Making the Climate Connections: Bridging scales of space and time in the U.S. GLOBEC program

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Introduction

"Strange whales, playful porpoise, out-of-place sailfish and marlin - these are just some of the offshore oddities accompanying El Niño's dramatic ocean-warming along the Pacific Coast [of California] this year" (Stienstra, 1997).

How did we get so far so fast as to confidently link changes in tropical climate to marine ecosystem changes thousands of kilometers distant? For many years now the fishery oceanography community has been aware of the long reach and unusual power of the tropical El Niño-Southern Oscillation (ENSO). Early indications of an El Niño event are now routinely extended into predictions for ecosystem change not only in the equatorial Pacific, but also in the California Current and even into the Gulf of Alaska. Such predictions are largely based on experience developed from past El Niño events, yet in most cases our understanding of cause and effect has failed to keep pace with our observations and expectations.

The spectacular late-20th Century decline of cod stocks on the Georges Bank, repeated decades-long boom/bust cycles for Pacific salmon in the northeast Pacific, and the year-to-year waxing and waning of krill biomass and penguin populations in the Southern Ocean all highlight aspects of dynamic ecosystem variability that beg for an improved scientific understanding. Can these ecosystem changes be linked to ENSO events or other variations in the global climate system? If so, can the pathways of interaction be understood?

In the examples listed above, efforts to disentangle natural climate impacts from direct and indirect anthropogenic (e.g. industrial fishing) impacts have been of great interest for fishers, fishery managers, and fishery scientists alike. A growing body of empirical data and analyses have highlighted many local environmental and ecosystem changes that appear to be part of much larger scale and sometimes longer term changes playing out in the climate system (e.g. Mysak, 1986; Francis et al., 1998; Dickson and Brander, 1993; Loeb et al., 1997). Thus, an alphabet soup of oscillations and acronyms first introduced in the climate research community—the North Atlantic Oscillation (NAO), El Niño-Southern Oscillation (ENSO), the Pacific Decadal Oscillation (PDO), and the Antarctic Circumpolar Wave (ACW), for example—has found a hungry audience in the world of fishery oceanography.

To better understand and more skillfully predict climate impacts on marine ecosystems, U.S. GLOBEC scientists are often faced with significant hurdles that come with working across traditional disciplinary boundaries. In this article we discuss some of the challenges in bridging scales of time and space that are required to link large scale climate dynamics to local scale marine ecosystem dynamics. First, we review aspects of hemispheric-scale climate variations to provide a broad-spatial and long-temporal context for aiding our understanding of ecosystem dynamics in U.S. GLOBEC regional programs. Second, our perspective shifts to that of the modeling efforts now used to bridge the space-time scales linking "local" ecosystem processes with hemispheric scale processes in the global climate system.

We conclude this article with a brief discussion of the avenues of research that we believe offer promise for advancing our ability to "make the climate connections" with marine ecosystem dynamics.

Modes of Climate Variability

Modes in the climate system can be understood as naturally occurring patterns of variability in the atmosphere and/or ocean, with each pattern exhibiting unique spatial characteristics but typically vague temporal characteristics that often bear resemblance to red noise processes. Some modes arise from atmospheric processes alone, while others are considered to be *coupled modes* of the climate system that arise from interactions between the atmosphere and the ocean (and/or sea ice). Characteristics of climate modes are influenced by factors like topography, the distribution of continents and sea ice, land-sea contrasts, the size of ocean basins, and seasonally varying large scale horizontal temperature gradients (across distances of 10^3-10^4 km). What follows is a brief discussion of several atmospheric and coupled modes and how they influence environmental conditions in U.S. GLOBEC study regions. We focus on aspects of atmospheric forcing and how it typically influences ecologically important aspects of the ocean environment. A glossary of the climate terminology that follows is given in Table 1.

Climate mode influences in U.S. GLOBEC study regions

Northeast Pacific

The pair of schematics in Figure 1 show typical November-March average sea level pressure and surface wind fields during periods with either weak or intense Aleutian Low conditions. The Aleutian Low (AL) is a climatological feature of the North Pacific atmospheric circulation: every winter the AL develops as a region of consistently low sea level pressure and active storminess. The AL gradually weakens in spring as the equator-to-pole temperature difference relaxes and the storm track weakens and moves poleward. In some years, the wintertime AL is especially intense (top panel of Figure 1), while in others it is quite weak and actually exists as a pair of low pressure cells, one located just east of Kamchatka and the other located in the northern Gulf of Alaska (middle panel of Figure 1). Changes between strong and weak AL conditions are among the primary modes of wintertime atmospheric variability over the North Pacific, and these changes are strongly linked to the Pacific North America (PNA)

Table 1. *Glossary of climate terminology.*

Antarctic Circumpolar Wave (ACW): A westward propagating, wavenumber 2, pattern of sea-ice, surface temperature (air and sea), and sea level pressure anomalies that appears to circle the Antarctic every 8 to 9 years. The amplitude of the AACW is greatest between 50°and 60° S. Because of the paucity of historic surface data for the Southern Ocean, it is difficult to determine the long-term behavior of the AACW.

El Niño-Southern Oscillation (ENSO): An ocean-atmosphere mode of climate variability arising from strong air-sea interactions in the equatorial Pacific; impacts of ENSO variability reach many regions outside the tropical Pacific via atmospheric and oceanic teleconnections; ENSO has peak variance at 2 to 7 year periods, but occurs on irregular return intervals (see Figure 3).

North Atlantic Oscillation (NAO): The NAO is the leading mode of atmospheric variability over the North Atlantic consisting of a north-south see-saw in sea level pressure with peak variance in the boreal winter; one center of action is located near Iceland and the other located near the Azores; indices tracking the NAO exhibit a "red noise" power spectrum, with enhanced variance at decadal time scales (see Figure 2).

