GLOBAL CLIMATE VARIATIONS AND POTENTIAL IMPACTS ON THE GULF OF GUINEA SARDINELLA FISHERY

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Abstract:

Two separate classes of global-scale climatic effects could conceivably have controlled the dramatic coastal pelagic population changes that have occurred in the Gulf of Guinea over the past two decades. One is a long-term intensification of coastal upwelling that may be related to global climate change. The other involves global climatic teleconnections to the Pacific ENSO system. Each appears to suggest opposite scenarios concerning the future of the local fishery. Presently, there is no sound scientific basis available for choosing between them, illustrating a need for basic research progress to support policy and management decisions.

Résumé:

Deux catégorie d'effets climatiques à l'échelle du globe peuvent conceptuellement avoir causé les brusques changements qui ont affecté les populations de poissons pélagiques côtiers dans le Golfe de Guinée, au cours des deux dernières décades. L'une est une intensification à long terme des upwellings qui serait liée au changement global des climats. L'autre suppose une téléconnection climatique avec le phénomène El Nino, dans le Pacifique. Chacune semble engendrer des scénarios différents pour le futur de la pêcherie locale. Actuellement il n'y a aucune raison précise de choisir entre l'une ou l'autre. Ceci illustre la nécessité de recherches fondamentales pour soutenir les choix de politique d'exploitation et de gestion.
1. Background

The marine ecosystem along the northern coast of the Gulf of Guinea has been the site of remarkable biological population changes during the 1970s and 1980s. Sardinella aurita was the major species harvested until the 1970s, with the bulk of the early production being in Ghanaian waters. However, during 1972, the fish appear to have been exceptionally available to the fishery (Binet, et al., 1991) and Ghana alone harvested over 90,000 tons (Koranteng, 1991). Following this unusually high catch the population collapsed and the species essentially vanished from the catches. According to the conventional conceptual framework of fisheries science, such a sudden and total collapse would imply that MSY (maximum sustainable yield) had been grossly exceeded.

The collapse of the S. aurita population roughly corresponded to the initiation of one of the most phenomenal episodes in the history of fish population dynamics, the massive «outbreak» and domination of the ecosystem by the triggerfish Balistes carolinensis (Caverivière, 1991). Before the 1970s Balistes carolinensis was rather rare in the eastern Atlantic. But by 1981, some 500,000 tons of Balistes were estimated off Ghana and Côte d'Ivoire between the 10 m and 200 m isobaths. This was 83% of the total pelagic biomass. However, following the mid-1980s, the population again has declined and Balistes no longer is a dominant factor in the ecosystem.

In the late 1970s, S. aurita again began to rebuild its population off Côte d'Ivoire and Ghana. In the 1980s production grew to very high levels. Recently, annual catches comparable to the disastrous (apparent) overcatch in 1972 have become routine and seemingly sustainable. Clearly, if catches grossly exceeding MSY had caused the earlier collapse, then MSY for this population must have undergone a very large increase within one decade. If so, it would seem to add to the questions concerning the suitability of the concept of MSY to such populations. Associated with this apparent increase in stock productivity have been changes both in fishing areas and in fishing seasons. In the earlier period, the bulk of the catch of S. aurita came from Ghana during the major upwelling season (July-September). Lately, the much larger catches have also been spread westward over the Ivoirian coast to a much greater degree and occur all year round (Binet, et al., 1991). Climate-related alterations in ocean processes are considered to be the most likely explanation for the dramatic changes (Binet and Marchal, 1993).

2. Global Climate Change

The climatic trend that is receiving most public attention in recent years is the potential global warming effect of carbon dioxide, methane, chlorofluorocarbons, and other «greenhouse gases» that are building up in the earth’s atmosphere due to the burning of fossil fuels and other human activities. There is no doubt that a «greenhouse effect» exists on earth. Greenhouse gases, which have been a feature of the earth’s atmosphere for eons, actually are what has
served to make life possible on our planet. If it were not for the warming effect of these gases, which allow short-wave solar radiation to penetrate the atmosphere but trap much of the long-wave radiation of heat back to interplanetary space, the earth would be a frozen, lifeless lump of rock and ice. And there is no doubt that the burden of these gases in the atmosphere is being rapidly increased (Fig. 1).

