Global Climate Change:

Policy Implications for Fisheries

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The prospect of global climate change is forcing government agencies to plan for the mitigation of environmental impacts prior to their occurrence. In this paper we examine the implications of climate change on fisheries resources by considering changes extrapolated to regional scales and selecting a few detailed case studies to illustrate important points.

Climate Change

The recent historical record of atmospheric carbon dioxide (CO_2) concentrations, as monitored at Mauna Loa, Hawaii; Point Barrow, Alaska; and the South Pole, shows an unmistakable upward trend (Keeling et al. 1989). Combined with the paleoclimate record obtained from CO_2 gas bubbles in deep ice cores from Greenland and Antarctica, the record shows that preindustrial CO_2 concentrations of 280 ppbv (parts per billion by volume) have crept to 350 ppbv for the present era (Keeling et al. 1989). Most of this rise can be linked to estimates of carbon dioxide releases from human activities. Schneider's (1989) extrapolation suggests that CO_2 will double (i.e., 680 ppbv) by the years 2040 to 2060. The anticipated result will be a warming of the earth's troposphere because CO_2 traps infrared energy radiated from the earth back to space (i.e., the greenhouse effect). The exact temperature rise is debatable because of our inability to predict exactly how much heat will be stored as atmospheric water vapor- itself a greenhouse gas-or in clouds, which can reflect radiation back into space.

We do not fully understand the role of terrestrial and marine plants in regulating the global carbon budget, nor do we know how much additional CO_2 the upper ocean layers will dissolve and store if CO_2 increases as predicted. These uncertainties will affect the time required for a doubling of carbon dioxide, assuming no attempt is made to reduce anthropogenic inputs to the atmosphere. The rise in global average temperature may range from 2°C to 6°C (Schneider 1989). The rate of climate change will be much faster than is thought to have occurred after the ice ages of the paleozoic eras. We do not thoroughly understand how large scale ecologic systems respond to so rapid a change, but it is instructive to attempt to forecast some of the changes and model the expected impact on ecosystems.

Change in Freshwater Systems

If climate change proceeds as is generally thought, freshwater aquatic systems may be affected in drastic ways. Changes in the ratio of incoming to outgoing radiation (the energy balance), expected to be more pronounced at high latitudes (Dickinson 1989), will result in changes in mean temperature of the atmosphere, surface water, and groundwater (Meisner et al. 1988). Precipitation patterns are likely to change in magnitude, distribution, timing, form (e.g., snow, sleet, rain), and degree of variability (Gleick 1987; Williams 1989; Regier and Meisner 1990, this issue), causing shifts in the hydrologic cycle. Stream flow patterns, ground water recharge and release, and lake levels will be altered (Sanderson 1987), as will current velocity and turbidity of streams. Streams may also be affected by changed runoff and altered sediment loads, which will influence channel morphology and stability, substrate composition, and habitat complexity (Williams 1989). Changes in precipitation patterns will cause changes in nutrient contributions from nonpoint sources. Oxygen levels in hypolimnetic waters may be reduced from effects of stratification and increased oxygen demand from organic loadings that come with increased sedimentation.

Changes in energy balance may alter the timing of the spring runoff. If that leads to altered flow during the spawning runs, spawning and nursery areas of anadromous fishes may be unavailable. Fish populations that are characterized by rigidity in life cycles may not be able to adapt to such demands. Vegetation disturbance under changing climate, e.g., fire, pests, disease, and dieback is likely to increase sediment runoff during transition. Useful prediction of effects impending climate change for such waters clearly requires considerable accuracy in the forecasts, and will require detailed knowledge of regional constraints that determine the steady-state conditions for lakes, rivers, ponds, and bogs. Climatic effects and multiple human uses of water bodies may exacerbate problems (e.g., reduced precipitation will create increased demand for water for irrigation, require changes in flow regulation for hydropower generation, and change the ratio of river volume to treated sewage discharge volume, creating the potential for pollution impacts and presenting a need to reassess the concept of assimilative capacity for waste).