Pacific Decadal Oscillation (PDO): Spatially, the PDO is an ENSO-like pattern of climate variability defined as the leading eigenmode of monthly north Pacific SST variations for 1900–1993. This pattern consists of a dipole structure in which SST anomalies in the central north Pacific coincide with opposing SST anomalies in the northeast Pacific. Indices tracking PDO variations are strongly correlated with smoothed PNA and Aleutian Low indices, and have elevated variance at 15 to 25 and 50 to 70 year periodicities.

Pacific North America (PNA) pattern: The PNA is the leading mode of North Pacific/North America atmospheric variability in the boreal winter consisting of a 4-celled standing wave pattern. PNA centers of action are located near (1) Hawaii, (2) the Aleutians, (3) northwestern North America, and (4) the southeast U.S. The surface expression of the PNA is highly correlated with variations in the intensity of the cool season Aleutian Low pressure cell. During positive phases of the PNA, the Aleutian Low is intense (see Figure 1).

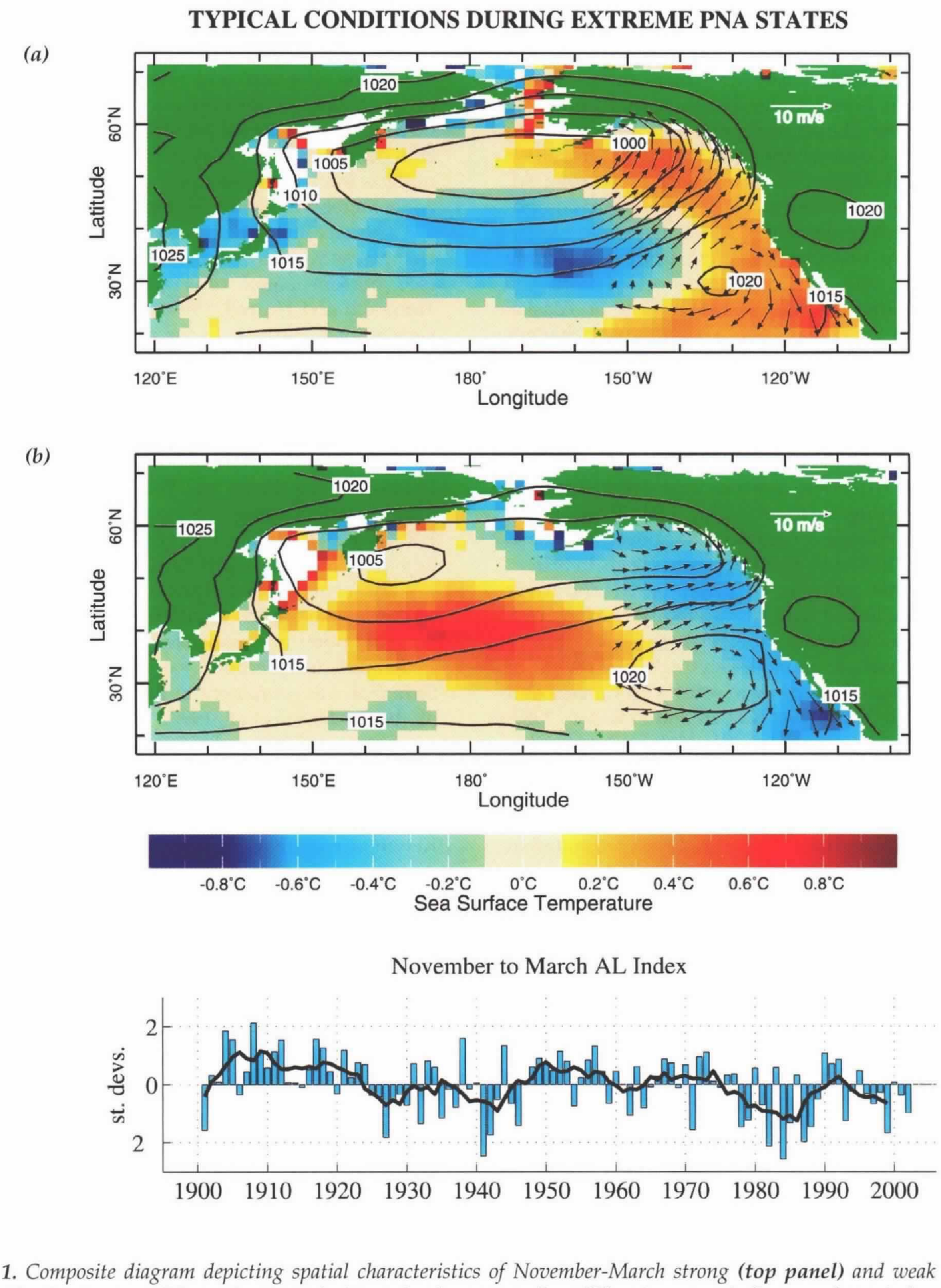

Figure 1. Composite diagram depicting spatial characteristics of November-March strong ***(top panel)*** *and weak* ***(middle panel)*** *Aleutian Low conditions. Contours depict sea level pressures (in millibars), vectors indicate surface winds, and shading indicates SST anomalies. The bar graph in the lower panel depicts a time series of Hurrell's November–March Aleutian Low index (http://www./np.html). A 6-year running-average AL index is shown with the solid curve. Composite fields are based on years in which the PNA index is either + or - one standard deviation from its mean value. Gridded data are from the NCEP/NCAR reanalysis data set (CDAS-1) for the period 1949–2001. Winds are at the 10-m level, SST is from the surface temperature data, which over the ice-free ocean are given by a blend of satellite and ship data.*

pattern that is a prominent mode of variability in the mid-troposphere (Wallace and Gutzler, 1981).

