The CEOS Comparative Analysis Framework: Motivations and Perceived Opportunities

ANDREW BAKUN

Food and Agriculture Organization
of the United Nations (FAO)
Fishery Resources and Environment Division
Viale delle Terme di Caracalla
00100 Rome
ITALY

ABSTRACT

A number of features of the CEOS (Climate and Eastern Ocean Systems) scientific analysis framework are cited and discussed: (1) the specific focus on application of the comparative method, (2) the use of nonlinear empirical techniques, (3) inclusion of both biological-ecological and socioeconomic aspects within a common investigative design, (4) installation of integrative conceptual bases (e.g., the 'triad') for organizing multidisciplinary research activity.

Radical interdecadal variability may be intrinsic to many important fish populations and may introduce serious difficulties with respect to certain conventional tools of fisheries science. If, however, the apparent global synchrony in interdecadal-scale fluctuations reflects true mechanistic linkages, it may signify some substantial simplifications in the problem of developing scientific predictive capability.

RÉSUMÉ

Un certain nombre de caractéristiques du réseau scientifique CEOS (climat du bord est des océans) sont énumérées et discutées : (1) l'application de la méthode comparative,

(2) l'utilisation de techniques d'exploration dans le domaine non-linéaire, (3) l'intégration des aspects biologiques-écologiques et socio-économiques au sein d'une même approche, (4) mise en place de concepts de base (par exemple, la "triade") pour organiser une recherche pluridisciplinaire.

D'une décennie à l'autre des changements drastiques peuvent être observés pour de nombreuses populations de poisson et cela est difficilement explicable avec les outils classiques développés en halieutique. Si, cependant, la synchronie apparente de ces fluctuations décennales reflète l'existence d'un véritable mécanisme causal, cela peut singulièrement simplifier le problème de la capacité prédictive.

1. BACKGROUND

The oceans cover nearly four-fifths of the earth's surface and more than a billion people rely on fish as their main source of animal protein. In some countries, fish are nearly the sole source of animal protein. Demand for food fish and various other useful attributes obtainable from the sea has been accelerated by population growth and by the global trend toward population migration toward coastal areas.

Fisheries and fish products provide employment to nearly 200 million people. Globally, the bulk of the people employed in fisheries are poor and many are without acceptable alternative sources of work and sustenance. In addition, fish and fishing are enormously important to the cultural life of many coastal societies, and may often define a 'quality of life' for people having a cultural tradition of harvesting the sea. Hence, maintenance of viable fishery resources may be extremely important to preserving traditional ways of life, associated economic activities, tourism, etc. In addition, fish represent the fastest growing food commodity entering international trade. Accordingly, fish and fish products represent an extremely valuable source of foreign exchange to many countries, in some cases providing as much as half of total available foreign exchange income.

The methodologies of fisheries science are intended to ensure sustainable resource populations to support productive and profitable fisheries. Unfortunately, the conventional methodologies are not working very well. Over and over again, extremely important fish stocks around the world have been collapsing, causing economic dislocations and personal suffering to people whose livelihood depends on fishing or on related commercial activities. Some would say that it is not the methodologies that are at fault, but that the problem lies in imperfect application of the methodologies; there is always somewhat of an adversary relationship between conservation-minded fishery scientists and the fishing industry, and at any time there are always some who say less fish should be taken. But it seems fair to say that the sudden onset of most of the collapses comes as a relative surprise to the 'mainstream' of fishery scientists involved.

Figure 1 is an illustration of an aspect of the conventional conceptual basis for scientific management of an exploited fishery. The concept is one that may apply well to many terrestrial systems, such as to the management of buffalo on a prairie grassland or of wild deer in a natural forest area. The idea is that at high population sizes (to the far right of the diagram) the population may be using up its available resources of food, habitat space, etc. In such a case, if the population size is reduced by harvesting, the productivity of the stock may actually be improved (i.e., in the diagram the system moves to the left toward the 'peak' of the stock-recruitment curve where the rate of production of new members of the population is highest). This has the comforting implication that accumulation of new individuals that would tend to increase the population to stock sizes that lie to the right of the peak, represents a 'surplus production' that can be safely (and, in fact, beneficially) harvested.

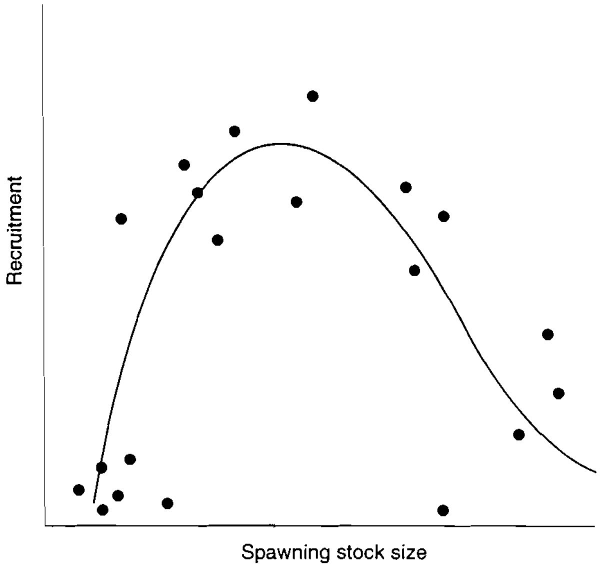


Fig. 1: A dome-shaped 'stock-recruitment curve' fitted to the same data points as used to construct Fig. 2 (modified from Bakun, 1996).