Lakes in temperate zones with strong seasonal temperature cycles are typically dimictic (i.e., the lake overturns semiannually). Where global climate change prevents lake surface water from cooling below 4°C, overturn may not occur for large or deep lakes, reducing nutrient and oxygen recycling. Climate change is likely to increase the period of summer stratification, and the depth of the thermocline, thereby increasing the available warm water habitat and reducing coldwater habitat in lakes (Schertzer and Sawchuk 1990; Magnuson et al. 1990; Regier and Meisner 1990). Increased stratification and lack of overturn may result in hypoxic or anoxic bottom waters during summer.

Change in Ocean Systems

A change in the atmospheric energy balance is predicted to lead to greater relative atmospheric warming at high latitudes compared to tropical and subtropical regions. Poleward transport of heat by atmosphere and ocean surface waters would be reduced. In low latitudes the great ocean currents, including the Gulf Stream off the eastern United States and Canada and the Kuroshio off Japan and the Kuril Islands, may weaken. The meanders of the currents spin off both cold and warm core eddies, which may decline in frequency and size (Frank et al. 1988). Cold core eddies are one of the dominant mechanisms for introducing nutrients into the oligotrophic waters of the Sargasso Sea in the North Atlantic and into the central gyre of the other world oceans. In low latitudes there will be increases in the salinity of ocean surface waters due to evaporation, which may slightly enhance the down welling of surface layers. More importantly, upwelling zones in low latitudes, such as the area of the coast of Peru and Ecuador, off the west coast of Africa, and even monsoonal upwelling, such as the region off the Somalian coast of east Africa, may be reduced, or perhaps even disappear, though controversy on this subject remains (Bakun 1990).

We do not know if tropical instabilities in the atmosphere, i.e., the easterly waves, which can give rise to hurricanes and typhoons, will intensify or lessen, but a warmer subtropical sea surface can presumably allow individual hurricanes to become more powerful. This may have consequences for fisheries operations and may affect inshore and estuarine nursery grounds.

Greater warming at higher latitudes may intensify ocean dynamics because relative differences in cold and warm currents may increase, while the higher sea-surface temperatures may lead to increased thermal stratification. Cold, southward flowing currents, e.g., the Labrador current, may intensify; the effects of potentially greater runoff from northern continental regions may displace coastal fronts offshore (Kennedy 1990, this issue) and change the intensity of water mass exchange on the broad continental shelves off eastern North America. Reduced continental runoff and rising sea level (Bolin et al. 1986; Oerlemans 1989) may allow intrusion of more saline water farther into estuaries (Ayers and Leavesly 1988; Kennedy 1990) and affect spawning and nursery habitats for some anadromous species.

Change in Solar Radiation

The depletion of stratospheric ozone by man-made chlorofluorocarbons has largely been treated as a problem separate from that of climate change. There may be interactions between resulting increases in solar ultraviolet-B radiation (290 to 320 nm) in marine systems and climate effects that go beyond direct impacts on fish populations. These may release additional carbon dioxide from ocean regions and enhance impacts from climate change. Additional solar ultraviolet-B radiation may directly affect primary productivity and food web dynamics of zooplankton and ichthyoplankton (Hardy and Gucinski 1989). Reductions in primary productivity will reduce oceanic uptake of carbon dioxide and may allow releases during transition periods (Viecelli 1984; Oeschger and Dutsch 1989). Ozone depletion is predicted to be maximal at high latitudes; here solar ultraviolet-B radiation is likely to add stress to aquatic systems that must also adapt to the stress of rapid climate change.

Consequences for Fisheries

Assessment of the consequences of anticipated change for specific fisheries will require detailed analyses by fishery, aquatic, hydrographic, and meteorological experts that go well beyond current work and also will likely involve sociologists and political scientists. The details of the knowledge required should not obscure the need to understand the problem on several levels, and it should be possible for scientists, managers, policymakers, and resource users, such as fishermen, to see the "big picture."

