SCOPE 27 - Climate Impact Assessment

6 Fisheries

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6.1 THE NATURE OF THE FISHERIES RESOURCE

A natural resource may be defined as a substance which can be extracted from the earth (including the ocean and atmosphere) and usefully transformed by human labor. Natural resources are generally classified in two categories. One category, exemplified by mineral resources, is `non-renewable'; on relevant time-scales the stock of the resource decreases irreversibly by the amount that is removed. The second category, exemplified by living resources, is ·renewable'; stocks may recover readily after harvesting by man. Living resources may further be classified according to the time required for renewal. Forest resources, for example, tend towards one side of the recovery time-scale while fishery resources tend to the other.

Although many species of fishery resources are capable of rapid recovery following exploitation (for example, herring, sardines, scallops, oysters), some may be very slow to recover (for example, whales and seals). This rate of recovery may also be significantly lengthened if the intensity of harvest is higher than some species-specific optimum.

The renewable nature of fisheries and the inherent spatial and temporal variation in stock size are primary characteristics of fisheries. It is the primary goal of fisheries scientists to understand and ultimately predict the timing and extent of this variation. Spatial and temporal variation in stock size are species-specific characteristics and require knowledge of the species life history such as reproduction, growth, etc. Predicting fluctuations in abundance is further complicated because the oceanic milieu is neither static nor homogeneous in its composition. Furthermore, since the ocean and atmosphere are coupled, both the distribution and abundance of fishery resources are capable of being modified by climate.

6.2 THE CLIMATE/OCEAN/FISHERIES LINKAGE

6.2.1 General Description

Climate exerts an as yet incompletely understood linkage with fisheries. The linkage, however, occurs through the transfer of energy from the atmosphere to an ocean surface layer of variable thickness. The depth of this layer varies with latitude, distance from shore, and seaon but is generally less than 100 meters and may be considerably shallower in the presence of a pycnocline, or density gradient. Below 100 meters less than 1 percent of sunlight penetrates even in the clearest ocean water and wind-generated currents, with the exception of western boundary

currents like the Kuroshio or Gulf Stream, are seldom important. In the surface layer or euphotic zone, however, several components of climate, including solar radiation, wind and temperature, may impact fisheries. These variables are of course correlated, but their oceanographic implications and hence their impact on fisheries differ.

Solar radiation influences the ocean through heating and evaporation at the air/sea interface and by providing light energy for photosynthesis throughout the surface layer. Biological production in the sea originates with primary production, a photosynthetic process whereby chlorophyll-containing phytoplankton generate organic matter. In this process, phytoplankton take in dissolved phosphorus and nitrogen-containing compounds, nutrients necessary for growth. The phytoplankton are eaten by zooplankton, or by some clupeids, such as sardines, and shellfish. Zooplankton generally are utilized by small fish, which in turn are consumed by larger ones.

The bodies of organisms and feces are then subject to bacterial decomposition or autolysis. The remains, being denser than sea water, slowly sink or are turbulently mixed downward, resulting in a flux of nutrients from the euphotic zone. Unless compensating upward transport of nutrients occurs, the euphotic zone will become impoverished. Turbulent mixing in the arctic and shallow margins of temperate oceans, as well as upwelling, are primarily responsible for the return of nutrients to the surface layer.

Vertical mixing occurs primarily during winter when solar radiation is low, vertical density gradients weak, and winds are strong. Mixing occurs through turbulence and the depth to which it occurs depends on wind speed, direction and duration. A useful index of turbulent mixing in fisheries studies is simply to use the cube of the wind speed which can be employed in exploratory analysis with fisheries parameters through correlation or regression analyses (Murray *et al.,* 1983). Turbulent mixing results in the redistribution of nutrients which, with the vernal warming due to increasing incident radiation, leads to a flowering of phytoplankton termed the spring bloom. The spring bloom is primarily a high latitude process which is followed by the propagation of animals of higher trophic levels. Tropical areas are generally less productive than higher latitudes. This lower productivity is partly explained by the greater incident radiation and hence deeper euphotic zone, which is not mixed with deeper nutrient-rich waters, and partly by lower inputs of continentally derived nutrients via rivers.

In addition to turbulent mixing, wind also impacts fisheries through wind-generated surface currents which may result in egg and larval transport away from nursery areas and hence, fluctuations in year-class strength (Murray *et al.,* 1983). Wind-generated surface currents may also control productivity through upwelling. This is a process of water motion whereby cold, deeper waters move upward toward the surface as a result of winds displacing warm surface water. While upwelling may occur anywhere, it is most common along the western coasts of continents. The movement of surface water in response to wind is described by a simple mathematical model and is referred to as Ekman transport. In this model, if the wind blows in the same direction for a sufficient duration, say a few days, it will set a surface layer in motion. This surface current is approximately 2 percent of the wind speed and to the right of the wind direction in the northern hemisphere (to the left in the southern hemisphere). The movement of this layer sets in motion the layer below it which in turn sets in motion a deeper layer. The speed of each layer is slower than the layer above it and the direction is displaced further to the right (northern hemisphere) or left (southern hemisphere) than the layer above. For modeling egg and larval transport occurring in the upper few meters of the water column, however, it is preferable to use the modified transport model of Stolzenbach *et al.* (1977) in which current speed is 3 percent of the wind speed and 15° off the wind direction. However, Ekman transport involves a deeper water column (basement is usually taken as the depth at which the currrent speed decreases to 4 percent of the surface speed) and the net transport is 45° to the right or left of the wind direction. Therefore if the wind is blowing approximately parallel to the shore, the surface water will be displaced seaward and replaced by deeper (down to 200 meters), colder nutrient-rich waters. As a result, upwelled waters are highly productive of fish and other organisms. The most marked coastal upwellings are found off western North America, South America, Africa and Australia. The upwelling along the boundary of the Peruvian Current maintains the large stocks of plankton-feeding fish such as the Peruvian anchovy, *Engraulis ringens* (Paulik, 1981). Diverging currents also cause upwelling. Where adjacent surface waters flow away from each other, deeper water must also rise. Such divergence and associated upwelling are found around Antarctica, along the Aleutian Island Chain, along the equator, and along the northern margin of the Equatorial Countercurrent.

6.2.2 El Niño

One of the most dramatic impacts of climate on fisheries occurs every few years off the Peruvian coast. This phenomenon occurs during the southern hemisphere summer months of December to March, when a transequatorial flow of warm low-salinity water originating from the equatorial countercurrent displaces the northbound Peruvian current. Called El Niño, or Christ Child, because of its arrival during the Christmas season, this intrusion of high-temperature and nutrient-poor water 5−10 degrees further south than normal results in mass mortalities of fish, as well as increased evaporation and, consequently, increased precipitation on the adjacent land. Dead fish are washed ashore where they decay; the subsequent formation of H_2S, when combined with sea fog, may even blacken the paint of ships. Sea birds feeding on fish die of starvation and the decline in bird population results in reduced production of guano, the basis of the fertilizer industry.