The surface winds associated with AL variability drive important variations in upper ocean currents and temperatures. During weak AL winters surface winds from southern British Columbia to central California are onshore and Ekman transports are equatorward in the California Current region but weakly downwelling in the Gulf of Alaska. In contrast, during strong AL winters surface winds have a strong poleward component over much of the northeast Pacific where Ekman transports are onshore, causing strong wintertime downwelling and onshore advection in both the California Current and the coastal Gulf of Alaska. These surface wind changes also drive major changes in the structure of the upper ocean in the northeast Pacific via changes in heat and momentum fluxes (e.g. Miller et al., 1994). Sea surface temperature (SST) anomalies along the Pacific coast of North America, for instance, switch from being cooler than average during the weak AL winters to warmer than average during strong AL winters (Emery and Hamilton, 1985). Concomitant changes in surface fluxes over the interior North Pacific Ocean yield opposite effects in SST.

Large scale patterns of precipitation and river runoff are also linked with AL variability. During weak AL winters precipitation, snow pack, and spring/summer river runoff are anomalously high in the Gulf of Alaska but anomalously low in southwest Canada and the U.S. Pacific Northwest (Cayan and Peterson, 1989; Mantua et al., 1997). Anomalously high freshwater discharge in the Gulf of Alaska increases the stratification of the Alaska Coastal Current, and may influence zooplankton productivity (Gargett, 1997; Royer et al., 2001), while at the same time the reduced precipitation and runoff in the northwestern U.S. leads to a reduction in the size of the springtime Columbia River plume, which may be an important habitat for juvenile Columbia River salmon (William Peterson, NMFS, personal communication, 2002). The opposite precipitation, snow pack, and river discharge patterns hold for strong AL winters.

Thus, for both the California Current and Gulf of Alaska GLOBEC study regions, AL variability has an especially strong influence on important upper ocean processes like the relative intensity of coastal downwelling, horizontal upper ocean transports, and stratification. Polovina et al. (1995) also report on basin scale changes in northeast Pacific mixed layer depths related to interdecadal changes in the AL. During a period of intense AL winters, the mixed layer shoaled and warmed in the Gulf of Alaska, but warmed and deepened in the California Current (*cf.* Roemmich and McGowan, 1995).

Assuming that phytoplankton production is light limited in the Gulf of Alaska, but nutrient limited in the California Current, Gargett (1997) hypothesized that the coast-wide coherent changes in northeast Pacific stratification linked to AL variability may explain the observed north-south inverse production pattern in Pacific salmon via the differential impacts of stratification on phytoplankton productivity: increased stratification in the coastal waters of the Gulf of Alaska related to the warmed and shoaled mixed-layer keeps phytoplankton in the euphotic zone and enhances productivity, while increased stratification via a warmed and deepened mixed layer in the California Current reduces the entrainment of nutrients into the euphotic zone, thereby reducing phytoplankton production.

The AL intensity has shown strong year-to-year changes as well as changes at interdecadal time scales (see bottom panel of Figure 1; Trenberth, 1990; Trenberth and Hurrell, 1994). Although part of the AL variability is intrinsic to the atmosphere, a significant part of the interannual variability of the AL is associated with the ENSO cycle. The ENSO-AL interaction owes its existence to ENSO-related changes in the distribution of tropical rainfall that generate disturbances in the atmospheric circulation that radiate away from the tropics (e.g. Horel and Wallace, 1981; Hoskins and Karoly, 1981). During El Niño periods (warm phases of ENSO) the AL tends to be intense and centered over the eastern half of the North Pacific, while during La Niña periods (cool phases of ENSO) the AL tends to be weak. Multiple-year stretches with the same sign anomaly in the AL index are associated with the PDO, or the ENSO-like interdecadal variability of North Pacific SSTs that was prominent in the 20th Century (Zhang et al., 1997; Mantua et al., 1997).

ENSO variability also influences the oceanography of the Northeast Pacific via oceanic teleconnections. During El Niño events, a relaxation of near equatorial easterly winds generate downwelling equatorial Kelvin waves that, as they reach the coast of South America, generate poleward propagating coastally trapped waves in both hemispheres. These internal waves enhance poleward flow in the mid-latitude eastern boundary currents (Enfield and Allen, 1980; Chelton and Davis, 1982; Strub and James, 2001). The combined influences of ENSO on North Pacific SSTs project strongly onto the PDO SST pattern, thus ENSO variability contributes to interannual variations in both AL and PDO indices.

Georges Bank

In the North Atlantic, each winter the Icelandic Low develops as a region of consistently low sea level pressure and active storminess. To the south, the Azores High develops as a region of persistently high pressure and generally fair weather. Typically, in years when the Icelandic Low is unusually deep the Azores High is unusually strong and westerly winds over the mid-Atlantic (including the Georges Bank) are especially strong. This synchronous behavior of the Icelandic Low and Azores High pressure systems is referred to as the North Atlantic Oscillation (NAO). The NAO is particularly strong in winter but can also be discerned with less prominence in other seasons.

The pair of schematics in Figure 2 show typical December-March sea level pressure and surface wind fields during periods with positive and negative phases of the NAO. The phase of the NAO is said to be positive when the pressure in Iceland is lower than average and negative when it is higher than average (top panel of Figure 2).

Wind and SST changes associated with NAO variability affect many aspects of ocean climate, including the degree of storminess, the intensity of water mass formation and flow, and the position of the Gulf Stream. During positive NAO periods strong and anomalously cold westerly surface winds produce anomalously cold SSTs in the far NW Atlantic and Labrador Sea, enhancing the formation and transport of sea ice in the southern Labrador Sea and intensifying the flow of the cold Labrador Current along the North American seaboard. At the same time, winds tend to be anomalously weak over most of the Atlantic coast of the U.S., but anomalously strong and southwesterly in the northeast Atlantic. During negative phases of the NAO the core of the westerly winds shifts southward, producing opposite effects in the Labrador Sea and causing a tripole pattern of SST anomalies in the North Atlantic, with anomalously cold temperatures across the mid-latitudes (including the Georges Bank region) and anomalously warm SSTs to the north and south (middle panel of Figure 2).

