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Fisheries

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EXECUTIVE SUMMARY

Any effects of climate change on fisheries will occur in a sector that already is characterized on a global scale by full utilization, massive overcapacities of usage, and sharp conflicts between fleets and among competing uses of aquatic ecosystems. Climate-change impacts are likely to exacerbate existing stresses on fish stocks, notably overfishing, diminishing wetlands and nursery areas, pollution, and UV-B radiation. The effectiveness of actions to reduce the decline of fisheries depends on our capacity to distinguish among these stresses and other causes of change. This capacity is insufficient and, although the effects of environmental variability are increasingly recognized, the contribution of climate change to such variability is not yet clear.

While overfishing has a greater effect on fish stocks today than does climate change, progress is being made on the overfishing problem. Overfishing results from an institutional failure to adjust harvesting ability to finite and varying fish yields. Conventional management paradigms, practices, and institutions—inherited from the period when fish stocks were plentiful—are not appropriate for the new situation of generally full exploitation, especially of important fish stocks. Although the Law of the Sea represents an important step in the proper direction, only a few countries have adopted the institutional arrangements needed to regulate the access of fishing fleets to critical areas. The United Nations (UN) Conference on Highly Migrating and Straddling Stocks and the Food and Agriculture Organization (FAO) Code of Conduct for responsible fisheries are likely to accelerate the adoption and effective implementation of regulatory mechanisms. Should climate change develop according to IPCC scenarios, it may become even more important than overfishing over the 50- to 100-year period covered by this 1995 climate assessment.

- Globally, under the IPCC scenarios, saltwater fisheries production is hypothesized to be about the same, or significantly higher if management deficiencies are corrected. Also, globally, freshwater fisheries and aquaculture at mid- to higher latitudes could benefit from climate change. These conclusions are dependent on the assumption that natural climate variability and the structure and strength of wind fields and ocean currents will remain about the same. If either changes, there would be significant impacts on the distribution of major fish stocks, though not on global production (Medium Confidence).
- Even without major change in atmospheric and oceanic circulation, local shifts in centers of production and mixes of species in marine and fresh waters are expected as ecosystems are displaced geographically and changed internally. The relocation of populations will depend on properties being present in the changing environments to shelter all stages of the life cycle of a species (High Confidence).
- While the complex biological relationships among fisheries and other aquatic biota and physiological responses to environmental change are not well understood, positive effects such as longer growing seasons, lower natural winter mortality, and faster growth rates in higher latitudes may be offset by negative factors such as a changing climate that alters established reproductive patterns, migration routes, and ecosystem relationships (High Confidence). Changes in abundance are likely to be more pronounced near major ecosystem boundaries. The rate of climate change may prove a major determinant of the abundance and distribution of new populations. Rapid change due to physical forcing will usually favor production of smaller, low-priced, opportunistic species that discharge large numbers of eggs over long periods (High Confidence). However, there are no compelling data to suggest a confluence of climate-change impacts that would affect global production in either direction, particularly because relevant fish population processes take place at regional or smaller scales for which general circulation models (GCMs) are insufficiently reliable.
- Regionally, freshwater gains or losses will depend on changes in the amount and timing of precipitation, on temperatures, and on species tolerances. For example, increased rainfall during a shorter period in winter still could lead to reduced levels in summer in river flows, lakes, wetlands, and thus in freshwater fisheries (see Chapter 10). Marine stocks that reproduce in freshwater (e.g., salmon) or require reduced estuarine salinities will be similarly affected (High Confidence).
- Where ecosystem dominances are changing, economic values can be expected to fall until long-term stability (i.e., at about present amounts of variability) is reached (Medium Confidence). National fisheries will suffer if institutional mechanisms are not in place that enable fishing interests to move within and across national boundaries (High Confidence). Subsistence and other small-scale fishermen, lacking mobility and alternatives, often are most dependent on specific fisheries and will suffer disproportionately from changes (Medium Confidence).
- Because natural variability is so great relative to global change, and the time horizon on capital replacement

(e.g., ships and plants) is so short, impacts on fisheries can be easily overstated, and there will likely be relatively small economic and food supply consequences so long as no major fish stocks collapse (Medium Confidence).

- An impact ranking can be constructed. The following items will be most sensitive to environmental variables and are listed in descending order of sensitivity (Medium Confidence):
  - Freshwater fisheries in small rivers and lakes, in regions with larger temperature and precipitation change
  - Fisheries within Exclusive Economic Zones (EEZs), particularly where access-regulation mechanisms artificially reduce the mobility of fishing groups and fleets and their capacity to adjust to fluctuations in stock distribution and abundance
  - Fisheries in large rivers and lakes
  - Fisheries in estuaries, particularly where there are species without migration or spawn dispersal paths or in estuaries impacted by sea-level rise or decreased river flow
  - High-seas fisheries.
- Adaptation options providing large benefits irrespective of climate change follow (Medium Confidence):
  - Design and implement national and international fishery-management institutions that recognize shifting species ranges, accessibility, and abundances and that balance species conservation with local needs for economic efficiency and stability
  - Support innovation by research on management systems and aquatic ecosystems
  - Expand aquaculture to increase and stabilize seafood supplies, help stabilize employment, and carefully augment wild stocks
  - In coastal areas, integrate the management of fisheries with other uses of coastal zones
  - Monitor health problems (e.g., red tides, ciguatera, cholera) that could increase under climate change and harm fish stocks and consumers.

16.1. Current Status of Fisheries

16.1.1. World Fisheries Conditions and Trends

Marine fishing generates about 1% of the global economy, but coastal and island regions are far more dependent on fishing. About 200 million people worldwide depend on fishing and related industries for livelihood (Weber, 1994). Marine fish account for 16% of animal protein (5.6% of total) consumption, but developing countries are more dependent on this protein source (Weber, 1993, 1994). Marine catches peaked in 1989 at 85 million tons; freshwater catches were 6.4 million tons, about 7% of the total (FAO, 1993). The potential sustainable yield of marine food fish may be about 100 million tons (Russell and Yonge, 1975); the limit may have been reached. Some 40% of total world production enters international trade (FAO, 1992a), with the top fishing nations being China, Japan, Peru, Chile, Russia, and the United States (FAO, 1993).

World fisheries are characterized by a general state of full or overexploitation of wild stocks and excess harvesting and processing capacities. Some small pelagics, some very-deepwater fish, and some oceanic tunas and Antarctic krill are among several exceptions. Globally, fishing costs are about 20% greater than revenues, with much of the deficit provided by national subsidies (FAO, 1992a). The World Bank (1992) and FAO (1992b) estimate total economic rent and subsidy losses at $79 billion annually, and the situation is likely to worsen.

The quantity of landings is declining (Garcia and Newton, 1994) in 13 of the 15 major marine areas. Only Indian Ocean fisheries continue to increase. Further, there is a deterioration in quality caused by declines in the sizes of highly valued species and a move to bulk landings of lower-value species (Regier and Baskerville, 1986). Thirty percent of global fishery catches are discarded because they are too small, they are prohibited from being landed, or no profitable market exists (Alverson, 1994). This practice of discarding by-catch is more common in industrial fisheries than artisanal ones. Most important stocks are fully or overexploited (Sissenwine and Rosenberg, 1993). In most regions, there is little or no surplus biomass to buffer climate-induced fluctuations in stock abundance relative to current demand. Reduced numbers of year classes also increase stock variability and risk of collapse.

This situation is rooted in the ocean's finite production capacity and in the deficiencies (including concepts and enforcement) of current institutions for adjusting fishing capacities to stock productivity. Present systems were developed when underutilized stocks were available and freely accessible to large-scale fishing operations. Most have not been adjusted to the situation of resource scarcity. Adoption of the UN Convention on Law of the Sea and Exclusive Economic Zones, generally out to 200 miles, has led most countries to control foreign fleets and is a critical step toward improved institutions. However, few countries have taken steps to improve domestic management, even though 90% of production comes from EEZs (Sherman and Gold, 1990; FAO, 1993).

With the advent of EEZs in the mid-1970s, foreign fleets received allocations of stocks that exceeded domestic capacities. Domestic capacity then rapidly increased, often via joint-venture (JV) partnerships with foreign companies. Upon reaching full domestic exploitation through direct replacement and domestic-controlled charters, most JVs were phased out. JVs have not disappeared, however, and foreign fishing continues in some developing regions. Less desirable species and areas or certain species taken by specialized fleets working both international waters and EEZs are most of what remain available to foreign licensed fleets.

Access to high-seas, highly migratory, and straddling (EEZ/high seas) stocks remains mostly open and free, although participants in some fisheries voluntarily limit catches. Without management, fishing cannot be adequately adjusted to average stock abundances, let alone to fluctuations. The 1995 UN Conference on Highly Migrating and Straddling Stocks and the FAO Code of Conduct for responsible fisheries are likely to accelerate the adoption and effective implementation of regulatory mechanisms. With effective management, depleted fisheries could yield another 20 million tons annually (Weber, 1994).

Competition occurs at all levels: countries fishing the same stock, a single country involved in different fisheries in its own or others' waters, and different fishing methods competing within a fishery. In most cases, excess catching power is deployed, and conflicts among competitors often become acute and pervasive.

With few exceptions, governments have not recognized the customary use-rights of traditional fishing communities. Growing demands for fish, water, and space; encroachment by large-scale fishing and aquaculture operations; population concentrations; urban expansion; pollution; and tourism already have harmed small-scale fishing communities in shallow marine waters, lakes, and rivers. These fishers have limited occupational or geographic mobility. With climate change, global and regional problems of disparity between catching power and the abundance of fish stocks will worsen—particularly the interaction between large mobile fleets and localized fishing communities. Aquaculture will develop in new areas, sometimes assisting, sometimes disrupting existing artisanal fishers.

The productivity of freshwaters and sea margins has become stressed by human density and societal actions to benefit non-fisheries sectors. For example, freshwater diversions for agricultural use have resulted in water-level and salinity changes, leading to ecological disasters in the Aral, Azov, and Black seas, and San Francisco Bay (Caddy, 1993; Mee, 1992; Rozengurt, 1992). The artificial opening of the sand barrier at the mouth of the Cote d'Ivoire River to clear floating weeds allowed seawater to enter the lower part of the river and has changed species dominances (Bard *et al.*, 1991; Albaret and Ecoutin, 1991).

On the Nile, the Aswan dam so thoroughly regulates flows that the delta has become degraded ecologically. Local sardine populations that once thrived and provided food for the region have collapsed with the decline in local primary production that depended on the strong surges of flood waters and their pulses of nutrients (Sharp, 1994). Where the Sahelian drought is causing increased salinity in the lower parts of Senegalese rivers, a dam erected near the mouth of the Senegal to stop the rising salinity and ease severe problems to local agriculture prevents fish migration (Binet *et al.*, 1995). Hydroelectric dams in the Dneiper River basin have suppressed spring flows, increased salinities, and left local marshes unflooded at the time of peak fish migration, decreasing fish landings by a factor of five (Mann, 1992).