In 1972, El Niño was very intense; total average production in the euphotic zone during this event was 0.39 g C/M^2/day, three times lower than the long-term average off southern Peru. The catch of Peruvian anchovy, which had been 13 million metric tons (19 percent of the world

catch in 1970) declined dramatically, while other species increased notably during the following year. In 1972 jack mackerel *Trachurus murphyi,* until then accounting for under 2 percent of the catch in northern Chilean fisheries, suddenly increased to 10 percent. Dramatic increases since 1972 have also occurred in the catch of the Chilean sardine *Sardinops sagax,* paralleling the rise of jack mackerel and accompanying the decline in anchovy (Figure 6.1). The decline in anchovy catch may be explained by intense exploitation as well as by ecological disruption from El Niño in 1972–73 (Caviedes, 1981).

An important feature of El Niño is that it may be predictable several months in advance in the larger context of the Southern Oscillation, one of the major irregular, periodic fluctuations of atmopheric circulation. Wright (1978), Thompson (1981) and Ramage and Hori (1981) discuss causal relationships concerning the Southern Oscillation and El Niño. Basin-wide atmospheric and oceanic anomalies appear to be as important as local winds in creating El Niño. Large-scale changes in wind fields far out in the Pacific are of particular interest. The trade winds were unusually strong in 1970 and 1971, but were unusually weak in 1972. The eastward flowing North Equatorial Countercurrent intensified and the South Equatorial Current weakened during the 1972 El Niño. It appears that warm water accumulated in the eastern Pacific, deepening the usually shallow thermocline and covering the colder upwelled waters (Wooster and Guillén, 1974).
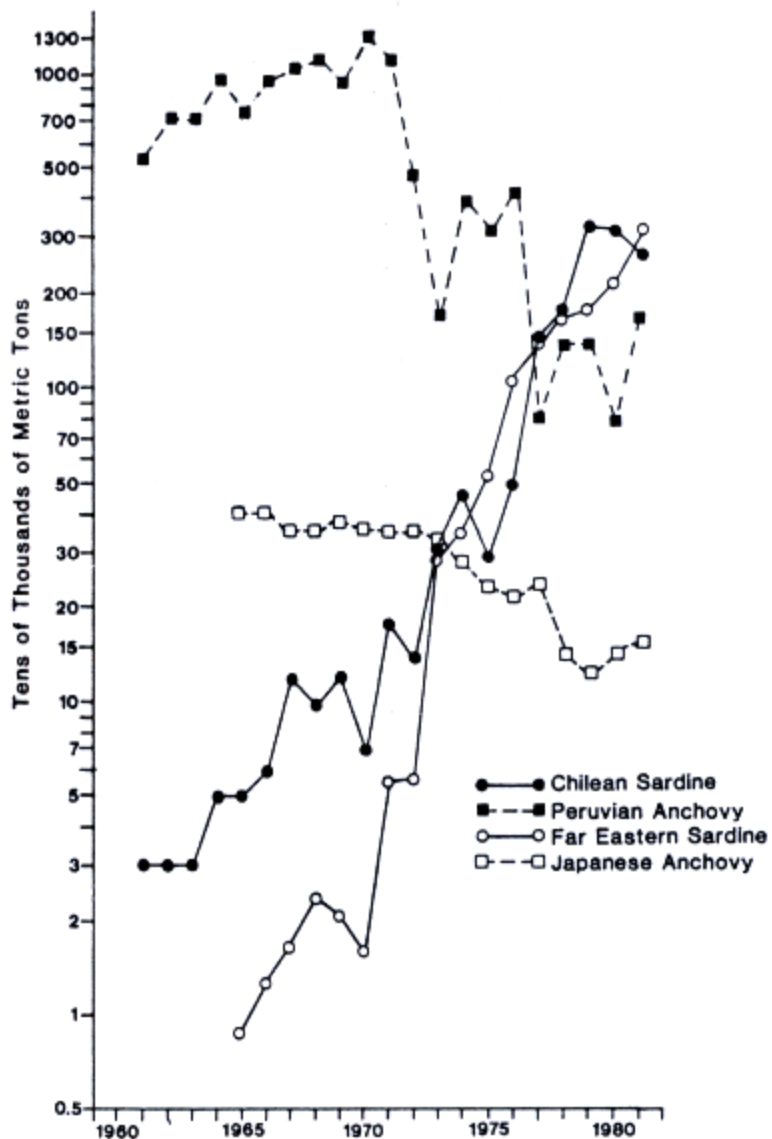

Figure 6.1 Interannual variation in catches of sardine and anchovy

The 1982–83 El Niño was perhaps the strongest event of the century and has certainly been the best studied. While analyses are still underway, it is clear that this was not a classical occurrence, but one with a pattern different from earlier events of the century (Barber and Chavez, 1983; Cane, 1983; Rasmusson and Wallace, 1983).

6.2.3 Current Meanders and Oceanic Rings

Other examples of ocean/climate phenomena with important implications for fisheries are the variation in western boundary current axes and the formation of eddies or rings from these currents. It has long been observed that the stream axis of currents like the Kuroshio, Gulf Stream and East Australian current meander. These meanders in turn influence the circulation of water on the continental slope and shelf. Since fish stocks may be associated with particular water masses, their distributions will also be modified. If the current meander grows large enough it can separate from the current as either a warm-core or cold-core ring, depending on the temperature of the entrained water relative to that of the current remnant encircling the core. Rings that separate seaward of the current rotate cyclonically in the northern hemisphere (anticyclonically in the southern hemisphere); those that separate landward rotate in the opposite direction. These features are 100−300 kilometers in diameter, rotate at several knots, and maintain their integrity for as long as several years. During a ring's life they drift and exchange nutrients, biota and energy with the adjacent water mass. Backus *et al.* (1981) have reviewed the dynamics of cyclonic Gulf Stream rings which are comparable with those of the Kuroshio and with the anticyclonic rings of the East Australian current. These scientists point out that to preserve mass the formation of one ring type (cold- or warm-core) must be in equilibrium with the formation of an opposite type. Based on this assumption and their study of cyclonic rings, they estimate that warm-core rings transfer $3-20 \times 10^{15}$ grams of salt and 10^{21} calories of heat from the Sargasso Sea to the continental slope annually. They further estimate that cold-core rings transfer 5×10^{11} grams of carbon as living organic matter from the slope water to the Sargasso Sea, increasing productivity in 10 percent of the Sargasso Sea by 50 percent. The importance of rings to fisheries lies only partly in their role in determining the distribution of oceanic properties. Rings have also been implicated in the destruction of deep water crab pots in the Baltimore Canyon and larger catches of swordfish have been reported from ring boundaries than from adjacent waters (Chamberlain, personal communication).