However, there is controversy as to the exact nature of the climatic changes that may result. Unfortunately, the available climate models are not very skillful at producing reliable predictive scenarios on regional scales. Nevertheless, to assume that no climatic change may occur, merely because precise predictions are not possible at this time, seems quite a forlorn hope. Actually, the surprising thing, given that greenhouse gases have now been building up for decades, is that there have not been stronger effects observable up to now. Indeed, there is evidence of a long-term global warming trend (SCOR-IOC, 1992), but it is more subtle than most experts would expect.

One greenhouse effect that can be predicted with quite a high degree of certainty is an increased contrast in temperature between the heated land masses and the oceans during the spring-summer heating seasons (Bakun, 1990, 1992). This is because the large heat storage capacity of water causes the oceanic temperature cycles to lag the terrestrial cycles. For example, in coastal upwelling regions the development of a thermal low in atmospheric pressure in the continental coastal interior, which warms much more rapidly due to solar heating than does the adjacent ocean area, is one of the reasons that coastal upwelling tends to be a spring-summer seasonal phenomena in extra-tropical regions. Geostrophic winds flow along isobars in the same sense as geostrophic currents and so continental lows help to support the alongshore wind stress that drives the upwelling process (Fig. 2). The resulting cooling of the near-coastal ocean in turn further increases the onshore-offshore temperature gradient, tending to produce a feedback loop which may further intensify the process. Another potential feedback loop involves the stabilization of onshore air flow by the upwelling-cooled coastal ocean surface; this suppresses the vertical motions involved in cloud development and so may tend to favor further increases in continental heating by solar radiation.

Thus, an increased atmospheric greenhouse effect would, by adding to the continental-oceanic temperature contrast, tend to intensify the upwelling feedback system. This would lead to a long-term upward trend in upwelling intensity (Fig. 3a), assumedly leading in turn to a similar upward trend in the total primary productivity of the associated marine ecosystem. Indeed, there have been indications (Bakun, 1990, 1992; Roy, 1990) of substantial multi-decadal increases in upwelling-producing wind stress already occurring during the heating portion of the year in many coastal ocean regions of the world. There is a complicating factor in the situation in that time series of wind strength constructed from summaries of maritime wind reports may contain an artificial increasing trend due to increasing proportion of anemometer measurements relative to Beaufort estimates in the report (Ramage, 1987; Cardone et al., 1990). However, Bakun
(1992) concluded that this artifact explained only a fraction of the increasing trend in the subtropical eastern ocean upwelling systems where particularly strong rising trends have been noted.

Wind is probably the single environmental variable that has been most widely identified in studies of environmental effects on population dynamics of coastal pelagic fishes (e.g., Lasker, 1975, 1978; Bakun and Parrish, 1980; Cury and Roy, 1989; Bakun, 1993). For subtropical upwelling systems, empirical studies (Cury and Roy, 1989) have indicated a consistently dome-shaped relationship (Fig. 3b) where reproductive success is highest at an intermediate wind intensity and decreases at both higher and lower intensities. Accordingly, a long-term trend toward increased coastal winds might be expected to cause substantial rearrangements of the habitat geography of coastal pelagic fish populations (Bakun, 1993), with the tendency toward either increased or decreased favorability depending upon which side of the «optimal environmental window» the local situation might lie.

In upwelling systems of near-equatorial regions, because of the latitude-dependence of the Coriolis effect, the beneficial effects of strong upwelling tend to be counteracted to a lesser degree by detrimental effects of turbulence generation, and even of offshore transport (Bakun et al., 1991). And indeed, spawning peaks in tropical upwelling systems tend to be timed so as to coincide with seasonal maxima in upwelling intensity (Roy, 1990; Roy et al., 1991), whereas in higher latitude systems the peak spawning tends to be timed so as to avoid the seasonal upwelling peak. Thus the tropical systems would seem to generally lie toward the low wind side of the local «optimal environmental window». In such a case, increased intensity of wind-induced upwelling would tend to favor population growth of coastal pelagic fishes. And indeed, some tropical systems are exhibiting such long-term upward trends. For example, the Indian oil sardine (*Sardinella longiceps*) had a reputation, dating well back into the previous century, for being the most unreliable of fishery resources (Longhurst and Wooster, 1990). But recently, its population dynamics have appeared to have become much more robust. For example, for over a decade and a half, starting in the mid-1970s, the catches have consistently maintained a level near 204000 tons. This is nearly an order of magnitude greater than the average catches in the era previous to 1955, even if one totally disregards the intervals of total absence and considers only the intermittent periods of availability.