What are the elements of the "big picture?" Some of them are the classic problems of fisheries science and management, namely understanding the relationship of the environment to fish production, growth, and abundance. Managers, conservationists, and fishermen want to understand fish recruitment, population dynamics, and the sources of destructive impacts in order to predict harvests, set effective regulations, and plan for long-term sustained yields in the face of human and natural change and uncertainty. We need to understand interactions and impacts on the organism, population, community, and ecosystem levels, and we need to understand these interactions in the face of potentially rapid climate change.

Primary Productivity

The capacity of aquatic systems to sustain fisheries fundamentally depends on the existence and availability of primary producers, the plants that fix carbon dioxide into living organic matter. In aquatic systems, nutrient availability sets limits on production; changes in upwelling, increased stratification, or changes in runoff patterns could reduce or shift nutrient inputs and cause swings in productivity. There are situations where nutrient-rich oceanic waters are limited by deficiencies in trace metals such as iron (Martin and Fitzwater 1988). Such deficiencies will affect carbon dioxide fluxes from ocean to atmosphere (P. P. Murphy, NOAA Pacific Marine Environmental Laboratory, unpublished data). Conversely, production may be stimulated by windborne deposition of terrestrial trace metals; thus, with climate change, greater fluctuations in oceanic productivity will affect carbon exchange and ultimately fish populations.

Community Structure and Species Distribution

Changes in food availability, species-specific differences in thermal tolerance and disease susceptibility, and shifts in the competitive advantage of species will alter species assemblages. Such changes propagate through the food web and alter the success of recruitment, change population stability in a fish community, and lead to species displacement. An analysis of increasing temperatures and changing precipitation patterns over the northwestern North Atlantic and the Canadian maritimes shows that a northward expansion of cod, *Gadus spp*.; halibut, *Pseudopleuronectes americana*; plaice, *Paralichthys dentatus*; wolfish, *Anarhichas lupus*; and capelin is likely. At the southern limit of the same region these fishes and cusk, *Rissola marginata*; redfish, *Sebastes spp*.; and yellowtail flounder *Limanda ferruginea*; might be replaced by menhaden, *Brevoortia tyrannus*; butterfish, *Poronotus triacanthus*; hake, *Merluccius spp*.; and herring, Clupeids (Frank et al. 1988). Clearly, renewed efforts are required to link productivity, recruitment, and fish yield to climate variables on wide temporal and spatial scales.

Migration and Invasions

Drastic changes in native populations have been observed following the accidental and intentional introduction of exotic species into ecosystems. The rapidity and impact of such invasions are likely to differ when climate change imposes a new stress on native populations (Mandrak 1989). Such stress may be sufficient to trigger migrations of desirable species, provided migration pathways are available.

Synchrony of Biological Cycles

The co-dependence of species in an aquatic food web over long, stable periods has allowed patterns to evolve that regulate responses to quite different stimuli for each member species. Thus, the rapid growth of phytoplankton is stimulated by the joint effect of nutrient availability and longer photoperiods in spring, while consumer populations may respond to a temperature stimulus, as in the onset of oyster spawning. The synchrony of these events may be disrupted when climate change alters the timing of such spawning activity, and a mismatch of prey predator abundance could have significant consequences. For example, Holtby (1988) reported that clear cut logging operations in the Carnation Creek drainage of British Columbia increased stream temperatures by 1- 3°C, which in turn stimulated earlier emergence and increased summer growth of Coho salmon, Oncorhynchus kisutch. Subsequent earlier seaward migration of smolts resulted in poorer ocean survival, likely due to a mismatch in the timing of prey or predator abundance.

Population Isolation and Entrainment

Alterations in temperatures and patterns of current flow in lakes and in the coastal ocean can cut off populations in embayments and estuaries by forming thermal barriers that will block normal routes to and from spawning and nursery grounds. Such effects are most likely for species at the limit of tolerance for warm or cold waters. Changes in stream flow combined with temperature effects can similarly isolate species, just as there is likely to be shrinkage in habitat space for the same reasons. In nutrient-enriched estuaries and eutrophic lakes, the problem may be exacerbated by oxygen depletion in deeper, colder waters that will normally be sought by species seeking refuge from warm surface layers (Coutant 1981).