The fact that the methodologies based on a conceptual model that reflects experience with wild terrestrial populations are not generally working very well for marine fish populations has led some to the notion that marine ecosystems may represent 'chaotic systems', in which unexpected results are a feature intrinsic to the system's dynamics. Certainly, the coupled nonlinear equations that describe the dynamics of predator-prey systems represent classic examples of mathematical chaos (May, 1979). Even very simple models of biological population interactions tend to exhibit chaotic behavior. But, the idea that one is working with chaos in attempting to manage fishery resource populations seems defeating. If tiny changes in initial conditions could indeed lead to widely differing outcomes, then there would appear to be little hope of beneficially affecting the outcome by intelligent and prudent adjustments of the rate of exploitation. Happily, there are some recent developments that seem to contradict such a point of view.

2. RADICAL INTERDECADAL POPULATION VARIABILITY

It is only recently becoming widely recognized by fishery scientists that extreme variability may be an intrinsic feature of many fish populations. Contributing to the developing change in outlook has been the evidence derived from deposits of fish scales in sediments (Soutar and Isaacs, 1974; DeVries and Pearcy, 1982; Baumgartner *et al.*, 1992). These sedimentary records indicate that radical fluctuations in fish population abundance have been common occurrences long before the advent of large-scale fishing.

Moreover, in the period for which data records from fisheries have been available, abrupt population declines have been recurrent features. The decadal period from the mid-1970s to the mid-1980s was particularly remarkable in this respect. A pattern of population increases during that interval, followed by population declines after its end in the mid-1980s, seems to have been extremely widespread and consistent (Lluch-Belda *et al.*, 1989, 1992; Bakun, in press). For example, this mid-1970s to mid-1980s period was one 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, 1993). Conversely, since the mid-1980s these populations are in decline, in spite of continuing elaborate stock assessment activities and state-of-the-art fishery management efforts. Alaskan salmon stocks also increased dramatically during the mid-1970s to mid-1980s period. 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 (Polovina *et al.*, 1994); conversely, since the period ended in the mid-1980s, lobster landings from this area have dropped by two thirds (Anon., 1993) and other biological populations are in a downward trend.

On the other hand, North Pacific Albacore tuna appear to have suffered a steep population decline during the mid-1970s to mid-1980s period (FAO, 1993). Many salmon stocks of the California Current also declined during this period (Pearcy, 1992; Francis and Hare, 1994).

Remarkably, 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 somewhat 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 at extremely low numbers 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. Now, toward the latter part of the 1980s, the above-mentioned additional simultaneous reversals in trend have occurred (Lluch-Belda *et al.*, 1989, 1992).

Since the advent of substantial fisheries, anchovy populations have been generally out of phase with the sardine populations in the three regions. In the California Current, after a time lag of about a decade following the sardine collapse, the anchovy population increased to the point that over 340 000 tonnes were taken in 1981. Off Japan, the anchovy catches grew during the period of low sardine abundance following the initial sardine 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. More recently, as the Japanese sardine population declined, extremely large shoals of anchovy were reported (Lluch-Belda *et al.*, 1992)

In the Peru-Humboldt Current system, the fishery for anchovy (anchoveta) peaked in 1970 at more than 13 million tonnes, constituting by far the largest single fishery that has ever existed on earth. It then collapsed to less than 1 million tonnes after the 1972 El Niño, rebounded briefly to about 2 million tonnes for several years, and then fell back following the 1976 El Niño to below 1 million tonnes and remained at this relatively low level during the period of sardine abundance up to the mid-1980s (see contributions in Pauly *et al.*, 1989). Now as the sardines are plunging, once again the anchoveta population is explosively building to the point that it promises to return Peru to its former position as the world's 'number one' fishing nation (Mendo, 1994), at least until the next El Niño event. These radical alternations between sardines and anchovies occurring on interdecadal time scales have been given the name 'regime change' by Lluch-Belda *et al.* (1989).

Thus, we have a situation in which fish populations distributed in widely distant parts of the Pacific, and in other oceans of the world as well (Bakun, 1996), appear to be fluctuating in a degree of synchrony. The populations are certainly far too widely separated to interact in any direct way. For example, the populations of sardines in the different 'corners' of the Pacific were considered until very recently (Parrish *et al.*, 1989) to be separate distinct species. But as one views the variability of more and more populations, and notes the same apparent rhythms, the idea that the variabilities are somehow interlinked becomes compelling.

3. THE BAD NEWS

This presents us with somewhat of a 'bad news' versus 'good news' situation. In large part, the parameter estimations for the various conventional models used in fisheries science depend in one way or the other on equilibrium assumptions. Without the assumption that the various data points can be regarded as reflections of an identical process, albeit with a substantial random noise component superimposed, the degrees of freedom available to produce estimates vanish. Thus one can't obtain the needed parameters even if the methodologies should be appropriate.

