THE INTERNATIONAL RESEARCH INSTITUTE FOR CLIMATE PREDICTION

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IRI

Climate and Fisheries

INTERACTING PARADIGMS, SCALES, AND POLICY APPROACHES

The IRI-IPRC Pacific Climate-Fisheries Workshop Honolulu, 14-17 November, 2001

Co-organized with
The International Pacific Research Center (IPRC)

SUPPORTING CO-SPONSORS OF THE WORKSHOP:
The North Pacific Marine Science Organization (PICES)
The Center for Sustainable Fisheries (CSF), University of Miami
The GLOBEC International Project Office
The IDYLE Project of the French Institut de Recherche pour le Développement (IRD)

OTHER ORGANIZATIONS PROVIDING SUPPORT FOR ATTENDEES:
The Intergovernmental Oceanographic Commission (IOC)
The Food and Agriculture Organization of the United Nations (FAO)
The NOAA Office of Global Programs
The National Aeronautics and Space Administration (NASA)

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The IRI-IPRC
Pacific Climate-Fisheries Workshop
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14-17 November, 2001

EDITORS
Andrew Bakun and Kenneth Broad

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WORKSHOP DISCUSSIONS: 2. FUTURE DIRECTIONS

An international workshop on research issues related to interactions between climate variations and fisheries was held at the East-West Center of the University of Hawaii in Honolulu from November 14th to 17th, 2001. Forty-eight invited participants represented a sampling of top-tier international scientific expertise with respect to climatic effects on fishery resource populations, fishing operations, and fishery-related socioeconomic issues. An unusual aspect was the interaction of physical, biological, and social scientists at all levels of the discussions. No prepared papers were delivered. Rather, the intended focus was on interdisciplinary and interregional "cross-education" and cross-sharing of insights and ideas among scientists with experience ranging over a variety of species and industry types, intended to support a collaborative process of:

- identifying alternative conceptual frameworks and ideas that may better support fruitful interdisciplinary collaborations (particularly between climate scientists and fishery scientists of both the "ecological/biological" and "social science" types);
- exploring associated implications for innovative fisheries management approaches;
- considering potential applications of the comparative method as a means for effective multilateral research on climate/ecosystems/fisheries issues in the Pacific basin;
- exploring in this regard the potential utility of certain newly available technologies and methodologies.

The discussions both in plenary sessions as well as in various separate "focus group" sessions were wide-ranging and animated. General consensus emerged on a variety of issues. It was widely agreed, for example, that: (1) as our available records of data and experience grow longer, the observations are not adding up to picture that conforms to conventional scenarios. Effects of environmental variability on fish stocks and fisheries can no longer be ignored, but we remain stuck in a paradigm that has existed for half a century and that is not solving the problem in any general way; (2) we need to move away from focusing so much of our available effort on identifying particular specific relationships and on producing empirical models fitted to specific sets of data, but rather to undertake efforts at more general synthesis that can generate testable general hypotheses (i.e., we need to search for mechanisms and processes, not correlations); (3) climate forecasts (e.g., ENSO forecasts, etc.) do have significant potential value for the fisheries sector, but the information content must be relevant, communicated properly, and compatible with available decision-support models; (4) downside risks related to reliance on a poor forecast might in many cases outweigh potential benefits; however, we should not abandon the search for means to produce good forecasts; (5) inter-decadal-scale "regime shifts", along with associated large-scale synchronies in resource population variations and resultant socioeconomic issues, probably represent the "hottest" current set of climate-fisheries research topics. The apparent large-scale synchronies would seem to indicate a rather direct link of climatic events to resource population dynamics, which led to optimism among a significant portion of the workshop participants that major progress on the "climate to fish" portion of the problem might be possible on the near term.

On the other hand, there were also areas where broad consensus seemed to be lacking. For example, some participants were quite excited about the potential role of rapidly-evolving adaptive response mechanisms, but there was a general level of concern over a lack of clear evidence for their actual operation and significance in real ocean ecosystems. Likewise, certain participants advocated the idea of a comprehensive collaborative global empirical (statistical) study of available time series of relevant data, but there were questions as to exactly how and by which groups such a grandiose multilateral "desk study" of historical data would be conducted.

On the social science side, there was emphasis on identifying the range of potential decision-makers in the fishery sector beyond just managers, and matching the temporal and spatial scales of their decisions to our current knowledge and predictive capabilities concerning climate and marine ecosystem interactions. There was also widespread consensus on the need to seriously consider communication issues, including interactions with the media, industry, and policymakers in order to avoid misinterpretations and resulting unintended consequences (e.g., exacerbation of inequity) of the provision of uncertain information. Along those lines, there was intense discussion around the question of when is the science good enough to "go public", specifically in regards to the topic of regime shifts.

