CHAPTER 3

Ocean Circulation, Productivity, and Exchange with the Atmosphere

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Chapter 3 Contents

3.1 Overview

3.1.1 Organization of this chapter

Four themes are addressed in this chapter:

- The interaction between the atmosphere and ocean across the sea surface
- The role of the oceans in the Earth's heat and hydrologic cycles
- The causes of sea-level change
- The ocean's biological system and its interplay with the Earth's carbon cycle

The chapter is organized as follows:

- In Section 3.2 we introduce the above four scientific topics and clarify the important issues.
- In Section 3.3 we discuss the observational requirements both from satellite and from other sources.
- In Section 3.4 we lay out the Earth Observing System (EOS) plans for addressing these scientific issues with these data sets.

3.1.2 Oceans and climate

The Earth's climate is driven by heat. Because the world ocean absorbs about half of the solar radiation the Earth receives, the ocean is an equal partner with the atmosphere in the climate system. The climate system redistributes the heat it gains in the tropics towards middle and high latitudes. The ocean again is an equal partner with the atmosphere in this poleward redistribution, yet much about how this climate engine functions, and certainly how its functioning changes over years and decades, remains only qualitatively known; EOS will change this.

Forecasts of the timing and geographic extent of seasonal-to-interannual climate anomalies at least a year in advance are within our reach. Such lead times can be envisaged primarily because the thermal inertia of the coupled climate system rests in the upper ocean, which has a relatively slow response compared to the atmosphere.

Of great influence on the surface climate of the Earth—where people live—is atmospheric transparency to solar radiation and opacity to longwave radiation. Carbon dioxide is typical of the gases that give the atmosphere these properties. The abundance of carbon in the atmosphere is tied to the chemistry and biology of life both on land and in the ocean. Here again, in the Earth's carbon cycle, the ocean's role of absorbing and sequestering CO_2 in ocean sediments is crucial.

These are the motivations for EOS's strong oceanographic component in its plans for Earth system research.

3.1.3 Oceans and humanity

The oceans not only play a role in modulating climate and weather, but they also provide food and mineral resources. The oceans support tourism. They serve as a waste repository. Coastal regions are the center of worldwide population increases; by 2020 over 65% of the world's population will live along continental margins. Changes in climate with their associated changes in sea level, in patterns of temperature and rainfall, have major impacts on the global economy and on the distribution and abundance of oceanic resources and on the industries that pursue them.

In particular, coastal waters are of immense economic and environmental importance. Almost 95% of the world's commerce is transported by ship through coastal waters; waterborne commerce for the U.S. for 1990 is estimated at $465 billion. Coastal ocean oil and gas extraction currently accounts for about $16 billion annually. According to estimates of the National Oceanic and Atmospheric Administration's (NOAA's) National Weather Service, the damages due to Hurricanes Hugo (in 1989), Andrew (in 1992), and Iniki (in 1992) caused a cumulative loss in excess of $40 billion.

In 1992 U.S. commercial fisheries produced $3.9 billion in revenue to fishermen at U.S. ports, with a total impact on the Gross National Product (GNP) of over $50 billion. Yet fish populations and their associated fisheries are enormously variable, with interdecadal fluctuations of different fish populations that appear related to basin-wide oceanographic variability. The implication is that climate changes affect this resource in presently unknown ways. Past failures to modify fishing pressure in response to patterns of natural variability have produced disastrous collapses. Sardines off the U.S. west coast are just now recovering, the cod and haddock fishery is virtually closed, and many Northwest salmon species are threatened while Alaskan salmon are at record high levels.

These issues of resource management, marine-centered commerce, and safety are the second motivation for EOS's strong component of both physical and biological oceanographic studies within its investigations of Planet Earth.

3.2 Major scientific questions

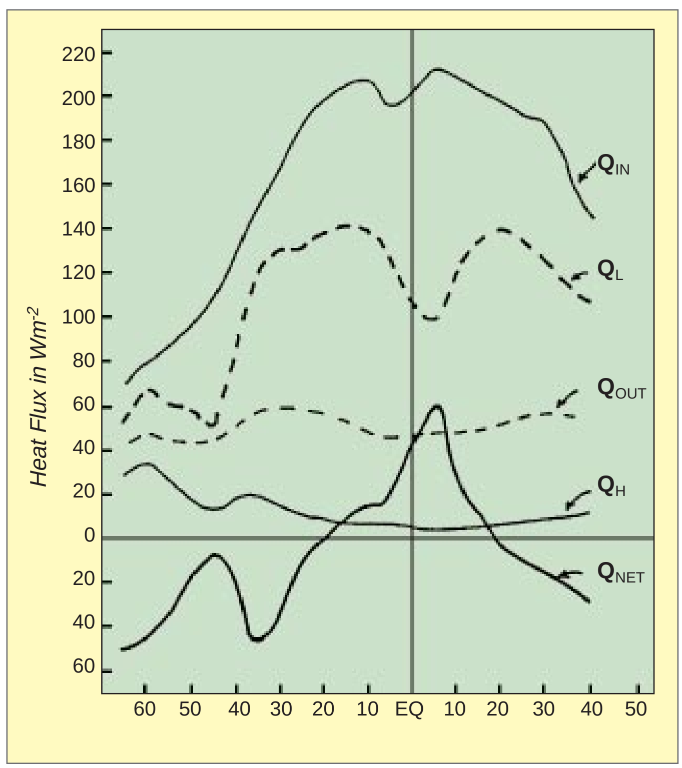
3.2.1 Ocean-atmosphere surface coupling

One of the major scientific requirements of climate research is to quantify the roles of the ocean and atmosphere in regulating the momentum, heat, water, and gas exchange at the air-sea interface. The ocean is not "forced" by the atmosphere but is coupled to it as part of the climate system. Understanding of these exchanges can be conceived of in two parts. The first is the fundamental knowledge of the physics and chemistry of seawater, sea ice, and air, and of the dynamical processes in both atmospheric and oceanic boundary layers. These can be loosely thought of as the "rules of air-sea exchange." The second part is the large-scale atmospheric and oceanic states that together determine the magnitude and direction of the exchange by setting the relevant variables: near-surface winds, air-sea temperature and humidity differences, atmospheric water content and ensuing precipitation, and clouds that control the net surface radiation balance. Both clarifying the "rules" governing air-sea interaction and understanding the role of this interaction in the coupled atmosphere-ocean climate system are important elements of EOS research.

The linkage between the upper ocean and the lower atmosphere operates on relatively short time scales by processes such as seasonal formation of sea ice, stratification of the ocean through surface warming, and the spring bloom of phytoplankton. However, one of the great challenges in climate research is the coupling between the rapidly-varying upper ocean and the slowly-varying deep ocean. If the ocean were just a shallow layer of water, climate prediction would be much simpler. However, the mid ocean and the deep ocean have time scales of years to centuries. For example, deep water formed in Greenland and Labrador seas may not re-encounter the atmosphere for two centuries. Thus the ocean acts as the "memory" of the ocean/atmosphere system. These long time scales lead to teleconnections between widely-separated regions of the ocean (Trenberth and Hoar 1996) with unexpected impacts on climate and ecological processes. Thus climate studies must include both the short-term processes that couple the lower atmosphere with the upper ocean and the longer-term links between the upper ocean and mid- and deep-ocean processes.

The primary mechanisms of local air-sea interaction are well known and qualitatively understood. Sea-surface evaporation tends to cool and salinify the upper ocean, as well as supplying latent heat and water to the atmosphere. There is a strong feedback between water in the troposphere and ocean surface heating: clouds absorb and re-emit outgoing terrestrial radiation and scatter and absorb incoming solar radiation. They also tend to cool and freshen the near-surface water through rainfall. Ocean circulation depends on the net surface fluxes, which are subtly balanced between large incoming and outgoing components, e.g., the near balance between latent heat loss and the solar radiative gain in the heat budget, or the differences between precipitation and evaporation in the surface freshwater budget. The thermal components have equivalent heat transfers on the order of 100 Wm^{-2}, but the variations and differences necessary to understand many climate problems are on the order of 10 Wm^{-2}. This

Figure 3.1



Zonally-averaged heat flux across the air-sea surface (annual meridional profile for three oceans). Q_{IN} is the net incoming solar radiation, Q_{OUT} is the net outgoing longwave radiation, Q_H and Q_L are sensible and latent heat fluxes, and Q_{NET} is the sum of Q_{IN} - Q_{OUT} - Q_H - Q_L *(Hsiung 1986).*

is a severe requirement for both observations and climate models.

More than half of the annually-averaged solar energy entering the climate system is absorbed by the ocean (Sellers 1965). The fate of that oceanic heating is illustrated in Figure 3.1. Although the upward flux of longwave radiation from the ocean surface is large, it is nearly balanced by the downward flux from the atmosphere, and the net radiative flux is therefore dominated by solar radiation. Ninety percent of the net radiative heating of the global ocean is balanced by evaporative cooling, with the remaining ten percent coming from sensible heat exchange with the atmosphere.

Evaporation plays a major role in the freshwater budget of the ocean (Baumgartner and Reichel 1975). On a global and annually-averaged basis, the ocean loses ten percent more water through evaporation than it gains through atmospheric precipitation. Approximate balance is maintained on an annual basis by river runoff. On longer time scales, gradients of these freshwater and thermal inputs and their mixing with the upper ocean constrain the thermohaline component of ocean circulation.

Spaceborne observations provide unprecedented spatial coverage of air-sea interaction parameters; clearly these are crucial EOS observations. A fundamental condition for developing confidence in the ability of global coupled models to simulate climate change is that they be able to reproduce aspects of the observed fields to within the observational errors. To have a significant impact on climate research, we plan for simultaneous observations of these parameters to be continued for a sufficient period to document synoptic, seasonal, and interannual variability of the climate system, and to begin building the database for exploring decadal-to-centennial variability.

One of the most graphic examples of how air-sea interaction affects people's lives is its role in severe storms. The probabilities and actual occurrences of severe storms are affected by ocean variability. The linkages are complex. The Kuroshio carries warm, equatorial waters along the coast to Japan, then enters the interior of the Pacific. Recent analyses show that planetary (Rossby) waves caused the Kuroshio to shift northward during 1993, changing where the ocean releases heat to the atmosphere. The more-remarkable issue, however, is that the Rossby waves were themselves a consequence of the propagation of Kelvin waves associated with the 1982–83 El Niño—first eastward along the equator, then northward along the coast of North America. This is a striking example of the ocean's memory and the time scales of the coupled ocean-atmosphere system (see Jacobs et al. 1994). Another example occurred in 1993 when the jet stream became stuck south of its usual path. This allowed intense cyclone activity to propagate directly into the U.S. Midwest, and also allowed the atmosphere to acquire more moisture than usual from the Gulf of Mexico and transport it in storms lasting 122 days into the Mississippi basin and eastern United States, causing disastrous flooding.

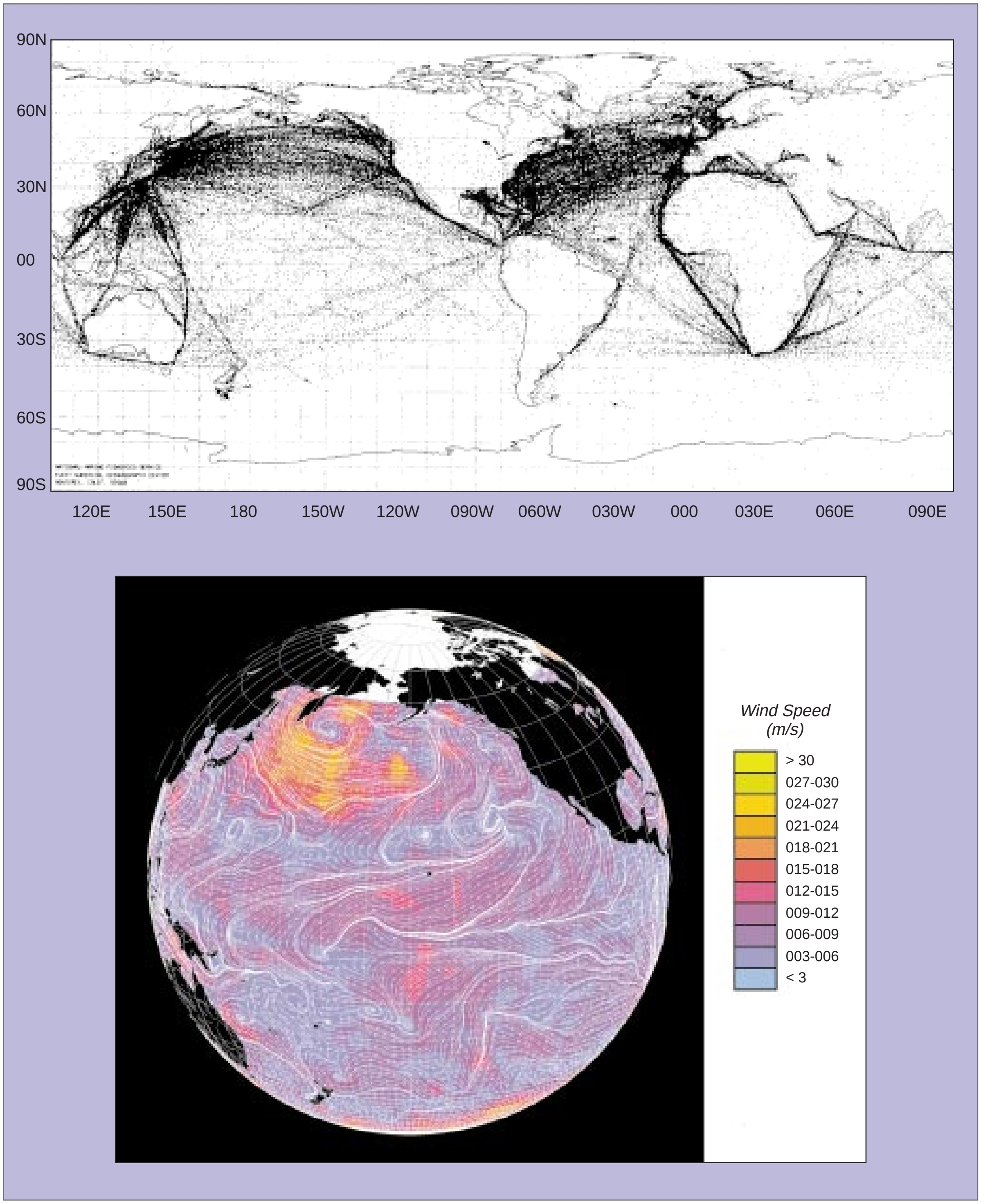
3.2.1.1 Momentum exchange

The exchange of momentum between the atmosphere and the ocean plays a critical role in determining climate (e.g., Gill 1982). Wind stress is the largest single source of momentum to the upper ocean, and air-sea momentum fluxes substantially influence large-scale upper-ocean circulation, smaller-scale mixing, and, through wave generation, the detailed shape of the sea surface on scales from centimeters to hundreds of meters. The wind-dependent roughness (variable geometry) of the surface directly influences the air-sea fluxes of all other quantities (e.g., sensible and latent heat, water, and gases). Air-sea momentum fluxes and near-surface winds thus modulate the coupling between the atmosphere and the ocean. Understanding, measuring, and ultimately predicting air-sea momentum exchange and the partitioning of this momentum between oceanic motions on various scales are thus among the central tasks in climate research.

Most historical estimates of large-scale air-sea momentum fluxes were based on compilations of direct observations of near-surface winds and sea conditions (e.g., Hellerman and Rosenstein 1983). The great hemispherical disparity in ocean surface area (larger in the Southern Hemisphere) and density of shipping tracks (much larger in the Northern Hemisphere) resulted in large geographical differences in the accuracies of these climatologies. Thus, while typical annual-mean global wind stresses are 0.1-0.15 N m^{-2}, statistical uncertainties ranged from less than 0.01 N m^{-2} in the northern midlatitude and tropical oceans to more than 0.05 N m^{-2} in mid and high southern latitudes (Hellerman and Rosenstein 1983). Comparisons between climatologies produced by different investigators yielded differences that were often larger than the error estimates of each of the individual products (Harrison 1989).

More recently, large-scale air-sea momentum flux climatologies have been constructed from operational surface wind analyses produced by weather prediction centers (e.g., Trenberth et al. 1990). Although the analysis/forecast systems include sophisticated physics and attempt to assimilate all available surface and upper-air data, significant differences also exist between and among these climatologies and with conventional and remotely-sensed data sets (e.g., Mestas-Nunez et al. 1994), with the climatically important tropics and high Southern lati-

Figure 3.2



The top image shows locations of all ship observations of surface meteorological variables for 100 days beginning 1 July 1978; one acquires the same number of observations, globally distributed, in one day of NSCAT observing *(Freilich 1985, JPL Pub. 84-57).* The bottom image shows a synoptic wind field derived from interpolated ERS-1 scatterometer data for February 10, 1993. The color in the image represents wind speed, and the streamlines indicate wind direction *(courtesy of T. Liu and W. Tang).*

tudes exhibiting the largest uncertainties and intercomparison differences. Figure 3.2 illustrates the huge sampling advantage of a satellite.

Differences and errors in the wind stress fields used in ocean and coupled ocean-atmosphere modeling lead to significant differences in the models' predictions. As just one example, a recent comparison of tropical ocean model results driven by three widely-used wind stress climatologies concluded that large differences in the model predictions of equatorial oceanic circulation resulted primarily from differences in the wind-stress forcing (Bryan et al. 1995b). In addition, Milliff et al. (1996) have shown that modern ocean model predictions are sensitive to small-scale wind stress features that are undoubtedly present in the real world but are unresolved in all existing air-sea momentum flux climatologies.

The past two decades have witnessed a great advancement in our ability to measure near-surface winds and air-sea momentum fluxes using satellite-borne instruments. Microwave multichannel radiometers and active scatterometers have been proven capable of acquiring all-weather measurements of wind-stress magnitudes (radiometers) and vector stresses (scatterometers) over extensive areas with high spatial resolution. The accuracies of these measurements (discussed in more detail in Section 3.3) are comparable to those of in situ meteorological buoys, while their global coverage substantially eliminates the geographical disparity in data distribution that dominates historical wind stress climatologies. Construction of consistent, high-resolution, accurate wind-stress (air-sea momentum flux) data sets and their application in ocean and climate modeling represents a crucial component of the EOS science objectives.

3.2.1.2 Thermal fluxes: radiative and turbulent

Surface heat exchange can be divided into four components: sensible heat resulting from the vertical thermal gradient, latent heat of evaporation, shortwave radiation from the sun, and longwave radiation from the atmosphere and the ocean. Sensible and latent heat fluxes are transported by turbulence. The parameterization of turbulence in terms of average measurements (wind speed, air temperature, air humidity, and sea-surface temperature [SST]) in routine ship reports has been extensively studied in the last few decades. Spaceborne sensors can measure surface wind speed and SST over the ice-free ocean, but not air temperature and humidity.

The ocean has a thermal inertia that is much greater than that of the atmosphere, but it is an oversimplification to view the atmosphere as a slave to the ocean, consisting of independent vertical columns of air in equilibrium with a local value of the SST. As early as the mid-1960s, Bjerknes argued that it is likely that decadal-to-centennial variations in the thermohaline circulation depend on exchanges of heat and water with the atmosphere that are explained not solely by local air-sea interaction but more by changing modes of atmospheric and oceanic circulation. His insight is being proved correct. The theory of the El Niño-Southern Oscillation (ENSO), the periodic warming of the southeastern Pacific and all the attendant oceanic and atmospheric changes, depends on the ability of both the atmosphere and ocean to support equatorial waves that form coupled large-scale fluctuations that would not exist in either the ocean or atmosphere alone (Zebiak and Cane 1987).

Some recent theoretical studies have begun to isolate and quantify the most important processes that regulate air-sea exchanges of heat and water. Simple atmospheric boundary layer models containing only large-scale horizontal advection of heat and moisture, surface fluxes, and entrainment of dry air from aloft into the atmospheric boundary layer (Kleeman and Power 1995; Seager et al. 1995), can explain much of the observed pattern of sensible and latent heat fluxes over the global oceans, such as the observed seasonal changes in latent heat flux over the North Atlantic shown in Figure 3.3. Simple ocean-atmosphere column models have been used to explore the subtle relationships between radiation, convection, and large-scale divergent circulations in the ocean and atmosphere, and their role in regulating air-sea exchanges of heat and water (Betts and Ridgway 1989; Sui et al. 1991). EOS will produce data sets and analyses over the global oceans that are necessary to test these working hypotheses. In the data-sparse areas of the southern and tropical oceans, the utilization of satellite observations will provide the first reliable estimates of the near-surface turbulent and radiative fluxes.