However, radical variability on interdecadal scales may also introduce serious problems in the methodologies themselves. For example, consider the following heuristic example, taken from Bakun (1996). Let us artificially construct a stock-recruitment 'history' (Fig. 2) for some hypothetical fish stock that followed the dome-shaped productivity pattern discussed above, using only the concept that good recruitments contribute to population growth and poor recruitments to population decline. Let us say, for example, that in the early 1970s recruitment and stock size both remained low. Then suddenly, near the mid-1970s, a series of good recruitments caused the stock to progressively build (i.e., the points move progressively to the right in the diagram). Then, suppose that near the mid-1980s the recruitment levels fell back to a lower mean state and so stock size progressively decreased (i.e., the points move back toward the origin of the diagram).

If a 'stock-recruitment curve' is fitted to these points (see Fig. 1 which was purposely constructed from these same 'data' points), the fit is really quite good compared to many examples one sees in the fisheries scientific literature (e.g., see examples in Rothschild, 1986). Following the usual logic, the fact that the fitted curve turns sharply downwards at the high biomass side of the diagram would imply strong compensatory density-dependence and therefore surplus production that could be freely exploited with no damage to stock productivity (in fact improving average reproductive success) as long as the stock biomass is not allowed to fall to the left of the peak of the curve. Under such a logic, all management would need to do would be to keep the stock size somewhere toward the middle of the curve and all should be well.

But of course, this is a delusion. The concept used to generate the data points underlying this curve was not density-dependence, but simple addition: a group of good recruitments adds up at some later time to large spawning biomass (see for example, Sharp *et al.*, 1983). It is recruitment controlling population size, not population size controlling recruitment. Any apparent density-density dependence in this particular example is illusory. There is nothing in the example to support an implication of 'surplus production', and a methodology based on such an implication may be comforting to those trying to balance exploitation and conservation, but totally wrong in this case.

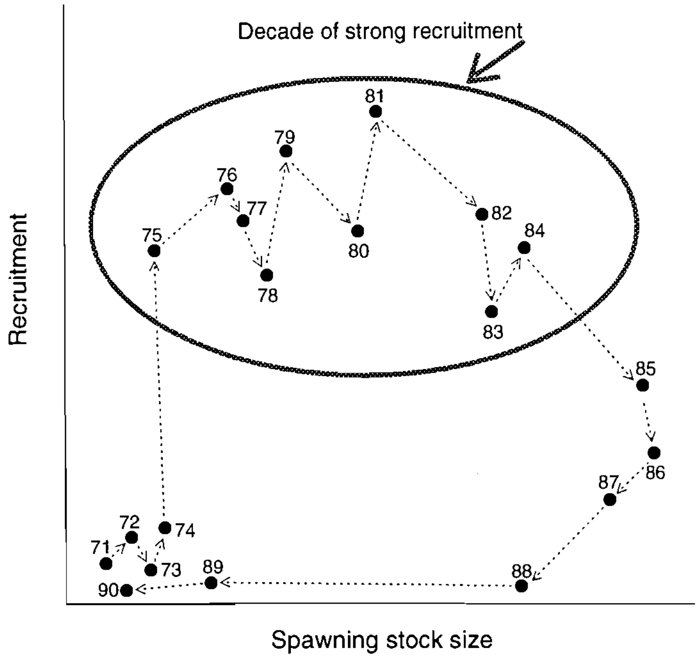


Fig. 2: Hypothetical stock recruitment diagram for a fish population that has exhibited a 'dome-shaped' productivity curve, with particularly high recruitments in the period from the mid-1970s to mid-1980s. Numbers next to each point indicate the year ('71' refers to 1971, etc.). Dotted lines connecting points indicate the temporal sequence (modified from Bakun, 1996).

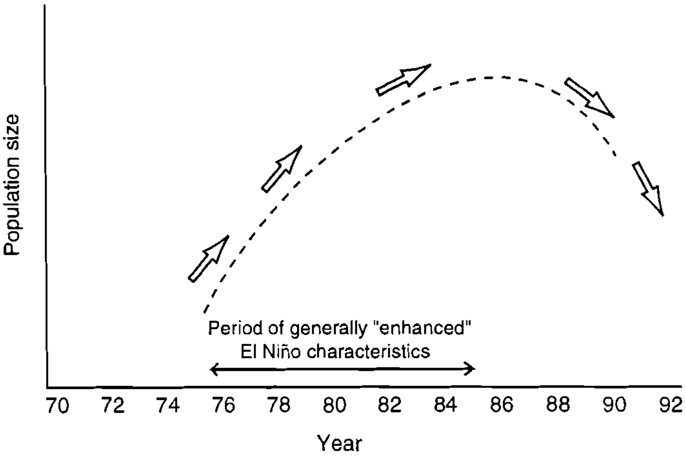
4. THE GOOD NEWS

But on the other hand, there may also be some good news in the situation. If radical interdecadal variability is indeed occurring synchronously in distantly separated fish populations distributed over the world's oceans, there would appear to be some very hopeful implications for the future of our science.

