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# Environmental Variability Effects on Marine Fisheries: Four Case Histories

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# ENVIRONMENTAL VARIABILITY EFFECTS ON MARINE FISHERIES: FOUR CASE HISTORIES

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*Abstract.* The changing nature of marine fisheries requires management approaches that recognize and include ecosystem and environmental effects. Therefore, we review some examples of exploited fishery stocks in which environmental control is a major contributor to structuring the abundance and distribution of the stock. Four examples, taken from studies of northern cod (*Gadus morhua*), cod and haddock (*Melanogrammus aeglefinus*) larvae, the eastern oyster (*Crassostrea virginica*), and Antarctic krill (*Euphausia superba*), are given that clearly illustrate environmental control on the fishery. From these examples, we argue that future management strategies for exploited fisheries must include effects of environmental variability. In particular, management strategies must be flexible enough to include delayed responses to environmental variations that result from the transfer of perturbations from larger to smaller scales and vice versa. This capability requires an understanding of where linkages between the physical environment and the species of interest occur. Development of this knowledge requires input from a variety of disciplines, coordinated research programs, and considerable cooperation at national and international levels.

*Key words: Antarctic krill; cod fishery; environmental variability; Gulf Stream rings; marine fisheries; North Atlantic Oscillation; oyster populations.*

## INTRODUCTION

There is an awareness in scientific and general communication that traditional fisheries management approaches do not work. Failure of existing models and management practices to anticipate or rectify crises in many commercially important fisheries stocks, most recently the Northwestern Atlantic cod fishery, shows that a more holistic view of how fisheries operate is needed, especially in their interactions with the environment. Increasing pressures from fishing and other human activities, such as pollution, as well as environmental variability, have resulted in fisheries that are less amenable to the management strategies of the past.

The changing nature of marine fisheries requires management that recognizes and includes ecosystem and environmental effects. Single-species management precludes a realistic ecological perspective. Multispecies models (Sparre 1991) recognize the importance and complexity of species interactions by accounting for predator–prey relationships among included species. This is an improvement over single-species approaches, but is still a step removed from ecosystem methods in terms of completeness and utility. Uncertainties of achieving success with multispecies management, and a lack of understanding of ecosystem

responses, have resulted in continued single-species management by default.

The role of habitat and environmental variation is becoming more incorporated into management decisions and, as a result, ecosystem-based approaches and models are taking on a role in management. For example, in models used to assess the stock of the Alaskan walleye pollock (*Theragra chalcogramma*), the world's largest single-species fishery (Schumacher and Kendall 1995, Kendall et al. 1996), the effects of environmental transport on the early larval stages must be taken into account. A qualitative index of advective losses (i.e., due to fluid transport) is now incorporated into the stock assessment models (Megrey et al. 1996). Moreover, as users gain confidence with these techniques, managers are confident that quantitative estimates for these important loss terms will become standard. It is instructive to consider the two most important elements that are needed to evaluate such environmental influences on this pollock fishery. These are: (1) detailed estimates of the currents in the spawning regions at, and shortly after, the release of the earliest larval stages; and (2) abundances of the larvae themselves as a function of space and time. The currents are presently estimated using a numerical circulation model (Hermann and Stabeno 1996), while the larval abundances involve collection of data at sea with traditional sampling methods. Note that one of these quantities, the velocity field in the spawning region, is strictly envi-

ronmental. The other, a population estimate of a single stage in an age/stage structured population, is a traditional ecological measure. Thus, the approaches used in support of fisheries management decisions will increasingly reflect an ecosystem perspective and as such will provide an opportunity to link fisheries and ecosystem management. This requires approaches and mechanisms that allow for understanding and quantifying the complex interactions between fisheries, other parts of the ecosystem, and the environment.

Our purpose is to provide examples for which environmental control on fisheries has been documented. These examples can help provide a framework for recommendations about how an ecosystem perspective can be incorporated into future models for fisheries management. First, we provide a brief summary of the space and time scales over which marine fisheries interact with their environment. Then four examples are given that illustrate environmental control on marine fishery populations. The examples have been chosen to highlight the wide range of effects that can arise from environmental variability. The final section provides a discussion and summary.

## TIME AND SPACE SCALES

Time–space diagrams were used initially to provide a conceptual framework for understanding interactions among oceanic physical processes (Stommel 1963). This approach was then extended to include interactions between marine populations and their environment (Haury et al. 1978, Steele 1978, Murphy et al. 1988, Denman 1989). The time–space diagram given by Steele (1978) indicates that the higher trophic levels, e.g., fish, are primarily affected by physical features that persist over long spatial scales, such as fronts, and long time scales, such as decades. While this is a useful construct, it is now more appropriate to regard fish populations as interacting with their environment over a hierarchy of scales in which they respond to perturbations at long and short scales (Fig. 1).