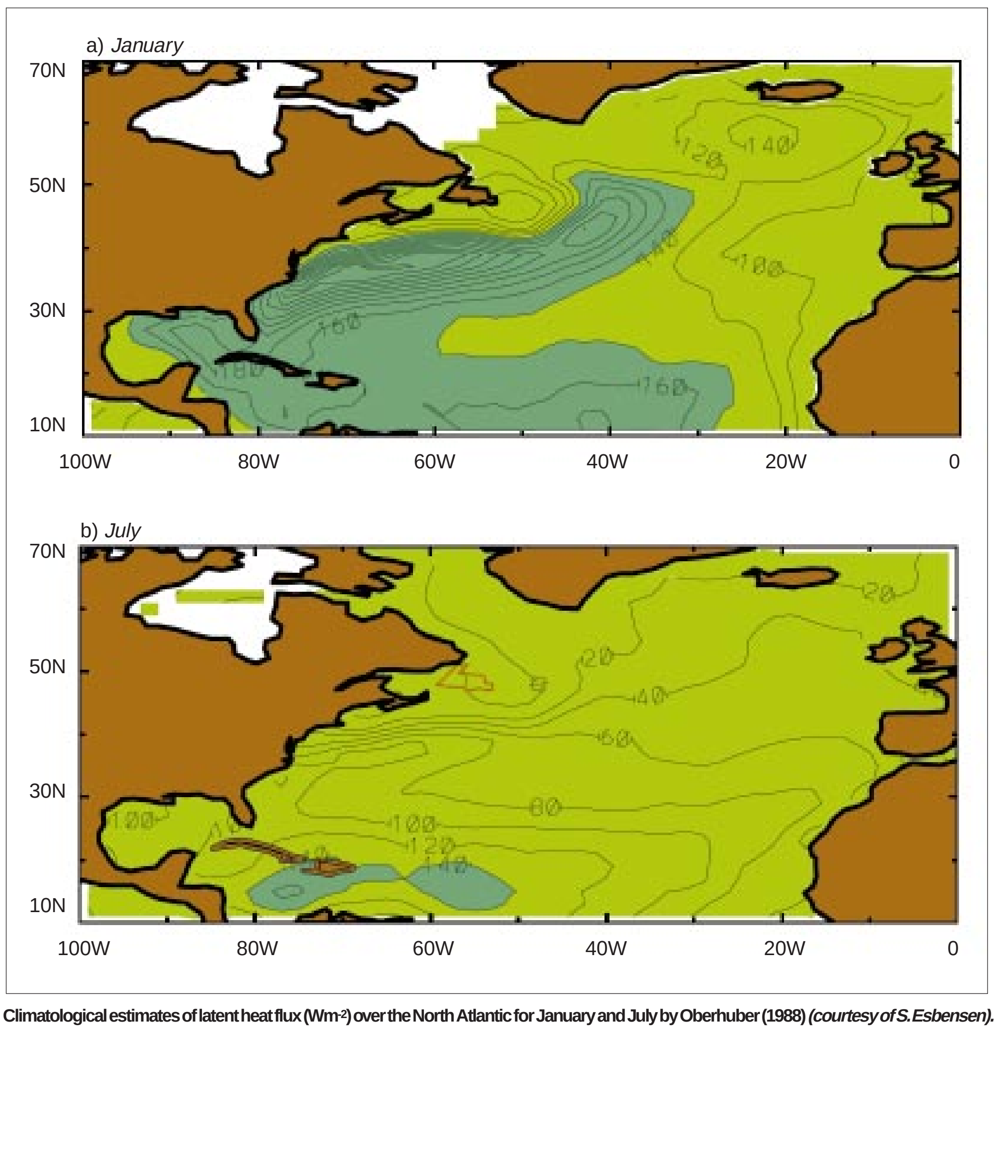
3.2.1.3 Freshwater forcing: evaporation, precipitation, and sea ice

The sources and sinks of freshwater at the ocean surface are a crucial component of the global water balance which is shown in Figure 3.4. The ocean loses about 10% more freshwater through evaporation than it gains through precipitation (Baumgartner and Reichel 1975). The remaining 10% is contributed by river runoff, with the change in storage of freshwater in the oceans being a much smaller residual. The surface freshwater flux determines upper ocean mixing and the thermohaline component of ocean circulation. The stabilizing effect of a local net freshwater surface input limits the efficiency of ocean-atmosphere communication: it impedes heat exchange with subsurface layers, nutrient transport to the upper ocean, and trace gas exchange with the atmosphere. In the atmosphere these fluxes determine atmospheric moisture content and latent heat that drive tropospheric convection, horizontal advection, and precipitation patterns.

Surface freshwater forcing is believed to play a primary role in setting the background state and timing of the large interannual phenomenon of ENSO. Theory suggests that equatorial upper-ocean heat content and mixed-layer depth are crucial in setting ENSO time scales (Zebiak and Cane 1987). Over the western Pacific warm pool region, the upper-ocean mixed layer is observed to be very shallow, on the order of 30 m, apparently due to a combination of stabilization by precipitation and highly intermittent wind forcing (Lukas and Lindstrom 1991). Long-term observations that permit the accurate estimation of precipitation, evaporation, and wind stress are therefore likely to be important for an improved understanding of ENSO, and for the development of a quantitative ENSO prediction capability.

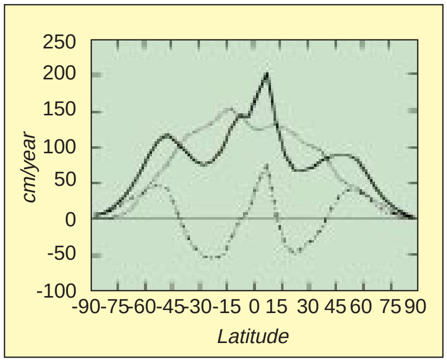
On longer time scales, the present picture of the global thermohaline circulation includes surface processes in both north and south polar seas. Sea ice melts and freezes, forcing the surface freshwater balance in complete analogy with evaporation and precipitation. The Arctic Ocean is a large ice-covered estuary that funnels freshwater from rivers and the North Pacific Ocean across the Pole and into the North Atlantic Ocean. In a sense, the Arctic acts as a global "choke point" for calculating the freshwater budget of the world ocean (Wijffels et al. 1992). Part of this freshwater is converted to sea ice during the winter and exits the Arctic Ocean through Fram Strait;

Figure 3.3



Climatological estimates of latent heat flux (Wm^{-2}) over the North Atlantic for January and July by Oberhuber (1988) ***(courtesy of S. Esbensen).***

Figure 3.4



Latitudinal distribution of the global surface hydrologic balance, showing evaporation *E*, precipitation *P*, and runoff Δf *(data from Baumgartner and Reichel 1975).*

the remainder stays in liquid form and exits through both Fram Strait and the Canadian Archipelago. This low-salinity Arctic outflow is delicately balanced with respect to the underlying water masses in the subpolar North Atlantic. Small changes in the amount and salinity of the outflow are sufficient to permit or restrain deep convection in the Greenland and Labrador seas, which in turn affects the global thermohaline circulation (Broecker and Denton 1989). Deep convection is thought to be controlled by rapid cooling and freezing of this cold, low-salinity outflow. Recent observations indicate that the formation of North Atlantic Deep Water (NADW) in the Greenland Sea experiences large interannual changes, and in fact may have shut down completely in recent years (Schlosser et al. 1991). In ways not understood at present, the supply of NADW is thought to be linked with the wind stress driving the Antarctic Circumpolar Current in controlling the world ocean's deep thermohaline circulation.

The Southern Ocean is the source of the coldest oceanic deep water, Antarctic Bottom Water (AABW). The density stratification of the Southern Ocean is weak compared to waters at lower latitudes and is largely determined by salinity. The lack of vertical stratification implies that the dynamical scales of ocean eddies in the Southern Ocean are very small and that topographically-induced disturbances extend to the surface. The large-scale geostrophic flow is not sufficient to explain the Southern Ocean heat budget in the AABW source region (de Szoeke and Levine 1981), suggesting that mesoscale eddies may be responsible for supplying the required advective contributions. Similarly, measured sediment fluxes and the apparent new nitrate production that is available for export do not balance (Honjo 1990; DeMaster et al. 1992; Smith and Sakshaug 1990). One possible explanation is that there may be considerable vertical transport of organic matter that is not explained by gravitational sinking. Thus, in addition to the physical processes associated with the Antarctic sea ice distribution, the freshwater input at the surface is thought to play a role in determining the location and characteristics of ocean disturbances responsible for AABW formation and the biological productivity of the region. Accurate long-term observations of surface thermohaline and mechanical forcing are required to understand such complex interactions between the physical and biological systems over the global oceans.

3.2.2 Ocean circulation

Ocean circulation is important for three reasons:

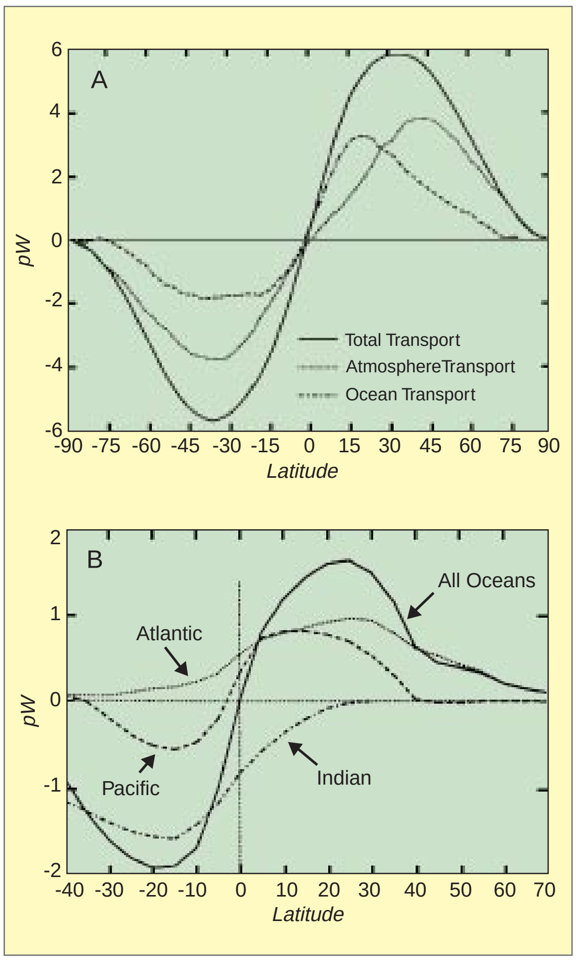
- horizontal heat transport,
- establishment of surface temperature patterns that are important to air-sea exchange, and
- transport of nutrients, chemicals, and biota for biochemical processes.

3.2.2.1 Oceans and the global heat balance

The oceans play a vital role in the heat balance of the globe by acting as a storage medium of thermal energy and by transporting thermal energy from the tropics to middle and high latitudes. In fact, as Figure 3.5 (pg. 124) shows, the ocean and atmosphere each transport about half of the total poleward heat flux in the global climate energy balance (Trenberth and Solomon 1994). Over large portions of the oceans, seasonal heat storage is very local because thermal energy cannot be transported over great distances during a single season (Gill and Niiler 1973). However, along western boundaries and on the equator a very different picture emerges. There is a net flux of heat into the equatorial oceans due to the intensive solar radiation, and this thermal energy is transported poleward by wind-driven currents of the surface layers (Wyrtki 1982). The poleward transport reaches a maximum in the Horse Latitudes (30-35° N and S), where the western boundary currents become well formed. The warm water moving poleward from these latitudes is intensely cooled by the dry and cold air masses that spill from the continents each winter. In each ocean basin this process is somewhat different; it is most intense in the North Atlantic and results in significant warming of the air in its journey to northern Europe. The British Isles are kept so much warmer than Siberia in winter not by oceanic heat stored locally in summer, but by the great northward flow of heat in the Gulf Stream (Stommel 1979).

Besides its ability to transport heat, the ocean is simply very efficient at absorbing and storing heat. Compare the situation with land. The ocean thermal capacity is several orders of magnitude larger than that of land because water is more absorptive to visible radiation, and the turbulent diffusivity of heat in the wind-blown sea is several orders of magnitude larger than that of soil (Niiler 1992). One consequence is that the seasonal range of the air temperature over the ice-free ocean is seldom more than 17˚C, while over the continental land masses the seasonal peak can be in excess of 70˚C. The exceptions are coastal land areas that possess a milder “maritime” climate and attract a much-larger population density than continental interiors.

Figure 3.5



A) Estimates of the annual mean meridional energy transport (positive northward) required by the energy balance at the top of the atmosphere, estimated from atmospheric observations by Peixoto and Oort (1984) and the Earth Radiation Budget Experiment, in petawatts (=10^{15} W). The oceanic transport is obtained by subtracting the atmospheric energy transport from the total transport required by the annual energy balance. B) Meridional profiles of the northward oceanic heat transport for the various oceans, computed indirectly from the surface heat balance *(Adapted from Hsiung [1985]).*

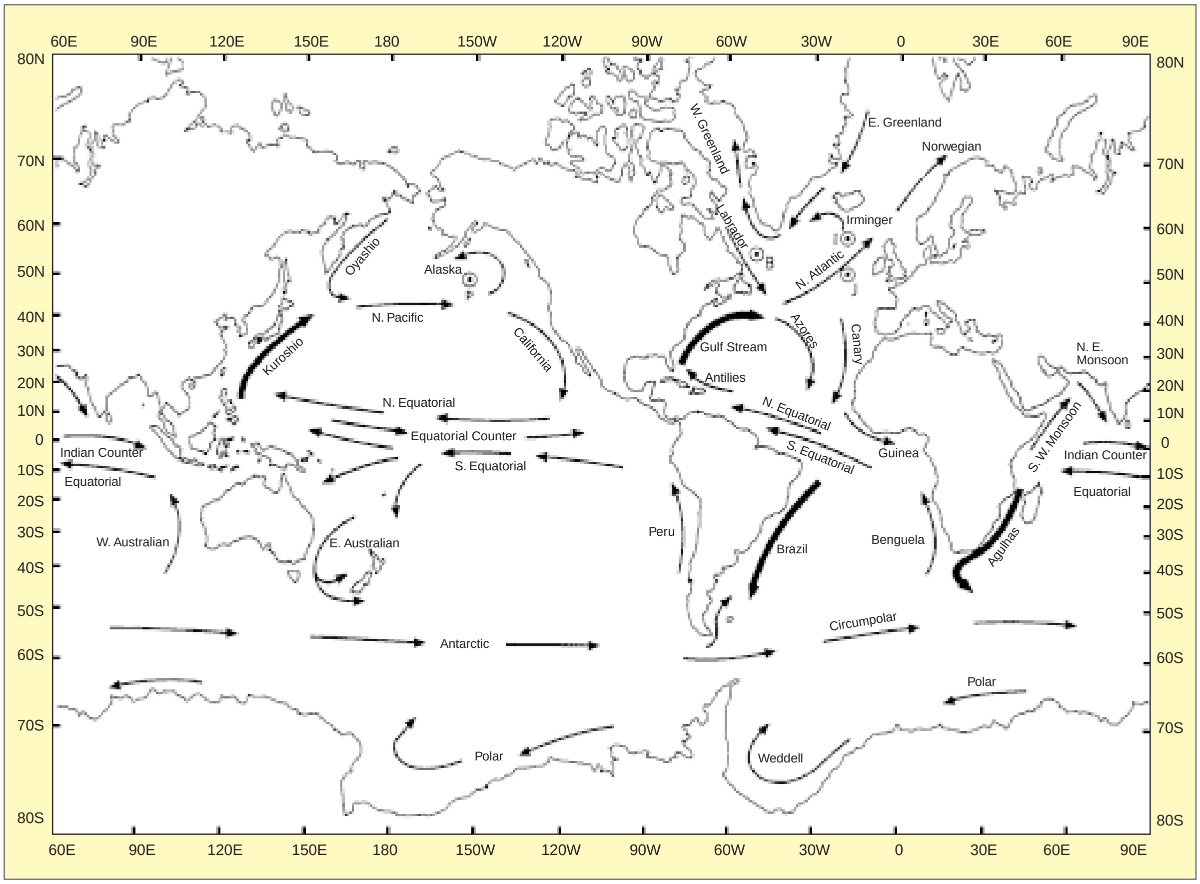
Although the importance of the ocean in determining weather and climate has long been recognized, we are now in the early stages of applying ocean-atmosphere forecasting to such practical uses as crop and fisheries management. For instance, the focus on the interannual variability of air-sea interaction in El Niño is elucidating the mechanisms by which global weather patterns are altered by the ocean. Correlations between El Niño and crop yields are significant; the presence of El Niño appears to cause a 15% crop decrease in the southeast United States. Twelve-month forecasts are leading to experimental efforts at crop selection on a year-by-year basis, for instance, in Brazil and Peru. These forecast techniques are at present a blend of statistical and physical models. The physical basis of these forecasts can be strengthened if better data sets are acquired to improve their initialization and the understanding of the model processes.

3.2.2.2 Ocean circulation

The ocean general circulation shown in Figure 3.6A is dominated by vorticity conservation and the mechanisms by which vorticity is generated and dissipated. Vorticity dynamics determine the position of major ocean current systems such as the Gulf Stream, the Kuroshio, and the Antarctic Circumpolar Current. Except near the equator, the horizontal circulation (barotropic or depth-averaged flow) is largely forced by the wind stress curl through Ekman dynamics. Wind stress supplies oceanic vorticity by imparting a convergence (divergence) within the mixed layer in the subtropical (subpolar) gyres. Western boundary currents return water poleward (equatorward) in the major subtropical (subpolar) gyres and provide a means for dissipating vorticity. Within a few degrees of the equator, wind stress, in combination with the variation in the Coriolis parameter, drives the equatorial current system. Bottom topography and coastlines constrain the flow and combine with both the north-south gradient in the Coriolis parameter and wind stress to determine the general circulation. Instability of the large-scale circulation and the interaction of this flow with the bottom topography are primary sources of energy for eddies that move heat poleward in concert with the mean currents. We still need to improve our parameterizations of bottom drag and the effect of unresolved eddies upon the larger-scale flow.

Thermohaline circulation determines the vertical distribution of heat, salt, and momentum. It is the thermohaline circulation that transports deep water formed in the polar regions to low latitudes and eventually to the surface in upwelling regions as shown in Figure 3.6B (pg. 124). Aspects of this transport are becoming known

Figure 3.6A



The principal surface currents of the World Ocean. Western boundary currents are shown bold *(Mann and Lazier 1991).*

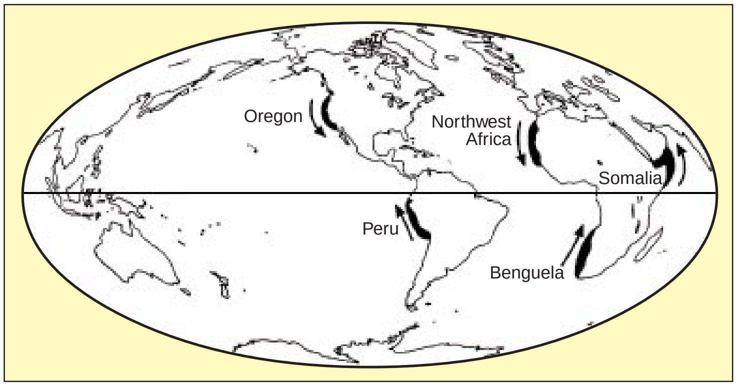
through analysis of in situ data, especially of deep tracers.

Forcing the thermohaline circulation is an interplay of atmospheric fluxes, solar heating, and oceanic flow that combine to determine the position at which isopycnal surfaces outcrop and largely control the temperature-salinity (T-S) characteristics of deep water during its formation at the surface. Vorticity dynamics remains a crucial element controlling the oceanic response to this forcing, although mixing and diffusive processes are also important. The oceanic mixed layer conveys most of the surface flux to the interior of the water column, and therefore upper-ocean processes are important to the thermohaline circulation. Seasonal cycles and the formation and dissipation of a seasonal thermocline are important in much of the midlatitudes.