The recent situation in the Gulf of Guinea has been characterized by similar sustained upward trends. The catches of *S. aurita* (Fig. 4) as well as other small pelagics (Anon., 1993a) have undergone sustained decadal-scale increases. Correspondingly, Pezennec and Bard (1992) have indicated an increase in the intensity of the «minor» upwelling season (January-March) off Côte d’Ivoire, corresponding to the westward extension of the *S. aurita* population. The linkage of increased upwelling intensity to population growth may be the most consistent theory presently available to explain the recent dramatic changes in these populations (Anon, 1993a). Moreover, indications of long-term intensification
of the thermal low pressure cell in the interior of the North African continent (Fig. 5) tend to support the greenhouse mechanism (Fig. 2) outline above, in that such lowered continental pressures would tend to support an increase in upwelling-favorable wind stress off Côte d'Ivoire and Ghana. In addition, the conceptual idea is supported by global circulation model simulations which have predicted lower atmospheric pressures over Northern Africa as a result of increased CO₂ in the atmosphere (Hsieh and Boer, 1992).

3. Global-scale Changes in Marine Populations

On the other hand, the pelagic fishes of the Gulf of Guinea and the coast of western India are not the only fish populations that experienced major inflection points in their population trends in the mid-1970s. But in most cases, the trend lines have since undergone an additional reversal. A pattern (Fig. 6) of population increases from the mid-1970s to the mid-1980s, followed by population declines after the mid-1980s, seems to have been remarkably widespread and consistent in a large number of marine ecosystems distributed over the world’s oceans. For example, this was a period of phenomenal productivity and growth of the major groundfish populations of the Subarctic North Pacific which sustained the massive expansions of the fisheries of that region through the period (FAO, 1992). Conversely, since the mid-1980s these populations are in incessant decline, in spite of continuing elaborate stock assessment activities and state-of-the-art fishery management efforts. The period appears also to have been particularly productive in the tropical central North Pacific. Total chlorophyll in the water column appears to have increased north of Hawaii (Venrick et al., 1987). Lobsters, sea birds, seals, and coral reef fishes in the northwestern Hawaiian Islands all seem to have experienced increased production; conversely, since the period ended in the mid-1980s, lobster landings from this area have dropped by two thirds (Anon. 1993b) and other biological populations are in a downward trend.

In addition, the very large populations of anchovies and sardines that dominate the fish biomass in the major eastern ocean upwelling regions of the world, as well as the northwestern Pacific off Japan, seem to have been rising and falling in phase (Kawasaki, 1983). Both the Californian and Japanese fisheries grew during the 1920s and early 1930s to peak in the mid to late 1930s. (There were no corresponding landings off western South America because no significant fishing occurred.) Both populations remained extremely depressed for some three decades. The sardine fisheries in both regions then commenced sudden rapid growth near the mid-1970s, the same period in which enormous numbers of sardines appeared off South America initiating a massive fishery in that region. In the period since Kawasaki originally called attention to the synchronous pattern, an additional simultaneous reversal in trend has occurred. Toward the latter part of the 1980s, sardine landings in all three systems have begun to rapidly fall (Lluck-Belda et al., 1992).

Since the advent of substantial fisheries, anchovy populations have been generally out of phase with the sardine populations in the three regions. Off
California, after a time lag of about a decade following the sardine collapse, the anchovy population increased with over 340,000 tons being taken in 1981. Off Japan, the anchovy catches grew during low sardine abundance after the initial collapse, attaining maximum levels of nearly half a million tons during the late 1950s and the 1960s. The anchovy catches then gradually declined as the sardine population proceeded in its rebuilding phase. Recently, as the Japanese sardine population is declining, extremely large shoals of anchovy are reported (Lluch-Belda et al., 1992)

In the Peru-Humboldt Current system off western South America, the fishery for anchovy (anchoveta) peaked in 1970 at more than 13 million tons, constituting by far the largest single fishery that has ever existed on earth. It then collapsed to less than 1 million tons after the 1972 El Niño, rebounded briefly to about 2 million tons for several years, and then fell back following the 1976 El Niño to below 1 million tons and remained at this relatively low level to the mid-1980s. The sardine catches were low while the anchovy was abundant, but the sardine population grew during the period of anchovy collapse to the point where nearly 6 million tons were taken in 1985, the highest yield of any sardine fishery to date (Lluch-Belda et al., 1992).

