

# Complexity of marine fisheries dynamics and climate interactions in the northeast Pacific Ocean

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## 12.1 Introduction

Much of the progress made in understanding climate–fisheries interactions can be traced to the long time series of data collected on commercial fisheries in the northeast Atlantic Ocean. Some European catch records date back to the sixteenth century or before (Southward *et al.* 1988). Backed by such a wealth of data, Ottersen and coworkers in Chapter 6 have posed the general question ‘how does the physical environment affect fish and shellfish?’ They conclude that ‘the interaction between ocean and atmosphere may form dynamical systems, exhibiting complex patterns of variation, which may profoundly influence ecological processes in a number of manners’. While that answer may seem general, from our point-of-view it is accurate; the impact of climate on fisheries is highly variable, indirect, and complex. Several dominant themes related to climate change and fisheries interweave in chapters of this volume (Chapters 2, 3 and 6), including: complex interactions, formation of patterns over large-scales, high variability over small-scales, and the desirability of forecasting tools. These themes are important not only to North Atlantic fisheries, but are focal issues in many of the world’s seas, including the northeast Pacific Ocean as we describe here.

In the northeast Pacific Ocean, the time series of fisheries data are not very long; in a few cases they may date back a hundred years, and for most species accurate statistics have been collected for decades rather than centuries. In the absence of long time series of catches, other methods have been employed to study fisheries–climate interactions. For example, process studies of ecological oceanography offer a different approach. Process studies are mechanistic and reductionist by necessity, and as described below, understanding climate–fisheries interactions from process studies is confounded by the complexity of extrapolating from small to large time and space scales. Strong climate disturbances, like El Niño, present opportunities for natural, but uncontrolled, experiments. In large part, the interest in climate–fisheries interactions in the northeast Pacific Ocean has been driven by the dramatic effects of El Niño events, especially those involving fisheries collapses. More recently, there have been gains in understanding of potential interactions between low frequency climate effects and fisheries. Large-scale responses in the dynamics of fish populations to changes in the Pacific Decadal Oscillation (PDO) and Arctic Oscillation (AO), the Pacific counterparts of the North Atlantic Oscillation (NAO), have been hypothesized, largely based on observations of a single cycle. Finally, sometimes catch

statistics can be supplemented by archaeological and geological records. Process studies, natural experiments, and climatological studies of fisheries are diverse, but complementary approaches, often offering a variety of perspectives of climate-fisheries issues on different scales.

## 12.2 A case study of processes: walleye pollock in the Gulf of Alaska

The impact of ocean conditions on the recruitment process of the central Gulf of Alaska walleye pollock population has been studied since 1985. This population of pollock, generally about 1 million tons, aggregates to spawn during the first week in April over a 40-km by 90-km area just off Cape Kekumoi in the Shelikof Strait. Such a predictable concentration of fish has provided a natural laboratory to study fisheries oceanography in one of the storm centres of the Western Hemisphere. The preliminary guiding hypothesis of these studies was that recruitment to the fishery was determined by wind effects on the drift of larvae (Hinckley *et al.* 1991). Initial studies showed that feeding interactions of early stage larvae (Canino *et al.* 1991; Theilacker *et al.* 1996), storms (Bailey and Macklin 1994), and predation on eggs and larvae (Brodeur and Bailey 1995) had significant effects on early mortality. Later, with accumulation of more years of data on the abundance of different life history stages and by analysis of life tables, it appeared that recruitment was not solely determined in the egg and early larval stage, but that in some years devastatingly high mortality occurred during the juvenile stages, meaning that the 'critical period' biologists have long searched for may vary from year-to-year (Bailey *et al.* 1996).

The 'variable life stage control' hypothesis took another complexion as more data accumulated. In the late 1970s the North Pacific Ocean experienced a 'regime shift' in environmental conditions that was accompanied by a major change in community structure (Anderson and Piatt 1999). Small pelagic fishes and shrimps decreased spectacularly in abundance and there was a long-term build-up of groundfishes, especially piscivorous flatfishes. While the mechanisms behind the shift in community structure are poorly known, it apparently had an effect on the process of recruitment in walleye pollock. During the early phase of the new regime period, larval mortality was coupled to eventual

recruitment and mediated by environmental conditions, but during the later phase of the regime larval mortality and recruitment became uncoupled, apparently due to increasing mortality of juvenile pollock with the increasing number of flatfish predators (Bailey 2000). Therefore, it appears that 'control' of recruitment depends on the status of a continually changing ecosystem. This serves as an example of the scenario described by Ottersen and coworkers in Chapter 1, where 'one variable may be a dominant forcing mechanism for a time only to be replaced later by another variable. . .'.