Mixing processes that allow the T-S properties of water to be changed away from the ocean surface, although qualitatively understood, must be quantified. These include roles of topographically generated mixing, internal wave breaking, and background turbulence in the cross-isopycnal mixing needed to raise the buoyancy of deep water so that this water may reach the surface at low latitudes. The role of mesoscale eddies and other transient events in mixing the deep water is not well understood, nor is the importance of seasonal cycles and decadal-scale variability, both as the result of internal processes and as driven by variations in surface thermohaline forcing. An additional aspect of the thermohaline circulation is the prospect of thermohaline catastrophe, a fundamental change in the thermohaline circulation; modeling studies have demonstrated the capacity of the thermocline system to undergo dramatic internal changes in response to small changes in the forcing.

While the general circulation of the upper ocean is known, the deep circulation shown in Figure 3.7 (pg. 127) is more speculative. Also, we do not fully understand the processes involved with specific regional circulation pat-

Figure 3.6B



Major coastal upwelling regions, with arrows indicating the prevailing winds *(Mann and Lazier 1991).*

terns, yet these currents can be important to the meridional heat transport. Deep western boundary currents transport deep water rapidly towards the equator, losing water into the midlatitude gyres and providing a source of deep water to the central gyres. The processes that determine the deep western boundary currents, the rate of flow, and the fate of water entrained into these currents, are not known. Strong upwelling occurs along the equator and in eastern boundary current regions. Both processes are driven by wind stress and significantly alter the local upper-ocean temperature pattern. In midlatitudes, the mean surface heat flux is into the ocean in eastern boundary current regions and into the atmosphere away from them. In the Southern Ocean, the heat balance of the Antarctic Circumpolar Current cannot be reconciled with existing in situ measurements; eddy fluxes have been hypothesized as the missing component of the heat balance. These aspects of the ocean circulation must be resolved and properly represented in climate models.

To understand the thermohaline circulation, we must know not only the wind stress but also surface fluxes of heat and freshwater that force the baroclinic circulation. In concert with mixing and advection, these fluxes produce a rich array of "water masses" with individual, distinguishable T-S properties that are tied to source and history of a parcel of water. Together, these processes constitute the "conveyor belt" that transports warm salty surface water poleward and colder, fresher deep water equatorward. The thermohaline and barotropic circulations are intimately linked, making it difficult to approach them independently.

To quantify temporal changes in the circulation, four measurements from space are essential.

- *Winds at 10 m.* We do not have an adequate global picture of the mean, the seasonal changes, or the daily wind stress curl, the input of vorticity to the oceans (see Section 3.2.1.1).

- *Surface temperature and surface radiative, sensible, and latent heat fluxes.* As argued in Section 3.2.1.3, the latter quantities force the thermohaline component of the circulation; SST is a crucial diagnostic not only of ocean circulation but of the Earth's climate.

- *Surface salinity and evaporation and precipitation.* Again, the latter quantities force the thermohaline component of the circulation; salinity is a diagnostic of this surface forcing.

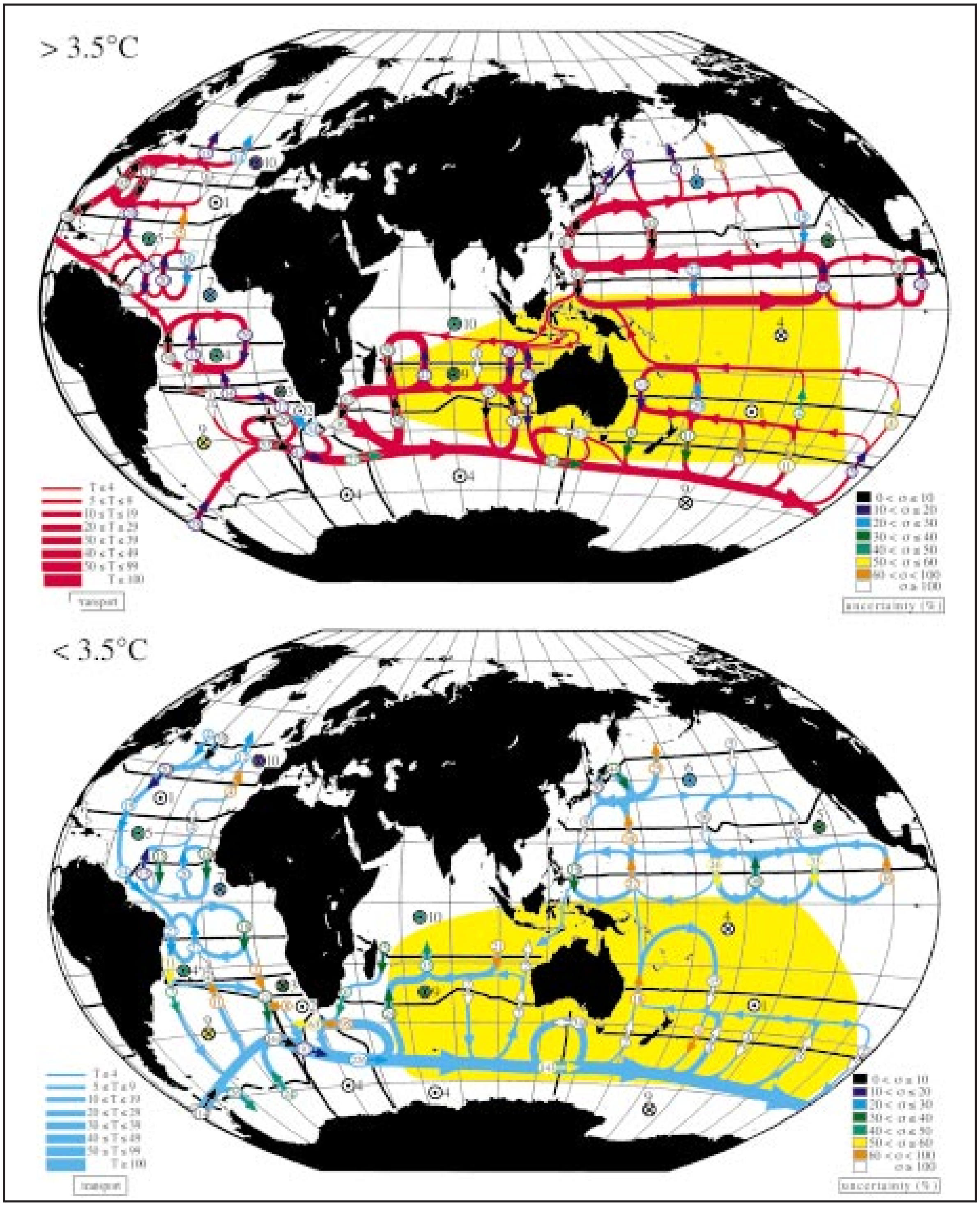
- *Surface geostrophic currents, as observed with altimetry.* They are the "response" to the "forcing," and through the density stratification they constrain deep currents. It is important to remember the strong correlation between the surface and deeper levels.

3.2.2.3 Ocean modeling and data assimilation

Numerical ocean models embody simplifications of the equations that govern the dynamics and thermodynamics of the oceans. Future versions may incorporate biological processes, and perhaps chemical ones—the transport of possible chemical tracers is already encoded in current numerical models. Two of these simplifications are the quasi-geostrophic (Holland 1986) and the hydrostatic (Marshall et al. 1993), which is embedded in most primitive equation models.

In order to complete a useful simulation in present-day computers, other simplifications are introduced. Global models with relatively coarse spatial resolution are on the verge of resolving mesoscale eddies (e.g., Semtner and Chervin 1992) as some regional models already do (Bryan et al. 1995a). However, the rapid increase in computer power keeps changing the boundary. Another trade-off is the representation of the vertical density structure and associated change of properties. "Level" models (with the vertical quantized by depth) are generally thought to have excessive cross-isopycnal mixing, while layer models (with the vertical quantized by density) impose restrictions in modeling an upper-ocean mixed layer (New and Bleck 1995). Of course, regional models require specifying the flow and other fluxes at the open

Figure 3.7



Schematic of the global ocean circulation deduced from the best-estimate model *(Macdonald and Wunsch 1996).* The two panels (red and blue) illustrate the flow pattern of waters of potential temperatures greater and less than 3.5° C, respectively. The strength of the flows (in 10^9 kg s^{-1}) are indicated where they cross the model sections and are further illustrated by the thickness of the lines. Color shading indicates the uncertainty of the transport values (given as a percentage of the transport value). Circles with dots indicate upwelling within a box through the 3.5° C interface. Circles with crosses indicate downwelling. The yellow shading indicates the deduced region of influence of the Pacific-Indian throughflow *(courtesy of A. Macdonald).*

boundary, which makes them unsuitable for long-term climate studies.

Lacking actual data for surface fluxes of fresh water and heat, most models simulate these fluxes as proportional to the difference between model values and either climatologically averaged values that drive the model to correct upper-ocean climatology or atmospheric values from an atmospheric general circulation model (GCM).

Assimilation models change the “state” (model variables at all grid nodes) predicted by a numerical model based on data that differ from the model predictions; the modified model state in turn influences the future model evolution (e.g., Bennett and Chua 1994). Various techniques for assimilation are still maturing, and range from simple nudging (Sarmiento and Bryan 1982) to adjoint models (Thacker and Long 1988) and Kalman smoothers (Fukumori et al. 1993). The key practical problem remains the trade-off between computational burden and accurately using information on errors in the data and in the model to give proper weight to both the data and the model predictions.

The key advantage of assimilation is its ability to “propagate” information given by one data type and location to other variables and locations. To the extent that the physical model is accurate, the model, after assimilation, gives a four-dimensional description of the ocean (x, y, z, t) that is consistent with all the data, within their errors, and thus useful to understand the ocean processes responsible for the ocean’s state. By examining the differences between the assimilation and the data, one can determine model deficiencies and what additional data are needed to further constrain the model.

3.2.3 Global sea-level rise

Major climate-related factors that contribute to sea-level rise are thermal expansion in the oceans (steric changes) as well as ablating mountain glaciers and polar ice sheets. Other factors include complex processes of air-sea interaction and ocean circulation, as well as geophysical causes such as the postglacial rebound and ocean basin uplifts. Major uncertainties exist in the contributions of the Greenland and Antarctic ice sheets to recent changes in sea level as well as predicted future changes. The paucity in observational data concerning the mass balance of the polar ice sheets is the primary contributor to these uncertainties. Nevertheless, the polar ice sheets hold the potential for a global sea-level rise of 75 m if they were to experience complete melting.

Even partial shrinkage of the polar ice sheets would inundate the major coastlines of the world and produce serious economic consequences. However, such a collapse does not appear to be imminent, although the West Antarctic ice sheet exhibits unstable characteristics. Of more-immediate concern are the effects of sea-level rise at the present rate of several mm/yr. The economic impact clearly increases as the rise increases. An example of the sensitivity of the coastal ecosystem to sea level is found in Louisiana, where balcypress trees on fifty thousand acres of wetlands were defoliated in 1993 by an insect to which the trees were made vulnerable by increased salt-water flooding. The exposure of coastal commerce and property to severe storms is clearly worsened by the gradual rise of sea level. A rise of 3 mm/yr sounds immaterial but produces a rise of almost 10 cm in 30 years, a rise that could threaten wetlands and produce increased coastal erosion. A goal of EOS is to reduce the uncertainties in these estimates and provide a capability to predict the future state and human impact of sea level.

3.2.3.1 Mean ocean surface height

During the last Ice Age, 18,000 years ago, the global sea level was more than 100 m lower than at present. Recent studies of global sea-level change (Warrick and Oerlemans 1990) have concluded that the average rate of rise during the last century has been 1 to 3 mm/yr and that sea level by the year 2070 A.D. may be 20 to 70 cm higher than today. The thinking is that the increasing concentration of atmospheric greenhouse gases leads to global warming, which strongly affects the distribution of stored water and ice on the Earth (e.g., Peltier 1988; Warrick and Oerlemans 1990). Nearly half of the predicted sea-level rise would be due to thermal expansion of the oceans. The remainder would be caused by melting of Antarctica, Greenland, and other ice sheets and glaciers and by geophysical processes. Over longer time scales of glacial cycles, the thermal expansion of the oceans can account for a rise or fall of at most several meters.

One basic strategy for testing the notion of greenhouse warming is to detect and monitor global mean sea level. The strategy for EOS is to measure both mean sea level with radar altimeters and ice-sheet volume with laser altimeters.

Until the availability of satellite altimetry, long-term observations of tide gauge measurements have been used to monitor sea-level change. Recent tide gauge measurement studies indicate that the global mean sea level has risen over the last century at a rate of 1-3 mm/yr (Peltier 1988; Douglas 1991), with a suggestion of possible acceleration since the middle of the last century. The poor global distribution of tide gauges (mostly in coastal regions, therefore significantly affected by the effect of postglacial rebound) and the use of a dynamically changing reference make it difficult to separate these effects. However, by coupling satellite measurements with global circulation models, these effects can be separated because they are expected to have quite distinct spatial and temporal patterns. The advantage of tide gauges is that they provide a multi-decadal observational record, and they can act as in situ calibration devices for radar altimeters.

Satellite altimetry missions in this decade and beyond (the Earth Remote-sensing Satellite [ERS-1], Ocean Topography Experiment [TOPEX]/Poseidon, ERS-2, Geosat Follow-On [GFO], Environmental Satellite [ENVISAT], and EOS Jason-1) will provide global measurements of long-term mean sea level and its variations with an accuracy approaching 1 mm/yr. The unprecedented accuracy of TOPEX/Poseidon enables a number of studies based primarily on the technique reported by Born et al. (1986). Figure 3.8 (pg. 130) shows that during a 42-month period sea level rises in some regions by up to 60 mm/yr and falls similarly in others while the global mean essentially shows a slight fall at 0 ± 2 mm/yr (Guman et al. 1996). There is evidence that the global-scale sea-level variations are due to dynamical phenomena such as El Niño with time scales of several years. This is a clear case where a monitoring period longer than a decade will greatly clarify our understanding. As the multi-year phenomena are "averaged out," the secular change in sea level will become more evident. An effort linking operational and scientific altimeters (Geosat, ERS-1, and TOPEX/Poseidon) from 1987 to 1995, with a 4-year data gap between 1989 and 1992, shows that the global mean sea level is rising at a rate of 1 ± 5 mm/yr (Guman et al. 1996). The large uncertainty is primarily due to the inaccurate calibration between Geosat and TOPEX/Poseidon and insufficient knowledge of the instrument drifts. The uncertainty will decrease with improved calibration and longer data span. Figure 3.9 (pg. 131) shows the Pacific mean sea-level variation over 9 years from both altimeters and tide gauges; the trend is 0 ± 2 mm/yr. The agreement between altimeter and tide gauge sea-level measurements is good. EOS will contribute 1) a longer data span and 2) improved modeling of ocean circulation and geophysical effects to allow the separation of the global warming signal and other natural processes.

3.2.3.2 Ice sheets, glaciers, and continental movements

Potentially the largest influences on sea level (up to 80 m of sea-level equivalent) come from land ice. The main reservoirs are mountain glaciers (0.5 m of sea-level equivalent), the Greenland ice sheet (7 m), and the ice sheets in West Antarctica (6 m) and East Antarctica (65 m). In the ordinary view, the sensitivity of the ice sheets to climate change, and the rate at which they are likely to deliver water to the oceans, is inversely related to their size. However, this generality would fail if dynamic processes destabilized an ice mass, such as the West Antarctic ice sheet.

The scientific challenges are to assess the modern state of balance of the ice masses, and especially to predict their future balance in a modified climate. At present, the combined uncertainties in the mass balances of land ice are larger than the uncertainty in sea-level rise and contributions from other sources, so the ocean is our most sensitive indicator of land-ice mass balance. As we wish to predict sea-level change, this is an unacceptable situation. The goals and requirements for measuring the mass balance of ice sheets and glaciers are described in Chapter 6, "The Cryospheric System."

3.2.3.3 Steric change and ocean circulation

Overall heating also changes sea level by causing thermal expansion of a column of seawater. In general, these changes give rise to an altered sea surface and ocean density structure. Repeated altimetric observations of the global mean sea-surface height determine the change in the total volume of water in the ocean. For this calculation, the geoid (the shape of the "locally level" sea surface) need not be known. In situ data on changes of the temperature and salinity structure determine what part of the change in the volume of the ocean is due to changes of state in the seawater; any residual should equal the net contribution from melting ice.

In addition to the global mean sea level, there is great practical importance to local mean sea level. To know how local mean sea level is changing requires much more knowledge, including changes in the major current systems. To know these, one needs to know the geoid, and the long-term changes in the ocean surface forcing—winds, and the net surface freshwater and heat fluxes.

3.2.3.4 Ocean tides

The astronomical tides result from the gravitational interaction of the Sun, the Moon, and the Earth. Tidal periods are well known and range from 12 hours to 18.6 years. Because tides are a nearly resonant sloshing of water in a rotating ocean basin with islands, trenches, and shelves, tidal amplitude and phase are difficult to predict accurately from first principles, particularly in coastal regions and semi-enclosed seas. Predictions based on harmonic analysis of tidal data also contain uncertainty, because non-tidal dynamical phenomena have similar natural frequencies.

Progress in quantifying tides depends on assimilating surface-height data into hydrodynamic models. The advent of satellite altimetry in the 1980s, along with space geodetic measurements such as satellite laser ranging

(SLR) to geodetic satellites, and advances in numerical tidal modeling and data assimilation have enabled the prediction of global ocean tides in the deep ocean with unprecedented accuracy. Ten global tide models developed since 1994 agree within 2-3 cm in the deep ocean, and they represent an improvement over the earlier Schwiderski model by approximately 5 cm rms (Shum et al. 1996).

Because tides cause a larger sea-level signal than temporal changes in ocean circulation and sea level, an accurate tidal model is required to remove the tidal signal for studies of ocean circulation with altimetry. Tides do more than contaminate ocean circulation signals; they directly affect the ocean loading of the sea bed and hence the geodetic shape of the Earth and its instantaneous gravity field. Their effect on gravity causes slight perturbations in satellite orbits. So knowledge of tides is crucial for extracting a full range of accurate geometric information from altimetric and geodetic measurements.

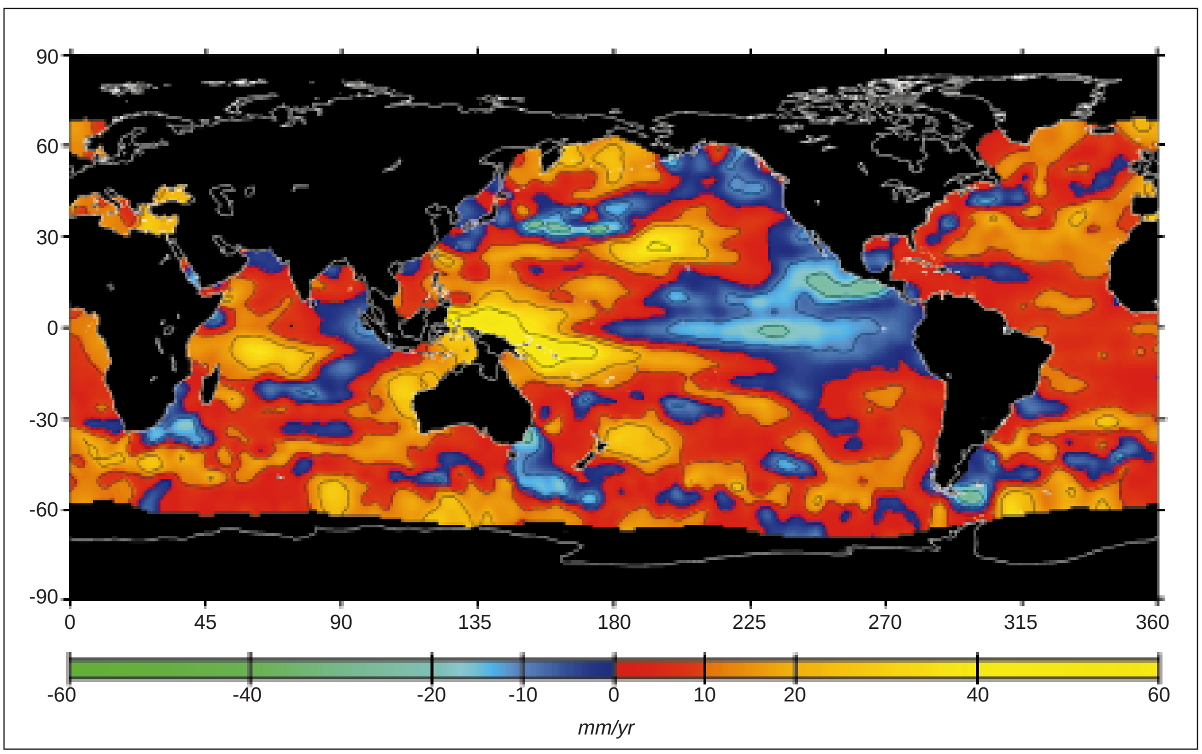
Tides have been of immense commercial importance for millennia, especially for coastal commerce. The better known deep water tides are generally used to constrain very-fine-resolution coastal models at their seaward boundaries. The largest differences in predictions by various tide models occur in precisely those regions most crucial for human activity—shallow coastal waters—where forecasts of waves, eddies, local sea-level changes, and storm surges vitally affect coastal populations, fisheries, and offshore oil exploration and drilling.