Lluch-Belda et al. (1992) note that the fluctuations in the sardine fishery in the Benguela system off southwestern Africa tend to be opposite in phase to those of the three Pacific regions. Here, extensive sardine fisheries began after World War II, peaked in 1968 at about 1.5 million tons, and then collapsed. Anchovy catches grew as the sardine catches decreased, reaching about 600,000 tons by 1974 and peaking at nearly 1 million tons in 1987. Recently a precipitous decline has occurred. Indications from seabird diets, etc., as well as fishery landings, indicate that sardine is now again replacing anchovy as the dominant low-trophic-level fish population of the Benguela ecosystem.

Previously, there had been reluctance to denote these alternations as being actual replacements of one population by the other. The question of the time lags were worrisome; sometimes the «replacement» did not begin to occur for a decade or more (i.e., at least several generation cycles) after the other population had collapsed to low levels. Moreover, in their analysis of annually-varved anaerobic sediments in the Southern California Bight, Soutar and Isaacs (1974) found that the numbers of deposited scales of sardines in their samples appeared to vary in phase with those of anchovies more often than they were opposite in phase. However, as more experience of regional-scale population variations has accumulated, with anchovies and sardines seldom being at high abundance levels at the same time, the evidence for at least some degree of actual replacement has become increasingly convincing. Lluch-Belda et al. (1992) draw the conclusion that regional «regime changes» in relative abundance of sardines and anchovies were initiated in all four regions (California Current, Peru-Chile, NW Pacific, and Benguela Current) in the second half of the 1990s.

Many other examples can be found of major marine population effects occurring during this same period of the mid-1970s to mid-1980s. For example,
this was a period of increasing survival of Greenland halibut (Serebryakov, 1992), a period of dramatic growth in the lobster landings in eastern Canada (Pezzack, 1992), a period of large increase in Newfoundland spawning northern cod stock (Paz and Larrañeta, 1992), etc. On the other hand, North Pacific Albacore tuna appear to have suffered a steep population decline during the period (FAO, 1992).

4. Potential Connections to Pacific ENSO Variability

Thus long-term unidirectional trends, such as one might expect from the «greenhouse» climate change mechanism discussed earlier in this paper, have not been the rule. Rather, shorter decadal-scale population «swings» have been more typical. Moreover these swings have the appearance of being synchronized globally by the singular conditions of the decadal period from the mid-1960s to mid-1970s. Indeed, if one examines the various series presented by Bakun (1990, 1992) or Roy (1990) it is clear that although multi-decadal coastal wind and upwelling increases are clearly indicated, these trends have not been steady and unidirectional on the shorter (~decadal) scales. The most rapid increases tended to occur from the mid-1950s to the early to mid-1970s. Then, the trends in widely separated regions, in both the northern and southern hemispheres and in both the Atlantic and Pacific, appear to «flip over» to negative trends, or at least to level off. Then, near the mid-1980s there is often a suggestion of another inflexion point where the earlier long-term upward trend seems to begin to be reestablished. The worldwide coherence of these trends and inflexion points is striking and quite extraordinary. This period (early to mid-1970s to mid-1980s) of temporary interruption of the longer term trends, is exactly the period of the remarkable global marine population episodes, including those involving the coastal pelagic fishes in the Gulf of Guinea. What could be the origin of these global decadal variations? The evidence suggests that it probably lies in the coupled ocean-atmosphere system of the equatorial Pacific Ocean.

The waters of the Pacific Ocean constitute the greatest mass of heat storage capacity on earth. The Pacific is so large that its atmosphere as a whole is only minimally subject to continental effects, and so is not nearly so strongly forced into seasonal climatic regularity as are the atmospheres of smaller, more continentally-influenced oceans. The result is that the coupled ocean-atmosphere system of the Pacific «wanders» from year to year, in response to its own internal dynamics, to a much greater degree than do other ocean regions. The most dramatic expression of this interyear variability of the Pacific system is the El Niño - Southern Oscillation (ENSO) phenomenon. El Niño episodes precipitate by far the strongest interannual fluctuations in conditions affecting marine populations in the equatorial and eastern boundary regions of the Pacific. These deviations from the norm tend to be so radical that they totally dominate any other mode of variability. The disastrous collapse of the Peruvian anchoveta fishery occurred contemporaneously with a major ENSO episode, the El Niño of 1972.