The cause of meanders and rings is poorly understood; however, Teramoto (1981) discusses the Kuroshio meandering as a local manifestation of a large-scale fluctuation in the ocean/atmosphere system. Temperature changes around Oshima Island south of Tokyo may be caused by the meandering of the Kuroshio, and this change is inversely correlated with change in the surface velocity of the Kuroshio. Changes in ocean surface temperature produce changes in heat transmission that are connected with movement in the lower atmosphere. This interchange between the lower atmosphere and oceanic circulation is depicted in Figure 6.2 as a feedback process.
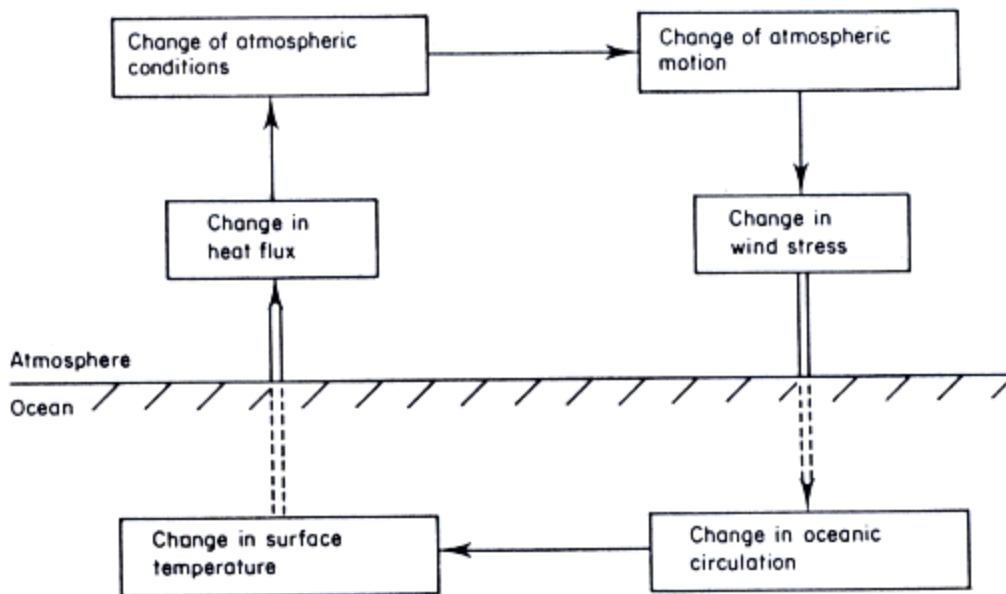

Figure 6.2 Large-scale feedback processes of the ocean/atmosphere system. (Source: Teramoto, 1981, 55)

While links between ocean and atmosphere are easily recognized on local or regional scales, there may also be identifiable distant linkages. So-called `teleconnections' exhibit significant relation to variations in widely separated areas of the ocean and atmosphere. Teleconnections that impact fisheries have been reviewed by Wyrtki (1973) and Teramoto (1981); for example: precipitation and cloudiness on Canton Island (3 °S, 172 °W) and Ocean Island (1 °S, 169 °E) in the central equatorial Pacific and the difference between water levels along the northernmost and southernmost areas of the North Equatorial Countercurrent (an index of the current); the preceding difference in water levels and El Niño; the difference between water levels and longitudinal components of the velocity of geostrophic winds on a 700 mb plane along 30 °N latitude. Statistical analysis suggests that these teleconnections are lagged by 3−8 months. This same series of teleconnections also seems to be associated with the variation of the Kuroshio. Changes in living resources which might be connected with the Kuroshio meandering will be discussed later.

6.3 NATURAL CAUSE OR OVERFISHING?

There is continuing controversy about the cause of fluctuations in many stocks, since natural (including climatic) causes, or overfishing, or both, can result in a major change in a given fishery. An example illustrating the often equivocal interpretations possible is that surrounding the halibut *Hippoglossus stenolepis* along the Pacific coast of North America. In the early 1950s it was argued that there was an approximately reciprocal relationship between the catch-per-unit of fishing gear and the number of sets of units of gear (Thompson, 1952). Fishing effort had been controlled based on this relation, and it was claimed that regulation of fishing effort was responsible for the recovery of catches, which had declined during the 1930s but had increased in the 1940s.

Others, however, disagreed. Burkenroad (1948) contended that in the decline in abundance of halibut on the Pacific coast west of Cape Spencer between 1915 and 1930, and the increase after that date, both may have been much greater than could be accounted for only by changes in the amount of fishing effort. He suggested that major fluctuations in abundance of this stock might be attributable to natural causes of a regular cyclical sort. Burkenroad thus held that the desirability of applying current theories of biological management to marine fisheries remained to be demonstrated.

Another example is the Far Eastern sardine *Sardinops melanosticta.* It can be seen in Figure 6.3 that the catch of this species is subject to large-scale fluctuation, and this has been recorded since ancient times. The leading causes of the fluctuation have been attributed to both environmental factors and overfishing.

The catch of this sardine fell abruptly from a peak of 2,730,00 tons in 1937 to 9000 tons in 1965, a drastic reduction in population size (Figure 6.3). Nakai (1962) noted that in an area south of the Kil Peninsula a cold water mass had developed during the years 1938–45. He argued that this anomaly of the Kuroshio Current caused mass mortality of the early life stages of this sardine resulting in the depletion of the adult sardine population.

In the early 1970s sardine abundance again began to rise and the catch increased rapidly, resulting in a take of 3,610,000 tons in 1981 (Figure 6.3). The fisheries of the Republic of Korea and the USSR were also high. Kondo *et al.* (1976) explained this increase by a combination of environmental factors. In the spring of 1972 the Kuroshio had shifted its pathway along southern Honshu, Japan, from a meandering to a non-meandering pattern, a condition favoring the distribution of copepod nauplii, a small crustacean fed upon by larval sardines. The increased supply of food for larval sardines enabled the 1972 sardine year-class to recover from the earlier stock reductions.