Problems are markedly more acute in smaller water bodies and fragile coral reefs, especially in areas of high human density. In these areas, habitat degradation often is more important than overfishing. As stresses intensify, impacts that for a long time were limited to freshwaters and littoral areas are now observed in closed and semi-enclosed seas (FAO, 1989b; Caddy, 1993). Some semi-enclosed seas, such as the Mediterranean, Black, Aegean, and Northern Adriatic, are already eutrophic. The diversity of uses in these areas also has introduced "one of the most pervasive and damaging anthropogenic impacts on the world's ecosystem" in the form of nonindigenous species (Mills *et al.*, 1994). Many of these organisms already have extensive invasion histories, are easily transportable, are highly fecund, and tolerate a wide range of environmental conditions. Their damaging effects on indigenous populations may only be enhanced by ecosystem fluctuations accompanying climate change.

Fish habitats are downstream of many impacts, and fish integrate the effects. Fish are symbolic in depicting the health of ecosystems and our ability to manage our resources. Lake Victoria exemplifies this situation and shows how caution must be exercised in introducing nonindigenous species to adapt to, or take advantage of, climate change (see Box 16-1).

Scientists are unable, in most instances, to quantify efficiently each of the man-made and natural stresses on fish stocks. This major constraint on integrated management of water bodies is exemplified by the U.S. fishery for yellowtail flounder on Georges Bank at the southern edge of the species range. The species does not do well when the waters are warm. If there is warming and efforts to rebuild the stock in U.S. waters suffer, it will be difficult to differentiate climate change from fishing as the primary cause (Anthony, 1993).

National and international trends appear to lead to more rational means of management and improved institutions. Among the more advanced concepts is that of Individual Transferable Quotas (ITQs)—in which a science-based catch quota is set and enforced, and fishers can buy and sell percentages of the quota. ITQ systems are being implemented in many areas. Most major fisheries in New Zealand, Canada, Chile, and Iceland; several in Australia; and two in the United States are under ITQ arrangements, with others under discussion (Sissenwine and Rosenberg, 1993).

Box 16-2 contains a regional case study. It is not unique. The steady decline of northeast Atlantic catches since the mid 1970s, the recent banning of cod fishing by Canada, and other situations also could serve as examples.

16.1.2. Aquaculture

Recent growth in total fisheries production is from aquaculture. Aquaculture has grown rapidly during the last few decades and accounts for about 10% of the total world fish production,

Box 16-1. Lake Victoria

Climate change will add to stresses now affecting large lakes and their fisheries. Lake Victoria has reached ecological devastation. Surrounded by urban and agricultural development, it suffers from high nutrient loading, causing eutrophication. Deforestation and erosion are putting sediments into the waters; papyrus swamps are declining with overharvesting; and snails are increasing in abundance. Landing beaches and piers are useless as water continues to recede from the shore. Exposed sand is being harvested, leading to the destruction of spawning grounds and fish refugia. Additionally, introduction of Nile perch contributed to the upset of the productive natural ecosystem and the socioeconomic balance of the region, as summarized below (Barel *et al.*, 1985; Ssetongo and Welcomme, 1985; Acers, 1988; Ogutu-Ohwayo, 1990a, 1990b; Bruton, 1990; Achieng, 1990; Kaufman, 1992):

- The former multispecies fishery has been reduced to three species, due largely to predation by Nile perch and overfishing. Two hundred species have become extinct.
- The decline of perch prey forebodes the collapse of that fishery.
- Subsistence fishers are unable to capitalize to compete in the new fishery. Surviving fishers have adapted by using large-mesh nets to catch perch.
- The local population prefers the native species, as reflected in the low value of perch.
- Perch cannot be sun-dried and must be smoked, requiring extensive use of firewood and leading to deforestation of some islands.
- The most important freshwater fishes in East Africa have vanished from the marketplace.

Box 16-2. The Barents Sea

Luka *et al.* (1991) considered causes of depression of Barents Sea fish stocks and options for recovery. In the late 1970s, total catches reached 4.5 million tons. Then, due to a decreasing abundance of cod, catches dropped, especially sharply in the early 1980s. In the second half of the 1980s, after the fishery on capelin ended, the total catches were about 300,000 tons. The main cause was overfishing, but the unfavorable climatic regime (cooling in 1977–1982) led to poor year classes of all main species. Fishing was very heavy in the 1970s and the first half of the 1980s, despite a declining biomass (Kovtsova *et al.*, 1991; Zilanov *et al.*, 1991). By the second half of the 1980s, herring, capelin, and polar cod—the main food for cod and haddock—were very scarce. This led to slow growth, starvation, and increased mortality. Moreover, predation of cod and haddock on juveniles of deepwater redfish, plaice, and wolffish increased greatly, reducing some strong year classes before they entered the fishery (Kovtsova *et al.*, 1991).

The total Soviet catch was unaffected by these depressed stocks. Fuel was inexpensive, and the fishing fleet moved to other regions [e.g., the Norwegian Sea (blue whiting), Irminger Sea (deepwater redfish), and Antarctica]; thus, there was little impact on the Soviet economy.

By the early 1990s, the Barents Sea spawning biomass was at its historically lowest level. However, there is now a sharp increase in the abundance of cod and capelin, perhaps associated with an observed warming of the northeast Atlantic and adjacent seas.

mostly of higher-valued products. Aquaculture contributes to the resiliency of the fisheries industry, tending to stabilize supply and prices.

Advancements are unevenly distributed across regions, farming systems, and communities. Growth is about 5% annually. The marine component is growing rapidly, but freshwater is still dominant. Aquaculture will not rapidly solve the scarcity of natural fish, and current industry growth will fulfill the demand only for certain commodities, regions, and consumer groups.

Large-scale systems specialize in a few high-value species (e.g., shrimp and salmon) and are developing wherever profitable. Small-scale systems (e.g., for freshwater finfish and shellfish) are restricted to regions where aquaculture and/or settled agriculture have existed for centuries (essentially in eastern and southern Asia and in Europe). This distribution reflects social and institutional factors (notably land and water property regimes) that change very slowly. The need for improved management is great. In Taiwan, for example, inadequate control of expansion of shrimp farming resulted in mass mortalities of stocks and the collapse of production in 1987–89 from 100,000 down to 20,000 tons.

Genetic engineering holds great promise to increase the production and efficiency of fish farming (Fischetti, 1991). However, fishers and resource managers are very concerned about accidental or intentional release of altered and introduced species that might harm natural stocks and gene pools. Around Scandinavia, escapees and nonindigenous reproduction may have reached or exceeded the recruitment of salmon wild stocks (Ackefors *et al.*, 1991). Introduction of pathogenic organisms and antibiotic resistant pathogens is also of concern.

Ranching (in which young fish are released to feed and mature at sea) and fish farming, like their equivalents on land, have self-generated and imposed impediments to success. The activities can compete for coastal space with other uses, and continued expansion can jeopardize the quality and quantity of fish habitat [e.g., through loss of mangroves and wetlands, competition for food with wild stocks, or other factors (NCC, 1989)].

16.2. Climate-Change Impacts

GCM results can be used to make some global inferences, but caution must be used in forecasting fisheries impacts until scientists are able to forecast regional and finer climate and ecosystem processes. Global warming will likely be accompanied by changes in water temperature, precipitation, winds, water and nutrient flows, water level, biogeochemistry, sedimentation, salinity, water mixing, upwelling, ice coverage, and UV-B radiation. Changes in amounts, structures, and timing will affect ecosystem components, including habitats, entire food webs, and species interactions. Chapters 8, 9, and 10 describe these changes and ecosystem impacts.

16.2.1. Freshwater Fisheries

The first indications of reaction by fish species to climate change probably will be among those populations living at the extremes of their temperature tolerance ranges (Holmes, 1990) or residing in streams with high rates of heat transfer from the air. In freshwater, population migration may be limited by watershed constraints (Regier and Holmes, 1991; Shuter and Post, 1990). In large drainage systems, the flexibility for migratory shifts to compatible temperatures will be greater in north–south flowing systems (Meisner, 1990).

It is intuitive to expect poleward range movement for species with climate warming (Shuter and Post, 1990). However,

Box 16-3. Temperature Preferences

Fish cannot regulate their internal temperatures; they try to maintain preferred temperatures through behavior. They seek habitat close to the optimum temperature for growth, foraging success, and protection (Magnuson *et al.*, 1979). Unless a water body has such temperatures for substantial space and time—with other factors also sufficient for well-being—a particular species will not likely thrive (Christie and Regier, 1988). Species have different preferred temperatures, with similarities between species within families. In the figure below (from Lin, 1994), with optimal food and other factors, two salmonid species prefer cold water at or below 25 °C; two percid species prefer cool waters; and two centrarchid species prefer warm waters and tend to "hibernate" in winter when water temperatures fall below 8°C.

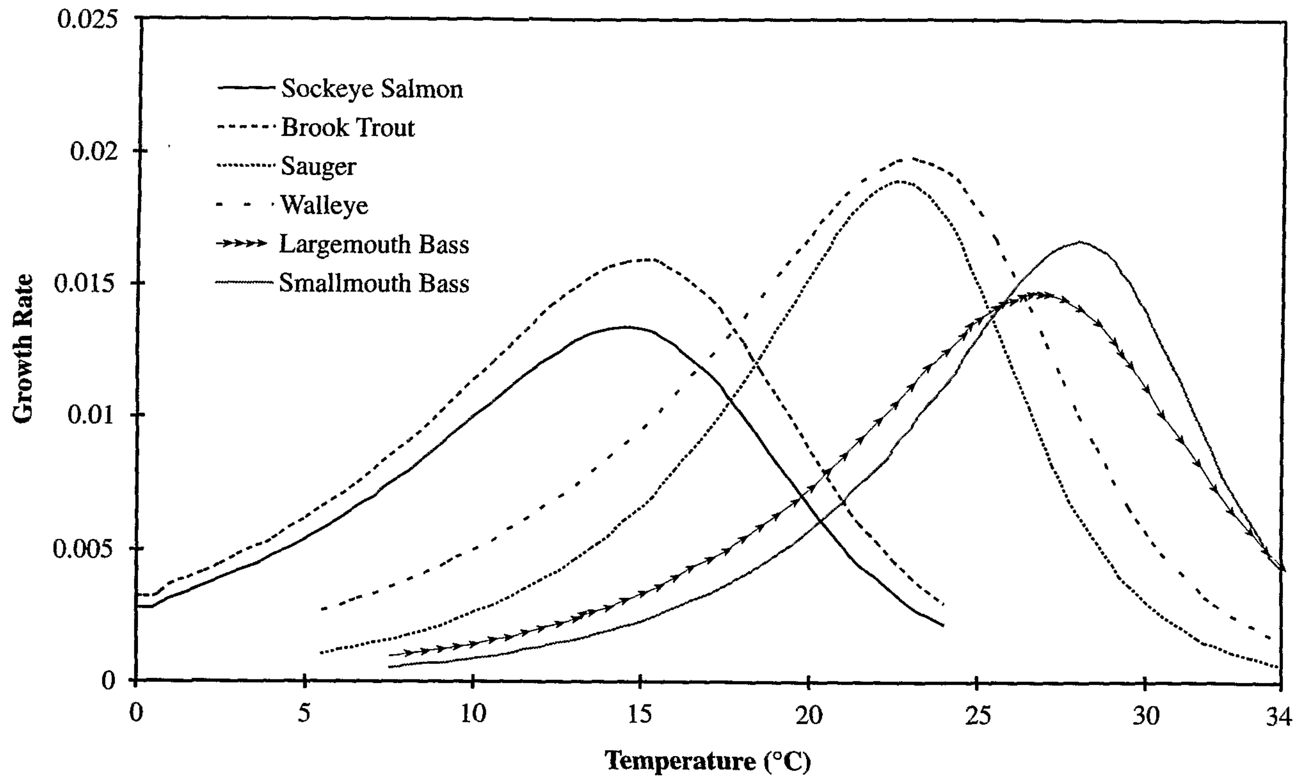

Figure 16-1: Growth rates as a function of temperature.

habitat, food supply, predators, pathogens, and competitors must be within the species' ability to cope. Further, there must be a suitable dispersion route, not blocked by land or some property of the water such as temperature, salinity, structure, currents, or oxygen availability. Movement of animals without a natural dispersal path may require human intervention or hundreds or thousands of years (Kennedy, 1990).