Biological Diversity

It is difficult to define the exact ecological value of biological diversity and the importance of species diversity in determining community structure and stability is still being debated. Loss of genetic diversity (e.g., fish stocks) may influence not only fisheries yield, but our ability to mitigate for potential losses of desirable, once-abundant species or populations. It will be particularly important to limit the anthropogenic stresses that diminish biological diversity and system integrity in the face of rapidly changing climate.

In terrestrial ecosystems, climatic variables are major controlling factors in species richness patterns. Currie and Paquin (1987) found that variation in species richness among trees across the American continent was correlated most strongly with total annual evapotranspiration, an indirect measure of productivity. For given evapotranspiration rates, species richness varied with topographic complexity. Rabenold (1979) reported a reversed latitudinal gradient in breeding bird species richness in eastern North America, one that peaks in New England and southeastern Canada, and is related to a brief pulse in favorable weather and associated high insect abundance during the breeding season. Biogeographic classification of oceanic zones (Hayden et al. 1984) and some freshwater systems (Barbour and Brown 1974) reveal latitudinal patterns in species richness despite what may be fundamental differences in aquatic and terrestrial food webs (Pimm 1989). In lotic systems, species diversity has been related to hydrologic characteristics of streams, particularly the frequency and predictability of extreme events such as floods and droughts (Poff and Ward 1989). Should these characteristics change as climate warms, species diversity would likely be affected.

Trophic Dynamics and Fisheries Yield

Several authors have summarized relationships between primary production and fisheries yield (Ryther 1969; Oglesby 1977). Nixon (1988) reviewed and re-analyzed these data and reported that fisheries yield varied as primary production raised to the 1.55 power, with a correlation coefficient of 0.84; thus, a 5% reduction in primary productivity would lead to a 6 to 9% reduction in fisheries yield (Hardy and Gucinski 1989).

Policy Options for the Future

The questions that translate into policy, namely "how do we plan for anticipated change?" and "what mitigation options, if any, should be exercised?" contain larger issues, issues that are as serious for fisheries as they are for other areas impacted by global climate change. Some of these arise from the uncertainty attached to present predictions. Others result from the severity, or lack thereof, of foreseen impacts. Still others relate the cost of investing present resources to ameliorate negative impacts against the uncertain gain of future protection. These aspects take the problem outside the realm of science and into the public arena, where values and interests conflict. Generally, there has been a willingness to assure present prosperity at the expense of future generations.

It is by no means clear how this ethos will influence decisions on climate change, or whether societal values will change. It is hoped that the state of science is sufficient to present options and assign probabilities for the likelihood of certain events. We also wish to know with what probability objectives will be met if we take a given course of action. Consider the uncertainties of Global Circulation Models. Within the climate modeling community, skepticism arises from present inability to model cloud formation and cloud effects, especially precipitation and reflectivity (Ramanathan et al. 1989). A recent study of 14 essentially similar models showed that when cloud cover was held constant, differences in model predictions were relatively slight, and uncertainty was well within acceptable limits (Cess et al. 1989). The use of a 500 km by 500 km grid size, for which uniform conditions must be assumed, makes it impossible to address effects at regional scales; this problem is exacerbated by the enormous computer demands of a coupled ocean-atmosphere model.

Table 1. Explicit assumptions underlying potential policy options for addressing climate change.

Option	Assumptions
Do Nothing	*Predicted change is improbable, will have no measurable negative impacts, or the market will allow adjustments through pricing; compared to other problems facing humanity, climate change is less important.*
Confine activity to research on global climate change	*There may be changes, but unless we have greater reliability in predicting change, taking action is premature and a delay in preventative or adaptive decisions is not critical.*
Confine activity to research on climate change and its predicted effects.	*A course of action is best decided on the basis of knowing probable effects there is time for such analysis.*
Take mitigating steps that achieve some reduction in green house gas emissions at low cost	*While not certain, climate impacts could affect food supplies, shorelines, and our "way of life". Action that is economically feasible could avoid a serious drain on resources later.*
Mobilize an international effort to cut green house emissions, protect fish stocks aggressively, breed hardy stocks, and expand aquaculture now.	*The global scale of the problem merits priority over other social issues, or this issue links and amplifies problems such as population growth, food supply, war, disease, and cultural and economic decline.*