One would think that the separation between the populations must in most cases be far too great for any significant population exchanges or other purely biological interactions that might provide linkage mechanisms which could explain the synchrony. And it seems unlikely that a set of separate autonomous ecosystems, each dominated by its own internal chaotic dynamics, could somehow 'self-organize' themselves to generate mutual synchronous variability on a global scale. Thus, if these populations are indeed varying synchronously, the conclusion seems to be that they must not be functioning primarily as chaotic systems, at least on the time scales of the synchronized variability. There would, in such a case, be no implied tendency toward unstable responses to minute changes in initial conditions and therefore no reason for the earlier-mentioned pessimistic viewpoint concerning potential benefits of careful, skillful fishery management.

It would seem that such synchronous behavior would have to be generated by some type of very large-scale external forcing, most probably through climatic teleconnections acting through the atmosphere. Actually, interdecadal modulations of the El Niño—Southern Oscillation (ENSO) system appear to this writer to be the most likely type of linkage mechanism (Bakun, 1996; in press) (Fig. 3). Moreover, since biological models representing anything but the simplest of marine trophic interactions are characterized by chaotic behavior, the implication of global synchrony would seem to be

Fig. 3: Diagram characterizing the 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 (modified from Bakun, 1996).



that the biological dynamics involved must be very simple. The synchrony must be a rather direct effect of the external physical forcing acting either on the fish themselves, or very directly on a primary food source, at some sensitive life stage. It must not be, for example, an effect working through a complex food web.

If so, then there would appear to be a realistic hope of success in gaining a real scientific understanding of the factors determining reproductive success and population dynamics of fishery resource stocks. If the large-scale linkage is principally through the atmosphere, as seems most likely, it must probably be transferred through the local sea surface, leaving various 'signatures' in the boundary layers of the ocean and atmosphere which exist on either side of the air-sea interface. Temperature trends have not been consistent in the various regions (for example, during the mid-1970s to mid-1980s period when the eastern Pacific was in a definite warm phase, the northwestern Pacific, where sardines were expanding equally dramatically, was in, if anything, a cool phase). Thus it seems most likely that the effect must be a mechanical one. Wind stress acting on the sea surface is the predominant mechanism for transfer of momentum and mechanical energy between the atmosphere and the ocean. Accordingly, we should expect that the causal mechanism we are looking for would be a process, or more likely a sum of processes, driven by the action of the wind on the sea surface.

5. THE COMPARATIVE APPROACH

The experimental method and the comparative method have been called "the two great methods of science" (Mayr, 1982). Drawing valid scientific inference requires multiple realizations of the process of interest, preferably over a range of differing conditions, in order to separate causality from happenstance with a reasonable degree of confidence. The most direct approach to assembling the needed suite of realizations is the experimental method, wherein experimental controls are imposed that allow the scientist to systematically vary conditions of interest while holding other factors constant. But marine ecosystems are hardly amenable to experimental controls. Fortunately, the comparative method presents an alternative. And potentially it is a powerful one. For example, Mayr (1982) credits the comparative method for nearly all of the revolutionary advances in evolutionary biology. The comparative method assembles the separate realizations needed for scientific inference by a process of recognition of informative patterns of naturally-occurring temporal and spatial variations in existing conditions and phenomena. That is, different sets of seasonal and/or geographical settings, encompassing a range of natural variability in conditions and mechanisms, substitute for controlled experimental 'treatments'.

CEOS was designed to apply this approach in a collaborative, multilateral manner, using different regional fish stocks and ecosystems as sources of the multiple realizations needed to draw scientific conclusions (Bakun *et al.*, 1992). Two different general approaches have been used to apply the comparative method to addressing the fish recruitment problem (Bakun, 1985). The first is to compare the seasonality and geography of spawning to the environmental climatologies of several regions in order to try to resolve patterns of correspondence that can point out the dominant common factors appearing to determine the temporal and spatial aspects of reproductive activity. The studies of Parrish *et al.* (1983), Roy *et al.* (1989, 1992), and Bakun (1993) are examples of this type of approach.

The second type of approach involves comparative time series modeling, where empirical model formulations are compared among similar species and ecosystems. Inter-regional consistency can then enhance confidence in empirical relationships. The "optimal environmental window" (Cury and Roy, 1989) is a prime example of an empirical relationship that bears greatly enhanced credibility and influence due to its high degree of inter-regional reproducibility.

6. GOING NONLINEAR

Fish stocks would have a natural tendency to adapt their spawning habits to represent choices of seasonality and geography that would most often yield the most favorable combinations of the principle factors controlling recent reproductive success. That is how natural selection works (Weiner, 1994). Accordingly, fish populations would tend to be adapted to, and therefore fare best under, conditions which are rather typical of their habitual spawning habitats. Therefore it would seem that highest success should be associated more with typical conditions than with atypical conditions on the spawning grounds (unless, for example, the atypical conditions represented favorable circumstances which were not normally available elsewhere within the range of the population). Consequently, one would generally expect 'dome-shaped' relationships, with highest success at intermediate values of a crucial factor and lower success at more extreme values on either the high or low sides. For example, temperature can either be too high or too low, with the optimum for a given species at some intermediate value.