While some scientists maintain that the ups and downs of stock level of the Far Eastern sardine have resulted from changes of food conditions of larvae due, to the shift of the Kuroshio, others emphasize the role of human intervention. Cushing (1975) points out that in 1930 there were 700 purse seiners for the Japanese sardine, 1000 in 1940. Peak catches occurred in 1936, but subsequently fell dramatically with the failure of the 1938–41 year-classes. The collapse in the early 1940s was followed by a period of decline in which Japanese fishermen concentrated on fish in their first summer of life, and a further decline in catch followed a period of high and sustained effort. While Nakai associated this failure in recruitment with an anomaly in the flow of the Kuroshio Current in the years 1938–45, Cushing disputes the suggested environmental source of recruitment failure, emphasizing that fishing effort was high on prespawning fish. Murphy (1977) also attributes the population collapse to intensive exploitation. He criticizes the environmental hypothesis on the grounds of the apparent lack of a consistent cause/effect mechanism for these years. Environmental arguments have been advanced to explain most fish population collapses, but usually a different causal mechanism has been ascribed to each collapse. Murphy points out that the source of, and difficulty with, these environmental hypotheses is that the ocean climate is highly variable; thus, it is possible to find `significant' shifts or non-shifts in ocean climate associated with almost any biological event one wishes to specify. Murphy concedes that poor year-classes are observable throughout the record, but he contends that they are associated with crashes only when the population is also heavily fished.

Certainly one must be careful in ascribing a change in a stock to a specific oceanic variation. As Murphy (1977) shows, it is not difficult to find an oceanic phenomenon which matches a specific change in a stock. Nakai (1962) and Kondo *et al.* (1976) explained the fluctuation in abundance of the Far Eastern sardine by shifts of the Kuroshio axis, more specifically, the occurrence and disappearance of a cold eddy south of Honshu. However, when the data are examined closely, it is apparent that it was 1934 when the long-lived cold eddy occurred, whereas stock decline began in 1938. Although recent recovery of the sardine population was promoted by a strong 1972 year-class, the origin of the recovery existed before 1970. In spite of the frequent occurrence of anomalies of the Kuroshio between 1945 and 1964, corresponding changes of sardine stock were not seen.

Advocates of the explanation that fluctuation in stocks lies in fishing intensity also face difficulties. The Far Eastern sardine has been known to fluctuate widely with an irregular cycle of decades to a century, and since ancient times the variation in catch has been associated with the history of success and failure of fishing villages. Such large-scale fluctuations in stock in days past, when fishing effort was very small in comparison with this century, are strong evidence that stock fluctuations can be caused by environmental change.

The solution to this problem does not lie exclusively in the alternatives of environment or fishing. It is an oversimplification to seek the cause

of stock changes only in a shift of the Kuroshio axis or solely from the effects of fishing. What is important is that we evolve both theory and methods which consider all sources of variation comprehensively. An effort in this direction is offered in the next section.
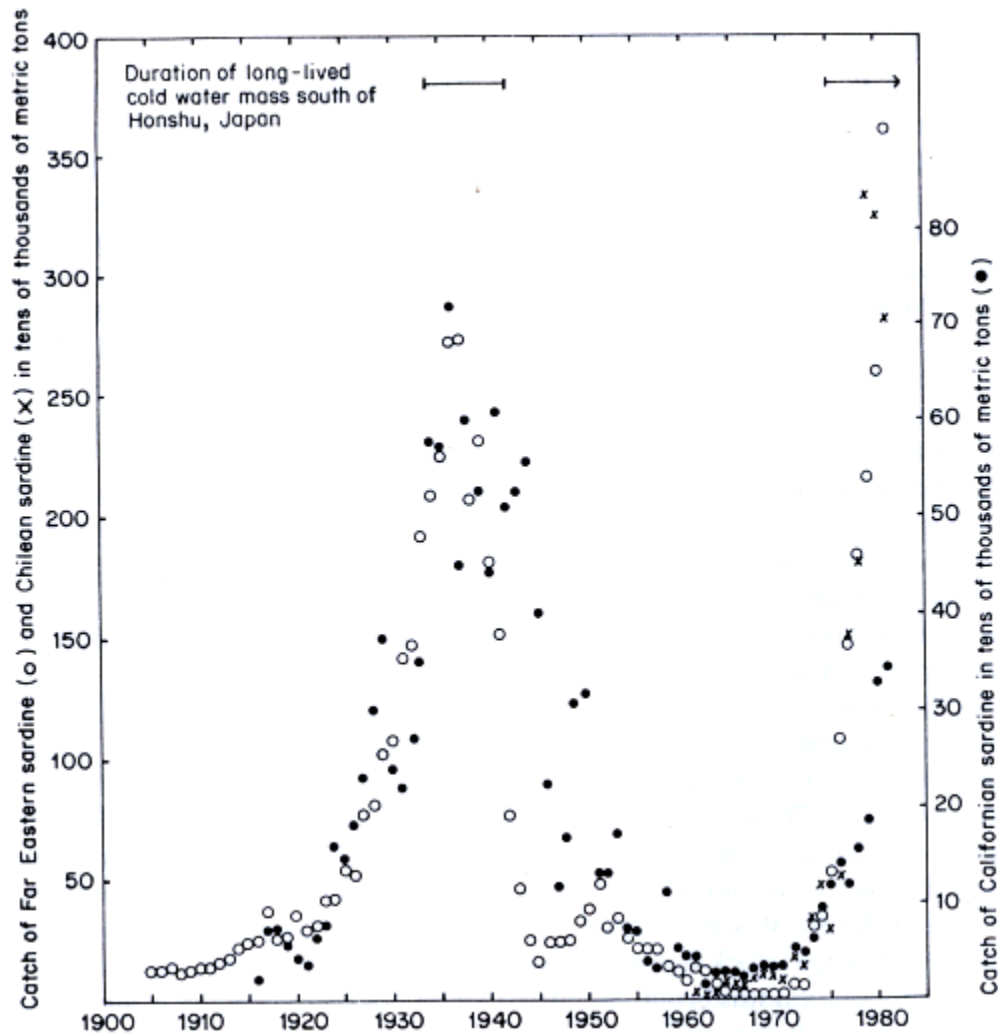

Figure 6.3 Large-scale variations in the catch of three sardine species, Far Eastern, Californian and Chilean

6.4 SPECIES-SPECIFIC PATTERNS OF FLUCTUATION IN NUMBER

6.4.1 General Description and a Methodology

Patterns of fluctuation in the number of marine teleosts (all fish except sharks and rays) can be assigned to two broad types.

Type I: unstable and unpredictable
    Subtype IA: irregular and short-term, e.g. Pacific saury *(Cololabis saira)*
    Subtype IB: large-scale and cyclical, e.g. sardines (genus *Sardinops*)

    Type II: stable and predictable, e.g. scombroids (tuna, mackerel, etc.)

Major ecological features of these types are elaborated in Kawasaki (1980).