Changes in the amount and timing of precipitation will affect freshwater fisheries production (Welcomme, 1985; Lowe-McConnell, 1987). Thus, expected precipitation increases in high northern latitudes—extending well into mid-latitudes in most cases—in winter (see the Working Group I volume) could provide largely positive benefits overall. However, if accompanied by higher evaporation in summer due to warmer temperatures or loss of habitat due to high flow rates in winter or spring, these benefits may not accrue. Species unable to move or adapt may suffer population declines or become extinct. Management to control critical temperatures of portions of rivers and streams using impoundments, and timing of water releases and runoff may mitigate the impacts of climate change on some species.

Warming should produce a longer growing season for species that have not attained their maximum temperature limits (Shuter and Meisner, 1992), but warming also may lead to reduced productivity in species at or near their maximum limits (Mathews and Zimmerman, 1990). Greater fish production should occur in high-latitude lakes and reservoirs (Schlesinger and McCombie, 1983). Tropical lakes have longer growing seasons and shorter generational times and usually produce higher fish yields than temperate lakes because fish mature at earlier ages. Mean annual air temperature is the most important factor in predicting lake fish production across latitudes (Schlesinger and Regier, 1982), but changing rainfall patterns and flood regimes may have profound effects on river fish (Meisner and Shuter, 1992; McDowall, 1992). In rivers, low oxygen at low flows can severely limit fish production.

Alterations in seasonal climate patterns should change the population distributions in larger lakes. In a study using fish bioenergetics models, certain Great Lakes fisheries were found to have potentially greater yields, whereas others were predicted to collapse (Hill and Magnuson, 1990). White perch—a species of low value—might be among those with increased range and improved recruitment because of a longer growing season and shorter, milder winters (Johnson and Evans, 1990). Yields in southern Lake Michigan and central Lake Erie are projected to remain about the same for lake trout and lake whitefish but increase for walleye. Thermal habitats are expected to increase except for cold-water species in Lake Erie, where the deep water could become anoxic in summer (Magnuson *et al.*, 1990). Large lake fish production could increase about 6% with a 1°C rise in average annual air temperature (Meisner *et al.*, 1987).

Warm-water exotic species may invade large lakes where invasion routes are available (Mandrak, 1989). For example, Coutant (1990) speculates that, with warming, U.S. east coast populations of striped bass, *Morone saxatilis,* could move further north and perhaps enter the Great Lakes—where they might thrive in the lower lakes—and compete with salmonids; in the Gulf of Mexico, Florida coastal waters, and southern U.S. lakes and reservoirs, their existence could be threatened.

Changes in species dominance may occur. Each population has adapted to specific temporal and spatial features. For example, in New Zealand, native species occur throughout the nation, whereas introduced species seem to be temperature-limited in their distribution—suggesting that indigenous species may be more resilient than exotics in a warming climate (New Zealand, 1990). Species invasions and removals occur frequently, even without human causes, but climate and habitat change should accelerate them. Indigenous species will be subject to greater pressures from shifts in ecosystem structures and introductions of opportunistic exotics (Lodge, 1993).

Positive factors associated with greater warming and precipitation at higher latitudes include faster growth and maturation rates, lower winter mortality rates due to cold or anoxia, and expanded habitats with ice retreat. Offsetting negative factors include increased summer anoxia, increased demands for food to support higher metabolism, possible negative changes in lake thermal structures, and reduced thermal habitat for cold-water species. Individual effects are difficult to integrate. However, warm-water lakes generally have higher productivity than cold-water lakes, and existing warm-water lakes will be in areas with the least change in temperature. It is reasonable to expect higher overall productivity from freshwater systems. Most warming should occur during fall, winter, and nighttime during the summer, improving the survival of fish that are less tolerant of cold and having little effect on many species near their upper lethal temperature. Streams may be no more likely to reach high lethal temperatures. Lastly, fishery managers heavily manipulate freshwater fisheries in much of the world. If species mixes continue to be changed to support angler and market preferences and changing habitats, climate-change damages may dampen and benefits may heighten.

16.2.2. Saltwater Fisheries

The linkage between climate and marine fisheries is complex and poorly understood. Physical changes influence recruitment and abundance, the center of distribution and range, and availability by concentrating stocks in fishable locations. There are so many interacting variables (such as currents, upwelling, cloudiness, nutrient flows, salinity, temperature, and solar irradiance) that predictions of changes in primary production are not clear (Bernal, 1991; Mann and Lazier, 1991; see also the Working Group I volume). However, understanding is growing. For instance, in the Pacific, the intensity of the Aleutian low clearly affects primary production (Venrick *et al.*, 1987; Beamish and Bouillon, 1993) and ecosystem production (Polovina *et al.*, 1994).

16.2.2.1. Sea-Level Rise

About 70% of global fish resources depend on near-shore or estuarine habitats at some point in their life cycle (Chambers, 1991; IPCC, 1990). The growing rate of human occupation—with associated pollution—and the high property values of littoral areas, especially in Western countries, will severely constrain the inland displacement of wetlands and other habitats as sea level rises. Fish production will suffer when wetlands and other habitats that serve as nurseries are lost (Costa *et al.*, 1994). Chapter 9 discusses these issues, and Box 16-4 provides an example of the potential effects of sea-level rise on active fisheries.

If sea-level rise is too rapid, natural succession of coastal ecosystems cannot occur, harming many species. With a half-meter rise by 2100—and with protection of all developed areas—more than 10,360 km^2 of wetlands could be lost in the contiguous United States (Park *et al.*, 1989). In the near term, fish production could rise as marshes fragment, flood, die, and decompose, improving fisheries habitat in some cases as the protective land edge increases. More nutrients would become available from leaching of soils and flooded peat. The southeastern United States, where land subsidence compounds sea-level rise, may be in this phase of temporary improvement now (Zimmerman *et al.*, 1991). Eventually, detritus-based food webs would lose the protective habitat and nourishment, as well as wildlife nesting sites and refuge (Kennedy, 1990). In the longer term, by 2050 the overall impact on fisheries will probably be negative. The brown shrimp catch in the U.S. Gulf Coast could fall 25% with a 25-cm rise in sea level (Park, 1991). A 34-cm rise could cause the loss of 40% of the extensive Puget Sound tidal flats—an important habitat for shellfish and waterfowl (Park *et al.*, 1993). In certain areas, already nutrient-rich waters may become eutrophic (Caddy, 1993). Rising sea level may particularly affect coastal ponds as flooding septic systems increase nutrient loading, an important loading mechanism (Valiela and Costa, 1988).

Wetlands, coral reefs, mangroves, and sea grasses require a healthy environment to keep pace with a rising sea, to continue coastal protection benefits, and to serve as fisheries habitat.

Box 16-4. The Caspian Sea

Fluctuation of Caspian Sea water levels provides insight on interacting impacts. An increase in sea level could have a positive economic result for fisheries but a high cost to land-based industry and tourism.

The main species harvested from the Caspian are sturgeon, roach, bream, sander, sazan, herring, and kilkas (Anon., 1989). In the second half of the 1950s, diversion of river waters and unfavorable conditions resulted in a series of low-water years, with reduction of sea area and volume and higher salinities. Roach, bream, sander, and juveniles of all other species declined as their prey decreased in response to the water changes. At the same time, river fish (sheatfish, pike, redeye fish, tench, etc.) increased as suitable spawning habitat expanded.

In the late 1970s, the water level started rising, and bioproductivity increased. Plankton biomass increased threefold and shad—which spawns in the northeast shallow brackish area—recovered (Vodovskaya *et al.*, 1978). By the mid-1980s, high natural reproduction and improvement of the hydrological regime in the northern Caspian resulted in strong year classes of roach, bream, and sander, and they increased to their highest level as favorable conditions stabilized.

As sea level continues to rise and inundate more developed areas, serious environmental implications confront productivity. The Caspian is heavily polluted with oil, phenol, and heavy metals from years of industrial dumping. As land is over-washed, additional oil and pollutants from industrial facilities will further threaten the sea's valuable stocks (Anon., 1994). If the shore is protected extensively, as is planned by Kazakhstan, there also could be significant losses of fish spawning habitat and production.

Sea-level rise with defense of properties, increased freshwater diversion, and human and industrial concentration in coastal areas would be detrimental to fisheries production.

16.2.2.2. Fishery Oceanography

Evidence in support of the view that environmental changes drive many changes in fish stocks has been accumulating in recent years (Mann and Lazier, 1991; Mann, 1992, 1993; Mann and Drinkwater, 1994; Polovina *et al.*, 1995). The question of whether overfishing, environmental change, or a combination of the two is responsible for major declines in fish stocks is still a matter for debate and is situation-specific.

The literature is rich with studies relating historical changes in the abundance and distribution of aquatic organisms to climate changes. The studies show that relatively small changes in climate often produce dramatic changes in the abundance of species—sometimes of many orders of magnitude—because of impacts on water masses and hydrodynamics (e.g., Sharp and Csirke, 1983; Kawasaki *et al.*, 1991; Beukema *et al.*, 1990).

Changes in temperature, winds, currents, salinity, and other physical parameters affect life in the oceans. With warming waters, larger fish tend to move to cooler or more offshore and higher-latitude portions of their habitat, or suffer reproductive stress responses that debilitate individuals and lead to lower viability (Sharp, 1994). Water temperatures will increase least at the equator and more toward the poles. In contrast to tropical and mid-latitude regions, where productivity is mainly nutrient-limited, the basic limiting factors in polar and subpolar regions are light and temperature. Warming in high latitudes should lead to longer growing periods, increased growth rates, and ultimately, perhaps, increases in the general productivity of these regions (Regier *et al.*, 1990). Each species might be affected differently. For example, early research results for northern Pacific salmon indicate that ocean distribution in a warming climate would decline to half its present area by about 2070, and winter habitat could completely disappear for 3 months each year (Welch and Beamish, 1994).