Several interesting ecological hypotheses were proposed and discussed. One of these that appeared to excite particular interest focused on gyre-wide variations in the content of mesoscale activity in the system as being potentially involved in basin-scale synchronous alterations between sardine and anchovy dominance. More generally along this same line, the basic proposition that the essential linkage of the large-scale climate forcing to fish population dynamics may act through smaller-scale processes such as occur in mesoscale ocean features excited considerable interest. Accordingly, the problems of "downscaling" from global-scale and ocean basin-scale models to regional eddy-resolving models were assigned high-priority for focused research efforts.

The subject of marine ecosystem regime shifts clearly stood out as an issue of major importance to proper scientific management of fisheries and fishery resource populations. It appears to be not yet entirely clear whether all, or even most, major marine ecosystem regime shifts are causally linked to climatic regime shifts. However, in the case of the mid-1970s shift, the prototype upon which the current concept of a marine ecosystem regime shift is largely based, a clear climatic regime shift was indeed roughly contemporaneous to the initiation of the impressive decadal-scale population increases, as well as some important decreases, noted in many of the largest fishery resource stocks of the world, especially in the Pacific. It appears that it might be time for some globally-focused institution (or group of cooperating institutions) to undertake monitoring and rapidly disseminating available information on evidence for large-scale ecosystem regime change occurring in the world's oceans.

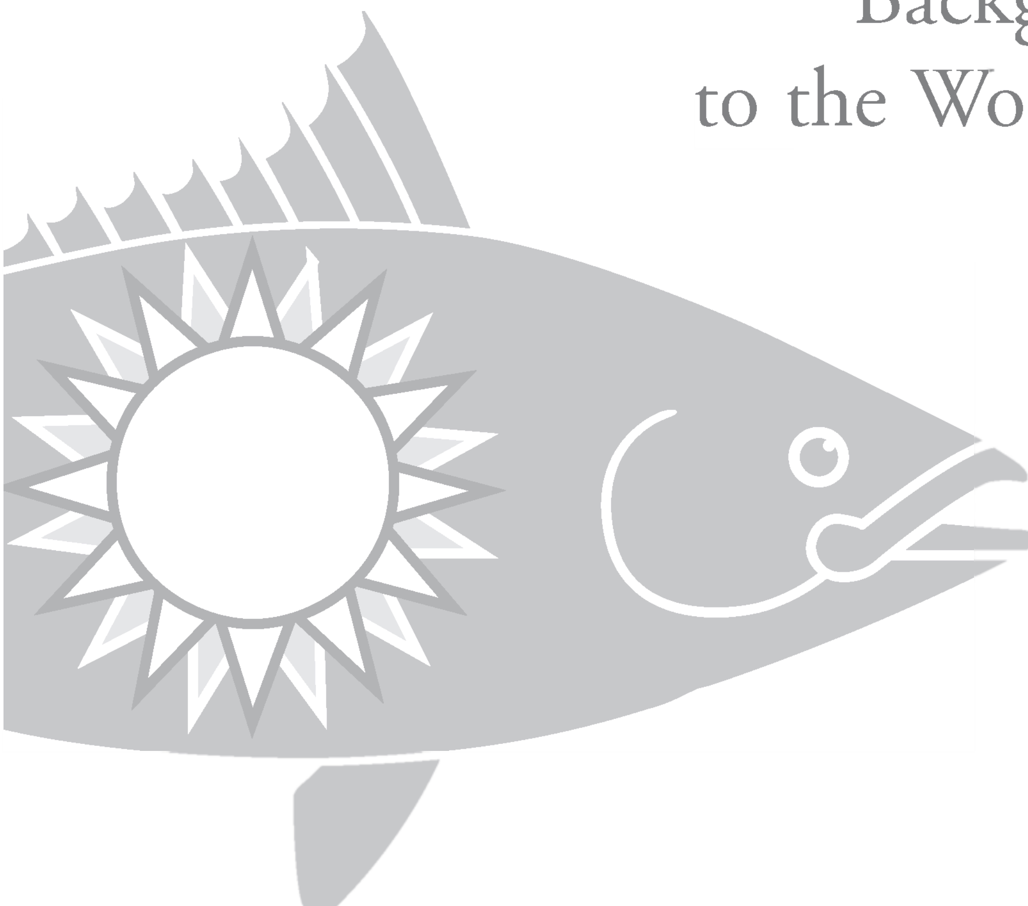
In terms of immediate fruitful application of state-of-the-art climatic analysis and prediction to current real-world fisheries problems, the relatively advanced available understanding of Pacific ENSO-related phenomena would appear to suggest that the most likely early successes might be attained with respect to the tuna fishery concerns of Pacific island nations and fisheries issues faced by the Pacific coastal nations of Latin America.