The above patterns seem to reflect the characteristics of environmental variation in the sea. Examination of the cycle of production of algae and herbivores may illuminate some of the underlying explanation. Cushing (1975) represents production cycles in different regions diagrammatically (Figure 6.4). He notes a single peak in the arctic midsummer, a double peak in temperate waters, and only minor oscillations in the tropics. Seasonal differences increase with latitude, as does the delay period between the production of algae and grazing by herbivores.
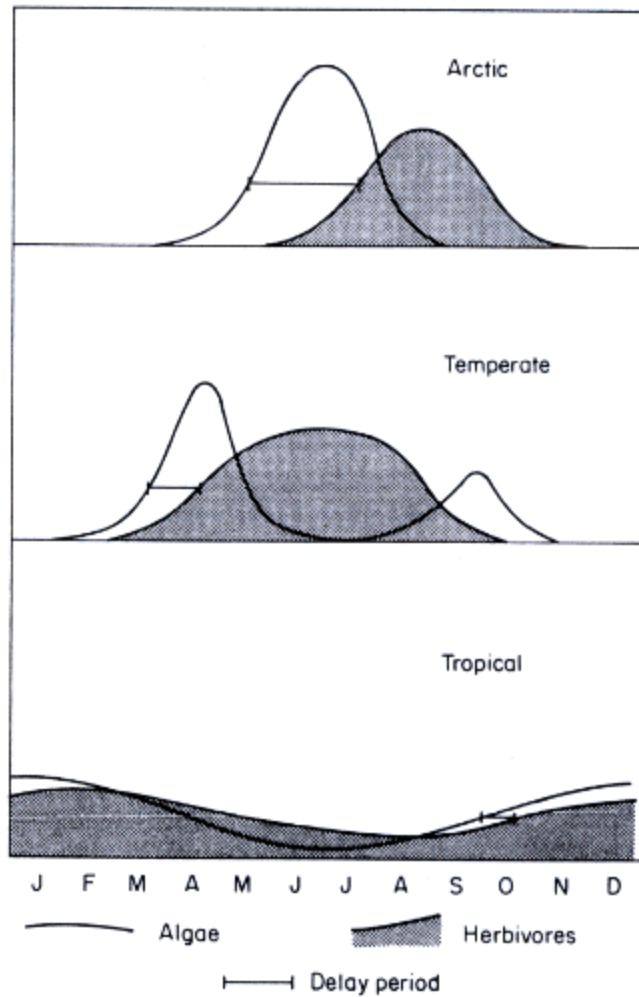
Figure 6.4 Diagrammatic representation of production cycles in different latitudinal zones. Reproduced by permission of Cambridge University Press from Cushing (1975)

Because the tropical cycle is of low amplitude and is continuous throughout the year in a deep euphotic layer, Cushing considers it an efficient cycle. Food is available throughout the year, and both growth and reproduction in the marine animals are probably continuous. In temperate and high-latitude systems, a large quantity of material is transferred from one trophic level to the next at low efficiency, whereas in the quasi-steady-state tropical system less material is transferred more efficiently. Cushing estimates that the transfer coefficients are three times higher in the `poor' areas than in the `rich' areas.

The different cycles correspond to different degrees of stability at higher trophic levels. Cushing notes that a stable community is diverse, that is, there are many species, each few in numbers, such as those found in the deep tropical ocean where the quasi-steady-state cycle of production is found. Because the cycle is of low amplitude, numbers are more or less stable. In contrast, in the high-amplitude cycle of high latitudes and upwelling areas, there are few species, each of high abundance; the community is neither stable, nor diverse. In the case of upwelling, a few types of plankton-feeding fish alternate in dominance with one another at short intervals, a phenomenon known as ·alternation between species'.

Cushing attributes the difference between the inefficient and efficient areas largely to the delay period in the cycle, which depends on the onset of grazing. In the open tropical ocean, production is limited by grazing, possibly at all stages of the cycles, whereas in the upwelling areas and in temperate waters production is controlled by grazing at a later stage in the cycle, by which time a considerable quantity of living material has been produced.

While Cushing's analysis considers the problem of the production cycle in the sea for high latitudes and upwelling areas versus low latitudes, its scope needs to be more comprehensive to reflect adequately the marine environment. In particular, it is necessary to examine the problem from the viewpoint of primary productivity. The productive areas in the sea are the high latitudes (subarctic and temperate), coastal areas,

upwelling areas and surface layers. These areas are not only highly productive and rich in biomass, but they are also highly variable. Food is readily available for animals of higher trophic levels in these areas. In contrast, low latitudes (tropics and subtropics), oceanic areas (in particular the central parts of the oceans), and subsurface and bottom layers are not only lower in productivity and biomass, but are also considerably more stable environments. Obtaining food is laborious for animals in these areas. This situation holds true interannually as well as annually. Contrasting patterns of fluctuation in number, which differ with life history stages, seem to have evolved in response to these environments. Type I matches the high productivity environment and Type II the lower productivity environment.

Type I, in turn, is divided into Subtypes IA and 1B, corresponding to specific temporal scales of environmental variation in the sea. The observed variation in subarctic and temperate seas is considered to result from short-term variation, with intervals of one to a few years, and tends to occur in a relatively small area. Large-scale variations, with cycles of several decades to centuries, tend to occur in ocean-wide areas. Each may drive the variation in abundance of a variety of species of fish in an area. Fish species of Subtype IA respond more closely to short-term variation in the environment, whereas those of Subtype IB respond more closely to large-scale variation. As shown in Figure 6.5, the Pacific saury, Far Eastern sardine, and scombroids, such as chub mackerel *Pneumatophorus japonicus* and albacore *Thunnus alalunga,* reveal the fluctuation patterns of Subtypes IA and IB and Type II, respectively.
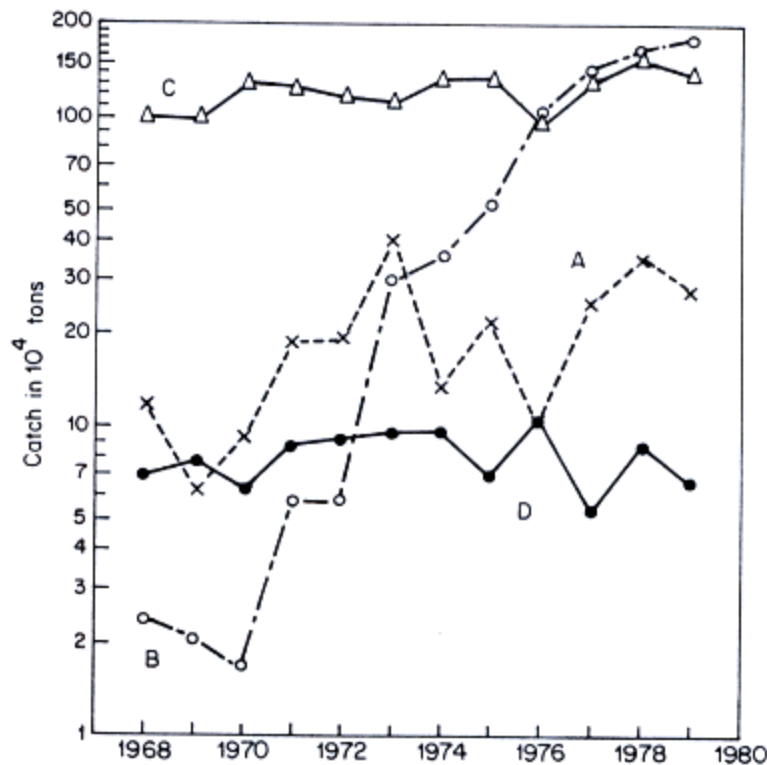