3.2.4 The marine biosphere and ocean carbon system

3.2.4.1 Introduction

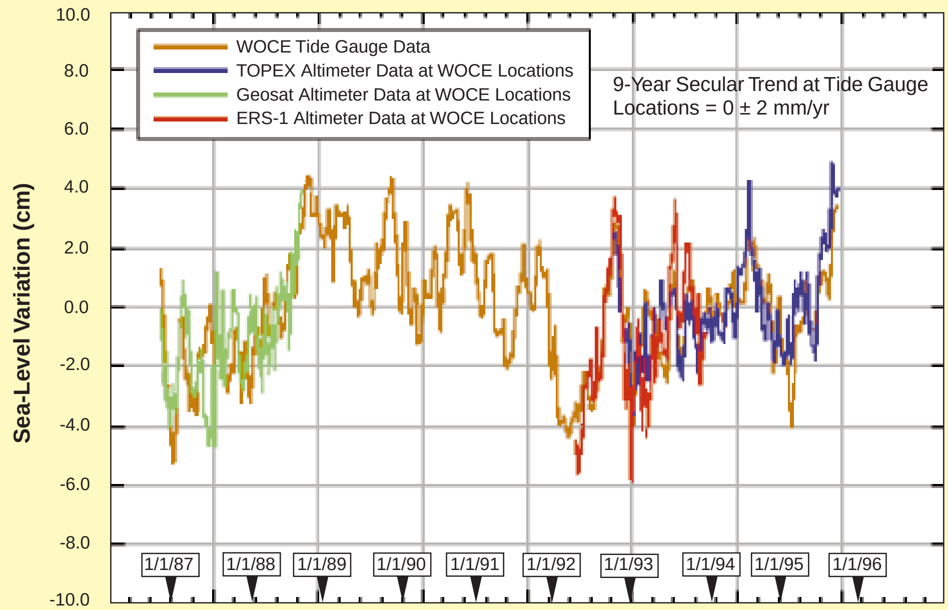
The importance of the ocean in the world carbon cycle is simple in concept: the ocean is an alkaline solution of vast size and in constant motion; carbon dioxide is an acidic gas with a rapidly rising atmospheric signal. The result is a gigantic chemical reaction, whose capacity is governed by the alkalinity of the world ocean, and whose rate is governed by the wind stirring of this solution, and by heating and cooling, with a mean turnover time of about 500 years. The relationship of rates, areas, and chemistry is such that the enormous oceanic presence on the plan-

Figure 3.8



Geographical distribution of sea level trends observed by pre-Earth Observing System (EOS) sensor TOPEX/Poseidon altimeter measurements from October 1992 through January 1996. The regional sea level rise and fall over the time span reaches 60 mm/yr *(courtesy of C. K. Shum).*

Figure 3.9



Pacific mean sea-level variations from 1987 to 1996 observed by three altimeters (Geosat, ERS-1, and TOPEX/Poseidon) and by WOCE tide gauges *(courtesy of C. K. Shum).*

etary surface accounts for the annual uptake of about 40% of the carbon dioxide emissions of humankind.

Due to the complex chemistry, the exchange rate of carbon dioxide with the ocean surface is quite slow; while atmospheric gases such as oxygen or nitrogen reach equilibrium with the upper-ocean mixed layer in about a month; CO_2 takes about a year to equilibrate. This slow rate allows complex patterns of disequilibrium between air and sea to occur. The pre-industrial pattern of this disequilibrium is now overwritten by the signature of human industrial activities. By this time the forcing of the industrial signal is calculated to drive an 8-9 microatmospheres mean difference in CO_2 partial pressure between air and sea, and the signal is climbing. The complex natural pattern means that this signal is hard to detect amidst natural variability.

While oceanic CO_2 cannot be detected directly from space, the forcing terms driving its distribution can. For example, biological activity from photosynthesis is a very large driver of variability and can be remotely sensed as ocean color. Temperature alone is a diagnostic of solubility; however, given enough time, either warm or cold water would reach equilibrium with the atmosphere. It is the rate of temperature change with season or circulation, relative to the surface gas exchange rate, that is critical in driving variability of CO_2 uptake.

The primary challenge for ocean research is to understand the coupling of the physical, chemical, and biological components, as well as the processes and pathways by which the ocean system interacts with the land and atmosphere. Satellite remote sensing plays a critical role by providing the global view over long time periods and with sufficient temporal and spatial resolution to study the non-equilibrium aspects of the upper ocean. However, many important components of the upper-ocean system, such as gases in the ocean, cannot be remotely sensed. Nonetheless, the exchange of gases, and in particular CO_2, between air and sea is a crucial part of the climate perturbation equation, and as such is a critical area of research for the EOS program. Interpretation of satellite observations in concert with in situ measurements, laboratory studies, and numerical models provides a comprehensive framework with which we can make predictions about ocean behavior in response to changes in natural and anthropogenic forcing.

Answers to the following questions are required to predict the ocean's biogeochemical response to, and its influence on, climate change:

- How do changes in surface forcing of heat, momentum, and nutrient fluxes affect carbon cycling in the upper ocean?

- What are the fluxes of gases such as CO_2, CO, and dimethyl sulfide (DMS) across the air-sea interface?

- What regulates the presence of nitrogen-fixing and carbonate-producing organisms, and how are they affected by natural and anthropogenic processes?

- What role do organisms play in the production of DMS and subsequent cloud formation?

- How well do SST and pigment-based models predict large-scale seasonal and interannual movements of economically important fish species?

- What are the long-term trends in phytoplankton concentrations in coastal waters off major human population centers, and what is the link, if any, between biomass and eutrophication and between biomass and diseases? How do interannual differences in river discharge affect coastal ecosystems?

- How do these processes vary on seasonal and interannual time scales as well as on mesoscales and basin-wide spatial scales?

These issues are complementary to goals of major international research programs such as the Joint Global Ocean Flux Study (JGOFS), Global Ocean Ecosystem Dynamics (GLOBEC) program, and Land Ocean Interactions in the Coastal Zone (LOICZ).

The second critical application of marine biology is managing and preserving ocean food stocks. World fisheries as a whole are now considered to be fully or excessively exploited. Total catch has declined in recent years, and there have been some spectacular stock collapses, such as the collapse of the Canadian Atlantic cod fishery. Fisheries managers have increasingly recognized the need to understand and account for environmental effects on fish stocks, particularly interannual-to-interdecadal changes in stock recruitment and distribution, which are generally attributed to climate variability. As stocks are fully or over exploited, they become more vulnerable to interannual changes in recruitment. Alternatively, managers need to understand the likely nature and impact of future environmental change in order to set ecologically sustainable policies that properly allow for precautionary principles. The practical short-term problem faced by a manager confronted with sudden declines in catches or stock size is to decide whether this is due to changes in the habitat or to overfishing. Failure to recognize the interaction of these factors can lead to dramatic and long-term consequences: the collapse of the Peruvian anchovy and California sardine fisheries, as seen in Figure 3.10, are oft-quoted examples.

3.2.4.2 Ocean carbon in relation to global carbon cycle

Although the annual gross uptake of atmospheric CO_2 by the oceans and land is similar (ca. 100 Gigaton [Gt], where 1 Gt = 10^{12} kg), carbon pools and exchanges are very different in the two systems. Three unique characteristics of the ocean carbon system are of particular importance to EOS scientific investigations. First, carbonate dissolved in seawater accounts for ca. 35,000 Gt of carbon, a reservoir approximately 20 times greater than the carbon in terrestrial biota, soil, and detritus. The annual net flux of CO_2 into the ocean is now believed to be about 2 Gt per year, and, based on model results, most of this net flux is accumulating in the transient sink of the ocean carbonate system (Sundquist 1993). Second, annual photosynthetic uptake of CO_2 is 10 times greater than the carbon pool size of ocean biota, whereas the reverse is true for terrestrial biota for which photosynthetic carbon uptake is only a small fraction (about 20%) of their biomass. Thus, mean carbon-specific growth is much faster in the ocean than on land. Ocean plants also have much higher nitrogen and phosphorus content relative to carbon than land plants. Global estimates of the mean and time-varying components of ocean photosynthetic carbon production and its relation to nutrient (e.g., nitrogen and iron) cycles differ widely and will not be resolved without sophisticated analyses and models involving both satellite (e.g., from the Moderate-Resolution Imaging Spectroradiometer [MODIS]) and in situ data. Finally, the ocean stores 700 Gt of dissolved organic carbon (DOC), approximately equivalent to the soil and detrital carbon on land. Fluxes between oceanic DOC and ocean biota, and between DOC and the carbonate pool, are not well understood at present, particularly in the upper layers of the ocean where remote sensors can observe the signal from “colored” dissolved organic matter (CDOM). This represents a significant uncertainty in ocean carbon cycle models.

3.2.4.3 Air-sea CO_2 fluxes

Most of the exchange of carbon between the ocean and the atmosphere occurs by continuous CO_2 gas exchange across the ocean-atmosphere interface. However, because of the alkaline nature of seawater, the latter process is relatively slow compared to the rapid input of anthropogenic CO_2 into the atmosphere. Air-sea CO_2 fluxes are controlled by the transfer velocity and the gradient of CO_2

concentration in seawater and at the air-sea interface. A goal of EOS is to combine in situ and remote-sensing measurements with ocean models, and provide quantitative global estimates of sea-surface CO_2 flux. Furthermore, the neW measurements and models will improve the ability to predict the role of the ocean as a moderating influence on the rate of atmospheric CO_2 buildup.

The best estimates of CO_2 flux (F) across the ocean-atmosphere interface are computed from the gas-exchange flux equation (Liss 1983a,b) of the form:

$$F = K ([CO_2]air - [CO_2]sea)$$

in which the concentration gradient across the sea surface is multiplied by the transfer velocity K. $[CO_2]$air is not directly measurable but is derived by multiplying the measured atmospheric pCO_2 in the water-vapor-saturated air above seawater by the solubility of CO_2 gas in seawater (at the temperature of the water at the air-sea interface, using Henry's law). $[CO_2]$sea represents the concentration of dissolved CO_2 in the ocean mixed layer (upper 10 m) and is estimated by multiplying the measured pCO_2 in the ocean mixed layer by the solubility of CO_2 in seawater at the temperature of the mixed layer.

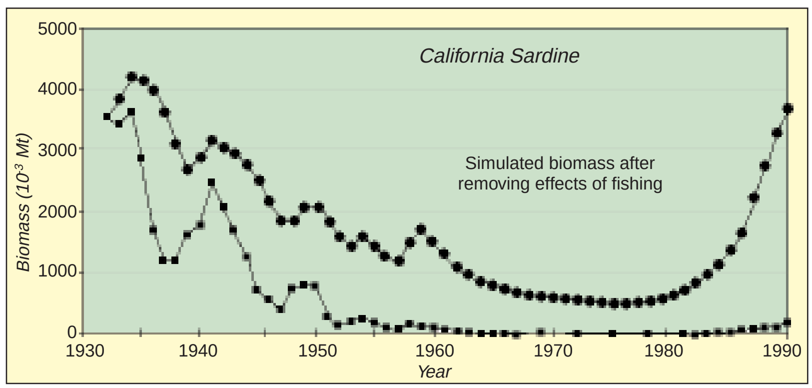
Although the complex hydrodynamic processes that determine K are poorly understood at a fundamental level, there are empirical equations for K as a function of wind velocity measured at 10 m above sea level (Liss and Merlivat 1986; Upstill-Goddard et al. 1990; Peng and Takahashi 1993; Watson et al. 1991) that have an uncertainty factor of about 1.7. Experiments are now underway to reduce this large uncertainty, which arises from a number of factors, including the influence of surface films, variable fetch, marine boundary layer instabilities, and the short-term variability of surface winds (Erikson 1993). These effects are largely manifested in the spectrum of the small-scale waves. The most promising approach appears to be an empirical parameterization of K in terms of mean-square wave slope (Jahne et al. 1987; Frew 1997). The latter parameter can be derived from backscatter measurements using microwave scatterometers and altimeters (Jackson et al. 1992).

In the troposphere, CO_2 is chemically inert and well mixed. The spatial and temporal variations of pCO_2 in the atmospheric boundary layer are well documented (Komhyr et al. 1985). However, sea surface pCO_2 is difficult to monitor and is poorly documented (Takahashi 1989); it undergoes large variations (up to 0.15 microatmospheres around atmospheric pCO_2) on short space scales, driven by thermal, biological, and mixing effects. Since temperature can be remotely sensed and biological activity estimated from satellite ocean color scanners, there is now an opportunity to estimate oceanic pCO_2 on a global scale with temporal resolution on the order of a month. In addition, remotely sensed microwave backscatter will simultaneously provide an accurate estimate of gas transfer velocities across the air-sea interface (Wanninkhof et al. 1991; Wanninkhof and Bliven 1991).

3.2.4.4 Land/sea interactions and fluxes

The coastal zone extends from the coastal plains to the outer edges of the continental shelves. This region approximately matches the area alternatively flooded and exposed in the late Quaternary period due to changes in sea level. The coastal zone encompasses about 8% of the surface area of the Earth and 26% of the biological production (Holligan and deBoois 1993).

FIGURE 3.10



Time series of sardine biomass (1932-1990) obtained from observations of the actual population and from a model simulation that removes the effect of overfishing *(courtesy of T. Strub).*

Rivers move carbon, nutrients, sediments, and freshwater from the land to the ocean, providing about 0.8 Gt per year of carbonate and organic carbon to the ocean. This is about twice the annual flux of organic carbon and carbonate to deep-sea sediments (Sundquist 1993). Rivers also provide 0.02 to 0.07 Gt per year of nitrogen, the nutrient that generally limits biological production in the ocean. This flux is only a small proportion of the nitrogen flux from deep water to the coastal zone due to upwelling but is a new source relative to the ocean and is greater than annual nitrogen fixation by ocean biota (Wollast 1993). Rivers are also the principal source of sediments and are important sources of phosphorus, silicon, and other nutrients. Human activities are directly and indirectly affecting river sources in ways that are presently difficult to quantify on a global scale. For example, widespread farming and deforestation have probably doubled river sediment fluxes compared to the pre-modern era (Meybeck 1993). There is, however, considerable uncertainty in present global estimates as well as the relative importance between large and small rivers (Milliman and Syvitski 1992).

In three very large regions of the ocean, productivity, and hence carbon fixation, is probably limited by the trace nutrient iron (Martin 1990; de Baar et al. 1995). These regions—the Equatorial Pacific, the North Pacific, and the Southern Ocean—are referred to as “High Nutrient, Low Chlorophyll” (HNLC) regions. In all three, substantial amounts of primary nutrients, nitrate and phosphate, are left unused, indicating that phytoplankton carbon assimilation is limited by other factors (Cullen and Lewis 1995). The major source of iron is iron oxide in dust carried on winds from African, South American, and Asian deserts. As aeolian transport is much greater during glacial than interglacial times, iron stimulation of ocean primary production, with subsequent full utilization of primary nutrients in the global ocean, was proposed as a possible mechanism accounting for the drawdown of CO_2 between interglacial and glacial periods (Sarmiento and Toggweiler 1984; Martin 1990). This “iron hypothesis” led to serious proposals to fertilize the Southern Ocean with iron as a biotechnological approach for decreasing the rate of fossil fuel CO_2 accumulation in the atmosphere (Cullen and Lewis 1995). Models show that the iron fertilization could lead to substantial increases in ocean carbon assimilation but would not provide a long-term sink of anthropogenic CO_2 (Sarmiento 1993). Nevertheless, the iron hypothesis is still considered a possible explanation for the HNLC regions, and large-scale field programs in these regions are underway (Cullen 1995). Aerosol fluxes to the open sea and their effects on phytoplankton chlorophyll distributions will be studied using MODIS and other EOS sensors.

The terrestrial biosphere is affected by coastal meteorology through extreme storms, air pollution, and localized patterns of fog, clouds, and precipitation. Until recently, the atmosphere was not considered to be an important conduit of plant nutrients from the land to the ocean, but recent studies contradict this traditional view. In fact, Cornell et al. (1995) show that atmospheric nitrogen deposition ranges from 0.056 to 0.15 Gt of nitrogen annually, which is equivalent to the nitrogen flux to the ocean from rivers. Most of this nitrogen originates from terrestrial sources (e.g., from dust and other aerosols), although human activities (e.g., combustion) may have increased this nitrogen supply by as much as 0.12 Gt per year (Cornell et al. 1995). If fully assimilated by marine phytoplankton in the Redfield carbon:nitrogen ratio of 6:1, this estimate implies that human modification of atmospheric deposition rates could be generating an additional 0.7 Gt per year of new photosynthetic carbon production in the ocean, and assuming mean nitrogen recycling rates of about 10%, could lead to a 10-to-20% increase in overall ocean primary production.

3.2.4.5 Productivity of the marine biosphere

Plankton. Plankton productivity of the ocean biosphere is principally supported by the primary production of microscopic plants, which grow rapidly compared to terrestrial plants. Since the dominant primary producers are microscopic, and are thus carried passively by ocean currents, time and space distributions of ocean primary production are very closely tied to ocean circulation patterns. Ocean currents transport and mix organisms laterally, and vertical density structure and vertical mixing rates generally determine the local rate of photosynthesis by affecting the light environment and nutrient supply. The close relation between the productivity of the ocean biosphere and ocean circulation means that the time/space patterns of ecosystem productivity are very complex and difficult to quantify at ocean-basin and global scales using traditional oceanographic sampling platforms. The traditional notion of stability based on maps of “average” biomass and productivity is a naive view, and the variability of the planktonic ecosystem is now thought to be of at least equal importance. This is essentially a non-equilibrium view of the marine biology in which variability is a critical component (Figure 3.11).

Ocean primary production cannot be directly measured from space, but is calculated from chlorophyll *a* concentration, and, depending on the sophistication of the algorithm, various other remotely-sensed and in situ data and climatologies (Platt and Sathyendranath 1988). Calculations and models, which begin with satellite-derived fields of chlorophyll *a* at daily and longer time scales, are the only practical approach to improve current estimates of mean ocean primary production at basin-to-global scales and to generate new knowledge of the time/space scales of its variability. Primary production is one of the most basic ecological measurements and is an essential component of all studies of trophic relations in the ocean. In addition, primary production is related to most other biologically-mediated carbon fluxes (e.g., the settling flux of organic carbon), including the annual yield of global fisheries (Pauly and Christensen 1995).

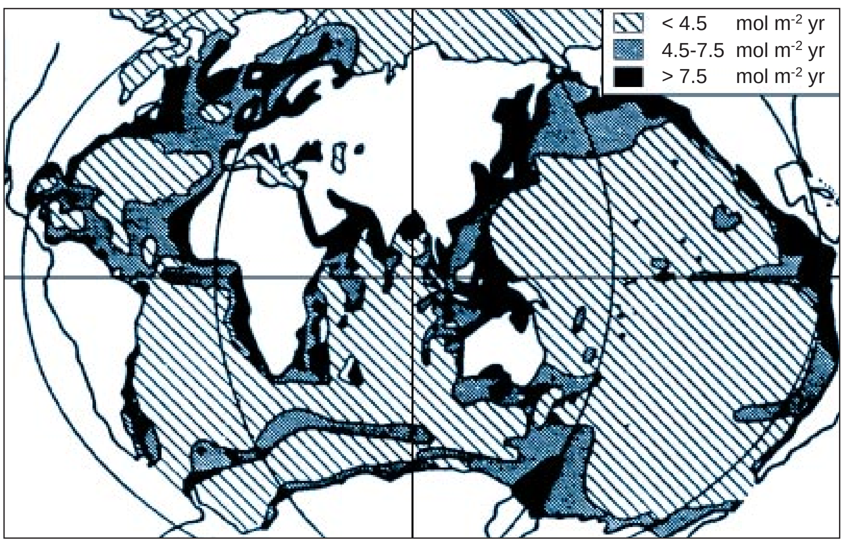
Light harvested by phytoplankton can be transformed into chemical energy through photosynthesis, heat, or re-emitted as light through chlorophyll fluorescence. The rate of fluorescence depends in part on the rate of light absorption and the rate of photosynthesis. As phytoplankton become stressed through processes such as nutrient limitation, the quantum yield of fluorescence generally increases. That is, less light energy is utilized in photosynthesis and more is re-emitted as fluorescence. In-water measurements have exploited this process to estimate photosynthesis. However, the variability in fluorescence quantum yield as a function of environmental variability appears to be a better indicator of the photosynthetic state of the phytoplankton.