The impacts of warming can be inferred from past displacements of transition zones—for example, the Russell cycle in the western English Channel (Southward, 1980) and the simultaneous discontinuities in the local occurrence of pilchard and herring (Cushing, 1957, 1982). Opposing fluctuations in these fisheries in the Channel and the Bay of Biscay have followed long-term changes in climate for three centuries (Binet, 1988b). Tropical Atlantic albacore recruitment is correlated with temperature anomalies during spawning (Leroy and Binet, 1986).

Warming would affect marine species in shallow, restricted impoundments long before deep oceanic species (Bernal, 1991). While fish can migrate, mollusks usually cannot move to favorable areas, although their progeny may develop and thrive in new locations—or be eliminated if suitable habitats do not develop. One example is the important fishery for soft-shelled clams in the Chesapeake Bay. These clams are essentially absent in warmer estuaries further to the south. They could disappear from the Chesapeake if there is substantial warming (Kennedy, 1990). Conversely, Dickie (1955) showed that Bay of Fundy scallop fluctuation from 1930–1953 followed water temperature but lagged by 6 years (i.e., the time for sea-scallop recruitment). Higher temperatures led to strong year classes (Frank *et al.*, 1990).

Warming and wind changes would affect the distribution and characteristics of polynyas (ice-free areas) and ice edges that are vital to polar ecosystems. Changes in the extent and duration of ice, combined with changes in the polar frontal zone and the circumpolar current in southern latitudes, also may affect the distribution, mass, and harvesting of krill. Krill is the fundamental link in the food web of the southern ocean; much of the fishery it supports is used as feed in aquaculture. Antarctic productivity also is closely related to spring retreat of pack ice. Warming could affect pack-ice movement and extent—in turn, affecting the distribution, abundance, and productivity of krill. However, little change is forecast in Antarctic ice for 100 years (see the Working Group I volume). Changes in wind strength also may affect productivity in the ice edge zone.

In the eastern Pacific, interdecadal natural variation resulted in warm periods of high sardine abundance during the 1940s and 1976–85, separated by cool periods of high anchovy abundance in between and in very recent years (Lluch-Belda *et al.*, 1992). While this suggests a direct correlation of high sardine abundance with warm temperatures, it is likely that there is a more complex relationship. At the time of these eastern Pacific warm periods, the western North Pacific has been generally cool, with very abundant Japanese sardines.

Major shifts in regional and global climate have major effects on the abundance and distribution of fish stocks. The 1976–77 climatic regime shift in the North Pacific Ocean (Beamish, 1995) was apparently the starting point for a high-sardine-abundance regime. Further, this period seems to be giving way to a new period of high anchovy abundance since 1985 (Lluch-Belda *et al.*, 1992). There is a long time lag before scientists recognize these events.

Warmer water and changes in circulation would substantially affect the structure and location of habitats. However, marine organisms as a rule have rather high genetic and behavioral plasticity, allowing them to adapt to constantly changing conditions. This property underlies the relative stability of zoogeographical patterns during natural climate variations (Odum, 1986). However, there may not be high plasticity with respect to temperature-dependent physiological and ecological rates and behavioral thresholds (Lin and Regier, 1995). While the mix of marine species constantly changes with naturally variable climates, the changes forecast by IPCC would happen relatively rapidly and be long-lasting. There will likely be food-chain disruptions that will destabilize certain marine populations (Kawasaki, 1991). Poleward shifts of some, but not all, elements of an ecosystem may result in discontinuous areas of high productivity (Lluch-Belda *et al.*, 1991).

Changes in currents could lead to changes in population location and abundance and the loss of certain populations—or the establishment of new ones—at the periphery of the present species distributions. Current GCMs do not adequately incorporate the ocean, and coupled physical/biological models are in their infancy. To date, only the Semtner-Chervin global ocean circulation model (Semtner and Chervin, 1988) has been generally used to provide information that is directly applicable to local and regional fisheries applications. If only the direction of potential changes in ocean circulation could be known, useful assumptions could be made on the likely impacts on fisheries (Troadec, 1989b).

A general poleward extension of habitats and range of species is likely, but an extension toward the equator may occur in eastern boundary currents. For example, the range of *Sardina pilchardus* prior to World War II was from south Brittany to Morocco. In warm years following the war, sardines were fished up to the North Sea. During the 1970s, new fisheries developed off the Sahara and Mauritania, with small amounts landed as far south as Senegal—perhaps due to upwelling and ecological processes related to tradewind acceleration (Binet, 1988a). Changes in the circulation pattern are likely to induce changes in the larval advection/retention rates in and out of favorable areas and may explain changes in abundance and distribution (Binet, 1988a; Binet and Marchal, 1992). Areal overlaps in closely related species may change in unpredictable directions (Ntiba and Harding, 1993).

Even if the major currents are unchanged (see the Working Group I volume), winds can change local currents and upwelling dramatically. If upwelling-favorable winds intensify, as some authors suggest (Bakun, 1990, 1993a), the mixing of surface and subsurface waters will increase, improving their nutrient contents but perhaps delaying the phytoplankton spring outburst in some areas. The total production and species dominance of the whole food chain will be affected (Aebischer *et al.*, 1990). Conversely, some authors suggest that global warming will lead to a reduced temperature gradient between the poles and the equator—and therefore to decreased oceanic winds and decreased mixing of surface and subsurface waters (Wright *et al.*, 1986).

A physical forcing may have opposite effects in different areas because ecological relationships are not necessarily linear. The 1950–1980 northerly wind increase in western Europe enhanced the Iberian west coast upwelling and is associated with decreased sardine production (Dickson *et al.*, 1988), whereas wind acceleration along the Mauritania coast favored settlement of a new sardine population (Binet, 1988a), possibly illustrating a dome-shaped environment–resource relationship (Cury and Roy, 1989). A gentle breeze enhances the recirculation of nutrients in the euphotic layer and hence the biological production, whereas a strong wind mixes the water and causes phytoplankton to sink below the sunlit layer. Other examples of the influence of changes in upwelling systems and circulation are provided in Box 16-5.

Skud (1982) found that in both marine and freshwater systems, changes in environment can shift species dominance. Dickson and Brander (1993) describe how a change in the west winds resulted in a major influx of West Greenland cod larvae to the 1957 Labrador cod stock. Moreover, winds and warming can interact powerfully—as is demonstrated by the tale of the tilefish. In 1879, the tilefish, responding to a temporary warming of the Atlantic, appeared in large numbers off New England. Three years later, northern gales cooled the water below the

Box 16-5. Upwelling Systems

Changes in circulation and upwelling systems affect the distribution and abundance of pelagic species (Bakun, 1993b), often in interaction with fishing pressure:

- Long-term fluctuations in sardine stocks occur in apparent synchrony off Japan, California, and Chile/Peru (Kawasaki, 1983; Sharp, 1992a, 1992b; Sharp and McLain, 1993). These broad processes link through atmospheric and oceanographic patterns spanning a few decades. Transitions from one pattern to another involve massive declines in populations of coastal upwelling species and the emergence of more oceanic forms to recolonize large expanses of the near-shore environment (*c.f.*, Pauly *et al.*, 1987, 1989; Yañez, 1991).
- Recent changes in the distribution and abundance of west African pelagic stocks correlate with upwelling system modifications (Binet and Marchal, 1992, 1993; Binet and Servain, 1993; Cury and Roy, 1991):
  - A shortened food web resulted in more phytoplankton and fewer zooplankton, benefiting phytoplankton-feeders.
  - New concentrations of *Sardinia pilchardus* appeared off Mauritania and Senegal; pilchard catches declined off northern Morocco.
  - *Sardinella aurita* strongly expanded in the Ivory Coast.
- Similar stock changes are documented from Namibia and South Africa (Crawford *et al.*, 1991; Payne *et al.*, 1987), Argentina and Brazil (Bakun and Parrish, 1990, 1991), California (Parrish and McCall, 1978), Peru/Chile (Pauly and Tsukayama, 1987; Sharp and McLain, 1993), and the subarctic Pacific (Beamish and Bouillon, 1993).

lower thermal limit, causing mass mortality (Freeman and Turner, 1977).

Freshwater flows to the sea lower local salinity, bring nutrients to increase primary production, enhance turbidity, and impact coastal ecosystems. Salinity changes and warming of coastal waters may lead to a latitudinal redistribution of fish stocks, with changes in timing and pathways for migrating species. Increases are expected in evaporation in mid-latitudes and precipitation in low and high latitudes. The 1972–1985 west African drought led to a large-scale ecological change over the west African shelf (Caverivière, 1991). The halving of river flows led to a small salinity increase along the coasts of Senegal and the northern Gulf of Guinea (Mahe, 1993) and greatly reduced sediment loading and turbidity.

In the Casamance—a long, narrow estuary in Senegal—a rainfall shortage that sharply raised salinity caused dramatic changes in fish populations. The total fish biomass remains the same but consists of small, low-priced species. High mortality can occur when the fish cannot escape the salt plug (Albaret, 1987). Shrimp production increased temporarily and then collapsed as salinity increased (Le Reste, 1992).

Higher temperatures and greater water-column stratification can result in less organic material reaching the bottom and thus favor pelagic over demersal fishes (Beamish and Bouillon, 1993). In addition, changes in phytoplankton production, such as shifting downward to smaller species, can lead to longer food webs or benefit smaller fish feeding at lower trophic levels (Frank *et al.*, 1990). Changes in wind, temperature, and precipitation can alter stratification processes and thereby affect the feeding and survival of larval fishes (Owen, 1981, 1989). Some species depend on turbulence at critical stages—for example, to oxygenate eggs or habitats—whereas others require stability to allow surface-water stratification and the concentration of food organisms. Thus, changes in stratification of local water masses could disperse or concentrate food organisms of young fishes (Bernal, 1991). Lasker (1981) hypothesized, and Peterman and Bradford (1987) demonstrated, that the larval mortality of anchovy (*Engraulis mordax)* was negatively correlated to the number of calm periods. Rothschild and Osborn (1988) note that minimal turbulence is useful to enhance the encountering rate of particles and predators, whereas strong turbulence breaks up aggregations of particles on which feeding is possible. This apparent contradiction illustrates the complexity of ecological relationships and the difficulty of prediction.

The nature of climate-change impacts on fish can be inferred, in part, from an analysis of current interannual fluctuations of marine populations. Catch statistics and research surveys can yield information on stock fluctuations. Fish variability has been classified on the basis of taxonomic groups and environments (e.g., Kawasaki, 1980; Sharp, 1986) and by temporal variations (Caddy and Gulland, 1983). These categories describe:

- Highly unstable and unpredictable stocks varying by several orders of magnitude due to sporadic climatic shifts (e.g., capelin, sand eel, and saury)
- Unstable and partly predictable stocks varying by a few to several times due to cyclic climate and fishing variations (e.g., sardines, herrings, and mackerels; Sahelian freshwater fish)
- Stable and predictable stocks varying by tens of percent to a few times due to fishing and climate trends (e.g., bottomfish such as cods and flatfishes and large pelagics such as tunas).