Over the scales in Fig. 1, fish populations are affected in many ways. At the shortest scales, populations are influenced by environmental processes that affect their ability to encounter food. Variations in physical structures, such as seasonal upwelling, represent intermediate scale processes that can affect fish populations. At longer scales, environmental effects are introduced through interannual variations in habitat structure and El Niño events. The longest scales, such as those associated with changes in the conveyor belt circulation, affect the evolution of individual fish species and food web structure.

The scales (Fig. 1) are not independent. Conventionally, one thinks of energy being passed from the smallest organism scales (Fig. 1b) to larger scales through consumption processes, i.e., larger organisms eat smaller ones. So, even in this simplest picture of ecosystem interactions, one that neglects, for example, the important role of organisms affecting others within a single trophic level, or at multiple trophic levels, changes at one scale are inherently coupled to neighboring scales. Moreover, these notions provide an avenue for physical disturbances to affect trophic transfers at several scales. For example, an increased wind stress event can modify coastal upwelling, altering nutrient injection into the photic zone. Such nutrient increases can change the stocks of phytoplankton rapidly (i.e., on daily time scales, where phytoplankton are located on the $y$ axis of Fig. 1b). Through trophic transfer, this physical event ultimately will be seen at the zooplankton, fish, and higher trophic level scales over longer time intervals. In this sense, perturbations that occur at one scale affect processes at other scales. Denman et al. (1989) exploited these linkages and the conventional view on the size spectrum of particles (organisms) in the sea to explore how perturbations in coastal physical processes, with known spatial and temporal scales, might alter trophic effects at different space scales (commonly larger) and time scales (usually longer).

The conclusion that many scales (actually all scales) are theoretically important is not a welcome one, because accounting for all these scales in fishery management is difficult if not impossible. Thus, the tendency is to focus on a subset of scales, and this may limit the long-term application of management decisions that include environmental effects. Even for the coastal upwelling example, the characterization of upwelling in Fig. 1a as occurring at a single temporal scale, for example monthly, must be modified in light of recent studies. Indeed, Bakun (1990) presents evidence for long time-scale (many decades) increases in upwelling indices that are likely to have profound effects at all trophic levels. Thus, the many possible direct and indirect interactions of the space and time scales that affect fisheries do suggest that a longer horizon is needed in management practices than is presently used.

## ENVIRONMENTAL EFFECTS ON FISHERIES: CASE HISTORIES

The following sections provide clear examples of systems in which environmental variability has an effect on marine fishery populations. Not all systems are as clear because fishing activity, pollution, or other human-induced change can dominate changes in many fisheries.