A major goal of EOS is to improve current estimates of mean ocean primary production, to describe its variability on regional-to-global spatial scales and from daily-to-interannual time scales, and to understand the basic ocean processes accounting for observed changes in productivity. These activities will build on research begun with Coastal Zone Color Scanner (CZCS) and Sea-viewing Wide Field-of-view Sensor (SeaWiFS) data. Advanced models of primary productivity utilizing the fluorescence bands on MODIS will provide a view with higher temporal and spatial resolution than more-traditional models.

Effects of vertical circulation. In regions where major nutrients in the surface layer are low (not the HNLC regions), vertical velocities play a critical role in bringing nutrients up into the euphotic zone and regulating primary production. There are three types of regions where upwelling is a persistent factor in enriching the ocean. Along the eastern boundaries of the major basins at low and midlatitudes, winds are equatorward for one or more seasons during the annual cycle, directing Ekman transport offshore and creating coastal upwelling (Smith 1992). For this reason, eastern boundary currents play a large role in global fisheries and most likely in the carbon cycle. The second type of region occurs along the equator where the westward Trade Winds cause surface Ekman transport away from the equator in each hemisphere, causing equatorial upwelling. Some of the equatorial upwelling areas are limited by low trace nutrients forming HNLC regions. Thirdly, strong positive wind stress curl causes surface divergences and upwelling, for instance, in the Arabian Sea. Any study of the spatial patterns in global primary productivity should place an emphasis on these regions. In the past, the U.S. JGOFS program has examined the equatorial Pacific and the Arabian Sea. The international GLOBEC program on Small Pelagic Fish and Climate Change includes comparative studies of eastern boundary currents as a goal but not yet a firm plan. A comparison of parts of several eastern boundary currents off Oregon, Peru, and northwest Africa was accomplished in the 1970s, but a truly global comparison has yet to be made.

Since light availability decreases exponentially with depth, photosynthetic organisms such as phytoplankton are constrained to the upper waters. As phytoplankton continue to grow, nutrients become depleted. However, solar radiation is absorbed largely near the surface and stably stratifies the upper layers. Only cooling or large inputs of momentum can overcome this stratification, resulting in entrainment of the cooler, more nutrient-rich waters at depth. Moreover, processes that break down this stratification increase the depths over which phytoplankton are mixed, causing them to spend an increasing amount of time in deep, poorly lit waters. Thus the fundamental challenge for phytoplankton is to balance light availabil-

Figure 3.11



Geographic distribution of plant productivity in the ocean ***(Broecker and Peng 1982).***

ity near the surface with nutrition at depth. This coupling between physical and biological processes is fundamental to ocean biogeochemistry. Understanding and predicting these processes will require both in situ observations at depth and the larger-scale horizontal patterns provided by the EOS sensors. Interpreting these data in the context of dynamical models will make it possible to predict the linkages between the ocean and climate change.

Coral reefs. Coral reefs are found along tropical and subtropical coasts. They support the highest biodiversity and productivity among all the ecosystems. At present, however, coral reef ecosystems are being degraded by local and global environmental changes. The increasing impact of human activities in the tropical coast contribute to the crises facing reef ecosystems through eutrophication and sedimentation, as well as direct mechanical destruction. Reef ecosystems are also adversely affected by CO_2 increase, global warming, sea-level rise, and increasing UV exposure, and the adverse effects will increase in the next decade. Our present knowledge of coral reefs and shallow seas is sketchy. In contrast to land, there is no basic map of the various types of ecosystems that cover the shallow seas. A goal of EOS is to provide such a map.

3.2.4.6 The marine ecosystem and climate change

The recent report by the Intergovernmental Panel on Climate Change (IPCC) focuses heavily on the responses and feedbacks in the Earth's climate system. In the area of the marine biosphere, the first involves the role of the continental shelves in the carbon cycle. The shelves are burial sites for organic carbon derived from both ocean and terrestrial sources. Increases in anthropogenic nutrient loading (due to effluents and land-use changes) could affect oxygen concentrations (through increased microbial activity), which in turn will have complex effects on nitrogen and carbon cycling. Another feedback results from increases in Ultraviolet-B (UV-B) levels, which can depress phytoplankton growth rates as well as affect the cycling of dissolved organic matter (DOM) in the upper ocean. The response to UV-B is species-dependent so there will be pronounced secondary effects on ecosystem structure and function.

Aside from these direct effects on phytoplankton and primary productivity, there are impacts on higher trophic levels that cannot presently be well quantified. Variations in atmospheric forcing cause changes in oceanic circulation, temperature, mixed-layer depth, stratification, and turbulence intensities that affect the reproduction and survival of early states of zooplankton and larval fish. Poor survival rates during these larval and juvenile stages is thought to be the primary source of mortality and a determinate of year-class population sizes for many marine species. The accumulation of year-to-year changes in the early-life survival rates creates strong fluctuations in community structure and food web dynamics of marine ecosystems, resulting in the natural rise and fall of commercially important fish species with periods of years to decades, even in the absence of fishery harvest. For fisheries management to be successful, these fluctuations must be understood. The variations in the environmental conditions named above can involve alterations of the mean levels or changes in the frequency, intensity, and structure of the environmental variability (such as the ENSO multi-year cycle). Unlike terrestrial ecosystems where vegetation is dominated by long-lived species that integrate environmental variability over many decades, many components of oceanic systems respond rapidly to subtle shifts in the environment, making the prediction of these rapid changes more critical.

Thus, an important scientific questions is: "What are the effects of climate change on the distributions, abundances, and productivity of living marine resources in the global oceans?" This is the central question addressed by the GLOBEC program of the International Geosphere-Biosphere Program (IGBP) (see Section 3.3.2.3).

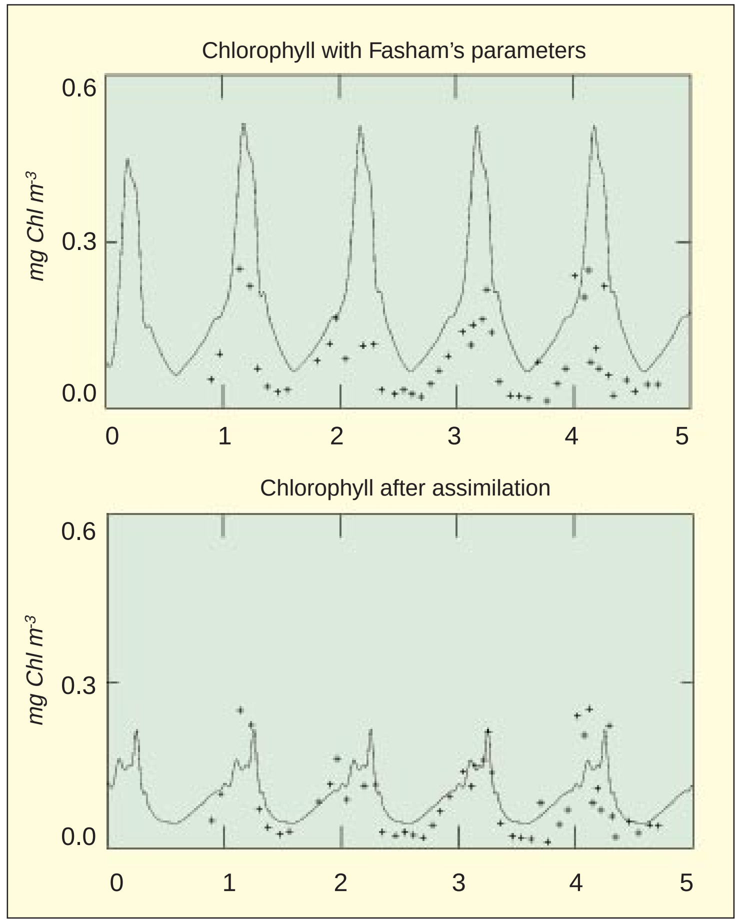
3.2.4.7 Modeling the marine biosphere

GCMs are in the early stages of linking together the ocean and atmosphere from a purely physical climate point of view. Coupling with biogeochemical models is only just beginning. However, it should be noted that physical circulation models themselves are still in their infancy. For example, different circulation models with identical physical forcing produce widely different fields of vertical velocity, as much as the difference between ENSO and non-ENSO years. As vertical velocity and mixing are critical to biological processes through their impact on light and nutrient supply rates, this suggests that coupling of physical and biogeochemical models must proceed carefully.

Various types of box models are used to study the linkages between climate and biogeochemistry. Models that focus on ecosystem dynamics generally explore specific processes, such as the spring bloom. Most of the present models include only simple ecosystems (one nutrient, one phytoplankton type, and one zooplankton type), but more complex models are beginning to appear. A general limitation of all of these models is that the parameterizations of biological processes have a quite limited domain of applicability. Thus models have tended to focus on short-lived phenomena in specific regions. Models that attempt to study large-scale processes generally degrade in performance over time because of inadequate characterization of the marine ecosystem. Another handicap has been that the physical models have been developed to study ocean circulation, not biogeochemistry. Thus the time and space scales as well as the model formulation are often inadequate for biogeochemical studies. Simplifications and parameterizations that are appropriate for physical circulation models may be inappropriate for biogeochemical models. For example, isopycnal models have revealed many insights into physical oceanography, but they are difficult to link with mixed-layer dynamics that are crucial for ocean biology. Clearly, coupled climate/biogeochemical models must have their climate and their biogeochemical components joined early in their development.

Data assimilation is just starting to be used in ocean ecosystem models. Phytoplankton-nutrient-zooplankton (PNZ) models have been widely used for the last 20 years. Fasham et al. (1990) have developed a more-advanced version of the basic PNZ model which includes microbial processes as well. However, one of the challenges in these models is estimating the more than two dozen free parameters, many of which cannot be measured directly. Relying on data assimilation techniques, these parameters can be estimated by using long time series of observations of some of the components of the ecosystem model. Figure 3.12 shows the performance of such an assimilation model where the data were assimilated and measured at the JGOFS Bermuda Atlantic Time Series site. The ecosystem model was modified to include a light adaptation function for phytoplankton, and it can be seen that this model fits the data quite well. In the EOS era, satellite measurements, such as phytoplankton chlorophyll, and photoadaptation derived from MODIS, will be used in more-advanced three-dimensional assimilation models.

Figure 3.12



A time series of chlorophyll modeled with Fasham's parameters (above) and by assimilating data from in situ observations (below) over a period of five years. The model calculations are given by the solid line, the data by the crosses *(courtesy of Yvette Spitz [OSU] and John Moisan [SIO]).*

3.3 Required measurements and data sets

3.3.1 Satellite observations

The purpose of this section is to put into a scientific context the oceanic observational requirements of EOS. Following the structure of the science questions addressed above, the observational requirements in this section are broken into the topics of ocean surface fluxes, ocean circulation and sea level, and marine biogeochemistry. Within each topic, a set of observations with accuracies and sampling requirements is listed in tabular form. The last column in the tables refers to an instrument and a product number; more detail about these data products can be obtained from the Algorithm Theoretical Basis Documents prepared by each Instrument Team.

3.3.1.1 Surface fluxes of momentum, heat, and moisture

The atmosphere and the ocean are coupled through air-sea fluxes of momentum, heat, moisture, and a variety of biogeochemically important compounds. Comparisons between predicted and measured air-sea fluxes provide sensitive tests of the accuracies of coupled general circulation and Earth system models; specifications of the fluxes are required as surface boundary conditions if oceanic or atmospheric models are to be examined separately. EOS science requires continuous global estimates of critical air-sea exchange parameters: air-sea momentum flux or "wind stress," sensible heat flux, net moisture and latent heat flux, and long- and shortwave radiative flux.

The turbulent fluxes of sensible and latent heat and of moisture can only be measured directly by exacting in situ instrumentation, but various parameterizations allow them to be derived from quantities observed globally from satellites. They are commonly estimated with bulk aerodynamic formulae or more-sophisticated boundary layer models; both approaches require surface winds and air-sea differences of temperature and humidity. As a rule, satellites measure surface properties and atmospheric properties aloft, but cannot provide air temperature or humidity at the desired height somewhere between 2 and 100 m above the surface. So the required air-sea differences and the resulting surface fluxes must be inferred from the available data and models. The air-sea temperature difference is a controlling factor because it determines the atmospheric boundary layer stability, which in turn controls the efficiency of these turbulent fluxes. The accuracies of air-sea flux estimates therefore depend jointly on the accuracies of the basic satellite measurements and the validity of the parameterizations used to calculate the fluxes from the measured quantities (Donelan 1990).

Wind stress is an exception. For seasonal and yearly means, analysis of remotely sensed wind stress will provide the best estimates of wind stress. For shorter time scales, the best estimates come from hindcasts by numerical weather prediction models (such as those from the EOS Data Assimilation Office) that wait for all available data and focus upon producing accurate analyses without concern for timeliness. These statements apply more strongly to other near-surface parameters that can only be derived from models that assimilate surface and tropospheric measurements. Direct conventional measurements (e.g., from buoys or ships) are essential to refine and validate the remote-sensing algorithms.

For radiative fluxes, we require the observations of clouds and the atmospheric profiles of temperature, humidity, and aerosols (described in Chapter 2) and the derived estimates of net surface long- and shortwave radiation.

This section outlines the satellite data sets that will contribute to calculation of air-sea turbulent and hydrologic fluxes as well as to prognostic and diagnostic analyses of atmospheric and oceanic circulation and coupling. The required observations are of SST, surface wind velocity, column water vapor for estimating near-surface humidity, precipitation, and sea-surface salinity.

SST. SST plays a crucial role in the global climate system. It is a critical aspect of the coupling between the atmosphere and the ocean (Gill 1982; Peixoto and Oort 1992). The ocean skin provides the lower boundary condition for the upwelling infrared radiation in the marine atmosphere and for boundary layer models that compute the air-sea temperature difference. Accurate satellite measurements also provide the possibility of generating a consistent global climatology of SST that can be used as time progresses to diagnose the rate of climate change.

SSTs are measured from satellites using infrared and passive microwave radiometry. The accuracy of satellite retrievals approaches that of conventional in situ thermometers (i.e. <0.5K) (Mutlow et al. 1994). Satellite measurements have the further advantages of global coverage and higher spatial and temporal resolutions than achievable by other means.

The infrared measurements from which SST is derived are taken in spectral intervals where the atmosphere is most transparent. To achieve accuracies in the derived SST field at a level of a few tenths of a degree, it is necessary that the individual channel radiance measurements, when expressed as brightness temperatures, should have an accuracy much greater than this, i.e., < 0.1 K. Typical spatial resolutions of existing and planned infrared radiometers, about 1 km at the surface, are adequate for most oceanic, weather, and climatic applications requiring SST. For climate studies, global coverage of the oceans is required; this can be achieved with broad-swath instruments every 2-3 days, cloud cover permitting.

Under cloud-free conditions, SST will be derived from the EOS/MODIS infrared channels in the 3.7-µm, 4-µm, 10-to-12 µm, and possibly 8.6-µm intervals (channels 20, 22, 23, 29, 31, and 32). Shorter wavelength channels (visible and near-infrared) will be used to identify cloud and aerosol contamination during daylight. The noise equivalent temperature differences need to be at the 0.05 K level or below to achieve accuracy goals for the derived SST product. Determining the spectral resolution for each band is a trade-off between narrower bands that avoid undesirable spectral lines and broader bands that maximize radiometric sensitivity. The current MODIS specifications (MODIS 1986) represent an achievable balance between these two goals.

Microwave radiometry provides critical and complementary observations of SST. Although the Special Sensor Microwave Imager (SSM/I) instruments presently flying and planned for the remainder of the decade do not include the low-frequency channels (6 to 7 GHz) required to extract SST information, both the European Space Agency (ESA)-supplied Multifrequency Imaging Microwave Radiometer (MIMR) and the National Space Development Agency (NASDA)-supplied Advanced Microwave Scanning Radiometer (AMSR) multichannel microwave radiometers will be capable of extracting all-weather (clear sky and cloudy) SST information with about 60-km resolution and accuracies of 1 to 1.5° C over swaths 1400 to 1500 km wide (Table 3.1, pg. 140).

Surface wind speed and direction. Near-surface winds over the ocean will be acquired under clear and cloudy skies and at night and day by satellite-borne scatterometers, multichannel microwave radiometers, and microwave altimeters. The measurement and analysis techniques are mature and have been successfully tested in space. Time series of wind measurements from all instruments were started in the 1980s and 1990s, well before the launch of the initial EOS instrument suites.

Scatterometers are active microwave instruments designed specifically to measure near-surface wind velocity (both speed and direction) and vector surface stress over the ice-free oceans. They are the only instruments with the demonstrated capability of measuring wind velocity and vector stress (as opposed to scalar wind speed and stress magnitude) in both clear-sky and cloudy conditions. The NASA Scatterometer (NSCAT) dual-swath, Ku-band scatterometer flew as one component of the Advanced Earth Observing System-1 (ADEOS-I) mission and the SeaWinds dual-pencil-beam, wide-swath scatterometer will fly as a NASA-EOS instrument on NASA's EOS QuikSCAT mission (planned for launch November 1998) and on the ADEOS-II mission (planned for launch in February 2000). Dual-swath dedicated C-band scatterometers are planned for flight on the ESA Meteorological Operational (METOP) satellite polar-orbiting spacecraft. All present and planned scatterometer wind measurements have spatial resolution of about 50 km and accuracies of approximately 10 to 12% (rms) in speed and 20 degrees (rms) in direction. Individual instruments achieve near-global coverage in 2 days; the planned constellation (SeaWinds plus an ESA scatterometer) should allow daily global coverage.

Passive microwave radiometers measure the brightness temperature of the Earth/atmosphere system at a variety of carefully chosen frequencies and polarizations. The multiple measurements can be combined to allow simultaneous estimation of many geophysical quantities including wind speed. Recent work (e.g., Wentz 1992, and references therein) suggests that it may also be possible to infer wind direction given proper polarization selections and instrument measurement geometry. However, considerable research is required before such measurements can be considered a substitute for scatterometry. Microwave radiometers (SSM/I) have flown on the operational Department of Defense (DoD) Defense Meteorological Satellite Program (DMSP) spacecraft since June 1987. Two SSM/I instruments are generally operational at any time, yielding nearly daily coverage with 25-to-50-km spatial resolution. Wind speed rms accuracies are 1-to-1.4 m s^{-1} (Wentz 1994), based on comparisons with buoy data. (SSM/I does not include the low-frequency [6-to-7 GHz] channels required to calculate SST, and wind-speed retrieval therefore requires independent knowledge of SST, typically from climatologies). Microwave radiometer wind-speed measurements will be available (through about 2002) from SSM/I instruments on DMSP (or the converged METSAT polar orbiters) as well as from advanced, high-resolution (10 km) radiometers: MIMR on the ESA ENVISAT, and AMSR on NASDA ADEOS-II. A slightly modified copy of the AMSR instrument, designated AMSR-E, is also scheduled to fly on the EOS PM-1 spacecraft. These advanced microwave radiometers will include channels needed to retrieve SST, although the polarizations and measurement geometries will not assure accurate retrieval of vector winds (direction as well as speed). Similar all-weather wind-speed products (with 50-km spatial resolution, 1600-km wide swath) will be obtained from the Atmospheric Infrared Sounder (AIRS) instruments on the EOS PM-1 spacecraft and possibly on future operational satellites.

Radar altimeters are nadir-viewing active radar instruments designed specifically to acquire accurate measurements of the distance between the spacecraft and the sea surface (see the sea-surface topography observations in Section 3.3.1.2). Empirical models have been developed relating the received backscatter power to wind speed under clear-sky and cloudy conditions. Altimeter wind speed measurements are accurate to 2 m s^{-1} (rms) based on comparisons with buoys, with resolution of 7-to-10 km. Altimeter coverage is restricted to the nadir sub-track only. Altimeters are presently flying onboard the TOPEX/Poseidon and both ERS spacecraft. Future altimeters are planned for the U.S. DoD GFO and EOS Radar Altimeter (now Jason-1) missions and the ESA ENVISAT missions (Table 3.2).