In most cases, temperature increase is not the direct reason for change in aquatic ecosystems and fisheries, although fish may react physiologically or behaviorally. The most crucial problems are associated with the whole complex of ecological changes. Fish have developed many patterns of behavior to deal with climate variability and migrating predators and prey. Some environments call for tightly constrained windows within which reproduction can succeed. Others require constant or prolonged spawning to cope with even finer-grained, less-certain opportunities. Because many fish early-life stages occur in shallow layers and estuaries where various climate components are important (Kawasaki, 1985), there is potential for significant effects on fisheries and dependent communities.

Individual species have adapted strategies to accommodate changes in their environment. Some even have fully diversified local population responses that would seem unlikely. Shad along the eastern United States spawn many batches of smaller eggs in their warmer southern range and, in the less variable north, produce larger eggs that they carry up rivers and spawn in single batches (Leggett and Carscadden, 1978). Thus, changes in patterns of climate variability can be as important as the magnitudes of the changes—and as much a source of uncertainty.

Descriptions of interrelated changes in oceanographic structures and bottomfish populations include: the 1962–1986 cod outburst in the North Sea and the Irish Sea (Hempel, 1978) and the rise and fall, with a maximum in 1945–1950, of Western Greenland cod stocks that were established from recruits of Icelandic stocks during the 1925–1960 North Atlantic warming (Cushing, 1982).

It is difficult to disentangle human and natural climate effects. For example, the environment adversely affected cod off eastern Canada, but the additional burden of heavy fishing probably caused the stock collapse—reducing the biomass, eliminating older year classes, and increasing stock vulnerability (Mann and Drinkwater, 1994).

There may be a synergistic effect between climate change and overfishing. With overfishing, the age composition of a stock becomes increasingly unbalanced: Fewer year classes and mature individuals are available, and fewer reproductive opportunities occur. Overfishing eliminates species characterized by low fecundity, slow growth, and late sexual maturation, while favoring species with opposite strategies, usually of less economic value. It introduces new trophic pathways, possibly produces empty ecological niches, and creates new competitive relationships. For example, there has been a change in fish sizes and species dominance in the Gulf of Biscay since 1800 (Quéro and Emmonet, 1993). Georges Bank also has been the scene of a "biomass flip," with skates and dogfish replacing cod, haddock, and flounder (Rothschild, 1991).

In the case of the Atlantic salmon (Pope *et al.*, 1961), the brown trout (Hardy, 1967), and the North Sea long rough dab (Ntiba, 1990), the larger, older fish lay larger eggs; Blaxter and Hempel (1963) showed that larger Atlantic herring eggs hatch into larger larvae. Larger eggs could influence survival and development and may have important ecological implications (Blaxter, 1988). Recruitment into the fishery is probably balanced on the number of larger and older fish in the population (Bagenal, 1970). Although some species can rebuild quickly (Beamish, 1993), most large species will have difficulty taking advantage of a favorable environmental episode that may come only once in several years. Overfishing also may reduce the genetic resilience of the population, with similar consequences. Climate changes may magnify the effects of overfishing at a time of an inherent instability in world fisheries (Stokes *et al.*, 1993).

Hydrodynamic structures are largely determined by wind fields, currents and fronts, temperature, salinity, and geographic topography. As new hydrographic structures stabilize, new populations may take advantage of the physical features. Colonization is determined by ecological constraints affecting reproduction (Sinclair, 1988). For species dependent on geographical features, there is less flexibility. For example, herring spawning in certain areas disappeared with the collapse of specific herring populations in the 1970s but reappeared in the same locations as the herring recovered (Daan *et al.*, 1990). Dislocations of and changes in density stratifications may affect the timing and location of fish availability for fishing and can be particularly significant in pelagic fisheries (e.g., tuna, salmon, herring, sardines):

- Most Peruvian anchovy concentrations moved into inshore waters after 1972: The percentage of catches made within 10 miles rose from 42% before 1970 to 91% after 1972 (Valdivia, 1978) as the areal extent of the upwelled water dwindled.
- The route by which sockeye salmon return to the Fraser River determines, in part, their availability to Canada and U.S. fisheries. In warm years—and especially in strong El Niño years (see Box 16-6)—80% of returning sockeye may use a cooler, northern route that favors Canadian fishing interests, compared to as little as 10% in some cold years (Miller and Fluharty, 1992).
- High salinity near the coast due to droughts can reduce the area of low-salinity waters, increasing the availability of some species to small-scale fisheries—for example, *Sardinella aurita* in the northern Gulf of Guinea, especially the Ghanaian canoe fishery (Binet, 1982), and *Sardina pilchardus* off northern Morocco (Belvèze and Erzini, 1983).
- Development of the Northeast Atlantic bluefin tuna fishery from 1920 to 1967, with a peak in the 1950s, has been related to the long-term warming of the North Atlantic until the late 1940s and subsequent cooling (Binet and Leroy, 1986).

16.2.2.3. Impacts on Fisheries

Global warming will likely cause collapses of some fisheries and expansions of others. It may be one of the most important factors affecting fisheries now and in the next few hundred years. The level of impact will vary widely and will depend on the complexity of each ecosystem, the attributes and adaptability of

Box 16-6. El Niño: How Short- and Long-Term Climate Events Can Affect Fisheries

Environmental processes, fisheries management, and population dynamics closely interact. The 1972 El Niño, coupled with anchovy overexploitation and resultant recruitment failure, led to a severe crisis in the following years. Although not the direct cause of the collapse (Sharp and McLain, 1993), the El Niño, nested within a much broader set of environmental changes, concentrated the anchovies—enabling the fishery to operate on the entire population, which previously was scattered over a broader area with some portions protected from continuous exploitation (Csirke, 1980). The anchovy collapse was an economic disaster for Peru. The production center for the Humboldt Current shifted southward, from north-central Peru to the Peru/Chile border, with sardines colonizing the coastlines from Ecuador to central Chile.

These short-term effects show how fish species react to some large environmental changes. They may be illustrative of effects from long-term changes. El Niño events, being anomalies riding on the long-term trend, may provide meaningful insights—particularly since some GCM results indicate reduced East–West temperature gradients similar to conditions found in El Niño events (see the Working Group I volume).

There also are less familiar El Niño impacts. Some can last for several years. For example, El Niño Southern Oscillation (ENSO) processes, combined with other natural variability, led to increased prices of salmon from 1980–1984, due to displacement of salmon migratory routes and complex ecological changes from warm-water intrusions along the Pacific coast of North America. Pacific gray whales moved far north of their usual locations, indicating that their habitat had moved northward and shoreward for the first time in decades (Sharp, 1994). The 1982–1983 El Niño led to increased stocks and catches of scallops and oceanic tunas and billfishes in Chile and Peru. The annual migration of whiting along the west coast of the United States and Canada is correlated with water temperature, especially with strong El Niño conditions. In warm years, more stock is available to Canadian fishers (Dorn and Methot, 1990). Temperate Sardinops populations in the Gulf of California are much less available during El Niños, whereas tropical thread herring are much more available (Lluch-Belda *et al.*, 1986).

each species, and the nature of the human communities that depend on them. Defining these contexts is the key to understanding and preparing for climate changes. If climate change occurs on the scale indicated by GCMs, we can expect significant effects, both beneficial and destructive, on the distributions and productivity of valuable regional fisheries and the local industries associated with them (Healey, 1990).

Over the long term, global changes in fish production may maintain some relative balance, but there could be important regional shifts in fishing areas and species compositions, with major socioeconomic impacts. These shifts may be in the relative abundance of particular species between contiguous EEZs or between EEZs and the high seas. Globally, fluctuations in fish abundances and distributions are expected to maintain similar ranges as previously documented due to natural variation (Sharp and Csirke, 1983; Sharp, 1987). In some cases, species may move poleward, but there may be little change evident to someone living in the middle range of a given ecosystem. However, significant differences may occur in habitat suitability and species dominances at the thermal limits of species ranges. Changes in climate near ecosystem borders could mask impacts from harvesting excesses and other anthropogenic changes, generating misguided international disputes. Local communities would be affected by changes in recruitment, distribution, and abundance.

Globally, overfishing and diverse human stresses on the environment will probably continue to outweigh climate-change impacts for several decades. However, fishing impacts are usually reversible—whereas climate-change and habitat-loss impacts are not (at least within the IPCC scenario)—and the overfishing problem may well be solved within the time horizon of this IPCC assessment. For fish production, climate variability is not a new problem. Social policies and controls needed to adapt to global change and those required for managing high-sea stocks are of similar geopolitical magnitude.

In some cases, fisheries on the margin of profitability could prosper or decline. For example, if there is a rapid retreat of sea ice in Antarctica or if the ice has reduced extent, the krill fishery—which is regulated by the three months that the continental shelf is ice-free—could become more attractive to nations not already involved.

In developing countries, fishers can be expected to follow shifting fish distributions—comparable to what happens now within natural climate variability. New fishing sites often have poor or nonexistent provisions for freshwater supply, sanitation, and refrigeration. As a result, seafood handling may be less sanitary than is needed, and cholera or other diseases may occur. Where there are no cold storage facilities, fishers may have to resort to either salting or smoking as alternative means for preservation. Such change can, in turn, lead to local deforestation, increased soil erosion, or loss of mangroves and associated fish nursery habitat. Long-distance migrations of small-scale fishers can be constrained by newly established national frontiers or by confrontation between local fishers and newcomers, as has already happened with west African small-scale fisheries.

In some communities—such as Fortaleza, Brazil—half or more of the fishing fleet may be dependent on wind and sails (Everett, 1994). Reductions in wind strength could cause significant costs to these small-scale fishers operating at the margin of profitability. Conversely, increased wind force in other regions will require more seaworthy vessels or other changes in fishing strategies. There are costs associated with these changes. Such costs are certainly less obvious, and may be less important, when they take place gradually over a longer time period than the life of the fishing vessels and other assets.

The ways in which societies have responded to past changes in the fisheries that support important components of their regional economies are instructive in guiding society toward developing better ways of adapting to the regional impacts of environmental change (Glantz, 1992). As an example, the industry collapses of the Chilean/Peruvian anchovy, the California sardine, and the Alaskan king crab led to varied socioeconomic responses. While the less industrially capitalized Chileans responded to perturbations in the anchovy catch with regulations and an adaptive restructuring of the industry to the more offshore jack mackerel (*Trachurus murphyi*) and secondarily the sardine (*Sardinops sagax*), the Peruvians continued peak extraction until the anchovy catch collapsed and only slowly shifted to alternative fisheries, with serious economic impacts (Caviedes and Fik, 1992). The California sardine bonanza, harvested at increasing levels for half a century, similarly collapsed—with perhaps even greater socioeconomic impacts on the region. When the industry collapsed in the 1960s, most of the fleet converted to less labor-intensive fisheries or was sold for pennies on the dollar; fishing and cannery crews, unneeded in the remaining fisheries, moved north to Alaskan waters, fished only seasonally, or left the industry; and much of the infrastructure was moved to South America, along with the expertise of many fishing captains and cannery operators (Ueber and MacCall, 1992). The 1981 collapse of the Alaskan king crab industry also resulted in economic disaster for the heavily overcapitalized industry, which was faced with foreclosure or diversification. The fleets that survived broadly expanded their fishing grounds, shifted to replacement species (other king crabs and Tanner crabs), or traded their former low-volume/high-value fishery for more high-volume/lower-value fisheries (e.g., pollock) (Wooster, 1992).