A recent and evolving perspective is that recruitment of pollock is a complex process, governed by the rules of complexity theory, but bounded by low frequency changes in the ecosystem (Bailey 2002). Larval mortality is highly variable and subject to many interacting high frequency factors, with feedback and non-linearity. Larvae show sophisticated behaviours involving choice and decisions when confronted with multiple and perhaps conflicting stimuli (Olla *et al.* 1996). For example, they avoid turbulence by descending (Davis 2001), taking them out of the photic zone and into colder water where growth is less optimal and prey are less abundant (Kendall *et al.* 1994). On the other hand, although juveniles also show complicated behaviours in response to the environment (e.g. Sogard and Olla 1993), they are less impacted by small-scale physics, and juvenile mortality seems to be more stable and predictable, occurring largely as a result of predation and cannibalism. The build-up of predators in the community represents a low frequency, slowly changing pattern with lagged effects. Patterns in recruitment have been well-described by preliminary models incorporating stochastic mortality weighted by environmental conditions during the larval period and by deterministic factors and constraints during the juvenile period.

## 12.3 A natural experiment: El Niño and fisheries

The effects of a strong environmental perturbation like El Niño on fisheries and community structure are well-documented in the tropical and subtropical waters off the west coast of the United States (e.g. Lea and Rosenblatt 2000). How El Niño has impacted subarctic fish stocks is less well-understood. Associated changes in environmental

conditions may be due to local effects, remote forcing, or atmospheric teleconnections.

El Niño is the warm phase of the El Niño-Southern Oscillation (ENSO). Extension of this signal to mid- and higher latitudes has been called Niño North (Hollowed *et al.* 2001). These warm events along the west coast of North America are characterized by poleward propagation of ocean long waves associated with deeper thermoclines, higher salinity and temperatures, increased sea-level, stronger poleward flow, and relaxed upwelling. Atmospheric teleconnections also impact the northern Gulf of Alaska, including intensification of the Aleutian low-pressure system, changes in the wind field, increased storminess and relaxed coastal upwelling. Individual El Niño-related events are characterized by their remarkable variability and strength in the subtropics and the occasional northward propagation of these effects. Strong tropical events are not always evident in subarctic waters. For example, the 1972–73 event was even anomalously cold in the northern Gulf of Alaska. On the other hand, moderate or even weak tropical events, such as that of 1976–77, can have relatively strong effects in that northern region.

Even moderate El Niño events clearly influence the distribution of fishes (Pearcy and Schoener 1987). These effects are most pronounced in the subtropics and diminish polewards. Furthermore, small pelagic species are expected to be affected more than groundfish species (Bailey *et al.* 1995).

The effect of El Niño on recruitment is not as clear. Bailey and Incze (1985) proposed that El Niño events initiated strong year-classes at the northern end of the species range through the beneficial effects of warming, and poor year-classes at the southern end. In a more recent evaluation, this picture has become more complicated (Bailey *et al.* 1995) and individual El Niño events have inconsistent effects on any one species. The confounding effect of many interactions with opposite effects appears to introduce complexity to the process. For example, warming is generally beneficial, but is accompanied by reduced nutrient input, which decreases prey production. Some generalizations may be possible; for example, it appears that pelagic species are more adversely affected than groundfishes, and this is demonstrated by catastrophic mortalities of piscivorous seabirds that feed on pelagic fishes. As well, offshore spawning species with inshore nurseries may benefit from enhanced onshore transport during warm events.

However, this may affect different populations dissimilarly. In the Gulf of Alaska, enhanced transport onshore and warming during Niño North seems to be associated with exceptionally strong year-classes of halibut, at the northern end of their range. On the other hand, arrowtooth flounder experience enhanced onshore transport as well, but are at the warm end of their range in the Gulf of Alaska and may not have benefited from warming. Arrowtooth flounder do not have strong year classes associated with El Niño (Bailey and Picquelle 2002). Temporal patterns of production of Pacific cod, walleye pollock, and Pacific hake tend to follow a pattern that is somewhat consistent with El Niño North. Warm years typically persist after tropical El Niño events that have reached northward. Patterns of production of these stocks show that strong year-classes occur more frequently in such years (Hollowed *et al.* 2001).