Near-surface humidity. Near-surface specific humidity cannot be directly measured using present or planned satellite instrumentation. However, a variety of column-integrated water, atmospheric water vapor, and liquid water quantities are routinely calculated from satellite-borne microwave radiometers, and empirical models relating near-surface specific humidity to integrated water vapor on monthly mean time scales have been developed (Liu 1986; Liu et al. 1991, Table 3.3)

Precipitation. The small spatial and temporal scales associated with rain events greatly complicates the design of global remote precipitation-measurement systems, yet knowledge of precipitation (especially over the ocean) is required to close the global hydrologic cycle (see Section 3.2.1.3). Accurate space-based measurement of precipitation requires high spatial resolution, frequent coverage, and the combined analysis of co-orbiting active rain radars, passive microwave radiometers, and infrared radiometers. The first such measurement suite is flying as the joint NASA-NASDA Tropical Rainfall Measuring Mission (TRMM) launched in November 1997. TRMM utilizes a low-inclination (35°) orbit to achieve frequent coverage and diurnal resolution, confining observations to tropical and subtropical latitudes. TRMM data will provide the basis for developing and refining accurate remote-sensing rain-rate algorithms and designing future precipitation sensor suites.

Although high-accuracy global precipitation measurements over the ocean are not planned for the period 1995 to 2002, qualitative, low-resolution precipitation estimates with 50% accuracy in rain rate, 1-3 day resolution, and 14 to 100 km spatial resolution will be produced from SSM/I, AMSR, and MIMR microwave radiometer data. In addition, AIRS/Advanced Microwave Sounding Unit (AMSU) data will be used to produce a precipitation index accurate to 2 mm/day and with 50-km resolution (Table 3.4).

Sea-surface salinity. There is very little information about the large-scale variability of ocean surface salinity. About 30% of the $1° \times 1°$ boxes of the ocean surface do not have a single salinity observation. Surface salinity is a major dynamic parameter that influences the density-driven ocean circulation, particularly the convective overturning in the North Atlantic. The ocean's influence on the global hydrological cycle is enormous, and the hydrologic budget cannot be balanced without closing the salt budget of the oceanic mixed layer. Surface salinity is a very strong constraint on the water and energy flux parameterizations of coupled ocean/atmosphere GCMs. Recent results from the Tropical Ocean Global Atmosphere (TOGA)/Coupled Ocean-Atmosphere Response (COARE) indicate that freshwater buoyancy flux in the equatorial warm pool of the western Pacific governs the thickness of the thermodynamically active mixed layer, and thus modulates the transfer of heat between the ocean and atmosphere in this region, which is the spawning ground for ENSO. Low-frequency microwave radiometry holds promise.

3.3.1.2 Circulation and sea level

Studies of ocean circulation and long-term climate change require continual observations of surface geostrophic currents and measurements of mean sea level. These can be provided by satellite-borne microwave altimeters, which directly measure the altimeter's distance above the sea surface. To determine the mean sea level and the mean current, the satellite's orbit must be known accurately, and the Earth's geoid and tidal contributions to the sea-surface height must be subtracted from the altimetric measurements. This section addresses this set of requirements. Other satellite measurements needed in the study of ocean circulation are measurements of the Earth's rotation rate, and, as described in Section 3.3.1.1, those that allow tests and diagnoses of ocean models—SST and salinity—and those that provide estimates of sea-air fluxes of heat, salt, and momentum.

Table 3.1

Parameter Name	Units	Accuracy Abs::Rel	Temporal Resolution	Horizontal Resol:: Cover	Vertical Resol::Cover	Comments
Sea_sfc Temperature (SST)	K	0.3-0.5 K :: 0.3-0.5 K	1/day, 1/wk 1/mon	1 km :: Ocean/L	N/A :: Sfc	MODIS (28)
Sea Surface Temperature (SST)	K	1 K ::		60 km :: Ocean	N/A :: Sfc	AMSR/ MIMR (06)
Sea Surface Temperature (SST)	K	<0.2 K ::	1/day	1.0 deg ::	N/A :: Sfc	AMSR/ MIMR (17)

Sea-surface temperature

Table 3.2

Parameter Name	Units	Accuracy Abs::Rel	Temporal Resolution	Horizontal Resol:: Cover	Vertical Resol::Cover	Comments
Wind Vectors, Near_Surface	m/s,dg	> of 2 m/s or 10% rms (speed); 20 dg rms (direction) ::	N/A	50 km :: Ocean (1600-km swaths)	N/A :: Sfc	SeaWinds (03)
Wind Speed Sea_sfc	m/s	1.5 m/s* ::		14, 25 km :: Ocean	N/A :: Sfc	AMSR/ MIMR (05)
Wind Speed, Sea_Sfc	m/s	<0.5 m/s* ::	1/day	1.0 deg ::	N/A :: Sfc	AMSR/ MIMR (16)
Wind Speed, Along-track	m/s	2 m/s ::		7 km :: Ocean	N/A :: Sfc	DFA (02)
Wind Speed, Sea_sfc	m/s		2/day	50 × 50 km :: Ocean	N/A :: Sfc	AIRS (06)

Surface wind velocity and speed

Table 3.3

Parameter Name	Units	Accuracy Abs::Rel	Temporal Resolution	Horizontal Resol:: Cover	Vertical Resol::Cover	Comments
Precipitable Water	g cm^{-2}	0.2 g cm^{-2} ::		14 km :: Ocean	Column :: Trop	AMSR/ MIMR (04)
Precipitable Water	g cm^{-2}	<0.1 g cm^{-2} ::	1/day	1.0 deg ::	Column :: Trop	AMSR/ MIMR (15)
Precipitable Water	mm	5% :: 3%	2/day [d,n]	50 × 50 km :: G	N/A :: Atmos	AIRS (05)

Column water vapor

Table 3.4

Parameter Name	Units	Accuracy Abs::Rel	Temporal Resolution	Horizontal Resol:: Cover	Vertical Resol::Cover	Comments
Precipitation (Ocean, 2 layers)		50% ::		14 km :: Ocean	N/A :: Sfc	AMSR/ MIMR (02)
Precipitation (Ocean)		10% ::	1/day	1.0 deg ::	N/A :: Sfc	AMSR/ MIMR (13)
Precipitation Index	mm/day	2 mm/day :: 1 mm/day	2/day [d,n]	50 × 50 km :: G	N/A :: Trop	AIRS (05)

Precipitation rate

Mean sea-surface height and geoid. Altimetric measurement of the sea-surface height is presently the only method for measuring ocean surface currents over large areas of the ocean every 10 days in a cost-effective and timely manner. Sea-surface height measurements observed by satellite altimetry consist of a mean component (the dynamic topography) and the time-varying component. Improved knowledge of large-scale mean circulation enhances understanding of the internal structure of currents and enables better estimates of global transport. However, the accuracy of the global marine geoid is required to fully make use of the altimetric dynamic topography measurements. To achieve an accuracy of 1 Sverdrup of transport, the geoid needs to be accurate to less than 2 cm over a length scale of shorter than 500 km. The current best geoid model, JGM-3, is accurate only to 11 cm over 3000 km, which enables surface current determination to an accuracy of only 5 cm/sec. Geoid models computed using satellite tracking data, altimetry, and shipboard gravity data will not satisfy the requirement. Future geopotential mapping missions have goals of producing a geoid model to enable surface currents to be computed to an accuracy of 0.5 cm/sec (Table 3.5).

Time-varying dynamic topography. Altimetric satellite orbits were designed so that orbits repeat exactly to within ±1 km at the equator at a specified interval, for example, 10 days. This allows the dominant marine geoid error to be eliminated when repeat-track analysis of altimetric measurements is conducted. The time-varying component of the sea surface height can be computed with an accuracy of 3 cm rms over a length scale of 7 km along the satellite groundtrack. The variations of the sea-surface height and hence of surface geostrophic currents can be computed directly using altimetric measurements. Eddy kinetic energy of the global ocean currents can be directly computed (Table 3.6).

Precision orbit determination. Accurate knowledge of the position of the altimeter antenna within a well-maintained terrestrial reference system is vital to the interpretation of the altimeter height measurements in terms of sea-surface topography. Improved gravity and tide models, nonconservative force models, and terrestrial reference frame models, and the use of SLR and Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) range-rate tracking data, have enabled determination of the TOPEX/Poseidon spacecraft radial position to within 3-4-cm accuracy relative to the center of mass of the Earth. The demonstration of satellite-to-satellite Global Positioning System (GPS) tracking has shown enormous potential for further enhancement of accuracy of altimetric satellite orbits. Together with the continued improvement of dynamic models and employing dense tracking data (e.g., GPS and SLR), the radial orbits of 2 cm can be achieved for the future altimetric satellite Jason-1 (Table 3.7).

Tidal component of sea-surface height change. Tidal variations in sea-surface height can be aliased into climate-sensitive time scales and therefore must be removed from altimeter measurements. Great care was taken in the choice of the TOPEX/Poseidon orbit to minimize aliasing of important tidal frequencies into climate-sensitive frequencies. In addition, analyses of TOPEX/Poseidon data have generated a number of improved deep-ocean tide models. Shum et al. (1996) have provided an accurate assessment of 10 such models and concluded that the tides in the deep ocean are accurate to 2–3 cm rms. Most global models have spatial resolutions of 1/2 degree (50 km). At present, tides in coastal areas and semi-enclosed seas are poorly modeled. In addition, long-period tides (e.g., Mm, Mf) and tides with meteorological origin are poorly modeled and are difficult to separate from astronomical tides. Improved accuracy from coastal and deep-ocean tidal prediction capabilities can be anticipated by using additional TOPEX/Poseidon data and other current and future altimeter measurements, along with improved methodology to assimilate data into hydrodynamic models. These models can be used to correct sea-surface topography measurements from altimetric missions (Table 3.8).

3.3.1.3 Biogeochemistry

Surface forcing and SST. The observations required for surface fluxes (Section 3.3.1.1) are also required for studies of the interrelationships between the physical state and processes of the ocean and the biological state and processes. In addition, we require, as described below, total incoming solar radiation at the Earth's surface on a daily basis, its spectral composition, including photosynthetically-available radiation (PAR) and ultraviolet radiation. We also require estimates of the fluxes of iron and major plant nutrients (e.g., nitrogen) from the atmosphere to the ocean.

The temperature dependence of the solubility of gases such as CO_2 requires accurate knowledge of the surface temperature of the surface mixed layer, as well as of the surface skin of the ocean. The skin temperature can be slightly cooler than the mixed-layer temperature; ignoring this difference can lead to a significant underestimation of air-sea gas exchanges. This surface

Table 3.5

Parameter Name	Units	Accuracy Abs::Rel	Temporal Resolution	Horizontal Resol:: Cover	Vertical Resol::Cover	Comments
Sea_Level Height, Along-track	cm	11 cm :: N/A		3000 km :: Ocean	N/A :: Sfc	[DFA02]
Topography Map, Sea_sfc	cm	5 cm or 10% ::	1/(10 day)	25 km :: Ocean	N/A :: Sfc	DFA03

Local mean dynamic topography

Table 3.6

Parameter Name	Units	Accuracy Abs::Rel	Temporal Resolution	Horizontal Resol:: Cover	Vertical Resol::Cover	Comments
Sea_Level Height, Along-track	cm	N/A :: 3cm	1/(10 days)	7 km :: Ocean	N/A :: Sfc	

Time-varying dynamic topography

Table 3.7

Parameter Name	Units	Accuracy Abs::Rel	Temporal Resolution	Horizontal Resol:: Cover	Vertical Resol::Cover	Comments
Precision orbit units	cm	2 cm :: N/A		7 km :: Global	N/A :: Sfc	

Precision orbit determination

Table 3.8

Parameter Name	Units	Accuracy Abs::Rel	Temporal Resolution	Horizontal Resol:: Cover	Vertical Resol::Cover	Comments
Ocean Tide Model	cm	2 cm :: 2 cm	2/day	50 km :: Ocean	N/A :: Sfc	DFA05

Component of tidal sea-surface height

skin effect, in fact, which is usually not considered in the calculation of the global carbon budget using conventional SST climatologies, can account for ~0.7 Gt C yr^{-1} of extra carbon flux to the ocean (Robertson and Watson 1992). This can be up to about 50% of the discrepancy between estimates of net oceanic CO_2 uptake derived from models calibrated by tracers when compared to models that integrate the air-sea exchanges over the global oceans.

Surface gas exchange. As discussed above, CO_2 fluxes cannot be measured directly and have to be estimated from various observations. On the global scale, the quantification of CO_2 fluxes across the ocean-atmosphere interface requires two complementary sets of observations: in situ observations of sea-surface pCO_2 on short temporal and spatial scales, and space-based observations of a limited number of parameters (such as ocean color and SST) with a lesser accuracy than in situ observations. Algorithms developed in the EOS program will couple in situ and proxy space-based observations to quantify the global absorption of CO_2 by the oceans.

Exchanges between the land and the ocean. Rivers are major sources of freshwater, sediments, nutrients, and DOM to the coastal zone, as well as pollutants that may be transported in soluble and particulate forms. Knowledge of the river flux, plume area, and salinity provides valuable information necessary for estimating plume thickness from space, data important to calculating the light field in and beneath the plume. To interpret the ocean color signal in the coastal zone, a significant improvement in the performance of the Land Remote-Sensing Satellite (Landsat) class of sensors is required, with a movement away from hyper-spatial sampling and toward hyper-spectral sampling. Improved signal-to-noise can be achieved by using larger pixels (e.g., 60 to 90 m) and increased dwell or integration time in order to cope with a need for 10-15-nm sampling with contiguous bands.

Bio-optical measurements. We need spectral measurements from satellite sensors to distinguish important biogeochemical components suspended and dissolved in the upper ocean and to correct for bottom reflectance in coastal waters. We also need in situ measurements to help interpret the satellite signals including water-leaving radiances, chlorophyll *a*, detrital carbon, accessory pigment (e.g., phycoerythrin), and CDOM concentrations. In addition, we need estimates of the abundance in surface waters of certain classes of phytoplankton including coccolithophorids and the floating mats of cyanobacteria, notably Trichodesmium. These observational requirements are described below.

Water-leaving radiance, integrated, spectral, surface PAR. Models of biogeochemical cycles in the upper ocean rely on appropriately parameterized mixed-layer physics. For example, solar radiation incident on the sea surface warms and stabilizes the upper ocean. It is also responsible for driving photosynthetic production of organic matter. Transfer of momentum from wind to sea mixes the upper ocean and is responsible for generating turbulence, which mixes nutrients and other dissolved and particulate constituents in the vertical. Excess latent heat losses drive convective motions responsible for deep water formation and the transport of both organic and inorganic carbon to the deep sea.

For estimates of light utilization by phytoplankton, we need visible and ultraviolet radiative fluxes. Total incoming solar radiation at the Earth's surface as well as PAR are required on a daily basis. Instantaneous PAR is needed for some of the primary productivity models. Ultraviolet radiation will be estimated from a combination of the incoming solar radiation and ozone concentration. These estimates will be made through a combination of visible radiometers (e.g., MODIS) and the Total Ozone Mapping Spectrometer (TOMS) (for ozone concentration) (see Tables 3.9 and 3.10).

Phytoplankton chlorophyll a concentration and fluorescence. Satellite ocean-color scanners measure ocean radiance, and from these data one derives accurate estimates of phytoplankton chlorophyll *a* concentration (a good proxy for phytoplankton biomass) and other in-water constituents. Algorithms based on the strong blue absorption by phytoplankton chlorophyll *a* work well in open-ocean and most continental-shelf waters but are difficult to implement in optically complicated waters near the coast owing to the interference of other strong blue-absorbing substances. Advanced ocean-color scanners like MODIS will have high signal-to-noise in bands near 683

Table 3.9

Parameter Name	Units	Accuracy Abs::Rel	Temporal Resolution	Horizontal Resol:: Cover	Vertical Resol::Cover	Comments
Level-2 Radiance, Water-leaving	mW cm^{-2}/ sr/µm	5-10% :: 5-10%	1/day, 1/wk, 1/mon	1 km :: Ocean/R,L	N/A :: Sfc	MODIS (18)
Downwelling Irradiance, Sea_sfc	Wm^{-2}	::	1/day	1 km :: Ocean	N/A :: Sfc	MODIS (22)
PAR, Sfc (IPAR) and Incident (IPAR)	quanta m^{-2} sec^{-1}	0.05 :: 1.05	1/day [d]	1 km :: Ocean	N/A :: Sfc	MODIS (22)
PAR, Daily	Wm^{-2} day^{-1}	0.1 :: 1.1	1/day	N/A :: G	N/A :: Atmos	MODIS (22)

Water-leaving radiance and photosynthetically active radiation

Table 3.10

Parameter Name	Units	Accuracy Abs::Rel	Temporal Resolution	Horizontal Resol:: Cover	Vertical Resol::Cover	Comments
Irradiance, UV Solar [1 nm res.]	Wm^{-2}	3-5% :: 1%	1/hr	N/A :: N/A	N/A :: N/A	SOLSTICE (02)
Irradiance, UV Solar [0.001 nm res.]	Wm^{-2}	3-5% :: 1%	1/hr	N/A :: N/A	N/A :: N/A	SOLSTICE (03)

UV radiation

nm to detect the sunlight-stimulated chlorophyll *a* fluorescence signal in coastal waters having relatively high concentrations of phytoplankton biomass (ca. >1.0 mg Chl *a* m^{-3}). This capability provides an alternative approach to the absorption-based algorithms to estimate phytoplankton biomass, particularly in coastal waters where the absorption-based algorithms often fail. MODIS measurements at 412 nm will be used to estimate the concentration of marine detritus (dissolved and particulate) and to improve estimates of chlorophyll *a* when these substances significantly affect blue absorption (Table 3.11).

With the CZCS, only total pigment concentrations could be estimated as there was insufficient spectral resolution to separate chlorophyll *a* from its associated degradation products. Several studies have shown that traditional bio-optical algorithms fail in the presence of DOM such as humic acids, which occur in coastal waters and in river plumes and even in the open ocean. SeaWiFS and MODIS will have channels near 412 nm to correct pigment estimates and to estimate the concentration of CDOM. Although there remain challenges for atmospheric correction at these short wavelengths, the availability of these measurements will extend the range of water types that can be observed quantitatively from space. Other accessory pigments, such as phycoerythrin, will require at least the increased spectral resolution of MODIS and probably additional bands between 580 nm and 610 nm. Extensive airborne data have shown that the phycoerythrin influence can be detected, but measurements at appropriate wavelength bands are required to extract pigment concentration.

Coccolithophorid and cyanobacteria concentrations, and accessory pigments. The concentration of coccolithophorids can be estimated with the next generation of ocean-color sensors, including MODIS. These calcium-carbonate-producing organisms play a critical role in two cycles. First, a shift from silica-producing organisms (such as diatoms) to carbonate-producing organisms may tend to increase the surface pCO_2 of the ocean. However, there is a complex balance between this reaction and the competing effects of sinking of carbonate skeletons. The second role is in the production of DMS. Coccolithophorids produce a precursor, dimethylsulphoniopropionate. DMS is the major natural source of sulphur to the atmosphere and acts as a cloud condensation nucleus. There appears to be a link between DMS production and increased cloud condensation nuclei, but this is a strong function of species composition, total biomass, and ecosystem structure. However, it is clearly an area worth further study.

It is theoretically possible to distinguish relative dominance by some phytoplankton classes based on the absorption characteristics of accessory photosynthetic pigments such as the phycobiliproteins (common in blue-

Table 3.11

Parameter Name	Units	Accuracy Abs::Rel	Temporal Resolution	Horizontal Resol:: Cover	Vertical Resol::Cover	Comments
Chlorophyll Fluorescence Line Curv	mW cm^{-2}/ sr/µm	0.25 :: 1.25	1/day, 1/wk	1 km, 20 km? :: Ocean/R,G	N/A ::	MODIS (20)
Chlorophyll Fluorescence Line Height	mW cm^{-2}/ sr/µm	.004 Wm^{-2} sr^{-1} :: .004 Wm^{-2} sr^{-1}	1/day, 1/wk	4 km, 1 km? :: Ocean/G,R,L?	N/A ::	MODIS (20)
Chlorophyll Fluorescence Efficiency	mW cm^{-2}/ sr/µm/mg-Chl m^{-3}	TBD :: TBD	1/day, 1/wk	1 km :: Ocean/ R,L	N/A ::	MODIS (20)
Chlorophyll_a Pigment Conc, Case II	mg m^{-3}	50%(0.05<[Chl]<1 :: 50%(0.05<[Chl]<2	1/day, 1/wk, 1/mon	1 km :: Ocean-II/ R	N/A ::	MODIS (21)
Chlorophyll_a Pigment Conc, Case I	mg m^{-3}	30%(0.1<[Chl]<1); 60%(1<[Chl]<10); TBD([Chl]>10) :: 30%(0.1<[Chl]<1); 60%(1<[Chl]<10); TBD([Chl]>10)	1/day, 1/wk, 1/mon	1 km :: Ocean-I/ L	N/A ::	MODIS (21)

Chlorophyll a concentration and fluorescence

green algae) and the carotenoids (common in diatoms and dinoflagellates). Some biogeochemically important types of phytoplankton (e.g., coccolithophorids and the blue-green nitrogen-fixer, Trichodesmium) significantly affect the scattering properties of ocean waters, and thus semi-quantitative estimates of their abundance will be possible.