### North Atlantic Oscillation and the cod fishery

Variations in the catch for four commercially harvested species on Georges Bank (Fig. 2) reflect the combined effects of biological interactions, the response to fishing pressure, and environmental variability. Some of the changes in these fisheries, such as
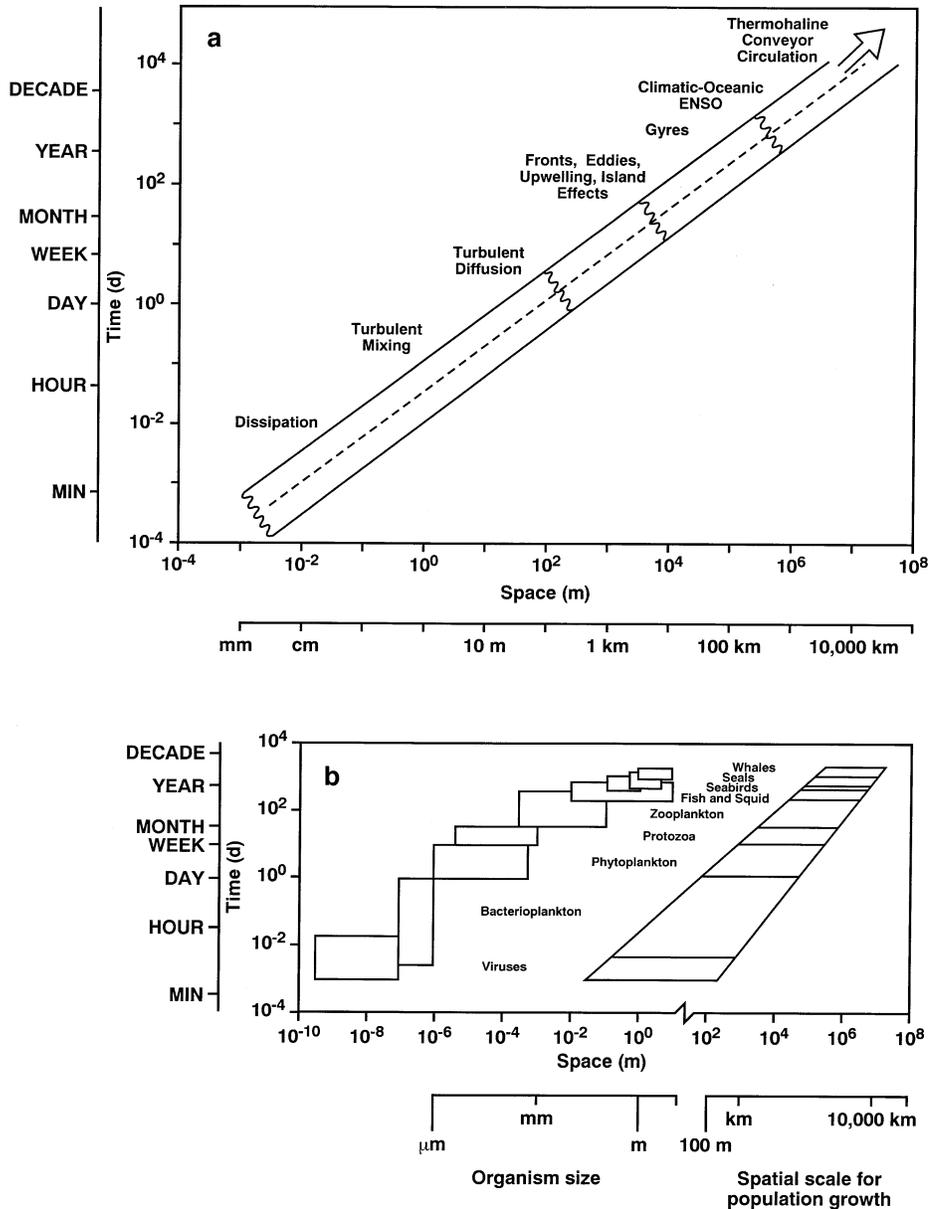
FIG. 1. Schematic showing the dominant space and time scales in the ocean for (a) physical motions and (b) biological populations. In (b) the overlapping boxes to the left represent typical size ranges (on the *x* axis) and typical times for population doubling (on the *y* axis) for each type of organism. The boxes to the right represent typical space scales for each organism during its lifetime. Figure adapted from Denman et al. (1996) (reprinted with permission from the author).

the peak in red hake (*Urophychis chuss*) catch in the mid-1970s, are due to changes in fishing fleet deployment and increased fishing pressure. Other changes, such as the increase in cod and haddock in the mid to late 1970s, are not directly related to fishing pressure. The increases in these two fisheries followed a period of mild winters in the early 1970s and a large increase in zooplankton standing stock on Georges Bank. The question is: how are these stock variations related to environmental processes?

A physical process that can potentially affect marine fisheries in the North Atlantic over a wide range of scales is the North Atlantic Oscillation (NAO), which is associated with variations in wind strength over the entire North Atlantic and with sea surface temperature anomalies (Bjerknes 1962, Rogers and van Loon 1979). Variation in wind strength, quantified by the NAO Index, is defined by the atmospheric pressure difference between the Azore Islands and Iceland (Walker 1924, Walker and Bliss 1932). The NAO Index is similar to the El Niño-Southern Oscillation (ENSO) Index and evidence suggests that the two are correlated at periods
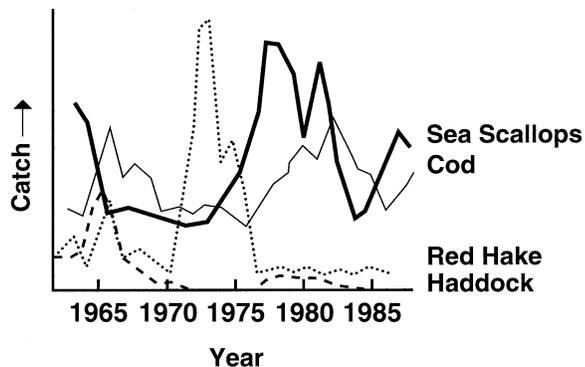
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Fig. 2. Schematic diagram showing variations in commercial catches of four economically important fisheries on Georges Bank from 1960 to 1989. Figure from GLOBEC (1991).

of ~6 yr (Rogers 1984). A decrease in the NAO Index during the 1960s (Rogers 1984) was correlated with changes in the 18°C Subtropical Mode Water at Bermuda (Talley and Raymer 1982), the cessation of Labrador Sea Water formation (Lazier 1981, Talley and McCartney 1982) and a maximum in sea ice extent around Iceland (Kelly et al. 1987) and Newfoundland (Hill and Jones 1990) in the late 1960s. The sea surface in the subarctic Atlantic also freshened and gave rise to a feature referred to as the Great Salinity Anomaly, which has been traced around the entire subpolar Atlantic after the minimum in the NAO Index in the late 1960s (Dickson et al. 1986).