Over the recent period of development of fishery-environmental science, reliance on linear statistics and empirical methods has been very much the fashion. This is in spite of the fact that one would intuitively expect 'dome-shaped' relationships rather than linear ones. Thus it may not be surprising that empirical studies of environment—recruitment linkages have often yielded inconsistent, and therefore intellectually non-satisfactory, results. For example, if an empirical study addressed a situation where in most instances conditions were on one flank of such a 'dome-shaped' relationship (e.g., near an extreme end of species range, etc.), then linear analysis might pick up a significant relationship. Likewise, in another situation where most of the data were on the other flank, an equally significant result, but having opposite 'sign', could be found. In such a case, comparison of the two situations would yield directly opposing results, even though the underlying dome-shaped relationship held consistently in all cases. And of course, if data were distributed on both flanks of such a 'dome-shaped' relationship, linear methods would probably fail completely to pick up any significant empirical relationship at all.

Recently, effective nonlinear methods of empirical analysis have been introduced to marine ecology and fisheries science (Mendelssohn and Cury, 1987; Mendelssohn and Mendo, 1987; Cury *et al.*, 1995). A problem with introducing the possibility of nonlinear relationships is that it is much easier to fit data when one has an indefinite choice of functional forms. Without the discipline of a single a priori choice, such as linearity, the problem of spurious fits becomes even worse than usual. In such circumstances, the discipline of comparative interregional consistency in functional form offers a very useful alternative.

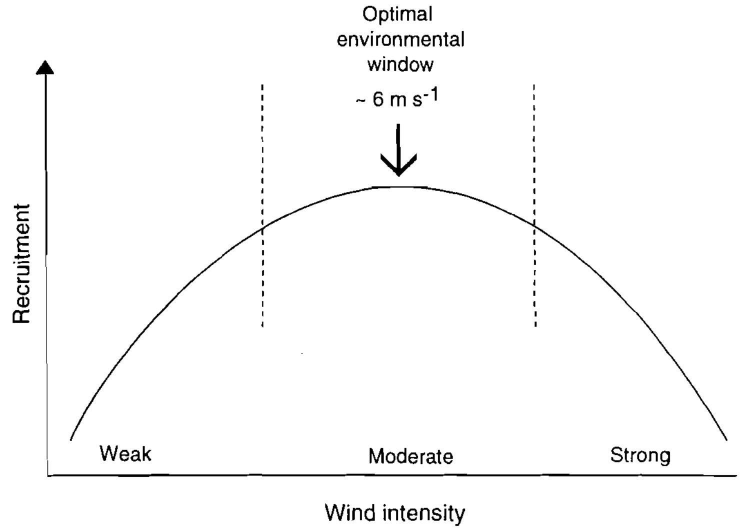


Fig. 4: 'Optimal environmental window' relationship between wind intensity and reproductive success in upwelling regions (Cury and Roy, 1989).

In the preeminent example that we have available up to this time, nonlinear methods were applied in a comparative context to an empirical investigation of effects of interyear variations in mean wind intensity on the population dynamics of various stocks of small pelagic fish in several coastal upwelling regions. The result (Fig. 4) was the famous, domed-shaped, 'optimal environmental window' relationship (Cury and Roy, 1989). This finding, and its follow-on extensions (many of which appear in this volume), finally provides some tangible empirical support for certain concepts (e.g., the 'triad' framework which is presented in the next section) that have been emerging 'inferentially' over the past decade within the context of the international SARP Project (IOC-FAO Sardine-Anchovy Recruitment Project), and more recently, within the CEOS context. It also provides empirical support to arguments such as presented above in Section 4, i.e., that the driving mechanism for synchronized 'regime'-scale population variability must most probably be simply and directly linked to inter-decadal-scale global climatic variability, probably transmitted locally through the sea surface by action of the wind.

7. THE 'TRIAD' FRAMEWORK

Comparative studies of geographical climatology of fish reproductive habitats (i.e., the first type of approach introduced in Section 5) have tended to identify a 'fundamental triad' (Bakun, 1993, 1996, in press) of three major classes of processes that combine to yield favorable reproductive habitat for coastal pelagic fishes and also many 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.

The importance of enrichment processes is quite intuitive and, moreover, tends to be clearly evident in geographical patterns of fish abundance. Most of the ocean surface area is quite unproductive because of scarcity of certain essential plant nutrients, which are trapped below the photosynthetic layers by ocean stratification. And clearly, areas where nutrients are supplied to the illuminated ocean surface layers by upwelling or mixing tend to be highly productive and to contain large, prolific fish populations.

Perhaps less widely appreciated is the importance of concentration processes. For very small organisms, such as fish larvae and other important components of the planktonic food web, sea water represents quite a viscous fluid; major energy expenditures may be necessary just to move from food particle to food particle. Thus large amounts of energy, needed for the rapid growth that is required for quick passage through the various size-related levels of intense predation that pervade the ocean environment, may be expended in feeding activity. Consequently, availability of processes whereby food particles are concentrated tends to be vital.