The final group of phytoplankton that perhaps can be detected from space are floating mats of cyanobacteria, notably Trichodesmium. Some preliminary results with historical CZCS data suggest that these mats can be quantified. As these organisms convert atmospheric nitrogen into organic nitrogen, they play a unique role in both nitrogen and carbon cycling in the upper ocean. Recent field studies suggest that their importance may have been overlooked, and that their abundance may depend strongly on variability in wind stress (Table 3.12).

DOM. The world ocean contains about 35,000 Gt of carbon. While the bulk of this material is in the inorganic form, approximately 700 Gt (2%) is in the form of DOM. Often referred to as DOC, this pool of carbon is comparable in size to all of the carbon contained in all of the living biota on the continents (750 Gt) and to the total atmospheric inventory of carbon (740 Gt) as carbon dioxide. The DOC pool likewise dwarfs the amount of carbon contained within the living biota in the ocean, estimated as 1-4 Gt of carbon. (All carbon pool size estimates are from Sundquist 1985.)

The seasonal variations in the size of regional DOC pools suggest that the flux of carbon between the inorganic and organic forms for the global ocean is on the order of 100 Gt annually. This "flux" is the major sink for inorganic carbon in the surface waters of the world ocean and is larger than all other sinks combined. For example, recent estimates of the various sinks of carbon in the equatorial Pacific Ocean suggest that 50-80% of the carbon loss was in the form of DOC (Murray et al. 1994), exceeding the vertical sinking flux of particles from the euphotic zone by a factor of 2-4 in all seasons and more than three times the gas exchange loss to the atmosphere.

Thus, any global model that attempts to define the carbon budget and includes interactions between the ocean and the atmosphere must deal with the process of incorporating carbon into the DOC pool. Most of these exchanges occur in the surface waters of the world ocean and intimately link the flux of carbon between the DOC and dissolved inorganic carbon (DIC) pools with the exchange of carbon between the oceans and the atmosphere.

TABLE 3.12

PARAMETER NAME	UNITS	ACCURACY ABS::REL	TEMPORAL RESOLUTION	HORIZONTAL RESOL:: COVER	VERTICAL RESOL::COVER	COMMENTS
Coccolith Conc, Detached	number/ ml	25000/ml (10-20%) :: 25000/ml (10-20%)	1/day, 1/wk 1/mon	20 km, 1 km? :: Ocean (in Coccolith Blooms)/G,R,L?	N/A ::	MODIS (25)
Calcite Conc, Estimated	mg-CaCO3 cm^{-3}	::	1/day, 1/wk, 1/mon	20 km, 1 km? :: Ocean (in Coccolith Blooms)/G,R,L?	N/A ::	MODIS (25)
Pigment Conc (in Coccolithophore Blooms)	mg m^{-3}	::	1/day, 1/wk, 1/mon	20 km, 1 km? :: Ocean (in Coccolith Blooms)/G,R,L?	N/A ::	MODIS (25)
Pigment Conc	mg m^{-3}	100% (Global); 35% (Case I, Clear Atmos) :: 100% (Global); 35% (Case I, Clear Atmos)	1/day, 1/wk 1/mon	20 km, 1 km? :: Ocean/G,R,L?	N/A ::	MODIS (19)
Phycoerythrobilin Conc	mg m^{-3}	0.5 :: 1.5	1/day, 1/wk 1/mon	1 km :: Ocean /RL	N/A :: Sfc	MODIS (31)
Phycourobilin Conc	mg m^{-3}	0.5 :: 1.5	1/day, 1/wk 1/mon	1 km :: Ocean /RL	N/A :: Sfc	MODIS (31)
Constituent Inherent Optical Properties (CDOM absorption, Chlorophylous absorption		::	During overpass of validation regions	1 km :: Ocean /RL	N/A :: Sfc	MODIS (31)

Coccolithophorid and cyanobacteria concentrations

For example, any carbon that gets incorporated into the DOC pool represents a draw-down of the DIC pool and a simultaneous reduction in the partial pressure of CO_2. Furthermore, any sensitivity of these fluxes to changes in temperature or ocean circulation will modify the carbon budget, as these parameters change in association with the global climate.

Developing the models to adequately describe these processes and make reliable predictions of the consequences of future climatic changes in response to various scenarios represents a formidable challenge. Linking satellite observations of ocean color, temperature, and circulation to ship-based observations is our best hope of developing a comprehensive model.

Unfortunately, one of the critical parameters to a comprehensive land-ocean-atmosphere carbon model, DOC, is not directly observable from satellites, although a portion of the DOC pool, the CDOM, is. There has long been an interest in observing CDOM from satellites. Initially, this was driven by the desire to correct estimates of chlorophyll and biomass for the interference by CDOM (Hochman et al. 1995). More recently, there has been an effort to directly observe CDOM from aircraft and satellite data and correlate this with in situ determinations of DOC (Vodacek et al. 1995).

The initial simple relationships between observations (Vodacek et al. 1995) have turned out to be somewhat misleading. Recent work shows the correlations to be quite complex, exhibiting both seasonal and regional variations. In addition, photooxidation reactions in the mixed layer ultimately lead to the degradation of CDOM and the bleaching of its absorption and fluorescence emission bands. Photobleaching occurs much faster than photooxidation of bulk DOC (Mopper et al. 1991), leading to an inverse correlation between DOC and CDOM in upwelling regions. Thus, on a global basis, one can not even be assured of the sign of the correlation without empirical in situ information.

This leads to the conclusion that the best hope for constraining global estimates of the distribution of DOC and how it impacts the oceanic carbon budget will involve a marriage of satellite observations and in situ (sea-truth) data. By combining the growing database of in situ measurements now becoming available via the JGOFS program with a variety of satellite ocean observations (e.g., SST, winds, and ocean color/chlorophyll), empirical correlations may make it possible to constrain the size of the DOC pool on a global basis and more often than is possible simply by accumulating ship-based observations (Table 3.13).

Water transparency. As noted earlier, bio-optical measurements of water transparency are essential in studies of the upper ocean heat budget. It is well-established that variation in phytoplankton abundance is the primary cause of variations in the light-trapping properties of the upper ocean. The absorption of sunlight is one of the primary processes determining mixed-layer depth. Many recent field and satellite-based studies have confirmed the importance of bio-optical properties for understanding the heat budget (and subsequent air/sea fluxes) of the upper ocean. Ocean-color measurements can be used to estimate water transparency at several wavelengths (Table 3.14, pg. 148).

Table 3.13

Parameter Name	Units	Accuracy Abs::Rel	Temporal Resolution	Horizontal Resol:: Cover	Vertical Resol::Cover	Comments
Suspended-Solids Conc, Ocean Water	g m^{-3}	0.5 :: 1.5	1/day, 1/wk, 1/mon	20 km, 1 km? :: Ocean/G,R?,L?	N/A ::	MODIS (23)
Organic Matter Conc, Dissolved	g m^{-3}	40%(open ocean best case); 100%(coastal for [Chl]<1) :: 40%(open ocean best case); 100%(coastal for [Chl]<1)	1/day, 1/wk 1/mon	20 km, 1 km? :: Ocean/R	N/A ::	MODIS (24)
Organic Matter Conc, Particulate	mg m^{-3}	TBD :: TBD	1/day, 1/wk	20 km :: Ocean	N/A ::	MODIS (24)

Colored dissolved organic matter

Primary productivity. To understand carbon cycling and the response of the marine biosphere to climate change, we must look beyond static variables of standing stocks to measurements of dynamics. Existing models rely on biomass estimates collected from ocean-color sensors to infer production rates. Empirical methods have been used to estimate light adaptation and other physiological parameters to improve these models. However, there has been much recent progress, and improved models have begun to appear in the scientific literature.

There are two promising lines of research. First, information on the photoadaptive state will significantly improve productivity estimates. Although the relationship of sun-stimulated fluorescence to photoadaptive parameters is not well-understood (especially for surface, light-inhibited populations), fluorescence bands will be included on MODIS, the Global Imager (GLI), and the Medium-Resolution Imaging Spectrometer (MERIS). This information will provide estimates of the physiological state of the phytoplankton and, when coupled with biomass estimates using measurements from other wavelengths, should improve productivity models. The availability of morning and afternoon MODIS sensors will allow the study of some aspects of diel variability, at least in regions of the world ocean that are not obscured by glint during one of the passes. Measurement of diel variations in sun-stimulated fluorescence might further improve models of phytoplankton growth rates. However, considerable field work remains before sun-stimulated fluorescence can become a standard tool for estimating productivity. The second line of research relies on productivity models that incorporate biological and physical processes explicitly. Clearly, such an approach must reflect increased understanding of the processes that regulate growth rates. A balance must be maintained between increasing the realism of the productivity models and adding unnecessary detail (Table 3.15).

Coral reef extent and ecosystem type. Current sensors, including Landsat and the Systeme pour l'Observation del la Terre (SPOT), are not able to observe coral reefs adequately. A Coral Reef Satellite Image Database is be-

Table 3.14

Parameter Name	Units	Accuracy Abs::Rel	Temporal Resolution	Horizontal Resol:: Cover	Vertical Resol::Cover	Comments
Ocean Water Attenuation Coef@490nm	/m	0.25 :: 1.25	1/day, 1/wk, 1/mon	20 km, 1 km? :: Ocean-I/R,L	N/A ::	MODIS (26)
Ocean Water Attenuation Coef@520nm	/m	0.35 :: 1.35	1/day, 1/wk	1 km :: Ocean	N/A ::	MODIS (26)
Absorption Coef, Total	/m	0.25 :: 1.25		::	::	MODIS (36)
Absorption Coef, Gelbstof	/m	0.25 :: 1.25		::	::	MODIS (36)
Clear Water Epsilon		2% (0.9 to 1.4) :: 2% (0.9 to 1.4)	1/day, 1/wk 1/mon	1 km :: Ocean	::	MODIS (39)

Water transparency

Table 3.15

Parameter Name	Units	Accuracy Abs::Rel	Temporal Resolution	Horizontal Resol:: Cover	Vertical Resol::Cover	Comments
Ocean Productivity, Primary, Daily	mg-C/m^2/day	35% (Goal) :: 35% (Goal)	1/day, 1/wk	1 km :: Ocean-I/ R,L	N/A ::	MODIS (27)
Ocean Productivity, Primary, Global Annual	GT-C/yr	35% (Goal) :: 35% (Goal)	1/yr	20 km :: Ocean/ G,R	N/A ::	MODIS (27)

Primary productivity

ing developed within the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) project to identify which coral reefs have not been observed by satellites and determine which ones ASTER should observe. This database covers the northwest Pacific Ocean (0° to 31°N, 90°E to 180°) with 0.5° mesh. Each mesh cell has been assigned a probability of finding coral reefs: A (probable), B (possible), or blank (improbable). The database will be expanded to the rest of the world in the near future. ASTER coral reef products will be generated using ASTER-calibrated and atmospherically corrected surface-reflectance products. In a pre-processing stage, the image is classified into "land," "deep sea," "shallow sea," and "cloud and its shadow." Then, by an algorithm that is being developed and validated, "shallow sea" pixels are classified into benthic community classes such as corals, algae, seagrass, and sand.

3.3.2 Critical surface observations and field experiments

Satellite observations are usually only indirectly related to desired geophysical parameters. Algorithms that convert satellite data to geophysical data need testing and improvement by comparison with more direct observations, particularly in situ observations. Furthermore, because of the variability of atmospheric constituents and sea-surface roughness, coincident surface and atmospheric measurements are needed to correct satellite-derived surface parameters. As these parameters become more accurate over time, motivation will grow for a well-designed set of continual in situ observations.

3.3.2.1 World Ocean Circulation Experiment (WOCE), TOGA, Global Ocean-Atmosphere-Land System (GOALS), and Climate Variability and prediction (CLIVAR)

Much of the recent progress in advancing our understanding of seasonal-to-interannual climate variability is due to the TOGA program. This decade-long program focused on understanding and predicting the ENSO phenomenon, long recognized as being the most prominent interannual variation of the coupled climate system and one with global consequences. TOGA successfully implemented a routine in situ observing system across the tropical Pacific basin, mounted a major field campaign (TOGA/COARE), remotely monitored critical parameters of the coupled system (such as SST and sea-surface topography, deep atmospheric convection determined from outward long-wave radiation), and initiated experimental predictions of ENSO events.

The ten-year TOGA program has now been completed and has gone far beyond the original expectations laid down in 1985. A new national program, GOALS, has been developed to both continue and expand research on seasonal-to-interannual variability. GOALS is a U.S. contribution to the international program, CLIVAR, which is a study of global climate on seasonal-to-centennial time scales. GOALS has an expanded scope of understanding and predicting connections between the tropical Pacific ENSO signal and climatic variations in other parts of the world as well as the predictability of climate variations not directly attributable to ENSO. EOS observations will support the GOALS goal of expanding its focus from the tropical Pacific to the entire global tropics. Related studies will improve understanding of the connections between tropical climate variability and significant climatic events at higher latitudes, with the goal of determining the feasibility of predicting these higher latitude events up from a season to a year in advance.

3.3.2.2 JGOFS

JGOFS, which began over a decade ago, is designed to study biogeochemical processes in the ocean and their role in climate change. The International Science Plan (JGOFS Report No. 5, SCOR, 1990) has set forth two goals:

1) To determine and understand on a global scale the processes controlling the time-varying fluxes of carbon and associated biogenic elements in the ocean, and to evaluate the related exchanges with the atmosphere, sea floor, and continental boundaries.

2) To develop a capability to predict on a global scale the response of oceanic biogeochemical processes to anthropogenic perturbations, in particular those related to climate change.

To meet these goals, the U.S. JGOFS approach is based on large-scale surveys, time-series stations, process studies, modeling, and data management. The large-scale surveys will provide a basin-scale-to-global-scale view of biogeochemical properties on seasonal time scales. Critical properties include surface pigment, primary production, CO_2, and export fluxes. The time-series stations will provide long-term, consistent observations to study seasonal variability of biogeochemical processes at a few sites. An improved mechanistic understanding of crucial biogeochemical processes is the objective of the process studies. These campaigns are conducted in critical regions of the ocean for a limited duration. Modeling activities will synthesize these data sets to provide a diagnostic understanding of ocean biogeochemistry as well as eventual use in predictive studies of the ocean's response to climate change. Lastly, these data sets and models will be maintained and managed so that future researchers can have confidence in the quality of the data as well as to facilitate data sharing and intercomparison.

The first three JGOFS process studies were the North Atlantic Bloom Experiment, the Equatorial Pacific program, and the Arabian Sea program. The final process study (Antarctic Environment Southern Ocean Process Study [AESOPS]) began in austral spring, 1996, and will conclude in 1998, just before the launch of the first AM-1 platform. High-quality satellite measurements from all of the ocean sensors (altimetry, scatterometry, visible radiometry, and infrared radiometry) will be available during this study of coupled ocean physical and biogeochemical processes. This represents a unique opportunity to develop and test models using observations analogous to EOS observations.

The next ocean program planned for IGBP is the Surface Ocean Lower Atmosphere Study (SOLAS), which will focus on event-scale processes and their role in air/sea fluxes. At this point, SOLAS is just beginning to be defined, but one of its primary objectives is to exploit the broad range of satellite observations of the ocean that will be available in late the 1990s and early 2000s. Building on JGOFS, SOLAS will expand our understanding of the coupling of physical and biological processes in the ocean. EOS observations will play a critical role.

3.3.2.3 GLOBEC

The U.S. and International GLOBEC programs have the goal of determining how marine animal populations respond to climatic variability and long-term climate change. The focus on zooplankton and higher trophic levels complements the focus of JGOFS on nutrients, primary production, and the carbon cycle. There is an international GLOBEC program and office at the Plymouth Marine Laboratory in the United Kingdom, and a number of national programs, including the U.S. GLOBEC program located at U.C. Berkeley. GLOBEC's approach includes:

- retrospective studies to elucidate the important scales of variability of ecosystem response to climatic change and to formulate hypotheses about mechanisms through which the components of the ecosystem respond,
- process studies to test the hypotheses and quantify the mechanisms, and
- ecosystem models that incorporate these mechanisms and provide a predictive capacity.

The first intensive process study of the U.S. program is a study of zooplankton, cod, and haddock on Georges Bank. The focus is on processes that control retention of larval and juvenile fish over the bank, looking also at their predators and prey. Retention is thought to be a key process in enhancing their survival and recruitment into the adult fish population. The second study is planned in the northeast Pacific (California Current and Alaska Gyre). This study is likely to concentrate on the processes that control mortality of juvenile salmon in the coastal ocean as they emerge from the rivers. Mortality during this period is thought to control ultimate yearly population strength. The general health of the coastal zooplankton ecosystem will also be a target, forming the prey field for the salmon, as will their predators. The survival of larval benthic invertebrate species may also be included, since these may be used as indicators of the health of the offshore zooplankton ecosystem.

These two studies are complemented by the national GLOBEC studies planned by Canada in the Atlantic and Pacific oceans and by Mexico in the Pacific. The international GLOBEC program has initiated modeling studies in the Southern Ocean (in cooperation with JGOFS), is planning field studies in the Southern Ocean concentrating on ecosystem dynamics that control the population of krill (beginning in 1999, following JGOFS), and is in the planning stage for studies in the regions where small pelagic fish (sardine, anchovy, herring, sprats) are the main fishery. Krill form the base of the marine animal food web in the Southern Ocean. Small pelagics are distributed globally, constitute about 1/3 the global fish catch, and cause much of the interannual variability in annual fish catch biomass. It will be important to coordinate GLOBEC process studies with EOS measurements and to combine EOS monitoring with GLOBEC ecosystem modeling in order to gain the most information from the two programs. Similar coordination with field studies carried out by JGOFS and its successor will be equally important.

3.4 EOS contributions: Combining the knowledge of ocean and climate systems

3.4.1 Air-sea flux plans for EOS

The focus of air-sea flux research in EOS is to make significant improvements in space-based observations required for global estimates of the air-sea momentum, heat, and freshwater exchanges, and to use this information to obtain a better understanding of ocean-atmosphere coupling on seasonal-to-interannual time scales.

Air-sea fluxes play crucial roles in six EOS Interdisciplinary Science Investigations—those of Abbott, Hartmann, Lau, Liu, Rothrock, and Srokosz—and are the focus of the Instrument Science Team for SeaWinds. Their combined goals regarding surface fluxes are listed below.

(i) Provide long-term, global, space-based observations of the surface wind stress from direct microwave observations of the ocean surface from both pre-EOS and EOS sensors.

The SeaWinds Instrument Team has the fundamental goal of providing ocean wind stress fields over 90% of the ice-free ocean every 2 days. The team will provide continuing long-term wind stress data for studies of ocean circulation, climate, air-sea interaction, and weather forecasting. The AMSR-E Instrument Team will provide continual observations of wind speed and stress magnitude.

(ii) Provide long-term, global, space-based observations of the variables relevant to the estimation of radiative and turbulent air-sea fluxes.

These observations are detailed in Section 3.3.1.1. The fundamental variables over both oceans and sea ice are surface temperature; temperature and humidity at as low a level in the atmosphere as can be observed (850 mb or lower); cloud water and ice content; radiative properties of the lower troposphere including atmospheric temperature and humidity profiles; and precipitation rates and amounts. Aside from the estimation of fluxes, SST and salinity are needed as diagnostic variables.

(iii) Assimilate surface and lower troposphere data into models that estimate wind stress, water vapor flux, sensible heat flux, and up- and downwelling components of radiation at the surface. Provide long-term global records of these fluxes over oceans and sea ice from both pre-EOS and EOS sensors.