Basin scale changes in storminess, precipitation, and cold air outbreaks over the eastern U.S. and western Atlantic are also influenced by variations in the NAO. During positive phases of the NAO, precipitation is anomalously high along the entire eastern part of the U.S., and North Atlantic storminess is generally enhanced. The opposite conditions hold with negative NAO periods. The frequency of cold air outbreaks over the eastern U.S. (and presumably the far western Atlantic) is anomalously low during positive NAO periods, but anomalously high during negative NAO periods (Thompson and Wallace, 2001). Such extreme events may influence the frequency and intensity of upper ocean mixing events due to a destabilized water column caused by strong surface cooling.

The existence of the NAO phenomenon has been known for centuries, due to its impacts on the severity of winters in Greenland and Scandinavia. In the 1920s, meteorologist began monitoring the NAO by calculating wintertime sea level pressure and temperatures in different key meteorological stations in Europe and the North Atlantic, forming an index to describe the NAO phase and intensity (e.g. Walker and Bliss, 1932). More recently it was discovered that the NAO index often displays remarkable persistence and remains in one phase for several years (bottom panel of Figure 2).

Southern Ocean

Among the many influences on Southern Ocean climate, ENSO affects oceanographic conditions around the West Antarctic Peninsula (WAP) via atmospheric teleconnections. A stationary deep tropospheric wave train associated with El Niño-related changes in tropical SST and rainfall, for example, favors a zonally elongated low pressure anomaly at 40°S and a strong, localized high pressure cell centered at 90°W and 60°S (just west of the WAP, top panel of Figure 3; Kiladis and Mo, 1998). The response to La Niña is opposite in sign, more coherent, and stronger in amplitude (middle panel of Figure 3). The phenomenon lags the peak ENSO effect in the tropical Pacific by about six months.

Atmospheric teleconnections between ENSO variability and circulation over the Southern Ocean affect surface temperatures (air and SST) and Antarctic sea ice concentration and extent (Kiladis and Mo, 1998; Yuan and Martinson, 2000 and 2001). During El Niño periods surface temperatures (sea and air) around the WAP tend to be anomalously cool, and sea ice concentrations and extent tends to be anomalously high. During La Niña periods the opposite conditions tend to hold. It is also plausible that the ENSO atmospheric bridge gives rise to a propagating element that manifests itself as the so-called Antarctic Circumpolar Wave (ACW) (White and Peterson, 1996). The time variability of ENSO, indicated by the time series in the lower panel of Figure 3, is dominated by strong year-to-year variations, with peak spectral power at periods ranging from 2 to 7 years (Rasmussen and Carpenter, 1982).

Predictability

Predictability in the climate system is intimately related to the mechanisms causing modes of variability (NRC, 1998). Because the NAO arises from chaotic variations in the midlatitude atmospheric circulation, the ability to predict NAO variations, including the likelihood for its persistence or the transitions from one phase to another, is very low. In contrast, because ENSO variability arises from relatively slow ocean adjustments to fast ocean-atmosphere interactions, there is predictability for ENSO variability at lead times of up to one year in advance (Battisti and Sarachik, 1995). Due to ENSO influences, there is also skill in predicting variations in the Aleutian Low at lead times of up to one year in advance. Presently, causes for the PDO are not understood, and the predictability for this phenomenon remains unknown. Recent studies by Seager et al. (2001) and Schneider and Miller (2001) identify aspects of PDO-related SST variations in the Kuroshio Extension that are predictable at lead times up to 3 years in advance.

Modeling in the U.S. GLOBEC program

Quantitatively linking local ecosystem processes with hemispheric scale processes like those described above is a major challenge. Within the GLOBEC program this challenge is being met with a vigorous numerical modeling effort, including physical circulation models of the ocean and atmosphere, as well as biological, and coupled physical/biological components of substantial complexity. While both prognostic