The large-scale changes that occurred in the North Atlantic as a result of the decade-long decrease during the 1960s in the NAO Index profoundly affected the marine environment and consequently fisheries, such as cod. The massive decline in the West Greenland cod fishery was associated with anomalous conditions in the Labrador and Irminger Seas (Koslow 1984). These conditions apparently affected cod stocks throughout the northwestern Atlantic (Koslow et al. 1987). Moreover, Dickson and Brander (1994) presented evidence that the increases in the West Greenland cod stocks that preceded these massive declines were a result of transport from southwestern Iceland waters, which was related to changes in the large-scale North Atlantic windfield, i.e., the NAO.

More recent changes in the cod stocks may also indicate the influence of the NAO, the Index of which has increased markedly since the minimum in the late 1960s (Dickson et al. 1996, Dickson 1997). A chain of reasoning suggests that the large shifts seen off Labrador and Newfoundland may be, in part, the result of large-scale climatic features associated with the NAO. Atkinson et al.(1997) and Rose et al.(1994) demonstrated a substantial range contraction and southerly shift in the northern cod (*Gadus morhua*) from 1981–1992. Following the notion advanced by de Young and Rose (1993) that cold ocean temperatures are associ-

ated with southerly distributions and poor recruitment, this range contraction coincided with intense cooling on the northeastern Newfoundland and Labrador shelves. Moreover, between 1990 and 1992, the cod concentrated in the southern regions with highest bottom temperature. Further, Prinsenberg et al. (1997) showed that the years of markedly decreased water temperatures, and range contraction and southerly movement of the cod, coincided with years of increased winter ice extent. Finally, completing the chain of reasoning, the mean winter ice extent is closely correlated with the winter mean NAO Index. Despite the circumstantial evidence for climatic effects that operate over many decades, the recent collapse of the northern cod stocks must be attributed to overexploitation (e.g., Hutchings and Myers 1994). Accordingly, future management of a renewable resource (in this case, the cod) will demand thoughtful studies of how processes like harvesting, and especially population renewal, interact with longer term climatic effects, like the NAO.

Although the NAO is a large-scale climate variation, its effects are not the same everywhere. Rather, it influences the marine environment at multiple space and time scales. Dickson and Brander (1994) and Dickson et al. (1994) have considered the oceanographic context of the North Atlantic over a large range of space and time scales, with special reference to the cod stocks found there. They focus on the importance of the windfield in determining the spatial and temporal variability of the cod. At the longest space scales, changes in wind stress alter the ice formation processes and hence, the salinity properties of the upper ocean, which in turn alter the large-scale advective flows. Variations in the circulation patterns affect larval fish dispersal and transport, which have considerable implications for inter-stock exchanges and population recruitment. These changes ultimately become manifest as variations in fish catch.

At intermediate scales, variations in the North Atlantic wind stress alter regional circulation, such as the inflow to the Baltic Sea. Dickson and Brander (1994) suggest that the success of cod is related to the inflow/stagnation cycle of the Baltic Sea, which is related to wind stress direction and magnitude. At shorter scales, variations in wind strength can alter mixing characteristics of the water column during critical feeding periods.

Perhaps effects of phenomena such as the NAO that are the most difficult to anticipate are those that are far displaced in time from the actual event. For example, the slowly propagating signal of the Great Salinity Anomaly arrived in the Barents Sea in the late 1970s, producing a minimum in surface and subsurface water temperatures and near-record cooling across the Barents Sea shelf in the late 1970s and early 1980s. Results of this were slow growth of larval cod, poor recruitment, and a series of poor year classes. This provides an example of a time-lagged effect of the changes
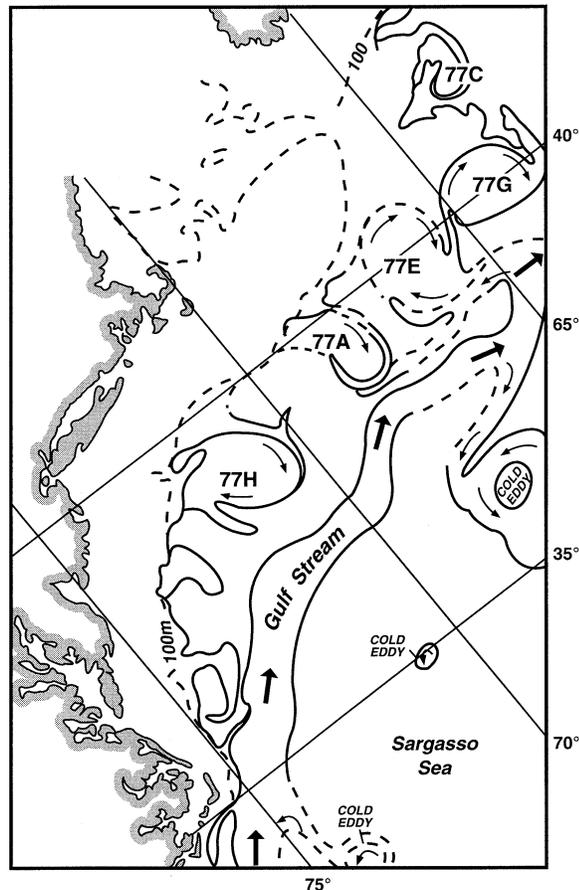
FIG. 3. Distribution of Gulf Stream warm-core rings along the northeastern coast of the United States during the week of 11 May 1979, as determined from the U.S. Navy Experimental Ocean Frontal Analysis of sea-surface temperature distributions. The numbers and letters indicate the year and order, respectively, in which a warm-core ring was formed. The arrows indicate permanent currents. Figure adapted (with permission) from Flierl and Wroblewski (1985).