Because the Pacific is so large, its effect on the earth’s climate system is global. Accordingly, ENSO constitutes the dominant mode of short term climatic
variability throughout the world. El Niño events have been associated with
drought and catastrophic wild-fires in Indonesia and Australia, with both drought
and flooding in different parts of Brazil, and with anomalies in monsoon rainfall
and drought in India. Apparent linkages with climate anomalies in the central
and eastern United States, western Europe, Africa, central Russia, China and
Japan have also been indicated. The atmospheric and oceanic «teleconnections»
that act to transmit ENSO-related effects to marine ecosystems distributed
throughout the world's oceans have become well documented and reasonably
well understood by the ocean scientific community.

But underlying the El Niño events occurring on the inter-annual scale, there
appears to be a decadal-scale variation that appears as lower frequency
modulations of both amplitude and frequency of interannual episodes. The period
from the early to mid-1970s to the mid-1980s clearly was one in which the Pacific
Ocean was characterized by a rather continuous state of elevated El Niño
characteristics (Norton, et al., 1985; Wooster and Hollowed, in press). For
example, if one looks at available time series of ocean properties and processes
off Peru, one finds the interannual El Niño signal dominant (Fig. 7). But one
also sees the underlying inter-decadal signal. Clearly, there was a change in the
time period from the early to mid-1970s to a situation of more frequent, more intense El Niño
characteristics. Whether the period actually began with the 1972 El Niño or the
1976 El Niño is problematic. The 1972 event was intense and, from a visual
inspection of the time series, seems to have established a new upper «peak»
level that carried through the following decade and provided an elevated base
out of which the «monster» 1982-83 event arose. However, between the 1972
and 1976 events, the system fell back briefly into an opposite cool phase. After
the 1976 event there were no more of what most would call «cool phases» until
after the mid-1980s.

The 1972 event, while intense in the tropics (Fig. 7), did not have much
effect in the northern part of the Pacific. For example, temperature time series in
the Gulf of Alaska show an abrupt shift from quite consistent negative anomalies
in the first half of the 1970s to consistent positive anomalies in the second half
of the 1970s and early 1980s (Royer, 1983; Cole and McLain, 1989). However,
many biological changes in regions of the world other than the North Pacific
seem to begin somewhat in synchrony with the 1972 event (e.g., the Sardinella
collapse and Balistes outbreak in the tropical eastern Atlantic). Also, if one
examines the series presented by Bakun (1992) for the North Atlantic, one finds
that the apparent inflexion points in most of the series, including those off western
Africa, seem to coincide better to 1972 (or 1973) than to 1976.

Bakun (in prep.) points to the fact that certain of the characteristics of 1972
event tended to be of greater intensity later in the year relative to other El Niños
as being perhaps at least part of the reason for its lack of effect in the high-
latitude northern hemisphere. The commonly cited «northward» ENSO
teleconnection is through the Subarctic Low pressure cells (Fig. 8). Accordingly,
this particular mode of teleconnection must be primarily a northern hemisphere
winter phenomenon; during the summer these low pressure cells tend to be nearly totally relaxed and the intense cyclogenesis that characterizes the cooler half of the year is absent.

Hisard (1988) has outlined the elements of a «tropical» teleconnection between the Pacific and Atlantic Oceans. He notes that the «Atlantic El Niño» of 1984 directly followed the particularly cold year of 1983 which was characterized by strong trade winds, etc., in the tropical Atlantic. This may have corresponded to a «build-up» phase, leading to an Atlantic analog of the type of episodic trade wind «collapse» that is well-known in Pacific El Niño (Fig. 9). He also notes that such paired annual events, in which a cold year is followed by a warm year, have been observed several times before in the tropical Atlantic (e.g., Fig. 10). There has also been a pattern of cold, dry years in the tropical Atlantic concurrent with warm, wet (El Niño) years in the eastern tropical Pacific (compare Fig. 10 with Fig. 11b, for example). Indeed, Hisard notes that the 1983 situation involved strong convergence of the trade wind systems of the two oceans over the northern part of South America, involving the reversed westerly (eastward-directed) trades associated with the El Niño in the Pacific and the strengthened easterly (westward-directed) trades of the Atlantic cold phase. This convergence was sustained by the strong rising air motion involved in the extreme rainfall and flooding of northern South America during the 1982-83 El Niño. Thus, El Niño in the Pacific may set up an intensified system in the tropical Atlantic. Then as the Pacific returns to a more normal situation characterized by descending air near and over the South American continent, this may collapse the intensified trade wind circulation in the Atlantic, lessening the equatorial upwelling, thereby bringing on a warm phase in the tropical Atlantic.