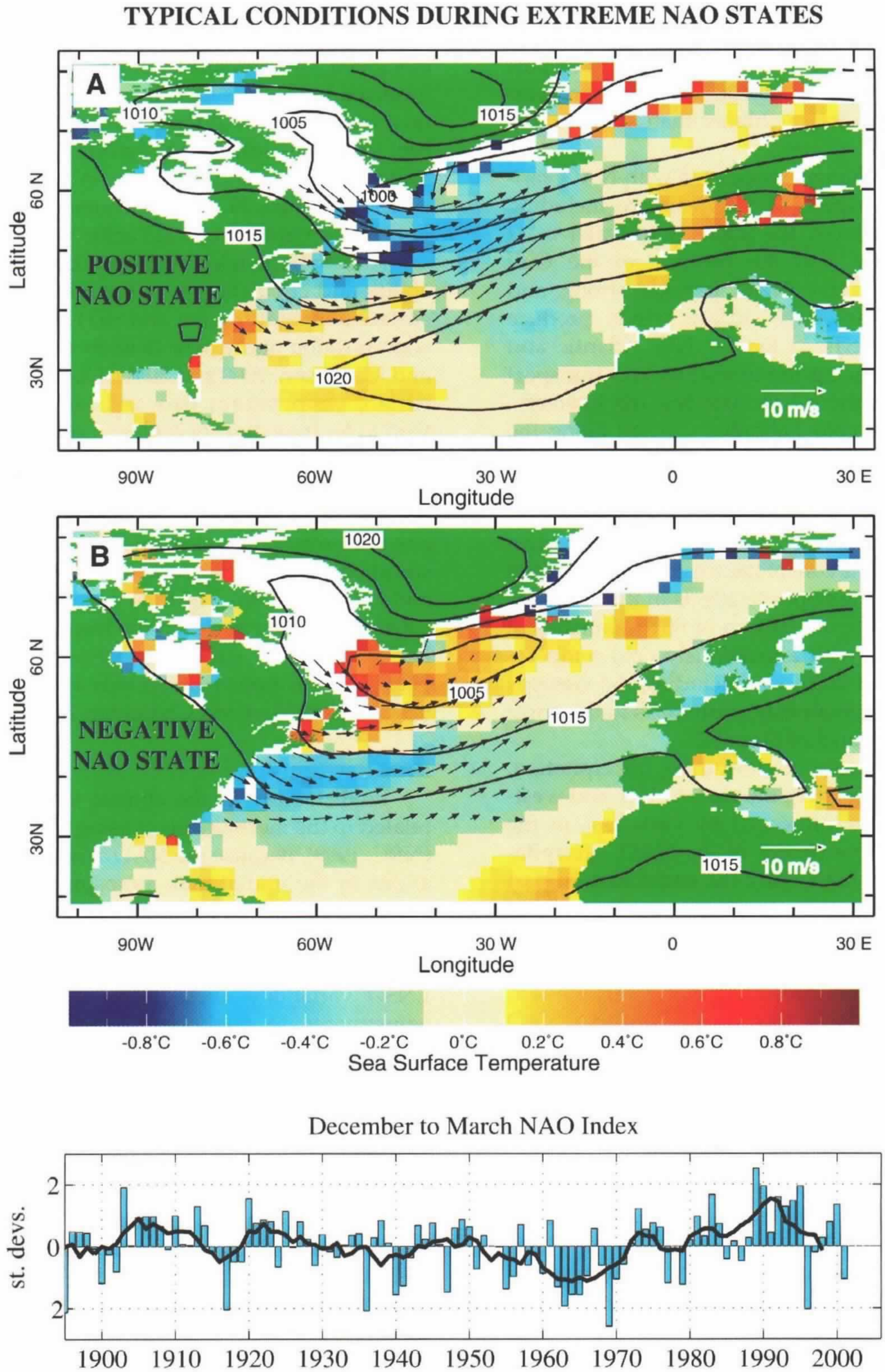

***Figure 2.** Schematic diagram depicting spatial characteristics of December–March positive **(top panel)** and negative **(middle panel)** phases of the North Atlantic Oscillation (NAO). Contours, vectors, and shading as in Figure 1. The bar graph in the **(lower panel)** depicts a time series of Hurrell's December–March NAO index (http://www./nao.html). A 6-year running-average NAO index is shown with the solid curve. Composite fields are based on years in which the NAO index is either + or - one standard deviation from its mean value, otherwise as in Figure 1.*