in wind stress that occurred in the 1960s over the North Atlantic.

### Gulf Stream rings and larval fish recruitment

After the Gulf Stream separates from the east coast of the United States at Cape Hatteras, it forms large meanders that can become unstable and form isolated eddies. The rings that form to the west of the Gulf Stream Front are characterized by a warm core and anticyclonic (clockwise) rotation and are 100–200 km in diameter. These warm-core rings move southward along the shelf/slope region and are eventually resorbed by the Gulf Stream at Cape Hatteras. At any one time, several warm-core rings are found west of the Gulf Stream along the shelf/slope region (Flierl and Wroblewski 1985; Fig. 3). As the warm-core rings move south, water in the shelf/slope region in front of the rings is transported towards the shelf by the ring cir-

culation. As the rings pass a region, the circulation in the wake of the ring transports shelf/slope water offshore.

The occasional occurrence of anomalously warm water on Georges Bank has been noted for some time. Colton and Temple (1961) hypothesized that large numbers of larvae of shelf fish could be transported off Georges Bank into warmer slope waters where they would perish in an unfavorable environment. This hypothesis, coupled with experimental observations that illustrated the detrimental effect of warm temperatures on cod and haddock embryos (Laurence and Rogers 1976), suggested that Gulf Stream warm-core rings could be a major factor regulating larval fish abundance. This hypothesis for the abundance and distribution of larval fish in continental shelf waters was evaluated quantitatively with a mathematical model (Flierl and Wroblewski 1985) that included the influence of Gulf Stream warm-core rings, as well as losses from predation, metamorphosis, and physiological death.

The model (Flierl and Wroblewski 1985) provided a framework for assessing the larval loss from mortality and advective transport in down-shelf currents as well as the changes in larval density produced by on-shelf or off-shelf flows that occur when a Gulf Stream ring approaches the shelf/slope region. In the simulations, across-shelf flows decreased larval fish abundance as much as biological losses did. The magnitude of the abundance decrease was strongly dependent on the rate of movement of the Gulf Stream ring. A stationary ring resulted in a 20–50% decrease in larval fish abundance, depending upon the strength and size of the ring and the along-shelf currents. Additional simulations showed that a slowly moving ring could potentially have an even greater impact on larval fish abundance. Not only does the ring circulation actively remove fish larvae from the shelf/slope region, but patches of larvae that are being transported by the faster down-shelf currents could encounter the back side of the ring and be transported off the shelf.

Flierl and Wroblewski (1985) compared simulated larval fish distributions with historical distributions of cod and haddock larvae in the Georges Bank region. This comparison suggested that the frequency of interaction of Gulf Stream rings and subsequent year class strength of cod and haddock stocks were correlated. They concluded that the presence of warm-core Gulf Stream rings is important in regulating larval fish survival and that the impact of the ring depends strongly on its translation velocity and on the speed of the along-shelf currents. Monitoring the presence of warm-core rings, as is possible with satellites, could provide initial estimates of changes in larval fish abundance.

### Freshwater inputs and oyster populations

The Eastern oyster, *Crassostrea virginica,* has been heavily fished along the Gulf of Mexico and eastern
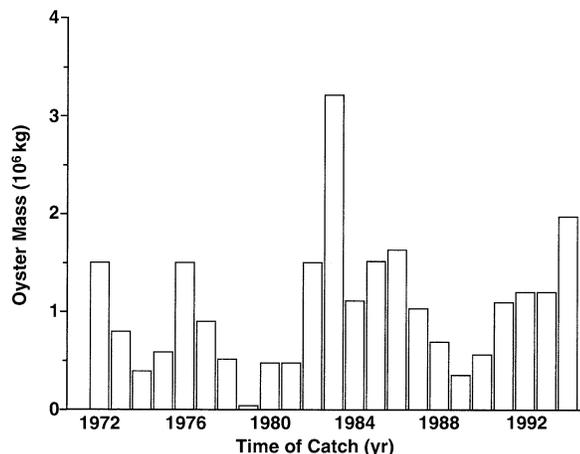
FIG. 4. Commercial landings of Eastern oysters, expressed in kilograms, in Galveston Bay, Texas, during 1972–1994. Data from Robinson et al. (1994).