## 12.4 Regime shifts and marine fisheries

Our case study and the contributions by Werner and coworkers in Chapter 3 and Ottersen and coworkers in Chapter 6 illustrate the complexity of processes underlying survival of individual larvae, patches of larvae, or cohorts from a specific population. Historically, fisheries scientists have utilized statistical inference to identify potential relationships between climate and fish production, and many times find interesting relationships. However, strong correlations between recruitment and environmental variables often deteriorate with time suggesting that the relationships might have been spurious (Drinkwater and Myers 1987), or perhaps indicating a shift in controlling factors (Bailey 2000). The results of single species statistical inference models can be strengthened, if similar responses are observed in several species. Comparative studies provide some evidence of the linkages between large-scale atmospheric forcing, ocean processes, and fish production. Time-series comparisons of recruitment patterns of several of the most abundant marine fish stocks have revealed that they exhibit temporal patterns of production that appear to follow spatial and temporal patterns of large-scale climate forcing (Francis *et al.* 1998; Hare and Mantua 2000; Hollowed *et al.* 2001).

Besides ENSO, two primary modes of atmospheric forcing have been identified in the North Pacific: PDO and the AO. These modes of forcing,

which reflect the large-scale atmospheric circulation of the region, impact ocean conditions in the north-east Pacific and Bering Sea.

The PDO is a decadal-scale oscillation in the North Pacific sea surface temperature (SST) with alternating positive and negative phases that have lasted 20–30 years during the twentieth century. Effects of the PDO are felt most strongly in the extratropical North Pacific, in contrast to the inter-annual ENSO signal, which is best developed in the equatorial region.

Indices of PDO and ENSO are commonly computed for boreal winter when the signals are strongest. Comparison of the time history of the two indices (Mantua *et al.* 1997) shows the difference in their dominant frequencies and emphasizes the inter-decadal, regime-like nature of the PDO. During the warm phase of the PDO, throughout much of the 1980s and 1990s, SSTs of the West Coast of North America have been warmer than usual and the thermocline deeper, conditions which appear to have reversed in the early 1990s.

The AO is a measure of the spin up (or spin down) of the polar vortex, which is indexed by the amplitude of the first principle component of sea-level pressure in the region during winter months (Thompson and Wallace 1998; see also Chapter 2). Temporal patterns of the AO revealed a potential shift from a negative to a positive phase in 1989 (Overland *et al.* 1999). The influence of the AO on ocean conditions is most notable in the Bering Sea. There, wind forcing is influenced by the impact of the PDO, El Niño, and the AO on the distribution and intensity of winter storm tracks as measured by indices of the Aleutian Low (Bond and Harrison 2000; Hare and Mantua 2000). Shifts in the intensity and distribution of storm tracks also influence the timing and distribution of sea ice in the Bering Sea. The distribution of sea ice and timing of its retreat has been shown to have a strong influence on the timing and intensity of spring blooms over the shelf and the location of a cold pool of water over the shelf (Wyllie-Echeverria and Wooster 1998).

Temporal patterns of fish production based on smoothed indices of recruitment of some species in the Gulf of Alaska and California Current ecosystems tend to be coincident with the two major atmospheric forcing processes influencing the region: El Niño (as discussed above) and the PDO (Hollowed *et al.* 2001). In these two systems, some stocks appear to follow temporal patterns of the PDO: Pacific sardine, arrowtooth flounder, Pacific

halibut, and Pacific salmon (Hare and Mantua 2000; Hollowed *et al.* 2001). Further evidence of the importance of large-scale forcing on fish production is noted in the marked synchrony of occurrence of strong year-classes of marine species in the North Pacific and Bering Sea (Hollowed *et al.* 1987; Beamish 1994). These findings suggest that fish (at least several commercial species) have adapted to take advantage of a common suite of conditions controlled by a number of climate–ocean processes.

## 12.5 Paleo-oceanography studies

The presence of fish remains in sediments and archaeological sites has been a valuable source of information when examining climate–fisheries–human interactions in the Pacific Ocean (Finney *et al.* 2000; Jackson *et al.* 2001). In particular, fish remains in varved sediments of anoxic basins have shown high resolution recording of marine fish abundances that can be compared to other indices of ancient climate. These studies have revealed historical colonization events and cycling of populations dating back thousands of years.