Air-sea fluxes cannot be observed directly from space. Rather, the fluxes must be deduced from estimates of more-directly-observable meteorological and oceanographic fields as called for in (ii). The problem of estimating climatological air-sea exchanges of momentum, heat, and freshwater may be thought of as a problem in data assimilation, in which observed data are used to tightly constrain the key variables in physical or empirical models of exchange processes. Because flux estimation often requires combining data from more than one sensor, Interdisciplinary Teams are actively developing multi-sensor and data assimilation techniques. Two Interdisciplinary Teams are ensuring that these flux fields extend to the Arctic and Southern oceans with no degradation in quality.

(iv) Apply air-sea flux data sets to the study of oceanic and atmospheric processes that control these fluxes and cause them to vary, and to the study of the role these fluxes play in forcing oceanic and atmospheric circulations and in the global heat and water balance.

Atmospheric processes such as air mass movement, convection and subsidence, formation of marine clouds, and development of storm systems all affect the strength of air-sea fluxes by controlling the temperature and humidity contrast between the sea surface and the atmospheric boundary layer. Similar control is exercised by oceanic processes such as the general ocean circulation, mixing, and upwelling. The contrasting point of view is understanding how surface fluxes transfer heat between the ocean and atmosphere and contribute to the global heat and water cycles. Local seasonal phenomena such as monsoon cycles and hurricane seasons must be characterized in terms of ocean-atmosphere phenomena.

(v) Utilize in situ data of surface and near-surface meteorological conditions to validate air-sea flux models.

Both space-based and in situ data are required to obtain accurate estimates. Space-based data provide global spatial coverage within the limitations of the satellite orbit. In situ data from ships, buoys, aircraft, and island stations provide point measurements of meteorological and oceanographic fields and the related fluxes. Space-based data therefore provide the spatial and temporal coverage needed to reduce sampling errors, whereas the in situ data provide a calibration standard and information on the detailed vertical structure of the atmosphere. There are numerous air-sea flux programs, some with attached field programs, in which EOS investigators are participants along with a wider community of investigators.

A central aspect of these studies is clarifying sampling issues so that space-based and surface-based flux estimates can be intercompared and jointly utilized in model testing.

(vi) Support the design, building, and validation of an interdecadal climate prediction system that correctly treats air-sea interaction including precipitation.

New knowledge of atmospheric and oceanic boundary layer processes is being used to test and improve model parameterizations. Modeled fields of air-sea fluxes will be thoroughly tested against independent space-based and surface-based flux estimates and estimates of closely related surface variables such as SST and salinity. The goal is a climate model that accurately transfers momentum, heat, and water across the sea surface. Some initial work is directed at examining the air-sea coupling in the Earth system model.

3.4.2 Ocean circulation and sea-level plans for EOS

EOS oceanographers are focussed upon assessing and understanding the distribution of heat and salt within the world oceans, and the ocean circulation. The fundamental task is collection and analysis of remotely sensed data describing the dynamic state of the ocean surface. The essential tools are an array of ocean and atmosphere-ocean models that permit the diagnosis of ocean dynamics and atmosphere-ocean coupling in both "forced" and "data assimilating" modes.

Contributions to studies of ocean circulation are being made by the TOPEX/Poseidon and Jason-1 Altimeter Teams, the MODIS Science Team, the AMSR Science Team, and the NSCAT and SeaWinds Science Teams, and by a number of Interdisciplinary Science Investigations—those of Abbott, Liu, Rothrock, and Srokosz. Their combined goals regarding ocean circulation are as follows:

(i) Determine the marine geoid to an accuracy of 1.5 cm by means of a gravity mission, determine multi-decadal global sea-level variations to an accuracy of 4 mm rms, and determine the long-term trend to <1 mm/yr.

These are fundamental observational goals for defining the mean ocean circulation and climate-driven sea-level change. They will enable the measurement of oceanic transports at the 1 Sv level.

(ii) Provide a multi-decadal record of the seasonal and interannual variability of ocean surface currents and of surface temperature and salinity, and validate these data with in situ observations.

A multi-decadal record of the sea-surface state is the underpinning of the contribution oceanography needs from satellite observations. Providing and validating this record is the central goal of many instrument and interdisciplinary investigators. Altimeter data together with in situ data are being intercompared in programs such as the TOGA/WOCE Surface Velocity Program and the Global Drifter program.

(iii) Utilize improved observations of surface fluxes, currents, temperature, and salinity to quantify the mean ocean circulation and its seasonal-to-interdecadal variability, assessing in particular the mean and variability of the poleward oceanic heat transport.

The determination of mean currents requires a better geoid. In the meantime, mesoscale processes and variability are being studied using higher-resolution sea-level fields generated by coupling multiple altimeter data sets. Coupled infrared and altimeter observations will be used to calculate high-resolution ocean circulation fields. Investigators are examining the relationship between the temporal and spatial variability of the atmospheric forcing and the variability of the oceanic response. Altimetry and SST data are being combined to study time-dependent eddies and seasonal variations in the position of currents such as the Agulhas Retroflection. Studies of SST data in the North Atlantic show high variability localized in the Gulf Stream and off Newfoundland. In situ observations of absolute current in the Drake Passage are being used to extend the interpretation of surface-height anomalies from altimetry. The circulation in the Arctic Ocean and its exchange with the North Atlantic are being studied to document variability in the stability of the Greenland and Labrador Seas and how this variability acts to control episodic deep water formation.

(iv) Advance methods for assimilating surface observations into ocean GCMs and into combined atmosphere-ocean and climate system models, and use the resulting improvements in ocean model physics to advance the predictive capability of combined models.

Investigators are developing fully assimilating ocean models. The assimilated variables can include surface height or current, and SST and salinity; over ice-covered oceans they include ice velocity and concentration. Model results are being studied to understand how physical processes regulate primary productivity in the Southern Ocean. These models will be used to understand the linkage between the intense variability observed on small scales and the larger-scale processes on monthly or longer time scales.

By assimilating data and forcing models with improved surface fluxes investigators will improve eddy-resolving ocean-circulation models, giving a more-realistic 4-D description than possible with present data. New techniques for assimilating sea-surface height data allow one to project the height data to recover the deep-ocean-water properties and circulation by assuming conservation of relative vorticity.

(v) Understand the role the ocean plays in determining the angular momentum and mass exchange within the Earth system.

Atmospheric pressure and ground water redistribution play a significant role in exchanging momentum with the ocean and solid Earth; the mechanism is not well understood. Sea-level changes occur from mass redistribution, thermal change, and ocean circulations. Changes in the Earth rotation are attributable to winds, currents, ground-water circulation, and mass redistribution within the Earth system. Changes in the gravity field, which can be inferred from satellite orbit perturbations, arise only from mass redistribution. Combining EOS observations and space geodetic techniques enables one to observe and interpret these global signals, to improve atmospheric and ocean models, and to improve the predictive capabilities of these models. The model improvements can be accomplished by using the global angular momentum, stress torques, and mass variations as a means of calibrating, interpreting, and constraining general ocean-circulation-model outputs.

3.4.3 Marine biogeochemical research planned in EOS

We presently lack basic observations of "ocean color" necessary to estimate ocean biogeochemical variables and to develop and test relationships between them in numerical models. Long-time series of well-calibrated satellite optical observations will provide these critical observations and allow us to quantify the linkages between climate and ocean ecology. The approach in EOS is based on a synthesis of ocean and atmosphere circulation models with satellite and in situ measurements of the ocean-surface biogeochemical variables. These studies are being undertaken by the MODIS Instrument Science Team and the Interdisciplinary Science Investigations of Abbott, Goyet, and Srokosz. We are pursuing the following objectives in parallel:

(i) Acquire long-term, calibrated satellite data sets of ocean biogeochemical variables.

The biological component of the investigation will utilize MODIS as well as other ocean-color sensors—SeaWiFS, Ocean Color and Temperature Scanner (OCTS), MERIS, and GLI—to obtain basic information on ocean biological processes. These sensors will be used to estimate phytoplankton abundance as well as growth rates based on models that incorporate biomass, fluorescence, and incoming solar radiation.

(ii) Acquire in situ observations of physical and biogeochemical data to complement satellite observations, to provide variables not observable by satellite, to intercompare with satellite data, and to assess sampling characteristics and accuracy of satellite data.

Investigators will make field measurements in the Southern Ocean of both biological and physical processes. Bio-optical moorings are planned for the Polar Front in late 1997. A test mooring was deployed at the Hawaii JGOFS Time Series station in early 1995. A cruise in the Weddell Sea used bio-optical drifters and photosynthesis measurements to improve models for estimating primary productivity from fluorescence measurements from MODIS. New buoy-mounted technology for in situ real-time sensing of pCO_2 is being developed to provide short-term and long-term time-series measurements and to gain better understanding of the temporal variations of pCO_2 in surface seawater. In-water optical properties are being related to phytoplankton biomass and pigment concentrations, including accessory pigments, as well as DOM concentrations. Algorithms to determine phytoplankton speciation and distributions are being studied. In addition, improved models for estimating primary production and DOC in the mixed layer from pigment concentrations, SST, mixed-layer depth, and mean incident solar irradiance are being developed. The output of these models will be compared with in situ measurements. Data will be analyzed in terms of the scales of variability from days to years and from kilometers to thousands of kilometers.

(iii) Quantify the mean and variability of the ocean surface biogeochemical state.

Models for mapping seawater partial pressure fields of several radiatively active gases are being developed. The field of pCO_2 in the ocean mixed layer will be derived from mixed-layer depth, salinity, SST, and phytoplankton biomass, and constrained by field measurements of alkalinity and TCO_2 from WOCE and JGOFS field observations currently underway.

(iv) Develop coupled ocean circulation/biogeochemical models, both with and without data assimilation, and utilize satellite and in situ data to provide model forcing and to test and improve model formulation.

Fluxes of CO_2, DMS, and CO over basin and global scales will be modeled using the air-sea gas-concentration gradients derived from maps of gas transfer velocities. Algorithms for a more-accurate gas-transfer velocity parameterization based on wind speed, CZCS-derived organic matter estimates, and microwave backscatter-derived wave slope measurements are under investigation. New production and the primary production contribution from below the mixed layer will be modeled. The results of these investigations will be incorporated in upper-ocean models: ecosystem models treating phytoplankton, zooplankton, nutrients, and detritus, as well as global eddy-resolving ocean models using sea surface total CO_2 and pCO_2 interpolated from satellite imagery.

(v) Develop a quantitative understanding of the relationship between the climate and the upper-ocean ecological state—both the mean and its variability.

Interdisciplinary studies are aimed at 1) understanding and predicting the response of the marine biosphere to variations in physical forcing, with particular emphasis on the Southern Ocean and North Atlantic and 2) understanding and predicting the air-sea exchange and fate of CO_2 and two other radiatively important gases, DMS and CO. Studies will determine processes near the Subtropical Convergence governing "new" production, which is the component of primary productivity supported by the input of nutrients into the ocean's euphotic zone from deeper waters or from the atmosphere. New production is related to the vertical flux of carbon in the ocean and thus plays a key role in the ocean carbon cycle. The Subtropical Convergence is one of the most important sites in the world ocean for new production and hence for the uptake of atmospheric CO_2. The approach is to use ocean-color observations as well as measurements of physical forcing by EOS altimeters and scatterometers to study the processes controlling the rate of new production. The role of atmospheric forcing and its impacts on ocean circulation and eventually on biological productivity will be analyzed using the full suite of EOS ocean sensors and numerical models.

3.4.4 Human dimensions of ocean climate

EOS will provide for the first time simultaneous observations of the major physical and biological ocean-surface variables. These observations along with simultaneous atmospheric and terrestrial observations will introduce a new era in predictive modeling capabilities with enormous benefits to oceanic, and, particularly, coastal human activity. Sea level, currents, and waves all affect transportation, oil and gas extraction, property loss through sea-level change and coastal erosion, recreational boating, and search and rescue. Storms and floods in coastal regions destroy infrastructure and living resources. The assimilation of EOS measurements will dramatically improve global and regional atmospheric and oceanic forecasts. Simultaneous and improved atmospheric and oceanic measurements over the open oceans will be especially critical to forecasts along the continental west coasts, where upstream atmospheric information is presently sparse. Specific benefits include:

- Improved prediction of circulation patterns that will aid oil/chemical spill cleanup, allow accurate environmental impact assessments, and improve waste management decisions.

- Improved prediction of coastal effects of storms and other marine hazards that will increase the safety of navigation, improve warnings and evacuations for storms, floods, and tsunamis, and provide guidance for long-term coastal planning.

- Improved prediction of wave heights and directions and of ocean tides will allow more accurate time-series measurements of coastal sea level.

- Improved understanding and modeling of sediment erosion/deposition, land subsidence, and sea-level rise that will allow long-term projections of sea-level change and its impact on coastal populations and economies.

It is critical that we define today's baseline condition of global coastal environments. EOS data and model products will provide a unique framework for quantitatively addressing changes in freshwater inputs and their relationship to precipitation in catchment areas, and exchanges of water and sediment between estuaries and the coastal ocean. Besides improvements in large-scale models, it is also important that we improve regional models that predict winds and precipitation over variable terrain at the shoreline transition and forecast potential damage caused by winds, waves, floods, and storm surges.

Understanding and predicting the effects of climatic variability on coastal and pelagic fisheries is another critical issue with tremendous human consequences. There is growing evidence that fish populations respond strongly and quickly to local and basin-scale environmental variability (Hunter and Alheit 1995; US GLOBEC Report Nos. 11, 1994, and 15, 1996). Examples include responses to interannual ENSO fluctuations in the Pacific Ocean and responses to interdecadal fluctuations in conditions in all basins. The affected species range from phytoplankton at the base of the food web to commercially and ecologically important fish, marine birds, and mammals. As a consequence of our ignorance of these natural cycles, we have overfished certain stocks during their natural collapse periods, depleting their stocks to actual or near extinction. A case in point is the California sardine, which is now thought to have been in a period of natural decline in the late 1940s. By overfishing this resource at a critical time, we drove the population to virtually zero off the U.S. west coast. The few remaining fish did respond to a change in oceanic conditions in the late 1970s, but instead of returning to their peak numbers by 1980 (as they would have, if left at natural levels), an additional 15 years were required until they reached moderate levels in the mid 1990s. Other examples include cod and haddock in the Northeast Atlantic and salmon stocks in the Pacific Northwest, although the interplay between natural fluctuations and overfishing in these cases is not yet as clear.

Most commercially important fish and benthic invertebrates, like crabs, begin life as passive larvae, subject to the forces of currents and other oceanic environmental conditions. EOS sensors will either observe or help models predict the environmental influences on their life cycle:

- the wind forcing, including turbulent mixing that affects larval feeding behavior;
- circulation patterns, which carry larvae to locations better or worse suited for their growth and survival;
- temperatures, which affect growth of the larvae and also the abundance of their prey and predators;
- phytoplankton concentration and primary productivity, forming the base of the food chain; and
- mixed-layer depth and stratification, which affect vertical motion and mixing of nutrients that support primary productivity.

In coordination with process studies aimed at specific mechanisms that affect growth and mortality of target species, EOS data sets will be invaluable for formulating and testing biophysical ecosystem models. Benchmarked against environmental changes seen in EOS data, these models will become management tools predicting changes that lead to natural declines in populations, allowing a rational approach to fishery harvests.

3.4.5 Atmosphere/ocean modeling

For many purposes, the ocean can be treated as an isolated component of the climate system. This is possible when adequate boundary conditions are available from observations for the issue to be studied, that is, when fluxes of momentum, heat, fresh water, and various chemical substances across the sea surface are available. Then numerical models of the oceanic circulation can be used to unravel some of the key processes involved in the ocean's role in climate change. In many circumstances, however, it is not possible to isolate the ocean from the atmosphere. It is, in fact, the interactions that feed from one of these components to another—often in both directions—that contain the essential mechanisms for global climate-change scenarios.

A good example of this is the feedback associated with perturbations within the ocean and atmosphere associated with changes in SST. Because of its small heat capacity the atmosphere quickly restructures its winds and thermal fields in response. This in turn results in changes in the forcing of the ocean that begins to create a new upper ocean structure and SST pattern. The potential for such interactions that can provide both positive feedbacks (leading to the combined system tending to move further from its initial condition) and negative feedbacks (such that the combined response is to damp the system back toward its initial configuration) is at the heart of coupled ocean/atmosphere modeling. Such models must play a central role in any strategy for unraveling the climate puzzle.

The lack of complete, global observations of many important variables and derived quantities presents major challenges to validation of component models of the atmosphere, ocean, and sea ice. In coupled models, concern with interactive system behavior exacerbates validation problems by increasing the available degrees of freedom. However, a great deal of data can provide indirect information about aspects of the coupled system. For example, heat and fresh water budget constraints can be used to validate coupled atmosphere-ocean-sea ice components. Estimates of evaporation minus precipitation from atmospheric measurements or analyses can be used to examine fresh water transports, oceanic salinity, and thermohaline circulation. Similarly, the sum of convergence of heat transports by atmosphere and ocean must balance net radiation at the top of the atmosphere. The combination of local budgets of these quantities in the atmosphere, the ocean, and at the interface produces over-specification, requiring conciliation among different answers and, thus, provides constraints on system behavior. Models provide another important insight: one can examine model sensitivities and discover which components are critical to the system's proper behavior and then focus upon observing these components and ensuring that they are well represented in the models.

3.4.6 Improved predictions of seasonal-to-decadal climate variability through global land-atmosphere-ocean models

Changes in climate, whether anthropogenic or natural, involve a complex interplay of physical, chemical, and biological processes of the atmosphere, ocean, and land surface. As climate system research seeks to explain the behavior of climate over time scales of years to millennia, focus necessarily turns to behavior introduced by physical, chemical, and biogeochemical interactions among climate subsystems. The need to understand climate as a coupled system is demonstrated by the paleoclimate record, which reveals large and related changes in atmospheric and oceanic circulations and biogeochemistry (e.g., Broecker 1987; Dansgaard et al. 1993). The challenges of modeling the role of anthropogenic emissions of CO_2, of reactive trace gases, and of changing land use in the Earth system likewise require a coupled climate system approach. While knowledge that land-ocean-atmosphere interactions influence climate is not new, the emergence of coupled climate system questions as central scientific concerns of geophysics constitutes a major realignment of the research agendas in atmospheric science, oceanography, ecology, and hydrology.

Two recent books, *Climate System Modeling* (Trenberth 1992) and *Modeling the Earth System* (Ojima 1992), document many aspects of climate system modeling and of the uses of such models for global change research and paleoclimate studies. Key questions include the coupling between processes occurring at different time scales (seasonal to interannual, interannual to decadal) that affect the longer-term behavior of the system. The interaction between seasonal and interannual (ENSO) processes discussed by Tziperman et al. (1994) provides one example. As a related but longer-term example, evidence—in the paleorecord and from models—shows that changes in ENSO frequency are a component of long-term climate variability (Meehl et al. 1993; Thompson et al. 1989). The possible existence of thresholds or multiple equilibria in the climate system arising from the thermohaline ocean circulation and perhaps related to the carbon cycle is another issue of scientific importance and great relevance to society (Taylor et al. 1993). This is because adaptation to abrupt change would be much more difficult for mankind than acclimatization to continuous change.

Relatively simple models will continue to play an important role in climate system research, but the most credible characterizations of the important processes, as well as the best predictions for future climate change, will come from comprehensive models of the climate system. Many relevant examples of component subsystem models exist, and several groups around the world have produced interesting prototypes for a comprehensive climate system model. However, no mature model of this type yet exists. It is vital therefore, during the EOS years, that such models be further developed vigorously and exercised fully in pursuit of more-complete understanding of climate-change issues.

3.4.7 Understanding of ocean's effect on carbon dioxide, the major greenhouse gas

In order to describe and predict climate variability due to the continuous increase of anthropogenic CO_2 in the atmosphere, it is essential to understand the present-day role of the ocean in the absorption of atmospheric CO_2 gas. Most of this absorption occurs by carbon input from the rivers and by continuous CO_2 gas exchange across the ocean-atmosphere interface.

As mentioned above (in Section 3.2.4.3) CO_2 fluxes cannot be measured directly and have to be estimated from various observations. On the global scale, the quantification of CO_2 fluxes across the ocean-atmosphere interface requires two complementary sets of observations: in situ and remotely-sensed observations.

The in situ observations, typically obtained from oceanographic research cruises, provide accurate sea-surface pCO_2 data sets on short time and spatial scales. The space-based observations provide global spatial coverage at frequent time scales of a limited number of parameters (such as ocean color and SST) with a lesser accuracy than in situ observations. The challenge is to develop algorithms that couple in situ and proxy space-based observations to quantify the global absorption of carbon by the oceans.

Providing a global estimate of the air-sea exchange of CO_2 will be a major contribution to quantifying the Earth climate system.

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