coast of the United States. Recently, the Chesapeake Bay fishery collapsed and the decline has been largely attributed to overfishing, disease, and degradation of the oyster's habitat. While management approaches have been tried for this fishery (e.g., Gludem 1962, Hofstetter and Ray 1988, Krantz and Jordan 1996), the effect of environmental control on the oyster populations has not been explicitly included. Yet processes that change ambient temperature or salinity affect oyster production. Oysters are susceptible to changes in salinity, which makes variations in freshwater inputs to estuarine environments important.

Galveston Bay, Texas has a large and viable fishery for *C. virginica.* On occasion, usually in spring, the Bay is inundated with large amounts of fresh water that result from spring storms. The freshwater reduces the salinity of the Bay dramatically, often close to zero. Because the flushing time of the Bay is relatively long, low salinity can persist for several weeks. Salinity affects oyster filtration (Loosanoff 1953) and respiration (Shumway and Koehn 1982); at salinities of ≤10, oysters become stressed and these physiological processes are reduced. Salinities <5, especially for extended periods, can result in mass mortalities. Thus, changes in the location of isohalines in the estuary have a large influence on the spatial distribution and productivity of oyster reefs.

The effect of fresh water is illustrated by the long-term trends in the Galveston Bay oyster fishery (Fig. 4). The substantially reduced landings, occurring about once every 7–10 yr, result from variations in fresh water inflow (Hofstetter 1983). In 1973, the inflow of the Trinity River, the major source of fresh water to Galveston Bay, was 2.5 times its typical capacity and thus reduced salinities in Galveston Bay from mid-March to June (Hofstetter 1977). This freshwater influx immediately depleted oyster populations in the northern part of the Bay and damaged oyster populations

through the central portion, affecting the most productive oyster reefs in Galveston Bay. The long-term effect of this flooding event was several years of poor oyster reproduction with poor recruitment in 1975–1977 (Hofstetter 1983). Juvenile and market-sized oysters began recovering and reached a maximum in abundance in 1975–1976. However, heavy winter fishing and more freshwater flooding in the spring of 1977, combined with years of poor recruitment, reduced this peak (Fig. 4). The final result was near depletion of the oyster stocks in 1978 and closing of the fishery in December. The closure of the fishery resulted from a flooding event that occurred 5 yr earlier. This again illustrates that fishery production can be attributed to environmental events that occurred several years in the past.

The impact of low salinity events on the Galveston Bay oyster fishery was further explored with a mathematical model constructed for post-settlement oyster populations (Hofmann et al. 1992, Powell et al. 1992*a*). Simulations (Powell et al. 1996) in which an oyster population is exposed to a 1-mo low salinity event result in mass mortality (Fig. 5). In fact, the influence of low salinity on mortality far surpasses those of interspecific competition for food, reduced food supply, increased turbidity, and disease (Powell et al. 1996). Other simulations (Hofmann et al. 1994) illustrate that the effects of low salinity can be ameliorated by increased food supply. For some combinations of environmental conditions, the effect of low salinity on the productivity of the oysters is reduced and the major effect of exposure to low salinity is postponed.

*Sea ice and the Antarctic krill fishery*

The first commercial harvest of Antarctic krill (*Euphausia superba*) was in 1961–1962 when two Soviet fishing vessels reported catches of $4 \times 10^3$ kg and $7 \times 10^4$ kg (Agnew and Nicol 1996). In 1972, the Soviet Union established a permanent krill fishery in the Southern Ocean and full scale commercial fishing for this species was well underway by the mid-1970s. Presently, there are five nations (Japan, Chile, Russia, Poland, and Korea) that are commercially fishing krill in the Antarctic. About $5.4 \times 10^9$ kg of krill have been caught and ~15% of this catch is from the Antarctic Peninsula region (Agnew and Nicol 1996).

