptual, theoretical, or empirical (i.e., based on observation)
Morphology	physical appearance or characteristics of an organism or habitat
Natal Stream	the stream in which a given population of salmon are born and to which they return to spawn
Nekton	as opposed to plankton (drifters), aquatic animals capable of swimming sufficiently to overcome currents
Nexus	a tie or link; in law, indicates that there must be a close relationship between the intent and application of the law
Nonpoint Source Pollution	chemical or other pollution that is accumulated in stream flow via runoff from many small, indirect sources
Normative Axioms	principles related to a norm or standard; very strongly held beliefs
Nutricline	an area of abrupt change in nutrient concentration
Oligotrophic	characterized by low productivity
Orographic	characterizing the process or area of increasing rainfall due to increases in altitude when air moves over a mountain range
Oscillations	cyclic or regular variations
Pacific Salmon	salmon that migrate into the northeastern Pacific Ocean; there are five species of Pacific salmon, all of the genus *Onchorhynchus*, including sockeye (*O. nerka*), coho (*O. kisutch*), chinook (*O. tshawytscha*), chum (*O. keta*), and pink (*O. gorbuscha*); sea-run cutthroat (*O. clarki*) and steelhead (*O. mykiss*), which have historically been considered trout, are sometimes included in this list
Paradigm	a commonly held view about the way the world works
Parameters	factors in model; variables in a system
Pelagic	living in the water column
Phenotype	the genetically and environmentally determined observable appearance of an organism
Phytoplankton	planktonic plants; the basis of most marine food webs
Piscivorous	eating a diet composed primarily of fish
Plankton	plants or animals that drift in water without sufficient swimming capability to counter currents

Pleistocene	the preceding geological epoch, characterized by glacial stages, beginning about 1.8 million years and ended about 11,000 years before present (BP)
Plume	traceable characteristics of a source of water in a larger body; for example, the Columbia River plume is traceable over a large area in the northeastern Pacific Ocean by salinity, temperature and turbidity
Pools	deeper segments in streams with reduced current velocities
Predation	source of mortality to an animal, due to being eaten by another animal
Press Disturbance	a disturbance that is a continuing, and often increasing, pressure on biological populations; generally applicable to human disturbances
Privatization	the practice of transferring public agencies or services to private ownership and/or operation
Producer Surplus	in economics, the amount that producers receive for a given quantity of product sold in a market minus minimum amount that they would accept in compensation. Roughly equals the area under the price line and over the supply curve
Production	in ecology, the generation or accumulation of living biomass, both by growth and reproduction; primary production is performed by autotrophs, and secondary and tertiary production by consumers; in economics, production is the process of using economic inputs (land, labor, capital) to create consumer goods or to create inputs for a further stage production process
Progeny	the young of a given species or population
Proxy	the use of one variable to predict the value of another
Pulse Disturbance	a disturbance that occurs sporadically, and to which the biota have evolved; generally applicable to naturally variable episodes
Pycnocline	a zone of rapidly changing density with depth
Quasi-Quintennial	cyclic in apparent time periods of 3-7 years (also quasi-quinquennial)
Recruitment	in ecology, the process by which new members join a reproducing population
Redds	gravel nests made by salmon during spawning and under which subsequent egg incubation and hatching occurs
Refractory	not readily utilizable; in ecology, refractory organic material is that which must be transformed before being available to most consumers
Refugia	habitats amenable to the survival of a particular species when or where when survival is difficult
Regime	in climatology and physical oceanography, a stated set of conditions in a system, as in the El Niño or La Niña regimes; in social science, a regime is a set of institutions, laws, conventions, or social rules that shapes and govern human action
Resiliency	the ability to recover from perturbation
Restoration	the act of restoring; restoration efforts are often directed towards specific species or habitats

Retrospective	looking to the past; retrospective studies analyze past events
Riffles	shallower segments in streams with increased current velocities and turbulent flow
Riparian Zone	upland and wetlands habitats immediately adjacent to a river or streambed
Rossby Waves	planetary waves, both in the atmosphere and ocean, propagated along a parallel of latitude
Sector	in economics, a specific grouping; such as the manufacturing or tourism
Sensible Heat	heat transferred by conduction and convection in the atmosphere
Silviculture	the industry of growing trees
Smolt	a salmon, usually a yearling, entering the ocean
Spawning	sexual reproduction; as in salmon spawning in freshwater
Splash Damming	the practice of transporting logs downstream by accumulating large amounts of water behind log dams, and then bursting the dams; this practice was widely used and especially damaging to coastal watersheds in the Pacific Northwest in the 19th and early 20th Centuries
Stable Isotope	a non-radioactive isotope of an element; differing ratios of naturally-occurring stable isotopes in plants and animals (such as carbon) can be indicative of their sources of nutrients or foods, respectively
Stakeholders	persons with an interest in a given issue
Steady State	a stable, unchanging state in a model or system; in equilibrium
Stochastic	based on probabilities, as opposed to deterministic
Stock	in fisheries, the basic unit of fish population management
Stratification	vertical layering, as in the water column; stratification is caused by changes in salinity or temperature (and resultant density) with depth
Subduction Zone	the place where one of the earth's crustal plates is "subducted", or dives beneath another; subduction zones are generally characterized the periodic earthquakes; in the Pacific Northwest, the Juan de Fuca plate is being subducted beneath the North American plate
Subtidal	habitat seaward of, or below, the intertidal; always submerged
Supply	in economics, the relationship between quantity offered for sale and price; generally, the supply curve slopes upward as producers offer to sell a larger quantity at higher price
Synchronous	occurring at the same time
System	a conceptual abstraction defining the object of interest in natural or social sciences that encompasses component elements, inputs, outputs and states
Tectonic	referring to the basic geological processes resulting in movement and structural deformation of the earth's crust

Teleconnection	a situation in the atmosphere in which events in seemingly distant places or times are related, such as the association between climatic events in the tropical western Pacific and coastal upwelling in the Pacific Northwest
Teleost	a bony fish
Terrestrial	living on land; pertaining to land
Thermocline	abrupt vertical change in temperature in the water column or atmosphere
Tidal Prism	the percentage volume or portion of water in an estuary exchanged on a given tidal cycle
Transition	in physical oceanography, the rapid change in surface water conditions in early spring; leading to upwelling (and resultant increases in biological productivity)
Trophic	in ecology, pertaining to the transfer of energy from producers to consumers
Tsunami	a very large ocean wave caused by the energy released by an earthquake or underwater volcanic eruption
Turbidity	a reduced ability of water to transmit light, usually caused by suspended sediments or organic materials; a serious non-point source pollution problem
Turbulent	flow that is agitated or disturbed and not moving in a flat layer
Uncertainty	degree or level of certainty as to an outcome
Upwelling	the process by which deeper water is delivered from depth to the surface, usually accompanied by high rates of primary productivity; occurs at divergences or along the continental shelf in the Pacific Northwest
Utilitarian Ethics	an approach that judges the rightness of an action by the consequences for individual welfare as defined by preferences
Usufructuary Right	the legal right to use property owned by another
Volitional	an action taken as a result of free choice
Vortex	fluid flow about an axis; circular
Vorticity	in a fluid, relating to angular momentum during flow in a curve
Watershed	the area of land drained by a river and its tributaries; alternatively, the sources of water to a drainage basin such as an estuary or lake
Watershed Management	contemporary approach to aquatic ecosystem management that encompasses broad-scale issues and processes
Wind Stress	the friction exerted by air moving across a water surface
Zonal	referring to a wind or ocean current propagating along a parallel of latitude
Zooplankton	planktonic animals

APPENDIX

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