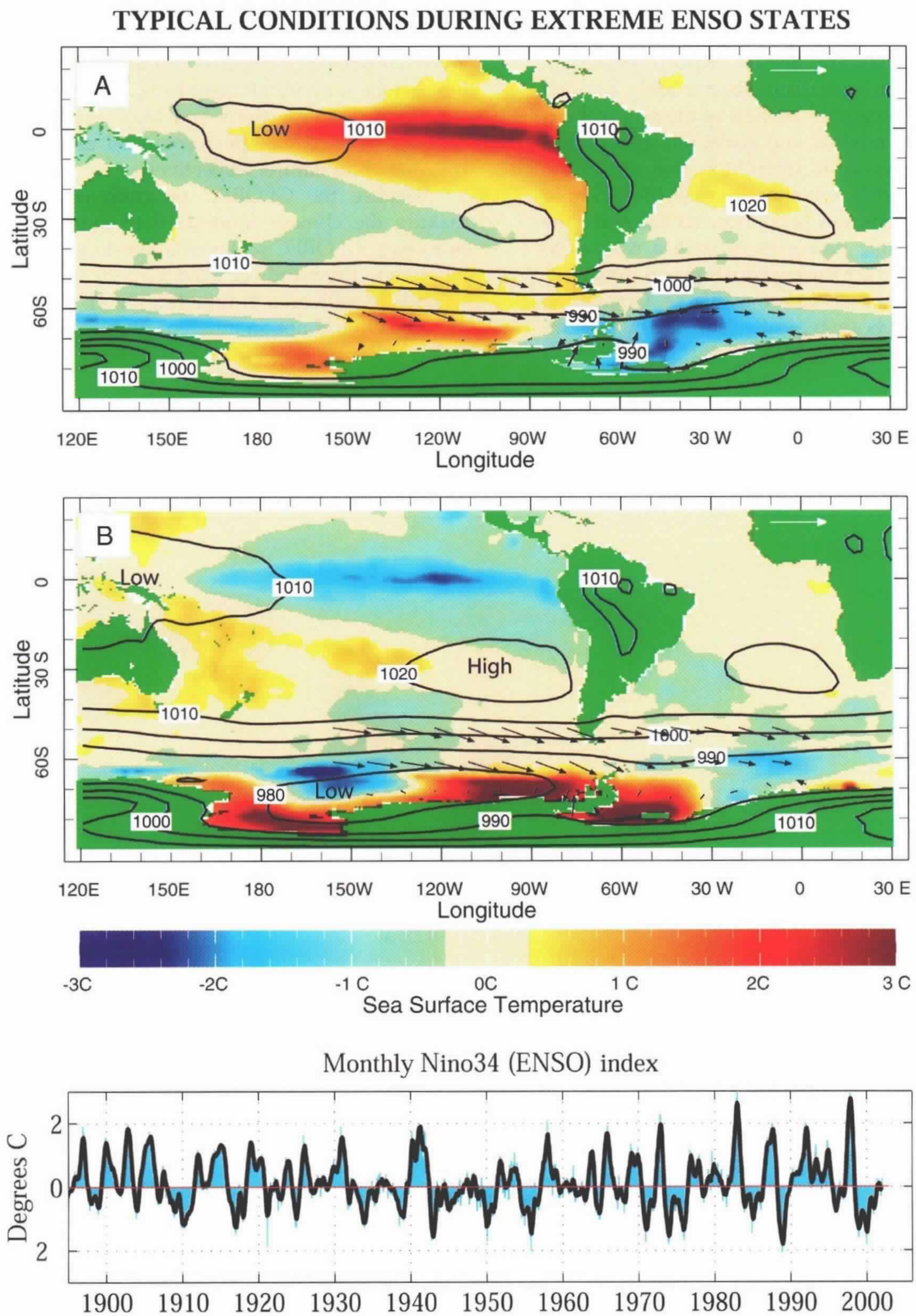

Figure 3. *Schematic diagram depicting spatial characteristics of El Niño* ***(top panel)*** *and La Niña year* ***(middle panel)*** *conditions in the Southern Hemisphere. Contours, vectors, and shading as in Figures 1 and 2.* ***Lower panel*** *depicts time series of the monthly and 5-month running average ENSO index (Niño3.4 SST index, simply the area average SST anomaly for 5°N-5°S, 160°W-120°E). Composite fields are based on years in which the Niño3.4 index is either + or - one standard deviation from its mean value for the years 1979–2001, otherwise as in Figures 1 and 2.*

(forward in time) and data-assimilative (inverse) models are required for this effort, the latter are less well advanced and we do not review them in detail here (see Hofmann and Lascara, 1998). Prognostic models in use for GLOBEC can be further, albeit crudely, divided into one of three categories: models of the physical circulation, food web models, and lastly, models of higher trophic level behavior (zooplankton, fish, etc.).

All of these models, whether physical, biological or coupled, share a common issue: how to discretize the continuum of oceanic processes in such a way as to allow solution of the governing equations on a computer. Two primary approaches are available. Circulation and food web models are typically "solved" by integration of the governing equations over fixed intervals in space and time (the "grid space" and "time step", respectively). In contrast, higher trophic level response is often modeled by explicitly tracking a large, but finite, number of individual organisms, taking into account their mutual interactions and local environment. The two approaches will be recognized as Eulerian and Lagrangian in nature, respectively.

Because the GLOBEC program is interested in making the climate connection to marine ecosystem processes, GLOBEC scales of interest extend from millimeters to thousands of kilometers in space, and from seconds to millennia in time (Figure 4). For the modeling effort this is not an inherent problem so long as we