This hypothetical «tropical connection» (Fig. 9), as opposed to the teleconnection through the Subarctic Low pressure cells (Fig. 8), might operate also during the northern hemisphere summer. If the 1972 El Niño was shifted later in the year relative to other El Niños, one might expect less teleconnection through the Subarctic Lows and perhaps greater effect through «tropical» teleconnections. Note that in the series presented by Bakun (1992), the inflection point for the Icelandic Low (the Atlantic Subarctic Low) is in the mid-1970s, even though in many of the Atlantic coastal wind series the transition appears to be in the early 1970s.

In any case, the substantial degree correspondence on the inter-decadal scale between time series as diverse as turbulence generation in the Pacific Ocean off western South America and African river outflow into the eastern tropical Atlantic (Fig. 11) is intriguing and certainly suggestive of global-scale linkages operating on these longer decadal scales.

5. Discussion and Speculations

Although the ideas are highly speculative at this point, it nevertheless appears possible that the drastic changes experienced in the Gulf of Guinea marine ecosystem during the 1970s and 1980s are intrinsically linked, through global
climatic teleconnections, to a large number of concurrent population events in other marine ecosystems distributed around the world. Comparative studies of fish habitat climatology (e.g., Bakun and Parrish, 1991; Bakun, 1993; Bakun, in prep.) have tended to identify three major classes of processes that combine to yield favorable reproductive habitat for coastal pelagic and other types of fishes: (1) *enrichment* processes (upwelling, mixing, etc.) (2) *concentration* processes (convergence, frontal formation, water column stability) and (3) processes favoring *retention* within (or drift toward) appropriate habitat. In certain habitat configurations, these may tend to be mutually supportive and so intensification of the dynamic aspects of the physical system tends to yield even more of what are «good things» for reproductive success (Bakun, in prep.) and resulting population growth. For example, Bakun (in prep.) has hypothesized intensification of the system in the Subarctic Pacific, which could explain the phenomenal growth of the fish populations of that regions during the period of enhanced «El Niño» character from the mid-1970s to mid-1980s. Conversely, the equatorial Pacific system should have been, on average, in an abnormally relaxed state during the same period. Correspondingly, the North Pacific albacore tuna, which migrate enormous distances to spawn in the equatorial Pacific, appear to have suffered steep population decline.

But in the environmental configurations of coastal upwelling regions, the three elements tend not to be mutually supportive. For example, upwelling implies divergent horizontal flow. Accordingly, convergence, which may promote enriched food particle concentrations, and upwelling cannot directly coincide. Likewise, mixing may lead to enrichment, but destroy vital small scale structure in food particle distributions (Lasker, 1975). Wind-induced coastal upwelling, because it is driven by offshore transport of surface waters, is directly linked to loss of larvae from the coastal habitat. Thus whether intensification of the physical ocean system is good or poor for reproductive success may depend on how the various opposing effects «balance out» in a local situation. Earlier, it was argued that pelagic fish populations inhabiting near-equatorial upwelling systems may generally be favored by such intensification of the physical ocean system.

According to the mechanism diagrammed in Fig. 9, the tropical Atlantic should have been, on average, in an intensified state during the period of enhanced «El Niño» character in the Pacific. This is certainly in conformity with the general decrease in precipitation indicated (Mahé, 1991) on the eastern side of the ocean (Fig. 11b). Precipitation is associated with rising air, and so increased subsidence (sinking air) on the eastern side of the ocean will tend to decrease precipitation. The indicated increase in equatorial sea surface temperatures during the major coastal upwelling season, both along the equator (Fig. 10) and in the coastal upwelling zone (Binet and Marchal, 1993) seems not to be in conformity with an intensified system. However, in the absence of substantial evidence, one can always speculate. For example, the major aspect in the mechanism outlined in Fig. 9 is increased intensity of westward-directed trade winds in the equatorial zone. Because the north coast of the Gulf of Guinea lies so near the equator
(~ 5° N latitude), this intensified westward-directed trade wind circulation may have interfered with the wind-induced portion of the local coastal upwelling, which would have to be driven by a generally eastward-directed alongshore wind stress component. If so, this could help to explain the lack of temperature decrease in the coastal upwelling zone.