Scientists who are not involved in climate modeling but who have expert knowledge in climatology or atmospheric science advance the argument that while global climate has changed on a scale commensurate with glacial epochs, the shorter-term fluctuations have always allowed a return to a fairly narrow range of conditions, implying that mechanisms for homeostasis exist (e.g., Kerr 1989; Roberts 1989). One such mechanism is the carbon "fertilization" effect. The rise of atmospheric carbon dioxide will accelerate the rate of carbon uptake and storage by the two dominant ecosystems, terrestrial forests and marine phytoplankton. Another mechanism is the production of dimethylsulfide by marine plankton. Dimethylsulfide oxidizes in the atmosphere to form condensation nuclei required for cloud formation (Charlson et al. 1987). While evidence for the existence of the process is good, the specific effect of the feedback link has not yet been adequately quantified. Given this state of knowledge, what are the options for fishermen, fisheries biologists, marine resource managers, or countries that have invested in large fishing industries?

Consider a hypothetical example that approximates present modeling forecasts. Assume that northern hemisphere temperatures have a 50% chance of increasing to an average of 2-6°C (Schneider 1989), a 5-10% chance of increasing 4-10°C, and that variability about that mean will be least between the equator and 40 ° N and will increase at higher latitudes (Rind et al. 1989). Such patterns will be accompanied by a largely unknown change in precipitation patterns, unknown in the sense that predictions exist, but the associated uncertainty is as large as the deviation from present conditions. Moreover, there is an added risk that quasipermanent increases in ocean stratification will take place (Hansen et al. 1985).

Fisheries biologists will ask at what point these changes will produce a "signal" among the "noise" of the normal population changes. Certainly we have learned that variations on the scale of El Nino-Southern Oscillations have drastic and geographically widespread effects (Sharp 1987; Glynn 1988), while even subtle changes in climatic conditions can introduce significant effects on fish populations.

Some of the options available and the assumptions they incorporate are listed in Table 1. Clearly, the options are selective and the assumptions are extreme. Assumptions can be refined and parts can be subject to verification, but they remain assumptions in that they lie partly outside of objective science and incorporate values that are embraced by some and despised by others. Moreover, the process listed above must be quantified and understood in the context of continued human pressure on resources, which often demands that yields grow at a steady rate. These pressures alone may undermine the options for corrective action. The decision for the course of action is a social one. The scientist, fisherman, and consumer must act as advocates once the spectrum of probable events is defined.

From the perspective of information needs, a number of recommendations suggest themselves. We need to encourage the global circulation modeling community to intensify efforts to produce coupled ocean-atmosphere models that deal with atmospheric moisture dynamics in a more realistic manner. We need to encourage the ocean modeling community to intensify their efforts to model circulation changes that occur with a changed radiation balance, particularly for the prediction of changes in the magnitude, location, and size of upwelling zones. A parallel effort in evaluating the effect of hypothesized deep ocean and near-shore circulation changes on primary production and food web dynamics should accompany the further elucidation of present and past patterns of climate variability on fisheries stocks. While we can only reduce the margin of uncertainty over time, it appears from the data presented in this issue, and in much recent research, that in a 5 to 10 year research framework we can combine the results of these parallel efforts to predict climate impacts with some confidence. We will know if the sum of the impacts on global fisheries resources merits a concerted effort to reduce or stabilize man-made additions of greenhouse gases to the atmosphere. Whatever our course of action, nature will remain indifferent. In the words of Margulis and Dobb (1990, p. 49): Even if the species were to perish, it would happen not because man and nature are at odds-precisely the reverse-because human societies are embedded in nature and thus subject to its natural selections. If the fossil record teaches anything about life, it is that nothing is more natural than extinction. Speaking bluntly, the evolutionary odds are stacked against us in the long run. Given this fact, and the fact that humanity today faces a number of serious problems . . [scientists] would do well to stop fretting and instead pitch in with the rest of us in the difficult and urgent work at hand.).

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