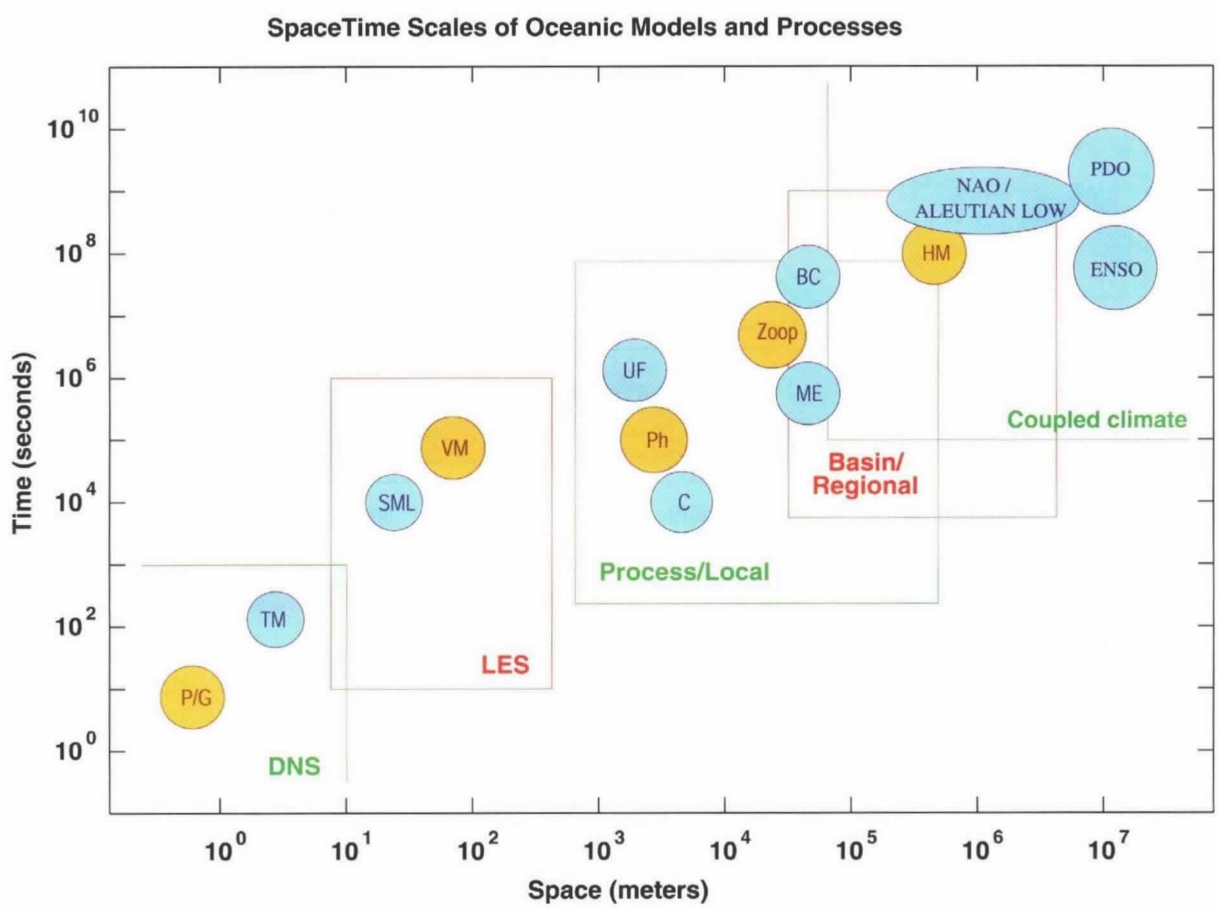

Figure 4. Space-time diagram showing some physical and biological processes of interest to the U.S. GLOBEC program. Physical processes are shown in blue, and include: turbulent mixing (TM), surface mixed layer processes (SML), upwelling fronts (UF), convection (C), boundary currents (BC), mesoscale eddies (ME), the North Atlantic Oscillation (NAO), El Niño-Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO). Biological processes (in yellow) are: predation/grazing (P/G), vertical migration (VM), horizontal migration (HM), and the natural scales of aggregation for phytoplankton (Ph) and zooplankton (Zoop). The rectangular boxes in green and red show the approximate space/time scales covered by five classes of ocean and/or ocean/atmosphere models: Coupled climate, Basin/regional, Process-oriented/Local, Large-eddy simulation (LES) and Direct numerical simulation (DNS).

can afford to discretize our problem appropriately (e.g. for an Eulerian model, with sufficiently fine grid spacing). Unfortunately, due to limitations in the speed and storage capacity of computers, ocean circulation models, and their atmospheric counterparts, are restricted to certain ranges of scales, and specialized classes of models have arisen for each. Global climate studies are focused on spatial scales from a thousand kilometers to global, and on temporal scales from a few months to many centuries. These scales encompass the modes of variability discussed above and are explicitly resolved by current ocean climate models, as shown in Figure 4. Biological processes on these largest scales—e.g., horizontal migration—are also in principle resolvable.

A difficulty with these coupled climate models is that the most energetic processes associated with horizontal redistribution of water properties (e.g., boundary currents, mesoscale eddies, etc.) occur on yet finer spatial scales, typically tens to a few hundred kilometers in the ocean. Such processes are under-represented, if not absent, in today's global models, and must in principle be parameterized. An alternative is to forsake the global spatial and centennial temporal coverage afforded by the climate models, and to utilize finer-resolution, basin-to-regional-scale models capable of explicitly representing the effects of boundary currents and mesoscale eddies (Figure 4). By reducing horizontal resolution to approximately 5 to 10 kilometers, several groups have successfully reproduced these finer scale processes on the basin-scale (e.g. Boening and Semtner, 2001).

Despite this success, the class of basin-to-regional-scale ocean circulation models in its turn omits yet finer-scale processes of significance to the near-coastal, biologically active regimes of interest to GLOBEC. As examples, tidal and upwelling fronts and other internally generated mesoscale features have native scales of 1 to 10s of kilometers, and temporal scales of a few days. In addition, the natural scales of biologically-induced variability of phytoplankton and zooplankton patchiness is believed to fall within this range of scales. Since basin-scale models are currently incapable of representing these processes, local models at even higher resolution are required to study them. Nor is that the end of the story. At scales of meters and below, turbulence and mixing, as well as biological processes such as vertical migration and predation and grazing, become important. Specialized modeling approaches are again needed to study these processes, and parameterizations of their effects are in principle required in models with coarser resolution in space and time.

Specialized modeling approaches are again needed to study these processes...

Given its emphasis on regional experiments in Georges Bank, the Northeast Pacific, and the Southern Ocean, GLOBEC PI's have thus far focused the majority of their efforts on coupled physical/biological response on scales from about 1 to 100s of kilometers. A variety of numerical models of the three general types noted above have been used. For the physical circulation, Eulerian numerical models based upon the hydrostatic primitive equations have been prevalent. Given the coastal emphasis of GLOBEC, the majority of these models have been terrain-following—that is, capable of computationally following the bottom topography; however, a wide array of numerical methodologies (finite difference, finite volume, finite element, and spectral finite element) have been employed. Although mostly sub-basin-scale in their geographic focus, several of these same models have been, or are being, applied to retrospective studies of the basin-scale circulation in (e.g.) the North Pacific Ocean (Hermann et al., 2002).

As with the physical circulation, for which models on different space/time scales are needed to encompass the relevant phenomena, several types of biological models, of varying formulations, need to be employed in order to adequately incorporate specific biological processes that are known to influence distributions and/or demography. The food web models in use within GLOBEC are evolved forms of the carbon- and nitrogen-based, nutrient-phytoplankton-zooplankton (NPZ) concentration models solved in an Eulerian framework (Edwards et al., 2000a,b). NPZ models commonly represent all primary consumers as being of one, or at most a few, types, and similar simplifications are used for other trophic levels. Thus, these models aggregate (and thereby ignore) inter-individual and inter-specific variability that exists in real ocean ecosystems.

Many plankton species undergo functional shifts as they grow, whereby, as young they may be planktonic and herbivorous, while as larger adults they are closer to nekton and consume different prey. Some of the largest species, particularly at the higher trophic levels (macrozooplankton, fish, birds, etc.), are capable of considerable directed movement, independent of the physical flows, and often influenced by an individual's recent experience. Often, too, bioenergetics of the individual organism hold the key to understanding processes of importance to its response to climate and ecosystem changes. These and other examples illustrate biological complexity that is not easily incorporated within aggregated Eulerian NPZ models. However, individual based models (IBMs), solved in a Lagrangian framework, are well suited to including this level of biological complexity (Batchelder et al., 2002; Hermann et al., 2001; Hinckley et al., 2001). In IBMs, each individual, or a cohort of identical individuals, is modeled separately. One difficulty that arises is providing two-way connections when linking Lagrangian models of higher trophic levels with Eulerian models of physical variables and lower trophic level concentrations (potential prey of the larger organisms). Forcing Lagrangian