However, it does not explain the lack of decadal-scale temperature decrease at the equator (Mahé, 1991). Of course, what is being discussed is a decadal-scale variation which is actually submerged within larger amplitude variability occurring on the interannual scale (i.e., the alternations of warmings and coolings (Fig. 10) which have corresponded to some degree to the interyear ENSO scale in the Pacific). This shorter-scale pattern of intensifications and relaxations may not produce symmetrical effects in the sea surface temperature distributions. (For example, the sea surface may warm more in a relaxed period, because water column stability may confine the effect nearer the sea surface as opposed to an intensified period where enhanced mixing may spread the effect over a broader depth interval.) Thus a decadal-scale period of alternating periods of intensification and relaxation of the dynamical system could conceivably produce an average warming in sea surface temperature on the longer decadal scale, even while producing an opposite effect on the shorter interannual scale. In the other hand, it is possible that the temperature increases do not reflect local-scale processes at all. Clearly, the period from the mid-1960s to mid-1970s was one of rapid global-scale temperature increase (SCOR-IUC, 1992). Thus it is at least conceivable that the increasing temperatures observed locally may actually have reflected processes occurring on a much larger scale.

In any case, the issue of what type of climatic mechanism may be controlling the observed population variations is certainly a salient one. For example, if the increase in the S. aurita population in the Gulf of Guinea were caused by the hypothesized greenhouse-related upwelling intensification (Fig. 4) the scenario for the future would seem to be a fairly rosy one of continued increase in stock productivity and corresponding population growth. If, however, the increase has been due to the climatic teleconnection to the Pacific ENSO system which may have produced the «dome-shaped» pattern of population growth followed by collapse (Fig. 6), the scenario for the immediate future would seem to be far from rosy. The year of the collapse in 1972 was an El Niño year in the Pacific. It appears that S. aurita may be highly anomalously available to the fishery during periods characterized by cool coastal temperatures and low rainfall (e.g., Bakun, 1978). Such conditions would characterize «intensified» periods, such as would characterize years of Pacific El Niño according to the scenario diagrammed in Fig. 9. Note that the peak catches in 1992 also corresponded to a Pacific El Niño. Thus if the population were already collapsing following the decadal «dome-shaped» pattern (Fig. 6), and the most recent year of high catches merely exceptional availability analogous to 1972, there would be obvious cause for concern for the immediate future of this important fishery. Presently, there is no real basis to confidently choose between a very «rosy» scenario (Fig. 4) and a
very «non -rosy» one (Fig. 12). In such circumstances, development of a basis for effective medium-term policy decisions (not to mention effective adaptive management) would thus seem to depend on the ability to make significant progress on some very basic scientific issues.

REFERENCES


CAPTIONS OF FIGURES

Figure 1. Monthly average carbon dioxide concentration (parts per million) measured at Mauna Loa Observatory, Hawaii.

Figure 2. Mechanism for «greenhouse»-related intensification of coastal upwelling.

Figure 3. (a) Diagram of long term upward trend descriptive of "green-house" related intensification of coastal upwelling.
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Figure 4. Annual catches of Sardinella aurita off Ghana and Côte d'Ivoire, with the linear trend diagram form Fig. 3a superimposed.

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Figure 8. Circulation anomalies at the jet stream level during El Niño (northern hemisphere winter).

Figure 9. Diagram illustrating a hypothetical «tropical» ENSO teleconnection between the Pacific and Atlantic. The figure represents the vertical plane along the equator.

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Figure 11. (a) Wind-induced turbulent mixing index off Peru (Panel “d” of Fig. 6) juxtaposed with (b) variations in river flow (mean of 13 rivers) in the Gulf of Guinea (after Mahé, 1991).

Figure 12. Annual catches of Sardinella aurita off Ghana and Côte d'Ivoire, with the dome-shaped trend diagram from Fig. 6 superimposed.
Figure 1. Monthly average carbon dioxide concentration (parts per million) measured at Mauna Loa Observatory, Hawaii. Annual cycle is due to local (central Pacific) seasonal uptake and release by marine algae, etc. The longer-term upward trend reflects the increase in global concentration.