The general perception had been that Antarctic krill behave and reproduce as marine zooplankton and thus long-term effects of removal need not be considered. This perception changed as increasing evidence indicates that krill abundance is cyclic, with years of high abundance interspersed with years of extremely low abundance (Bonner et al. 1978, Hempel et al. 1979, Croxall et al. 1988). The years of low krill abundance have been attributed to high mortality rates, overfishing, or natural fluctuations in stock size. These suggested causes are not compatible with the 6-yr lifespan of krill nor with the krill abundance data that

FIG. 5. The number of market-sized individuals (solid line) in the oyster population from a simulation that used environmental conditions that were characteristic of Galveston Bay, Texas. A low salinity event was superimposed in the summer of year 2 of the simulation. Mortality events, calculated as the fraction of the oyster population in a given size class that dies during a 1-mo period, are indicated by the shaded contours, with an interval of 0.1. Details of the oyster model and the simulation are given in Powell et al. (1996); figure adapted from Powell et al. (1996) with the permission of the National Shellfisheries Association.
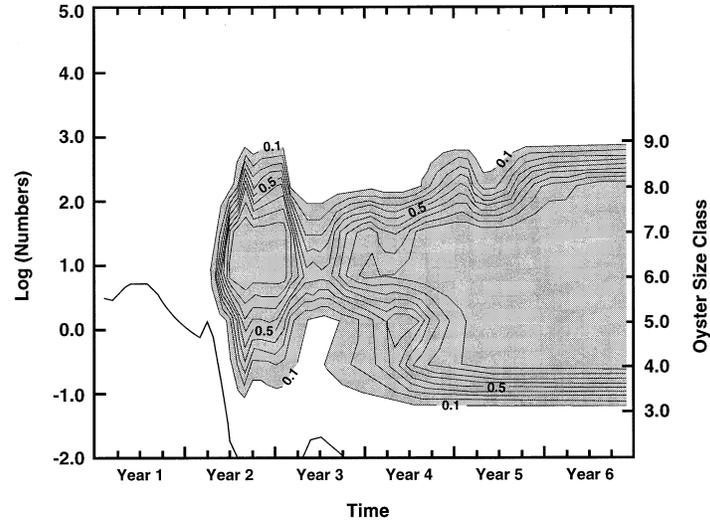
showed no reduction in stock prior to the low abundance years. Siegel and Loeb (1995) hypothesized that the interannual variability in krill abundance observed in the Antarctic Peninsula region could result from environmental conditions during the previous season because they affect spawning and recruitment success.

To test their hypothesis, Siegel and Loeb (1995) used krill abundance estimates in the Antarctic Peninsula region from 1977 to 1994 to construct a recruitment index. Good and bad year class success was directly and indirectly correlated with sea ice conditions during the previous winter, the date of krill spawning, and the occurrence of dense salp (*Salpa thompsoni*) concentrations, but not with upper water column temperature or krill stock/spawning stock size.

The recruitment anomaly index (Fig. 6) shows clearly that strong year class success resulted in 1980–1981
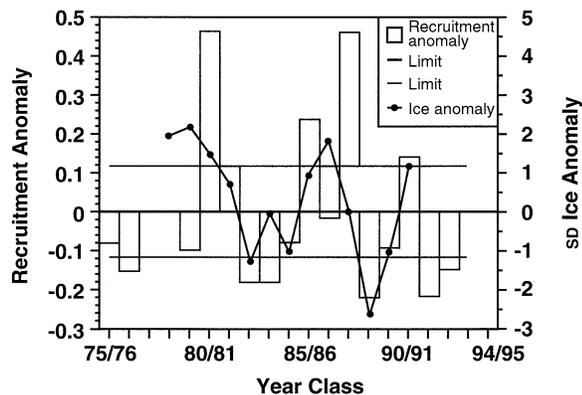


FIG. 6. Anomalies in the long-term running mean krill recruitment index and the standard deviation of winter sea ice anomalies for the Antarctic Peninsula region. The horizontal lines indicate half the standard deviation of the mean of the krill recruitment index. Figure from Siegel and Loeb (1995); reprinted with the permission of the editors of *Marine Ecology Progress Series*.

and 1987–1988 spawning seasons. The 1985–1986 season also had strong, but somewhat reduced, recruitment relative to the previous and following years. Weak recruitment, as indicated by the negative recruitment anomaly indices, occurred in 1988–1989 and 1991–1992 spawning seasons and in the 1982–1983 season. Recruitment was intermediate in the other years.

Krill recruitment success is strongly correlated with maximum sea ice extent. Positive sea ice anomalies near Elephant Island east of the Antarctic Peninsula were in years when sea ice extent was greater than the average; negative anomalies were in years when sea ice extent was less than average (Fig. 6).

Ice concentration and duration during winter were also related to salp abundance the following year (Siegel and Loeb 1995, Siegel and Harm 1996). High ice extent and long duration result in low salp abundance because salps are not able to use sea ice algae as a food source. Hence, salps were not present to compete with krill for food in the following austral spring and summer. Krill, by contrast, thrive during periods of extensive and long ice cover. Heavy austral winter ice appears to promote early female gonadal development and spawning, since sea ice algae are abundant and provide sufficient food for krill to satisfy energy requirements and to initiate early gonadal development. Early seasonal reproduction then favors high recruitment in the following year, because it permits larval growth and development over more of the austral summer. Thus, long ice cover duration and large ice extent result in a high krill recruitment rate.