Figure 6.5 Interannual variations in the catch of Pacific saury (A), Far Eastern sardine (B), chub mackerel (C), and albacore (D), caught in Japanese fisheries. (Source: Kawasaki, 1982, 211)

The variations of the three types are represented diagrammatically in Figure 6.6. The figure employs an assumption common in population biology,, that variation in stock size can be represented by a logistic model. Expressing the carrying capacity of the environment K (equivalent to maximum stock size)
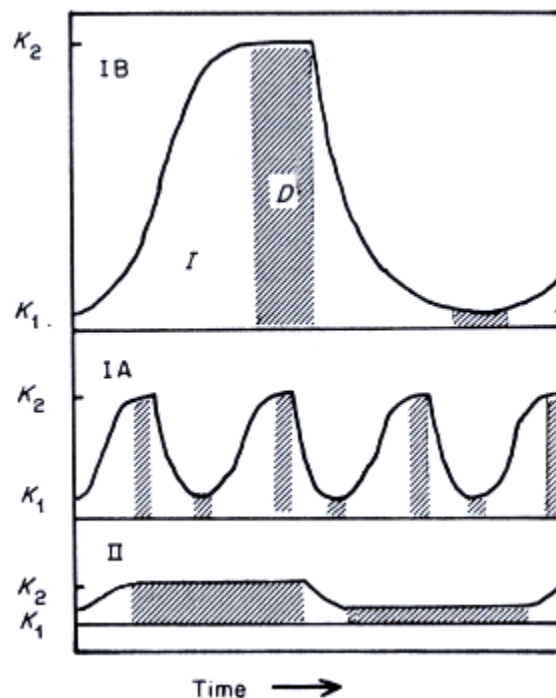
Figure 6.6 Three types of patterns of fluctuation in number of marine teleosts. K_2, high K; K_1, low K; D, period when density-dependent are dominant factors; I, period when densityindependent are dominant factors

under favorable environmental conditions as K_2 and under adverse conditions as K_1 the stock size, N, increases when K goes from K_1 to K_2 and decreases when K declines from K_2 to K_1. More formally,

$dN/dt = rN(K_2 - N)/(K_2 - K_1)$	represents the increasing phase	$(K_1 \rightarrow K_2)$
$dN/dt = rN(K_1 - N)/(K_2 - K_1)$	represents the decreasing phase $K_1 \leq N \leq K_2$	$(K_2 \rightarrow K_1)$

Now, suppose that the stock is fished. Then,

$dN/dt = rN(K_2 - N)/(K_2 - K_1) - aXN$	represents the increasing phase
$dN/dt = rN(K_1 - N)/(K_2 - K_1) - aXN$	represents the decreasing phase

 where X denotes fishing effort, and fishing is carried out at a rate proportional to stock density per unit effort.

As seen in Figure 6.6, the values r and $K_2 - K_1$ are species-specific attributes and vary between species, even if they inhabit a common area. In this figure I (unshaded area) denotes periods when density-independent factors (environmental factors) are the main influence, while D (shaded area) denotes periods when density-dependent factors (biological factors) are the main influence. The duration of I is long and D is short for Type I species, indicating that they are apt to be subject to environmental change. In contrast, the duration of I is short and D is long for Type II species, indicating that they tend to be more influenced by overfishing. Far Eastern sardine and halibut are examples of Types IB and II respectively.

6.4.2 Interannual Variation: Pacific Saury (Subtype IA)

The catch of Pacific saury around Japan has been characterized by shortspaced, interannual fluctuation (as shown in Figure 6.5). The fluctuation in catch is thought to reflect a change in stock size, and it is believed that variation of oceanic conditions, especially the pathway of the Kuroshio Extension east of Japan, has caused the fluctuation in stock (Fukushima, 1979). As shown in Table 6.1, the shift of the Kuroshio has given rise to a change of the Oyashio, the southbound cold current east of Japan, eventually resulting in changes in the distribution, size and catch of fish. This pattern of short-term fluctuation depends on the life history features of saury, which is short-lived (2

years), reproduces early, has a high intrinsic rate of natural increase *r* and feeds on zooplankton. For more detailed explanation, see Kawasaki, 1980.)

6.4.3 Long-term and Phenomenal Variation: Sardines (Subtype IB)

Figure 6.3 displays the large-scale fluctuations in catch exhibited by three species of the genus *Sardinops:* Far Eastern sardine, California sardine, and Chilean sardine. While these species are geographically distinct, occurring in the northwest, northeast and southeast parts of the Pacific Ocean respectively, their fluctuations are in phase with one another. This marked phenomenon suggests that variations in stocks of the three species are governed by some common Pacific-wide oceanic variation. If we accept the explanation in Section 6.2 about large-scale ocean changes as valid, it is understandable why the three sardine species have shown almost identical trends of variation in stock size. A long-lived A-type cold water mass associated with Kuroshio meandering may be regarded as the local manifestation of large-scale variation, such as occurred in 1934−43 and has been occurring since 1975 to the present, a period when sardine stocks have been most abundant (see Figure 6.3).