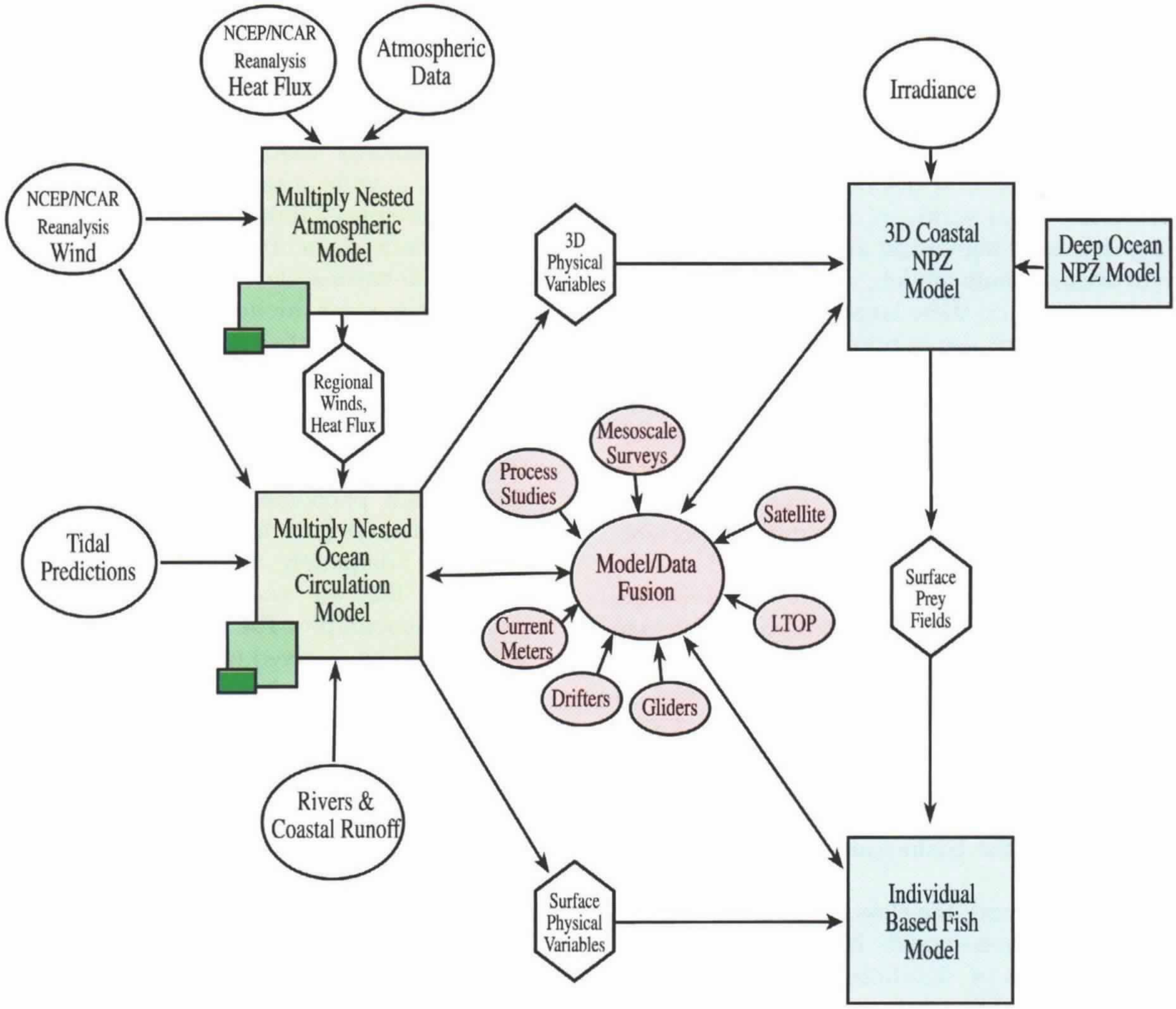

Figure 5. *Schematic diagram of one possible configuration for a multi-scale GLOBEC model of the future based upon the nesting concept. The primary elements of the modeling system include: (1) a nested hierarchy of (global/basin/regional/local) physical circulation models for the ocean (and perhaps the atmosphere); (2) one or more food web models of NPZ class embedded within, and evolving in response to, the physical environment predicted by the linked circulation models; (3) one or more individual based models for the relevant higher trophic level species; and, finally, (4) appropriate mechanisms (possibly utilizing advanced data assimilation) for comparison and/or fusion of these forward models with the available retrospective and contemporary datasets.*

models with Eulerian fields is simple compared to providing feedback from the Lagrangian models to the Eulerian models.

Discussion: Putting the Pieces Together

One of the great challenges for the GLOBEC modeling program will be to bridge the scale gap between the local GLOBEC regions and the global climate system. This will be necessary to fully assess the local impacts of larger-scale climate variability, and to allow intercomparative analyses among regions. Continued improvement of, and access to, enhanced computational resources will of course play a role in bridging this gap. Nonetheless, it is easy to show (e.g. Willebrand and Haidvogel, 2001) that enhanced computer power alone is insufficient without parallel improvements in numerical algorithms and the understanding of important physical processes. Several avenues are under intense exploration, including the utilization of unstructured finite element and finite volume techniques to allow multi-scale numerical simulations on a single heterogeneous grid and the one- and two-way nesting of multiple structured grids of differing (but uniform) resolution (Hermann et al., 2002).

Figure 5 shows a schematic diagram of one possible configuration for a multi-scale GLOBEC model of the future based upon the nesting concept. The primary elements of the modeling system include: (1) a nested hierarchy of (global/basin/regional/local) physical circulation models for the ocean and the atmosphere; (2) one or more food web models of NPZ class embedded within, and evolving in response to, the physical environment predicted by the linked circulation models; (3) one or more individual based models for the relevant higher trophic level species; and, finally, (4) appropriate mechanisms (possibly utilizing advanced data assimilation) for comparison and/or fusion of these forward models with the available retrospective and contemporary datasets. The challenge of developing and deploying such an integrated system is keen; however, as we have noted, many of the individual pieces are already in place within the three regional GLOBEC programs.

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