With the declaration of extended EEZs, long-range fishing industries have adjusted to the new access conditions through joint-venture agreements, further development of domestic fisheries and aquaculture, development of new processing methods to upgrade lower-value species (e.g., surimi), development of new fisheries within and outside the 200 miles, increased import and reduced consumption of fishery products, and the scrapping of long-distance vessels (Glantz, 1992; Yonesawa, 1981; Kaczynski, 1983a, 1983b). For long-distance fisheries, these adjustments often have entailed considerable costs. The new ocean regime has had more serious impacts on the fisheries sectors of long-distance fishing countries and on those of countries that extended their control over large resources (e.g., Iceland; Glantz, 1992) than would the effects of climate change.

Forecasting by analogy, therefore, can inform about the kind, but not the direction, magnitude, and geographic distribution, of economic and social effects of global change on fisheries. The lessons learned from experience include:

- The magnitude of effects depends on the importance of fisheries in an economy. Although all sectors may benefit from positive effects, the economies of traditional fishing groups and developing countries may be disproportionately impacted by negative effects. With little diversification, their means are limited and they are more vulnerable, particularly in developing countries bounded by major upwelling regions (e.g., Mauritania, Namibia, Peru, Somalia) (Troadec, 1989a).
- Small-scale fisheries, even in industrialized countries, maintain several characteristics of premercantile societies, such as autonomy, self-sufficiency, exploitation of local natural resources, self-limitation of demand, geographic mobility (to offset the law of diminishing returns), solidarity within family, and the original value systems. Industrialized, market societies are characterized by autonomy of individuals, professional specialization, mobility of production factors, development of new activities through technological innovations, and accumulation of profit. Because the economy of these organizations is different, it is difficult to compare their capacity to cope with variability and uncertainty; however, the former's frequent lack of means (poverty) is a major and new handicap.
- When climate change shifts the distribution of a fish stock within an EEZ, or between EEZs, or causes a stock to simply change in abundance within its previous distribution, the resulting mismatch between fish availability and fishing capacity will require greater management flexibility, both nationally and internationally. Because natural variability is so great relative to global change, and the time horizon on capital replacement (ships and plants) is so short, in most situations, there will likely be relatively small economic or food-supply consequences.
- There are three major institutional deficiencies: the allocation of access rights to fisheries and among competing uses of aquatic resources; regional fisheries bodies whose mandate and organization have not adjusted to the new requirements of shared and straddling stocks management; and international institutions whose development is lagging behind the globalization of the economy and uses of the ecosphere (Troadec, 1994).
- When fish stocks decline because of a combination of less favorable environmental conditions and overfishing—and even when there are initially abundant

> stocks—industries often have continued heavy fishing pressure, leading to fishery collapse. With such complex relationships, scientists are often slow to recognize declining resources. Further, under most prevailing institutions, administrators and producers cannot take proper account of the value of use (harvest) rights resulting from resource scarcity when regulating access and planning investments. As a result, industries and governments have been unwilling or unable to accept the advice of scientists and take meaningful action to protect fish stocks and enhance harvest efficiency.

A number of reviews have appeared that attempt to predict the impact of climatic change, based on past events, but of necessity they are generalized and deal more with the direction of ecosystem and population changes than their magnitude (e.g., Costa, 1990; Siegfried *et al.*, 1990; Mann and Lazier, 1991; Carpenter *et al.*, 1992; Shuter and Meisner, 1992; Everett, 1995). They provide a strong foundation for understanding the likely impact of climate changes on future fish production.

The ineffectiveness of many management institutions (Anon., 1994; FAO, 1992b; Neher *et al.*, 1989; Parsons, 1993; Troadec, 1989a) will aggravate the likelihood of collapse. This ineffectiveness stems from insufficient authority, unwillingness to act, or incomplete knowledge about resources and their relationship to the environment (Everett, 1995; Talbot *et al.*, 1994). Because many institutions have not adjusted to new conditions of resource scarcity and have not developed means to value and price the rights to use resources, efficient use of resources will be difficult to achieve.

If future fish abundance becomes less certain, regulatory institutions will have even more difficulty in managing fisheries. Many stocks will risk continued overexploitation. This is already a major cause of variability. Institutional inadequacies may result first in greater difficulties in adapting exploitation and management to climate-induced changes. The current crisis may become worse at first. Then, the worsening of the fisheries crisis could make the need for institutional change more obvious and acceptable.

Gains and losses at all levels of social organization may result from climate-change impacts directly or from human responses to those changes. Some nations, sectors, and groups may have the ability to respond or adapt to climate change, turning it to their advantage (Glantz *et al.*, 1990). Others will not. In general, societies have not coped well with declines in biological productivity, regardless of cause (Glantz *et al.*, 1987; Glantz, 1992). Case studies of societal response provide insight into how people and their governments can better prepare for regional changes in distribution and abundance that might accompany global warming. If, in the face of climate change, leaders desire to maintain fisheries at levels matching society's needs, higher levels of international collaboration will be needed—for which there is no global analog from the past.

16.2.3. Aquaculture

The effects of climate change on aquaculture generally will be positive—through faster growth, lower winter mortality rates, and reduced energy costs in shore-based facilities (Smit, 1993). Nearshore warming could result in increased production in higher-latitude farming operations because of the prolonged availability of nearly optimum air and water temperatures (McCauley and Beitinger, 1992). With expanded regions of warmer water, the economic incentive to develop cultivation of temperate and subtropical species could develop. A decrease in ice cover could substantially relax the geographic limits for commercial operations for species such as salmonids, oysters, and scallops. Major areas with winter ice cover could become ice-free (Frank *et al.*, 1988). Winter temperatures could move above the lower lethal limit for salmonids and allow their aquaculture to expand into northern Nova Scotia, into the Gulf of St. Lawrence, and along Newfoundland's south coast. Oysters and other cultured species would likely increase in productivity with warmer temperatures, through greater spawning success and higher growth rates—if salinity regimes and disease agents do not become limiting (Frank *et al.*, 1990).

Climate warming may prove deleterious to existing aquaculture industries in some areas. A significant increase in summer water temperatures in the Marlborough Sound in New Zealand may have serious implications for the salmon farming industry there because temperatures are already near the maximum for successful cultivation (New Zealand, 1990). Elsewhere, increasing temperatures may augment the growth and spread of disease agents. The limited genetic variability of farm fish may decrease their adaptability and increase their susceptibility to pathogens.

Sea-level rise could damage aquaculture facilities and reduce areas suitable for aquaculture (e.g., for shrimp culture in mangroves in tropical countries or the Bangladesh floodplain, and for shellfish culture in western Europe). However, in some regions, increased areas will become available. For example, in New Zealand, a rising sea is expected to make more areas suitable for oyster farming because many mud flat areas are a little too shallow for intertidal rack cultivation of oysters. This positive benefit may be offset by a warmer sea that would trigger earlier spawning in the oysters, thus reducing their value for the very important Christmas market (New Zealand, 1990). Even in the mangrove situation, all is not clear because land may flood inland of the mangroves, where conditions could be better than the existing mangrove areas that have high-sulfur soils and very acidic conditions.

Culturing fish for release into the wild for augmentation of wild stocks (e.g., cod) or for capture upon return (e.g., salmon) can be affected by a changing climate at the rearing facilities, along the path to the open ocean or large lake, or in the water bodies where growth is to take place. This type of aquaculture may account for half of the global total for aquaculture. Its further growth is hampered by ecological, institutional (e.g., property regimes), and technological factors. Some scientists believe that many bodies of water may be at their biological carrying capacity and cannot support more fish; others believe that there are great opportunities for expansion. In any case, fishery managers and hatchery operators need to consider possible interactive impacts of climate change and augmentation on wild stocks and other users of the ecosystem, such as marine mammals and birds.

New or stronger disease agents might flourish, while fish might have little time to build resistance. Farmed fish also may become increasingly susceptible to antibiotic-resistant strains of pathogens to which they had been accustomed, lowering or completely crippling aquaculture production, especially in developing countries.

In aquaculture facilities, fish often live in shallow structures at all life stages. Eggs and larvae near the surface and near-surface phytoplankton, zooplankton, corals, and wetland plants could be exposed to ultraviolet (UV) levels that could cause genetic abnormalities or death. In aquaculture, shallow ponds and unshielded egg and larval production facilities may be of particular concern; most eggs and larval stages of fish studied by Hunter *et al.* (1982) showed high sensitivity to UV radiation and often died if exposed in shallow containers.

16.2.4. Health Issues

One-fifth of global animal protein intake comes from fish, mostly marine species (Weber, 1994). Although there are large variations by country, fish is generally a much more important part of the diet in developing countries, where animal protein is relatively expensive, but per capita consumption is often highest in wealthier nations (Laureti, 1992). Even in the absence of climate change, fish production growth is not likely, and wealthy nations are importing more fish from developing nations that seek foreign exchange—with nutrition consequences for poor nations. With climate change, food production could change, affecting nutrition and health for societies highly dependent on fisheries.

There are natural toxins in ocean and freshwaters, as on land. The better-known toxins are "red tides"—found in both warm and tropical waters but also colder waters—and ciguatera, most often associated with warm or tropical waters. Red tides refer to high concentrations of toxic dinoflagellates that discolor the sea. Even when not abundant enough to discolor the water, they may toxify shellfish (Sampayo, 1989). Some researchers suggest that one red tide toxin, DSP, can cause liver cancer in humans. As plant toxins are concentrated through bioaccumulation at successive levels of predation, those fish at the top of food webs can contain lethal doses, particularly in fatty organs and tissues. Filter feeders such as mussels, clams, and oysters also concentrate toxins when they consume large quantities of these algae. Similarly, ciguatera poisoning occurs when algal grazers in tropical reefs consume toxin-bearing algae. Fish at the top of the food web, such as barracuda or grouper, can concentrate lethal toxin amounts. Cooking does not destroy these toxins. Ciguatera is usually kept in check by local fishing practices that avoid taking fish from affected areas. These areas usually occur in an erratic distribution. Climate change could alter the local habitats and change the areas where ciguatera toxin is produced, but the changes might be undetected by local fishermen or regulators. Warming would expand the range for ciguatera and other biotoxins and could lead to increased biotoxin poisoning.