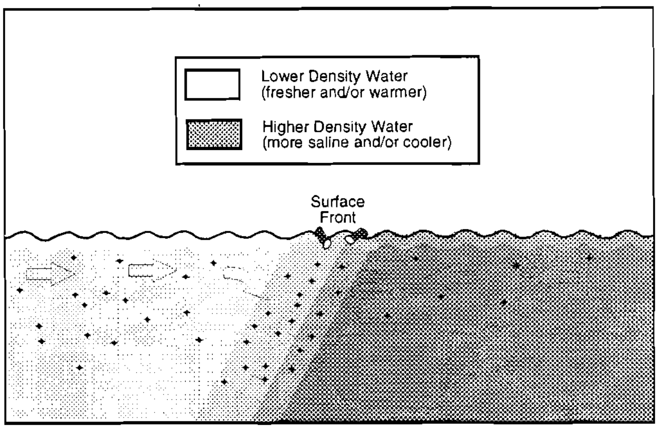
This is probably a major reason why various types of interfaces, or ergoclines (Legendre and Demers, 1985), tend to be sites of enhanced biological activity in the ocean. These interfaces tend either to maintain, or to be maintained by, mechanisms of concentration (Bakun, 1996). Ocean fronts (Fig. 5) are obvious examples. The importance of processes occurring in or near ocean fronts is suggested by the widespread attraction of fish and other marine animals to drifting objects. The actual convergent water motions associated with a front are probably too subtle to be directly sensed by pelagic organisms functioning in an environment devoid of fixed reference points. However, drifting objects tend to be carried into and to accumulate within frontal structures An innate attraction to drifting objects serves to position the fish within the zones of enhanced biological activity and correspondingly improved feeding conditions (Bakun, 1993, 1996).

Conversely, turbulence is a dispersive process and so acts counter to concentration processes. Thus intense turbulent mixing events have appeared to be detrimental to larval survival (Lasker, 1978, 1981a, 1981b). On the other hand, extremely small-scale turbulence may actually act like a concentration mechanism by increasing the encounter rate of small organisms with food particles (Rothschild and Osborn, 1988).

The third factor in the 'triad' is retention. Life cycles of marine organisms tend to include at least one stage of passive larval drift. Thus, in a dispersive fluid medium, loss of early life stages from the population habitat may represent serious wastage of reproductive resources. Consequently, fish populations tend to spawn in locations and seasons that minimize such losses (Parrish *et al.*, 1981; Sinclair, 1988). The triad concept thus incorporates many of the most promising current hypotheses about environmental regulation of fish reproductive success.

Certainly, the optimal environmental window result (Fig. 4) confirms well to an interpretation based on this fundamental triad. An obvious explanation for lowered reproductive success on the 'left flank', or 'low wind' side, is a lack of nutrient-enrichment by wind-induced upwelling or mixing, leading to inadequate production of appropriate larval food (Cushing, 1969). In addition, it is possible that under conditions where the interaction of feeding behavior with stable fine-scale food particle structure may be less important than the energy savings produced by turbulent diffusion of food particles toward feeding larvae, the mechanism of Rothschild and Osborn (1988) may exert some control on the 'left flank' by increasing larval survival toward the slightly higher wind speeds within the 'window'.

Fig. 5: Schematic diagram of a front between waters of differing density. Arrows indicate density-driven flows associated with the front. 'Particle' symbols indicate planktonic organisms capable of resisting vertical displacement. (Scales are distorted: vertical scale greatly expanded relative to horizontal; particles greatly magnified; surface waves not to scale, etc.) Redrawn from Bakun (1993).



The control on the 'right flank', i.e., the 'high wind' side, could come about either through (1) increased offshore transport leading to excessive offshore loss of pelagic larvae from the favorable coastal habitat (Parrish *et al.*, 1981; Sinclair, 1988) or through (2) overly intense turbulent mixing which could disperse fine-scale concentrations of appropriately sized food particles needed for successful first feeding (Lasker, 1978, 1981a, 1981b) as well as inhibit basic photosynthetic production by mixing phytoplankton cells beyond their 'critical depth' (Sverdrup, 1953; Steele, 1974). Strong turbulence might also impair a larva's ability to physically capture prey (MacKenzie *et al.*, in press).

As a framework for research activity, the triad concept has the advantage that it may appeal to both physical and biological scientists, and so provide a common basis for interdisciplinary studies. Moreover it avoids the defeating complexities of small-scale trophic processes that are impossible to observe directly on population scales and thus to formulate as indicator time series for empirical analysis and verification. (These of course must be extremely important processes in the overall trophic economy upon which fish populations depend. But in terms of influence on radical interdecadal population variability, if the 'good news' arguments presented in Section 4 are valid, one can reason that these trophic complexities must be operating somewhat in the background and not directly controlling the fluctuations. Thus, in this respect they would seem to be less important than the direct linkage of the physical climatic system, through the triad processes, immediately to the fish themselves).

8. INCORPORATING SOCIOECONOMICS

Fisheries scientists would like to think that if the industry would only do what the scientists advise, everything would be all right: populations would remain prolific and productive and fisheries would remain profitable and sustainable. This might not be true, and the notion may lead to a false sense of security that contributes to the disastrous level of overcapitalization of world fisheries (FAO estimates that world fisheries operate at an annual loss of US$53 billion, which must be offset by government subsidies). It seems rather likely that, for many highly variable populations, there may be no management system that would succeed in maintaining them continuously at population sizes approaching a large fraction of historical peak levels.