Krill recruitment in adjacent years is not greatly influenced by the success or failure of a single year class because the population has multiple-age stock structure. However, the apparent 4–5 yr cycle of ice duration and extent (Siegel and Loeb 1995, Stammerjohn and Smith 1996, White and Peterson 1996) results in a grad-

ual decline of krill stock sizes during years of reduced ice cover. The return to heavy ice conditions every 3–4 yr gives the krill stock an opportunity to benefit from improved environmental conditions and to recover. Hence, any management strategy put forward for this stock must include the cyclic nature of the environment.

## DISCUSSION

Environmental effects clearly played a decisive role in determining the recruitment in the four case histories discussed in the previous section. The effect of the environment was manifest at a variety of scales and at multiple trophic levels. In some systems, the response to environmental variability is delayed 1–5 yr into the future before the full effect is observed. These time lags are difficult to include in current management of exploited marine species. Most management is based on the present state of the fishery and frameworks that account for effects of environmental changes that occurred 1–2 yr earlier are not available.

The delayed response to a low salinity event was not built into the management of the Galveston Bay oyster fishery. The management was based on available catch data that initially suggested recovery from effects of low salinity, but such a recovery, in fact, did not occur. Thus, the decrease in the oyster fishery was more severe than anticipated, the fishery had to be closed, and the recovery time was lengthened. Models incorporating the delayed effects of a low salinity event would have facilitated a harvesting/management strategy that allowed the oyster fishery to recover while minimizing the negative effects on fishers and local economies. Moreover, the low salinity event of 1973 was part of an El Niño–La Niña cycle, which changes regional and local precipitation patterns throughout the Gulf of Mexico. Powell et al. (1992*b*) suggested that much of the Gulf-wide variability observed in oyster contaminant levels, disease prevalence and intensity, and population structure was driven by this large-scale climatic event. Management strategies for the Gulf of Mexico oyster fishery should be adaptative enough to respond to the cascade among scales and the responses to large-scale climatic conditions.

Environmental features, such as warm-core Gulf Stream rings and sea ice extent and duration, can be monitored easily from remotely deployed sensors on satellites. These data are acquired routinely in real time and are available for incorporation into marine fishery management. This requires that models on which fishery management decisions are based be versatile enough to incorporate a range of disparate environmental measurements. Use of such environmental data need not wait the development of models; much can be inferred about larval recruitment by combining satellite monitoring of the number, frequency, and size of Gulf Stream warm-core rings with occasional ship-based surveys (Flierl and Wroblewski 1985). Some progress in applying this approach to understanding recruitment to several fish stocks in the northwestern Atlantic has been made (Myers and Drinkwater 1989). Other western and eastern boundary current systems are known to be characterized by meanders and eddies that transport biological material offshore (e.g., Moisan et al. 1996). Thus, the effect on larval recruitment described for Gulf Stream rings is likely operative in other regions and potentially could be monitored from satellite and ship-based observations.

Similarly, Antarctic krill recruitment can be projected from combining measurements of sea ice extent and monitoring the diets of krill predators such as penguins (Fraser and Trivelpiece 1996) and seals (Croxall et al. 1988). This latter approach has been adopted by the Environmental Management and Monitoring component of the Committee for Conservation of Antarctic Marine Living Resources (CCAMLR 1995). It represents a significant departure from traditional approaches to fishery management, and will provide a test for such possibilities in other fisheries.

Isolating and quantifying effects of environmental variability on marine populations that are heavily exploited is difficult (e.g., Mertz and Myers 1994). The impact of heavy fishing may outweigh any effects induced by environmental variability. However, effects of environmental variability and heavy fishing can be comparable in their impact on survival ratios of exploited fishery stocks (Rosenberg et al. 1993). Thus, heavy fishing, sustainable during periods of favorable environmental conditions, cannot be maintained when environmental conditions become unfavorable. Fishing levels should be adjusted during periods of unfavorable environmental conditions.

Failure to consider environmental change can lead to management practices that harm a resource, no matter how well intended the approach. The complexity of managing exploited species in a variable environment requires a broad approach. Development of integrated sampling systems, the concurrent measurement of physical and biological properties, and advances in circulation, ecosystem, and fishery models are necessary to improve and develop management practices that will foster sustainable marine resources. Schumacher and Kendall (1995) and Kendall et al. (1996) present an example of this integrated approach for the Alaskan walleye pollock in the coastal Gulf of Alaska. As noted in the *Introduction,* the results of these integrated endeavors are now being used in the stock assessments for the operational management of this important fishery (Megrey et al. 1996). However, the incorporation of environmental information, currently a topic of considerable scientific and practical interest (e.g., Boehlert and Schumacher 1997), requires understanding of linkages between the physical environment and the species of interest. Development of this knowledge requires

input from numerous individuals, coordinated research programs, and considerable cooperation at national and international levels.

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