Table 6.1 Relation between oceanic conditions and distribution, size, and catch of the Pacific saury

Period northernmost path of the Kuroshio	Trend of the Oyashio	Major fishing area	Dominant size in catch	Amount of catch (Typical years)
38°00′N	The 1st branch develops	Coastal Long. 142°E−145°E	Medium-sized fish (27−28 cm)	200,000 (1950−53)
37°30′N	The 1st and 2nd branches develop	Coastal and nearshore Long. 142°E−146°E	Bimode of large and medium-sized fish (30 cm and 27−28 cm)	400,000 (1955−59)
37°00′N	The 1st branch is weak, and the 2nd branch develops	Offshore Long. 144°E−148°E	The same as above but some change in the medium sized fish (30 cm and 26-27 cm)	300,000 (1960−63)
36°30′N	The 1st branch is weak, and the 2nd and 3rd branches develop	Offshore Long. 145°E−149°E	Large in even years or medium in odd years for 1964−67, or large in odd years or medium in even years for 1972−75	200,000 (1964−67 = 1972−75)
36°00′N	The 1st and 2nd branches are weak, and the 3rd branch develops	Offshore Long. 145°E−151°E	Principally small fish (24−25 cm)	100,000 (1968−71)

Source: Fukushima, 1979, 4

Soutar and Isaacs (1974) studied temporal change in the scale-deposition rate of the California sardine in cores from anaerobic sediments in the Santa Barbara Basin off northern California. Radiometric methods were used to estimate the age of the laminae, and scale-deposition rates were obtained. Comparison of estimates of the sardine population derived from solution of a fishery catch equation and the scale-deposition rate in the Santa Barbara Basin indicate a parallel trend. Deposition rates of the sardine scale were very low in 1865−90 and 1940−70, suggesting long-term variation. Such large-scale fluctuation exhibited by sardines is a function of their ecological characteristics. They are long-lived, fast-growing herbivores living in coastal areas, and these features mean that they are especially subject to changes in oceanic conditions. To summarize, large-scale fluctuation of *Sardinops* appears to be caused by global-scale environmental variation and depends on whether the sardines are able to utilize a large quantity of phytoplankton or not.

6.4.4 Variation Caused by Man: Southern Bluefin Tuna (Type II)

Southern bluefin tuna *Thunnus maccoyii* is a Type II species distributed over the relatively stable waters of the deep oceans of the southern hemisphere. Fluctuation of stock size is density-dependent, and stock size changes little under unexploited conditions. Figure 6.7 shows a relation between the catch by longline and the number of hooks used. The hooked-rate as an index of stock density had been approximately 4 percent from 1954 to 1962, decreasing as fishing intensified, and has fallen to about 0.5 percent since 1975. This is a typical example where heavy fishing resulted in a decline in stock. While the variation in this stock is caused primarily by overfishing, there remains a need to understand the variation with the species-specific pattern of environmental fluctuation in mind.

6.5 CHANGES IN STOCK BASED ON INTERSPECIES RELATIONS

Changes in stock are brought about not only by environmental and human factors, but by relations between species as well. For example, it has been found that the catch of species of *Sardinops* (sardines) is inversely correlated with the catch of *Engraulis* (anchovies). This has been seen in different areas of the world oceans and may be explained by the partly overlapping ecological niches of sardine and anchovy (see Figure 6.1). The former feeds on both phytoplankton and zooplankton, while the latter depends mainly on zooplankton; both inhabit coastal areas. Murphy (1977), using the results of egg and larval surveys, maintained that as the sardine population off California diminished, the populations of northern California anchovies increased. The anchovy population lagged far enough behind the sardine that Murphy concluded it was filling the void left by the sardine, rather than causing the sardine population to decline.
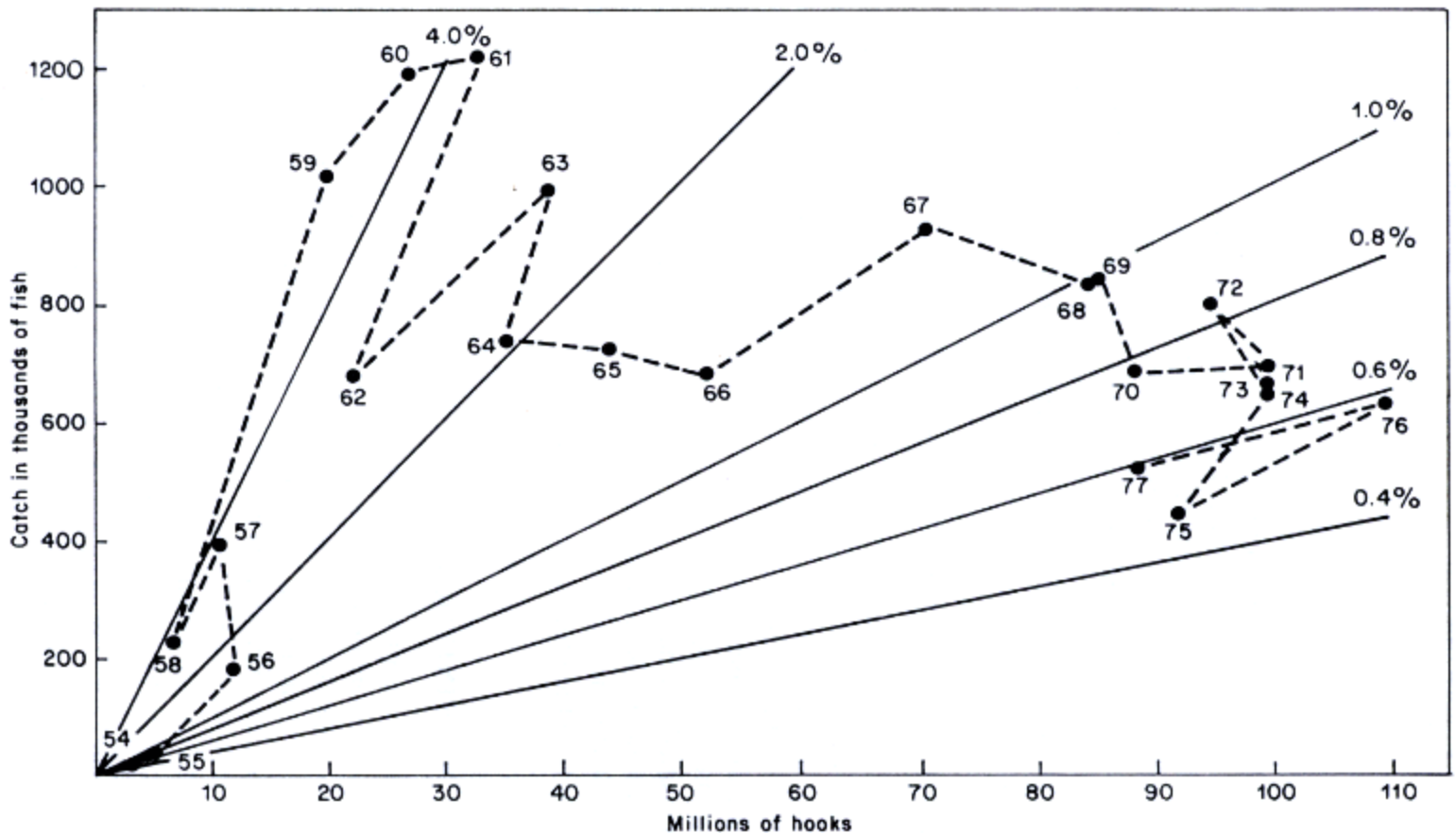