Even so we should be able to learn from experience to avoid some of the economic losses and social dislocations. In the cases of inherently variable classes of fishery resource populations, rather than clinging to the hope of managing the populations so as to provide secure bases for stable fisheries, it may be necessary to shift the focus toward directly managing the fisheries and to developing 'robust' strategies for economic viability under conditions of radically varying resources. For one thing, a holistic view of risk and uncertainty might help avoid the disastrous overcapacity that has made fisheries a net burden on other economic sectors. This in turn would tend to ameliorate the overfishing problems, and would certainly promote better economic return to those earning their livelihoods by fishing and associated activities.

In order to 'learn from experience' in dealing with such issues, CEOS incorporates both environmental biology and socioeconomics as major components of its comparative research framework. In fact, CEOS is the only international scientific program addressing small pelagic fisheries that includes both biology and socioeconomics as substantial components.

Of course development of robust strategies is one thing and specific scientific prediction is quite another. Taking an analogy (and jargon) from the American stock market, 'dollar cost averaging' is a robust strategy, i.e., one that may serve to maximize earnings by maximizing the likelihood that, on average, more shares are bought when the markets are in a lower price phases than when they are in higher price phases. This may a good type of strategy when no specific prediction is possible and when the markets are reasonably well-behaved. But every stock market player knows that 'dollar cost averaging' is no match for 'insider information' (i.e., specific foreknowledge of market events). In the sense of this analogy, one might say that the goal of CEOS is to generate some real, tangible 'insider information' on fishery resource variability and attendant socioeconomic consequences.

So, one might ask what level of prediction one might hope for. Well, maybe the least we might expect on the near term would be to be able to reasonably identify when we may be in a period of transition or 'regime change'. At such a time, for example, a particular level of precaution might be appropriate. One might be warned that the experience accumulated during a recent period of relative stability may not hold in the new conditions, or that equilibrium models that may have been valid to some level of approximation over the previous period may no longer be so, or that a recent high catch per unit effort may not indicate that the population is doing particularly well, but only that conditions have changed (recall the Peruvian experience of very high catch/effort occurring just before the disastrous collapse of the anchoveta fishery in the early 1970s). These may represent very valuable pieces of foresight. And that level of prediction indeed seems a realistic hope, particularly in view of the relative simplification (see Section 4) of the system response that may be implied by the apparent interregional synchronies.

9. PATHWAYS AHEAD

The retrospective analytical approach, making use of the new analysis techniques applied in a comparative context, has predominated in the first years of CEOS. The most extensive application has been on the biological-ecological side of the spectrum of issues. Here, the 'triad' idea has been implicit in the choice of independent variables (i.e., in the extensive use of wind-related indices of transport, turbulence generation, upwelling, etc.).

There would seem to be room for expanded use of a similar approach on the socioeconomic side. Of course, advances on an underlying conceptual framework (in analogy to the ecological side where we have the 'triad', for example) on which to structure empirical analysis activities will be extremely useful. To this end, some additional very basic interregional comparative 'pattern recognition' among the available histories, anecdotes, and informational fragments might be warranted. The conventional management approach of trying to keep the size of a resource population continually at a relatively high level by managing the level of fishery removals, and thus to provide a basis for a relatively static fisheries industry, is simply not working in a substantial number of cases. Fisheries science badly needs an alternative, but it must be one which can stand up to rigorous evaluation (Sissenwine, 1993). Although in many situations it may not be possible to maintain a desired population level by adjusting fishing pressure, it most clearly will always be possible to destroy a population by too much fishing. In a situation in which it is obviously in no one's interest (except perhaps in the very short-term interest of very selfish entities) to utterly destroy a resource, the conventional methodologies at least provide a formal basis for saying 'stop fishing now'. So, until there is available a specific well-founded alternative, it is clearly unwise to dismantle or discredit what is in place.

On the ecological side there seem to be some promising opportunities to become more process-oriented. The train of logic developed earlier suggested the probability that the interregional linkages are transferred from the atmospheric teleconnections to the ocean ecosystem through the sea surface. Many of the triad processes involve transfers through, or changes in properties of, the sea surface skin. Consequently they may leave 'signatures' that might be identified from satellites. This is a timely consideration because there will be shortly up to five separate ocean-specialized satellites in orbit and active; previously there has been no more than one at any one time (Kieffer, pers. comm.). This new generation of ocean-oriented satellites will also provide new tools. For example, useful direct estimates of ocean primary productivity from satellites are a strong possibility.

Satellite images represent a wealth of spatial detail that may be linked to triad processes. A key problem will be in converting this information to the longer time scales for which recruitment information, or other net population-scale outputs, may be obtainable. The standard method for transferring satellite information to longer time periods has been by making longer-term averages of the data. However, such an averaging process degrades the spatial detail which is the strongest feature of satellite-derived information. The trick will be to find a more intelligent way to deal with the short time-scale data flow.