A rising sea would lift the water table in low-lying land near the coast, releasing contaminants from dump sites and viruses and bacteria from septic systems into drainage systems and waterways. Such contaminants would enter estuarine and inshore food chains and pose a hazard for human consumers. Governments may close additional areas to the taking of fish and shellfish to protect citizens (IPCC, 1992). Also, some marine species may not have time to build resistance to disease agents that might come with a relatively rapid rise in temperatures. One example may be the susceptibility of North Atlantic green sea urchins to a waterborne disease to which they lack natural resistance at warm temperatures (Frank *et al.*, 1990). It is not just the exposure of organisms to new pathogens that is a concern; there is also the possibility of increasing susceptibility to existing ones as a result of environmental stress.

Changes in precipitation patterns also are expected. Reduced water flows in streams and rivers will concentrate pollutants, rendering some fish unfit for consumption. Areas receiving higher flows may have lower concentrations of pollutants in fish whose use is now restricted (or should be). When increased precipitation comes in the form of pulses and leads to sudden surges of runoff, increased coliform bacteria counts will be reached more often, leading to closures of shellfish beds (New Zealand, 1990). When increased flows of pollutants enter lakes having a high rate of evaporation relative to water discharge, increasing concentrations of pollutants may occur.

Chapter 18 warns that cholera can be more easily transported in ship ballast water when there is a high density of marine algae and that warming could increase the amount and range of algal blooms. Ships often release ballast water in harbors or nearshore areas, thus transporting cholera throughout the world. This is a primary means for the introduction of new cholera strains. Clams, mussels, and oysters can be carriers of cholera, and—since they are often eaten raw—they can transmit cholera to humans. Ballast water seems to be the means of introduction of PSP algae into Tasmanian waters, and reproduction of the algae is helped by warmer, nutrient-rich waters (New Zealand, 1990).

When fishers pursue fish over longer distances and have inadequate infrastructure (e.g., refrigeration, potable water), opportunities for pathogens and spoilage increase. Health issues can cause great economic damage to fisheries because societies will act to keep contaminated food out of the marketplace. Stories about people becoming ill from eating problematic food receive a great deal of publicity, thus depressing markets.

16.2.5. *Infrastructure Issues*

Modern industrial fisheries require complex support, including electronic positioning, weather advisories, transportation, cold storage, ports, processing, markets, electricity, potable water, search and rescue, and provisioning. Any redistribution or increased variability of fishery resources, or of aquaculture production, adds strain on this sector. Natural variability is so great that the provision of these services is generally quite flexible. However, when long-term redistributions occur, economic efficiencies change as the distance between fish and home ports changes. Over time, ports nearer to new fishing areas will gain an advantage. Home ports will change, families will move, and there will be winners and losers. In some cases, the retail market may respond to long-term redistributions, if the predominant species change and the new species require different processing and marketing approaches. Rapid loss of shelf space in markets and absence from restaurant menu listings occurs when species are unavailable. It is difficult to regain these markets, further exacerbating variability in revenues.

A rise in sea level will adversely affect infrastructure that supports fisheries. In less-industrialized areas—where artisanal fishers land catches in numerous remote fishing villages and transport them, often by foot, to commercial centers and tourist motels for sale—a significant rise in sea level will drown much of the existing network of roads and footpaths used by many poor coastal people who financially and nutritionally depend on their daily catch. Sea-level rise also will impact industrialized countries, as implied in the Caspian Sea example (see Box 16-4). Reduction in fresh water supplies due to sea-level rise and increased evaporation—where not offset by increased precipitation—could have significant impacts on fish processing, which uses large amounts of potable water (Smit, 1993).

Some technical adaptations can ease the impacts on industrialized as well as developing countries—such as faster vessels, portable processing plants, alternative transportation infrastructure, and on-board processing. Nevertheless, costs will be incurred to finance the changes, and profitability will be reduced.

16.2.6. *Recreational Fisheries Issues*

There is no significant difference in the impacts of climate change on recreational species as opposed to commercial or subsistence species. Many species are pursued by multiple user groups. However, increased storminess or changes in weather patterns will affect the desirability and effort involved in recreational fishing more than other types of fishing. Changes might include shorter ice-fishing seasons and longer seasons for higher-latitude fisheries. On New Zealand's west coast, expected decreases in westerly winds, higher temperatures, and sea-level rise may lead to a decline in the distribution and abundance of toheroa, a popular shellfish species sought by aboriginal and recreational fishermen (New Zealand, 1990).

Many anglers prefer cold-water species, which are associated with higher expenditures. The ranges of such species can be expected to shift toward higher latitudes. However, if the daytime summer temperatures do not change significantly when compared to changes in nighttime temperatures, the ranges and production of such species may expand.

16.2.7. *Sensitivities, Critical Rates, and Thresholds*

Most fish species are sensitive to the expected climate-change effects. The individuals, or centers of production, can shift rapidly if suitable habitat and paths exist. Fish species are cold-blooded; life processes, such as growth, are faster when warmer (within limits). Many species have narrow ecological niches, but there are many species to fill niches. In a varying environment, species mixes will change. Examples of sensitivities are:

- Fish eggs that rely on a gyre to return them to their habitat on a certain day or week
- Fish eggs in streams or on the sea floor that require a minimum current speed for oxygenation
- Species that require a certain influx of freshwater to induce spawning or to kill predators
- Temperatures above or below the stock's lethal limit.

At the societal level, there are other sensitivities. Species in more stable environments often are more valuable. Fishing interests often can follow fish, but political boundaries or economics can stop pursuit. Even if fishing interests can follow, communities may not. Developing nations dependent on fish as food or export earnings are most sensitive. Examples of societal sensitivities are:

- Immobility of communities or industries dependent on one type of species
- Societies without the money needed to buy replacement foods
- Fishers without the ability to deal with increased storminess.

Information on critical rates, thresholds, and sensitivities exists for only a few important species. Available information includes:

- The relationship between fisheries production and the health or extent of corals, mangroves, and wetlands
- The temperatures governing some fish movements, migrations, reproduction, and mortality (in general, fish are much more sensitive to cooling rates than to warming; Brett, 1980)
- The optimum temperatures needed for certain aquaculture systems
- Freshwater flows required for stock movements, migrations, reproduction, and aquaculture operations
- Nonlinearities: As temperature rises and nutrients increase, eutrophication may suddenly produce critically low values of dissolved oxygen.

Additional responses that have some quantification are:

- The shift in production centers of some oceanic fish in response to temperature changes (e.g., Murawski, 1993)
- The distribution of some fish in relation to northern ice cover (Shuter and Post, 1990)
- Mortality-rate changes of some Antarctic krill and some eastern Pacific pelagic eggs and larvae in response to changes in UV-B radiation (Hunter *et al.*, 1979, 1981; Damkaer *et al.*, 1980, 1981; Damkaer and Dey, 1983; Dey *et al.*, 1988). For some species, the apparent thresholds for development and survival are at current incident UV-B levels (Damkaer *et al.*, 1980). Significant changes in ecosystem function and functioning could occur as species sensitive to UV-B radiation are replaced by more-resistant species (IGBP, 1990).

16.2.8. Storminess

Major storms such as cyclones have major consequences for ecosystems. They cause mixing of ocean waters and internal upwelling over the edges of shelf seas, moving nutrients and organisms into the photic zone—which then helps local food-web production and can be likened to terrestrial plowing (Sharp, 1994). Such mixing, though, can disturb the stratification of water masses and their biological components, on which many species depend as part of their reproductive strategies. Storms also can be disruptive to reefs, mangroves, and shoreline habitats and to egg masses laid on substrate. Storm paths are also important. Path changes can affect the density of plankton forage on which young fish depend, thus modifying the recruitment success of pelagic stocks (Lasker, 1981).

Changes in storm frequency and intensity could have subtle and easily missed impacts in the coastal zone. For example, in regions of small tidal range, such as the Gulf of Mexico, there are wetlands found above the high-tide line that get inundated by storms and weather fronts or distant oceanic events (Swenson and Chuang, 1983). These high super-tidal wetlands are important in supporting marine species. In some interior areas, near and distant storms are the dominant flooding mechanisms and affect the production of shrimp (Childers *et al.*, 1990).

Storms are also of major significance for the fisheries industry. Increased storminess can damage fishery and aquaculture infrastructure and lead to increased costs for the strengthening of facilities. In some cases, increased storminess can lead to longer fishing seasons if ice is broken up or cannot form. Storms are a major threat to the safety of fishers. Increases in intensity or frequency could lead to additional losses in the occupation, which is already among the most dangerous; the fatality rate of commercial fishing is seven times the U.S. industry average (Hart and Perrini, 1984).

16.3. Adaptation Options

Events influencing fisheries are accelerating. Adaptations must be matched with the concept of an already highly stressed ecology and the inherent volatility of fisheries. Further, coincident problems such as pollution, resource degradation, and sea-level rise (or subsidence) also must be addressed.

There is a danger that if climate-change alterations are slow, inexorable, and generally irreversible, impacts resulting from climate change will not be recognized in time. Alternatively, abrupt shifts in climate-influenced factors may be too limiting for species acclimation or management adjustment. Some fisheries involve high capital investment, and others are very important to whole coastal communities. To minimize economic and social disruption, the possibility of permanent long-term changes in the regional availability of traditional fish stocks must be anticipated and new management philosophies developed. Local fishery managers also need to anticipate and take advantage of short-lived benefits (Sharp, 1991). As in any stock management planning, managers must recognize the need for flexible approaches and for greater foresight when establishing policies.

The faster the rate of climate change, the more difficult will be adjustments in human systems. Surprises and divergences from the predicted scenarios are to be expected and must be anticipated by resource and community managers. Preparation for the unexpected is important (New Zealand, 1990). In general, technological innovations are developed faster than are those of a biological or societal nature. Cultural attitudes, which are critical for the adoption of institutional innovations, have the greatest inertia.

Fisheries strategies should concentrate on those that are compatible with sound conservation principles and—like the earlier IPCC response strategies—are beneficial for reasons other than climate change and make sense now in their own right; are economically efficient and cost-effective; serve multiple purposes; are flexible enough to change with new knowledge; are compatible with sustainable economic growth; and are administratively practical (IPCC, 1990).

Table 16-1 provides an overview of key fisheries impacts and whether there might be societal responses or adaptations. An I, P, or T indicates that an important response exists; the right-hand column indicates the type of adaptation or issue involved.

16.3.1. Fisheries

Adaptation to existing climate variability may demonstrate ways to deal with climate change. A Canadian report (Smit, 1993) offers insights. In the short term, the timing of fishing and tasks such as trip preparation and maintenance are adjusted to match the weather. Most full-time fishing interests also have several licenses and gear to allow flexibility in the species and locations fished. Others maintain work options in activities such as construction, tourism, or other sectors, which reduces risk due to climate uncertainty. There also is risk-sharing within family businesses, extended families, and communities, which compensates for temporary setbacks in a particular fishery or enterprise. These may be formal or informal, involving cooperatives or financial institutions, based on a sense of mutual support. The vulnerability of communities to varying stocks, intense fishing pressure, and inappropriate government policies is graphically apparent with the current Canadian moratorium on northern cod, whose stock abundance and distribution may be partly related to water temperature and salinity (Smit, 1993; Mann and Drinkwater, 1994). The policy lesson here is that government fisheries managers should not lock fishing interests into narrow full-time activity within a single fishery. Flexibility in fishing, plus seasonal shifts to other sectors, will be a valuable approach to minimizing climate-change impacts, as long as fishing capacity is consistent with the resource base.