Figure 6.7 Relation between fishing effort and catch of southern bluefin tuna in a longline fishery. Unbroken lines show catch-per-100 hooks as an index of population density. (Source: Shingu and Hisada, 1980, Figure 2)

6.6 VARIATION OF FISH SPECIES AND FISH BIOMASS IN AN AREA THROUGH SUSTAINED ENVIRONMENTAL CHANGE

Variation in ocean biota attributable to sustained shifts in ocean climate may be illustrated by the events of the so-called Russell cycle, discovered by Sir Frederick Russell (Cushing and Dickson, 1976). A northward spread of warm water species occurred in the western English Channel, with warming in the north Atlantic from the 1920s to the 1940s, and was reversed some 30 years later during the early 1970s. The first event was the decline in recruitment of the Plymouth herring stock *(Clupea harengus),* which began with the 1925 year-class. In 1931, the last recorded year-class entered the fishery, which subsequently collapsed in 1936 or 1937. In the summer of 1926, pilchard eggs *Sardina pilchardus* were recorded in considerable numbers and remained so until 1960. Between 1925 and 1935, the winter phosphorus concentration declined by one-third. In the autumn of 1931, macroplankton (plankton in the 0.2–2.0 mm size class) declined by a factor of four and the numbers of summer-spawned fish larvae decreased.

When the catches in 1919–22 are compared with those in 1944–52, one of the northern species, ling *Molva molva,* virtually disappeared, while boarfish *Capros aper* decreased by an order of magnitude. During the same period, southern species like horse mackerel *Trachurus*

trachurus, hake *Merlucius merlucius,* red mullet *Mullus surmuletus,* and red bandfish *Cepola rubescens,* all increased by an order of magnitude. Phytoplankton in the 1920s resembled those in the 1970s in species composition, whereas in the intermediate years a number of southerly species were found. Furthermore, in 1965, the numbers of spring-spawned fish larvae (generally northerly species) increased again by an order of magnitude. In 1970, the macroplankton increased for the first time since the autumn of 1930, and in the following winter the phosphorus concentration rose to the pre-1930 level. This cycle is summarized in Figure 6.8.
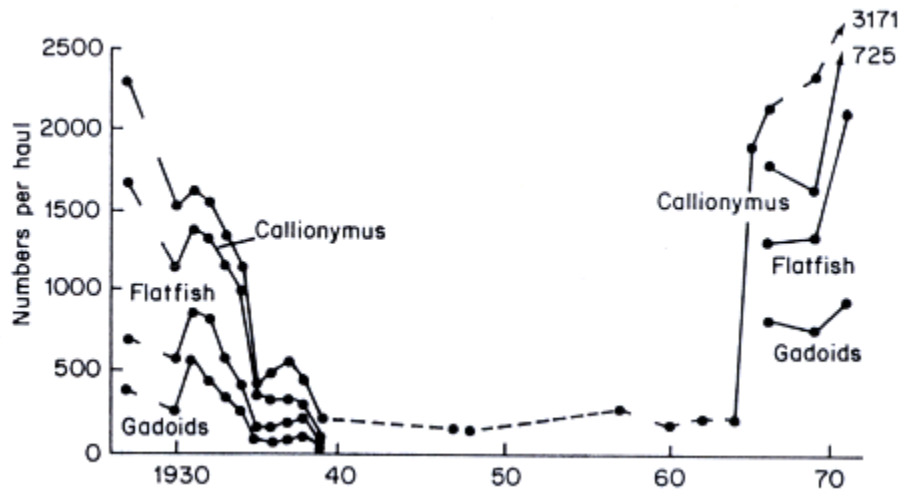

Figure 6.8 The Russell cycle in monthly averages of the planktonic stages of teleostean fish, excluding clupeids, between 1924 and 1971 in the vicinity of Plymouth, England. Reproduced by permission of Cambridge University Press from Russell (1973)

There are three events common to the two changes in the 1930s and the 1970s. In 1930 macroplankton and winter phosphorus declined, and the spring spawners decreased 5 years later. In 1965 the spring spawners increased in numbers, to be followed by increases in macroplankton and winter phosphorus in 1970. Thus, the later events are the mirror image of the earlier ones; if the decline of spring spawners in 1935 indicated the end of the earlier sequence of events, then their recovery signalled the start of the later ones.

It should be noted that alternation between herring and pilchard has occurred before. A summer pilchard period occurred in the first half of the seventeenth century, the early years of the eighteenth century, and in the first 30 years of the nineteenth century (Cushing and Dickson, 1976).

6.7 CONCLUSION

The linkage between climate and fisheries must be considered in two jointly coupled relationships. One coupling occurs in the relationship between climate and ocean, and the other in the relationship between ocean and fisheries.

The relationship between the atmosphere and the sea is a feedback system, a system of mutual influence. Of particular importance are processes where changes in ocean surface temperature cause changes in the atmosphere, especially changes of winds, which in turn cause changes in ocean circulation.

Patterns of fluctuation of oceanic conditions vary geographically, and the impacts of these fluctuations on fish stocks depend upon the ecology of a species. There are three typical types of fluctuation in recruitment in the marine fishes. While some fish fluctuate in recruitment unpredictably or irregularly (Subtype IA), recruitment of other species is characterized by large-scale fluctuation (Subtype IB). For some species, stock size is less changeable (Type II).

The Type I species (variable and unpredictable) are distributed in environments where sea conditions change widely—upwelling areas, high latitudes, and the surface layer. Species of Subtype IA are matched to short-term fluctuations of the ocean environment and include saury and sand eels. Species of Subtype IB correspond to large-scale fluctuations, and herrings and sardines exemplify the category. Fish of Type II inhabit stable environments, such as tropical areas and bottom or subsurface layers, fluctuate slightly, and tend to be more subject to overfishing than to environment. Flatfishes and tunas are typical of this type.

It may remain controversial whether changes in particular stocks are more attributable to natural causes, like climate, or to overfishing. Characteristic debates have been held on several species, for example, herring, sardine, and Pacific halibut. While the former two taxa,

belonging to Subtype IB, are less apt to be directly subject to drastic impacts from fishing, a stock of the latter species, typical of Type II, tends to be quite sensitive to fishing effort.

Mankind owes its existence in large part to the seas. Living resources of the seas continue to be a valuable source of food. For this reason and because of their intrinsic natural value, an increased understanding of the behavior of fish stocks must be sought. Understanding the relationship between climate and fisheries can be an important part of sustaining fisheries as a renewable resource.

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Back to Table of Contents