The triad framework may be of use in identifying features or qualities that may in some way be quantifiable to the extent that index time series could be developed. Advanced statistical techniques such as spectral EOFs (Mendelssohn and Roy, 1986) may be useful in this regard. Perhaps the techniques of 'artificial intelligence', using neural network computer software, etc., might be enlisted to make use of ever more available and less expensive computer power to deal with finding and resolving the pertinent features from within the enormous data flows produced by satellite-mounted sensors (i.e., to allow the computer itself, through shear computing power, to 'learn' to recognize the relevant attributes). Another technique to rationally carry the spatial detail provided by satellite observation systems to the longer time scales associated with population-scale recruitment success is to use the satellite information to drive coupled dynamic coastal ocean models that may correctly incorporate pertinent triad mechanisms. Testing of this approach is currently being implemented in a CEOS-associated study off Senegal (C. Roy, pers. comm.).

There appear to be some key biological—ecological questions involved in the development of greater understanding of the nature interdecadal regime changes and how best to cope with them. These are often questions that are particularly difficult to address. I have often felt (Bakun, 1996) that there are two types of questions in our business. One type are questions for which we can get answers but don't need them and the other type are questions for which we need answers but can't get them.

One major one of the second type is: 'What is the nature of the interaction between anchovies and sardines?'. The classic example of regime change involves a shift of dominance between anchovies and sardines within the extremely important small pelagic fish component of the trophic structure of an ocean boundary current ecosystem. But it is unclear by what mechanism these two groups might interact to effect displacement of one by the other. Some level of 'competition' seems to be implied if indeed there is a tendency for mutual exclusion. But if the dominant mechanism were some kind of predatory exclusion such as a very major effect of predation of adults of one group on the eggs of the other, etc., it would seem to be counter to the earlier arguments about global synchrony in populations (i.e., lack of major predatory interactions, corresponding absence of chaotic dynamics, etc.).

One evident difference between the two is that sardines are larger, correspondingly stronger swimmers, and more adapted to migration, while anchovies appear to be more adaptable, being able to utilize a variety of habitat configurations yielding appropriate 'triad' tradeoffs (Bakun, 1993). Since sardines have done well in several systems which evidently experienced intensification of dynamic aspects during the mid-1970s to mid-1980s period, Bakun (1996; in press) speculated that sardines could perhaps deal best with an intensified system (stronger flows, more intense ocean turbulence, etc.). But there is no information presently available as to exactly how such an effect might act. Moreover, this particular argument seems to imply a mechanism acting at the adult stage.

On the other hand, one might think it more likely that the linkage mechanism might be acting at the early life stages through differential effects of climate-mediated alterations in characteristic configurations of triad processes. In such a case, if one could define variability in characteristic triad structures through analysis of satellite imagery, it should be possible to design quite simple and feasible programs to sample spatial distributions of larvae in relation to such structures, and to find out where and if anchovy or sardine larvae were abundant and also where they were growing well; for example, larval growth could be gauged by measuring RNA/DNA ratios (Nakata *et al.*, 1995; Buckley, 1984). Similarly, temporal patterns in survival and growth of the respective species, in relation to temporal variability in the triad physical structures, might be investigated by analyzing daily marks on larval or juvenile otoliths (Campana and Neilson, 1985; Guitierrez and Morales-Nin, 1986) collected at some later time.

Clearly, it will be well to continue to try to find innovative investigative approaches to key issues. One might expect that much of the type of results that can issue from standard conventional sampling programs, 'shotgun' approaches to data gathering, etc., might already be largely in hand and that innovation and ingenuity should be the key to getting the answers we need. CEOS has a number of relative innovations incorporated in its analytical framework: (a) use of nonlinear empirical techniques, (b) a specific focus on application of the comparative method, (c) promising conceptual bases for organizing collaborative interdisciplinary activity (e.g., the 'triad', which integrates both physical and biological aspects in a simple, relatively comprehensive framework), (d) incorporation of socioeconomic aspects together with ecological aspects. This framework has already led to certain salient results, such as the demonstration of the remarkable robustness of the estimated optimal environmental windows.

According to the arguments presented earlier in this paper, the apparent tendency for a degree of global synchrony in interdecadal population variability and 'regime changes' may allow certain conclusions to be drawn, pointing the way to narrowing the range of possible processes and degrees of complexity in the problem. If indeed the biological complexity may be minimal, as appears to follow from the argument, substantial progress on issues that have been resistant for many decades, seems a distinct possibility.

Thus, if the apparent global synchrony is real, it is indeed a 'gift'. There is no reason that such synchrony would have had to occur. But if indeed it does occur, it is surely rife with significance. We should carefully decipher the full range of implications in order to make good use of the information in directing our research activities along particularly cogent pathways. In particular, it could be very meaningful as regards fisheries science itself. For example, it would appear to imply that the key problems in our science are problems we can address, without being lost in endless complexities. Ultimately, it could mean that fisheries management need not forever be a sort of operational craft, based on 'rules of thumb' and aphorisms, but rather have at its disposal real prognostic power based on understandable mechanisms and sound scientific laws. More immediately, it could mean that, after decades of frustration, real, tangible progress on the fisheries-environment problem may be within our reach. That would be very good news indeed.

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