Colonization by marine fishes of Saanich Inlet on the south-eastern side of Vancouver Island has been traced back to events subsequent to deglaciation about 12,000 years ago (Tunncliffe *et al.* 2001). After deglaciation and formation of an open marine bay, the area was colonized by hake and herring. Interestingly, it took the northern species of cod and pollock another 6000 years for their remains to deposit in the sediments. What explains the earlier arrival of the southern species hake? Pollock and cod are believed to spawn in fixed geographic locations, while hake spawning varies in location depending on environmental conditions. Perhaps this difference in spawning strategy could allow hake to opportunistically invade new habitats during a warming period, while pollock and cod may have gradually colonized coastal embayments in a stepping-stone manner. Alternatively, regional disruption of atmospheric circulation during the glaciation that caused a collapse of the California Current and a sudden warming of the ocean off California (Herbert *et al.* 2001) may have forced hake northward, and a more gradual warming off Oregon and Washington allowed them to invade new habitats.

A record of coastal fishes dating back around 1700 years is available off the coast of southern

California (Soutar and Isaacs 1974; Baumgartner *et al.* 1992). These data have shown that anchovy and sardine populations fluctuate with a high frequency period of about 60 years and with a low frequency period of 500–700 years. Comparison of these series to paleo-oceanographic climate records are being conducted, although contemporary harvest records indicate that sardine harvests and temperature vary in phase (Omori and Kawasaki 1995).

## 12.6 Forecasting

Can we predict the effects of climate changes on fisheries? Werner and coworkers in Chapter 3 state that ‘understanding and predicting the response of marine ecosystems to global change is essential’. On the other hand, climate and climate–ocean effects may themselves be hard to predict from shifts in the NAO, as Hurrell and Dickson (Chapter 2) report: ‘much of the atmospheric circulation variability in the form of the NAO arises from processes internal to the atmosphere, in which scales of motion interact with one another to produce random (and thus unpredictable) variations’. Although, the NAO may explain a lot of the variability in climate over the North Atlantic, the chaotic nature of atmospheric circulation causes substantial departures from the caricatured effects. Therefore, a first question might better be phrased: can we predict the impact of climate changes on the ocean, with what detail, and with how much lead time? In the case of El Niño, its development in the equatorial region can be followed from satellites and the TOGA mooring array leading to predictions of the event in the eastern tropical Pacific months in advance. The strength of the event and precise timing are still difficult forecasts. Whether these effects extend to higher latitudes may be a consequence of interaction between the El Niño and PDO signals. Predicting effects of large-scale climate shifts on the ocean and then on the biology within oceans will be even more difficult due to the compounding of uncertainty both on large and local scales.

Process studies examine interactions of climate and biology on relatively small scales, themselves imbedded within ever-increasing larger-scale

processes. The interactions of many such small-scale processes are complex. Complex processes like a population trajectory through time may be unpredictable (a possible exception is where initial conditions generate mortality that is catastrophic, so the population is unable to recover). However, coalescence of small-scale processes may lead to patterns at higher levels of ecosystem structure. Holistic effects of low frequency or large-scale changes, such as regime shift impacts on the flow of energy in the food web, species succession, and shifts in species ranges may be predictable. It is clear that large-scale climate cycles have a major effect on fish populations and productivity. And, while climate impacts may not accurately forecast a population’s trajectory through time, environmental regimes can set up boundary conditions that may influence the probability of an outcome. General patterns in recruitment, such as warming that favours strong recruitment of herring stocks at the northern end of the species range (Ottersen *et al.* Chapter 6), may also lead to predictions. However, these patterns may also fail, evidenced by disruptions in the cycle of Bohuslän herring. Likewise, with the latest warm regime in the California Current, recovery of the Pacific sardine lagged behind regime-shift related warming by 15 years or more, and population levels have not attained those observed in the 1930s. In the case of Pacific sardine and other heavily harvested populations, perhaps some population segments became extinct during a population retraction resulting in loss of local adaptation, or changes in trophic interactions have hindered recoveries. It may be reasonable to make short-term forecasts based on mechanisms or existing conditions to the next level or scale up, but forecasts become more imprecise at farther points, as expected in a complex system. For example, recruitment can be forecast from the number of pre-recruit juveniles but is poorly predicted from initial conditions during larval life (Helle *et al.* 2000; Bailey 2002). Better predictions in the future from a set of environmental conditions may arise from new tools, hybrid modelling techniques mixing stochastic and deterministic models, better understanding, or more general and larger targets for the forecaster’s arrow.