Figure 2. Mechanism for "greenhouse"-related intensification of coastal upwelling. Increased seasonal heating due to atmospheric greenhouse effect increases temperature contrast between continental land mass and coastal ocean. The thermal low pressure cell in the continental interior is intensified, increasing the cross-shore pressure gradient between the spring-summer continental "Low" and the offshore oceanic "High." This increased pressure gradient supports an intensified alongshore geostrophic wind. Correspondingly increased Ekman transport, directed 90° to the right of the wind (in the northern hemisphere) leads to enhanced coastal upwelling which may feed back as further enhanced land-sea temperature contrast.
Figure 3. (a) Diagram of a long-term upward trend descriptive of "greenhouse"-related intensification of coastal upwelling, as well as of associated increases in total primary organic productivity of affected marine ecosystems. (b) "Optimal environmental window" relationship between wind intensity and reproductive success in upwelling regions (re-drawn from Cury and Roy, 1989).
Figure 4. Annual catches of *Sardinella aurita* off Ghana and Côte d'Ivoire, with the linear trend diagram from Fig. 3a superimposed.

a. North Africa - 16N, 3W (FNOC Analysis)

b. Measured Pressure - Tombouctou, Mali

c. Measured Pressure - Mopti, Mali

d. Measured Pressure - Bamako, Mali

Figure 5. Spring-summer (April-September) time series of atmospheric pressure (mb-1000) in the interior of northwestern Africa. (a) Series produced from large-scale analyzed pressure fields obtained from the U.S. Navy Fleet Numerical Oceanography Center. (b), (c), (d) Three independent series of measured barometric pressure for three observing stations in Mali.
SARDINES (JAPAN, PERU-CHILE, CALIFORNIA)
BENGUELA ANCHOVY
NORTH PACIFIC GROUNDFISH (ALASKAN POLLOCK AND OTHER STOCKS)
LOBSTERS, SEA BIRDS, SEALS, REEF FISHES IN TROPICAL NORTH PACIFIC
NEWFOUNDLAND-SPAWNING NORTHERN COD STOCK

IN OPPOSITE PHASE:
ANCHOVIES (JAPAN, PERU-CHILE, CALIFORNIA)
BENGUELA SARDINE
NORTH PACIFIC ALBACORE

"CRASHING" FOLLOWING MID-1980s
BRAZILIAN SARDINE (Sardinella aurita)
NORTHERN COD STOCKS
BALISTES (W. AFRICA)

Figure 6. Diagram characterizing a pattern of variation, observed in many marine fish populations, showing a period of increased stock productivity and rapid population growth in the decade from the mid-1970s to the mid-1980s, followed by stock declines after the mid-1980s. Various fish populations whose stock fluctuations have been in phase with (or in opposite phase to) the pattern are listed.
Figure 7. Low frequency non-seasonal variations of several properties of the ocean area off north-central Peru (12-month running means of monthly averages of maritime reports). Series are re-drawn from Bakun (1987). Letter/arrow symbols at top indicate conventionally-accepted moderate («M») and strong («S») El Niño years.
Figure 8. Circulation anomalies at the jet stream level during El Niño (northern hemisphere winter). The stippled area indicates the eastward extension of cloud cover and rainfall in the equatorial Pacific (re-drawn from Horell and Wallace, 1981).
Figure 9. Diagram illustrating a hypothetical "tropical" ENSO teleconnection between the Pacific and Atlantic. The figure represents the vertical plane along the equator. (a) During a Pacific ENSO phase, the strengthened Atlantic trade winds, due to anomalous expansion of the zone of rising air to extend over northern South America, build up anomalous trans-Atlantic slopes in the sea surface and thermocline along the equator, and associated anomalous surface temperature contrasts. This sets the stage for (b) an El Niño-like collapse of the intensified Atlantic system the following year. (Re-drawn from Bakun, in prep.)
Figure 10. Near-equatorial sea surface temperature in the Gulf of Guinea (July-September averages, 2°N - 2°S, 8°W - 12°W). Values re-drawn from Mahé, 1991). Added trend line is fitted by eye. Letters/arrow symbols indicate conventionally-accepted moderate («M») and strong («S») El Niño years.

Figure 11. (a) Wind-induced turbulent mixing index off Peru (Panel “d” of Fig. 6) juxtaposed with (b) variations in river flow (mean of 13 rivers) in the Gulf of Guinea (after Mahé, 1991).
Figure 12. Annual catches of *Sardinella aurita* off Ghana and Côte d'Ivoire, with the dome-shaped trend diagram from Fig. 6 superimposed.