Climate change increases society's need to quickly adjust labor and capital to fish productivity. To have efficient fisheries, the capacity to control human inputs should precede and anticipate the development of technological intensification. This prescription is atypical of societal response. Overcapitalization problems are rooted in the uneven development of biotechnical, administrative, and regulatory systems.

Management systems developed when resources were not under intense fishing or environmental threat have become ill-adapted to resource scarcity. In traditional systems, resource access was regulated through the social structure of rural communities. These systems lose their effectiveness as population pressure and resource uses intensify. They are being supplemented by central legislation, with attendant lag times in addressing problems. These formal regulatory systems have also tended to become ineffective as the need for harvest rationing increases. As resources approach their production limits, administrators and producers have maintained the *status quo* even at the cost of greater economic inefficiency and overfishing. To function most effectively, economic systems need proper institutions (e.g., a market for pricing harvest rights), a property or ownership/stewardship regime for the functioning of that market, and an institutional context to administer the proper functioning of any allocation system based on such rights and markets.

There are several adaptation strategies:

- Develop international agreements for ecosystem research and management and for stock allocation before stocks of fish move due to climate changes. The dramatic decadal fluctuations in marine fisheries yields, considered in light of climate-change concerns,

Table 16-1: *Overview of key fisheries impacts.*

		Adaptation Example	
Global Change Impacts	**Certainty**	Institutional/ Policy/Technical	Possible Adaptations
Redistribution of Living Resources	very likely		
– Increase inshore[1]	possible	I/T	– Fish management/industry expansion
– Decrease offshore[1]	possible	I	– Government welfare assistance
– Poleward migration[1]	likely	I/P/T	– Welfare/industry assistance/mobility
– EEZ jurisdiction changes	likely	I/P	– Negotiation/confrontation
Faster Fish Growth Rates	likely		
Extreme Events	possible	I/T	– Forecasts, rescue/hardier equipment
Precipitation Changes	likely	T	– Water desalination for processing
River Temperature Changes	likely	T	– Water release from dams
Aquaculture	possible		
– Sites (freshwater, sea-level rise, temperature)		P/T	– Regulations/species, location
– Growth rates		T	– Species, feed
– UV-B		T	– Shelter
– Diseases		T	– Hygiene, prophylactics
Reduced Ice Cover	likely		
– Freer navigation		T	– New fishing zones, routes, ports
– Less ice strengthening		T	– Ships, facilities
Seafood Health Issues[2]	possible	I/P/T	– Define responsibility, certify safety, establish monitoring system
Flooding from Sea-Level Rise	likely	T	– Build on higher ground, use water-control structures, allow procession
Increased UV-B	likely	T	– Shelter for aquaculture, crew

[1]Generalization difficult.
[2]Increased frequency.

should accelerate the adoption of large marine ecosystems as the appropriate units for fisheries research and management (Sherman and Gold, 1990; Talbot *et al.*, 1994). Some post-United Nations Conference on Environment and Development (UNCED), ecosystem-scale research programs are being implemented (AAAS, 1993). These programs are designed to couple recent advances in ecological monitoring, management, and stress mitigation strategies with needs in developing countries (AAAS, 1990, 1991).

- Modify and strengthen fisheries management policies and institutions and associated fish population and catch-monitoring activities. In some areas, it takes many years to develop and implement changes in fisheries policies, even after the institutions are established.
- In coastal planning and environmental decisionmaking, consider that a healthy environment is a prerequisite for healthy ecosystems.
- Preserve and restore wetlands, estuaries, floodplains, and bottom lands—essential habitats for most fisheries. Cooperate more closely with forestry, water, and other resources managers because of the close interaction between land cover and maintenance of adequate fishery habitat. The adequacy of management practices in all sectors affecting fisheries (e.g., water resources, coastal management) needs to be examined to ensure that proper responses are made as climate changes.
- Monitor and ensure that the habitat needs of marine mammals (as they shift to remain in an optimum environment) are considered from the standpoints of coastal planning and ocean pollution control.
- Promote fisheries conservation and environmental education among fishermen worldwide.
- Be alert to possible increased health problems caused by biotoxins and the release of pollutants from a rising sea level; industry and seafood-safety agencies should take the lead. Take measures to prevent the introduction of undesirable organisms as climate changes.
- Tailor institutional innovations to ecological, technical, economic, and social features. Large-scale and small-scale production systems, in particular, require different regulatory arrangements. There is no standard institutional solution.
- Adapt to fish redistribution with faster vessels, portable processing plants and other onshore infrastructure, and on-board processing.
- Construct and maintain appropriate infrastructure for storm forecasting, signaling systems, and safe refuges for dealing with possible rising sea level and increased storminess.
- Take advantage of reduced need for ice strengthening of vessels and infrastructures in a warmer climate, except perhaps for areas with increased icebergs.
- Foster interdisciplinary research, with scientists meeting periodically to exchange information on observations and research results, and meeting with managers to ensure the proper interpretation of results and the relevance of research.
- In cases of species collapse and obvious ecosystem disequilibrium, restock with ecologically sound species and strains as habitat changes. Great care is needed to avoid long-term ecological damage.
- Consider, cautiously, the use of hatcheries to enhance natural recruitment when climate causes stocks to fall below the ecosystem carrying capacity for a given species. Such enhancement might increase stock productivity (per unit area), reduce recruitment variability (e.g., Héral *et al.*, 1989), and enable the colonization or recolonization of new areas (e.g., Peterman, 1991). Conversely, injudicious use may alter or impoverish the biodiversity and genetic pool of resources and possibly transmit parasites and diseases (Barg, 1992). Research on identifying warm-water species with wide temperature tolerances also could be useful.

16.3.2. *Aquaculture*

Economic development of coastal communities beyond capture fisheries to tourism and other activities has long been a goal in many areas. Development of aquaculture and tourism will make coastal communities better able to deal with uncertainties of climate change (Smit, 1993). In adapting to climate change, aquaculturists should consider the following:

- Warming will mean generally longer growing seasons and increased rates of biological processes—and often of production.
- Warming will require greater attention to possible oxygen depletion.
- In some areas, the species grown may have to shift to those more tolerant of warmer and perhaps less-oxygenated waters.
- Coastal culture facilities may need to consider the impacts of sea-level rise on facilities and the freeing of contaminants from nearby waste sites.
- Competing wild fisheries production (and indeed, agriculture) may not vary much at the world level, but there could be significant regional changes in quantity and species mix.
- Precipitation, freshwater flows, and lake levels will likely change. Strong regional variations are likely.
- Warming waters could introduce disease organisms or exotic or undesired species before compensating mechanisms or intervention strategies have become established.
- Less ice cover and thinner ice will generally mean less ice damage to facilities and a longer season for production and maintenance.
- Covering culture tanks, or keeping them indoors under controlled light, may be needed more often to protect larvae from solar UV-B.
- Several of the above and other factors, such as competing demand for coastal areas, may argue for technological intensification in ponds and noncoastal facilities.

16.3.3. Adaptation Constraints

Technology, trade, and industry change rapidly to take advantage of new situations and adapt to those that are adverse. The success of many entrepreneurs derives from their abilities to adapt rapidly to opportunities and dangers, but those adversely affected by climate change may not be in a position to take advantage of opportunities. Many fish stocks are of supranational scope, but institutions to deal with them are not or lack sufficient authority. Changes in fisheries institutions generally result from crises, yet impacts from a changing climate may be too gradual to trigger needed responses from these institutions—as evidenced by the failure of most governments to respond to the profound impact of the 1976–77 climate change event on Pacific fisheries over the last 20 years (Beamish, 1993). Nations that do not strongly depend on fisheries may react slowly. Also, negative actions such as polluting and overfishing add stress to fish stocks and may reduce society's options.

16.4. Research and Monitoring Needs

Information is most valuable if there are institutions and management mechanisms to use it. Research on improved mechanisms is needed so that fisheries can operate more efficiently with global warming as well as in the naturally varying climate of today. There is relatively little research underway on such mechanisms. While useful inferences can be made about global-change impacts on fisheries, GCMs are inadequate to forecast changes at the regional scale—and even more so at the smaller scales of the spawning and nursery areas that are critical in the relationships between environment and fish populations (Sinclair, 1988).

Knowledge of the reproductive strategies of many species and links between recruitment and environment is poor, but interest has been growing rapidly. Several international, broad-scale research programs are in place, some of which are aimed at providing a scientific basis and linkage to ecosystem sustainability programs (IOC, 1993; Sherman *et al.*, 1992; Wu and Qiu, 1993; Mee, 1992). The growing partnership among funding agencies, marine ecologists, and socioeconomic interests marks an important step toward realization of the UNCED declaration aimed at reversing the declining condition of coastal ecosystems and enhancing the long-term sustainability of marine resources.

The following lists focus on items needed specifically because of climate change. Other types of research, which are prerequisites for dealing with such concerns but which support the day-to-day needs of fisheries managers or relate more to understanding how ecosystems function, are not included.

16.4.1. Resource Research

- Determine how fish adapt to natural extreme environmental changes or latitudinal transitions, how fishing affects their ability to survive unfavorable conditions, and how reproduction strategies and environments are linked. Link fishery ecology and regional climate models to enable broader projections of climate-change impacts and improve fishery management strategies. Both of these model types are in their infancy for application to fisheries and require considerable additional specificity, in addition to linking with other models.
- Implement regional and multinational systems to detect and monitor climate change and its impacts—building on and integrating existing research programs. Fish can be indicators of climate change and ecological status and trends (Sharp, 1991). Assemble baseline data now so comparisons can be made later (Sharp, 1989).
- Develop ecological models to assess multiple impacts of human activities. Separate appraisal of individual impacts is no longer sufficient.
- Assess the effect of accrued global changes by compiling and analyzing regional data sources—globally containing information on fisheries distributions and the associated environment—to detect consistent trends over the last century and determine how societies have dealt with these changes.
- Determine the fisheries most likely to be impacted, and develop adaptation strategies.
- Assess the potential leaching of toxic chemicals, viruses, and bacteria due to sea-level rise and how they might affect both fish and the seafood supply.

16.4.2. Institutional Research

- Determine institutional changes needed to deal with a changing climate. Such changes are likely the same ones needed for mastering overfishing and coping with the variability and uncertainty of present conditions. Improved institutions would probably reduce stock variability more than climate change would increase it.
- Study the recorded ability of societies—including preindustrial ones, where fisheries are important—to understand how they have adapted their activities when their resources are impacted by climate changes (Glantz and Feingold, 1990).

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