The structure of a proposed multi-lateral Oceanic Fisheries and Climate Change project (OFCCP GLOBEC) designed to investigate the effect of climate change on the productivity and distribution of oceanic tuna stocks and fisheries in the Pacific Ocean was described and discussed. Its conceptual design and its goal of predicting short- to long-term changes and impacts related to climate variability and global warming were much-admired and its implementation was supported. In addition, the idea of initiating a worldwide comparative research project on tunas and other oceanic "top predators", of which the regional OFCCP project in the tropical Pacific could be a cornerstone, received strong support. This global "umbrella" project (code-named "CLIOTOP") would ideally be developed within the International GLOBEC context.

In addition to these tuna-related initiatives, there was consensus that general basic climate-fisheries research issues, common to a variety of species and ecosystem types, could be effectively addressed on a regional basis in the Pacific. The participants agreed that IRI, IPRC, and the PICES Secretariat should be asked to collaborate in identifying an effective conceptual framework for such a multilateral Pacific climate fisheries project, as well as a process for developing and implementing it.

There was widespread agreement that the inclusion of a strong group of fisheries-experienced social scientists together with climate scientists, oceanographers, and biologists had been a very productive and successful aspect of this workshop. It was recommended that follow-on research project development activities adhere to the same model.

Background to the Workshop



1 *Introduction*

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 practically 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 to 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.

Fisheries have become a very big business. Modern, highly capitalized fleets now range the oceans of the world, in some cases competing for a limited common property resource with traditional fishermen and communities. Massive overcapitalization of the global fishing industry is, in fact, an enormous problem. The Food and Agriculture Organization of the United Nations a few years ago estimated that world fisheries on a global basis operate at an annual deficit of US$53 billion. Thus present day commercial fisheries actually represent a large net burden on other economic sectors. This unfortunate situation is at least to some degree due to lack of a sound scientific basis to correctly gauge sustainable productivity of the resources and to effectively manage impacts in the face of large-amplitude variability in both physical and biological aspects of ocean ecosystems.

Observations and modeling have led to recent advances in understanding the influence of climate variability on ocean processes and to the recognition of inherent variability of marine biological communities on various temporal and spatial scales. In parallel, there have been dramatic improvements in our ability to conduct biological sampling, genetic identification, etc. In addition, there has been a very large surge of climate research activity in recent years. But with few exceptions, there has been little progress in bringing together results from these related frontiers in a comprehensive framework that can consistently rationalize the accumulating store of information and experience so as to provide a reliable basis for sorting out the various effects of fishing, natural climatic variability, and chronic alterations of environment and/or habitat. The result is that "sustainable fisheries" remains a theoretical ideal rather than a realistic operational goal.

One of the major obstacles involves the large component of climate-associated variance that commonly acts to obscure the results of human actions and to defeat attempts at prediction. Accordingly, ways need to be found to more effectively involve climate scientists in interdisciplinary research collaborations. Furthermore, the time may have arrived to begin to question some of the conventional dogmas, postulates and working assumptions that have guided, but also constrained, fishery science and management through the twentieth century. (These may include, among others, (i) long-term stationarity of basic fish – environment linkages, (ii) absolute uniqueness of specific regional situations, (iii) a predominant effect of trophic interactions, (iv) an expectation that a climate-driven stock oscillation should have essentially the same period as the climatic variation driving it, etc.) Also of great importance is the maintenance and expansion of research interactions with social scientists on the management, economics, and politics of the increasingly competitive use of marine resources and the ocean environment.

Due to major research advances in understanding the ENSO phenomenon, as well as significant progress in predicting it, the prospects for effective early applications of recent climate research progress to marine fisheries issues may be most promising in the tropical and eastern boundary zones of the Pacific Ocean. This is the context which led the International Research Institute for Climate Prediction (IRI) of

Columbia University (1) to undertake organization of an international Climate-Fisheries Workshop, which while having global international participation and treating the climate-fisheries problem in a generalized context, would focus particularly on the Pacific, and (2) to seek the collaboration of the International Pacific Research Center (IPRC) of the University of Hawaii in its implementation and in providing a Pacific venue for its setting.

One of the driving ideas behind the workshop has been that climate variability (on a variety of scales) may, if we are clever, provide us with "experiments" to probe the real mechanistic workings of these ecological-biological-social systems for which ordinary experimental controls are usually impractical (sustainable fisheries development requiring a more accurate understanding of those basic internal mechanisms). Furthermore, a better understanding of the interdependent spatial and temporal scales of "openness" or "closedness" of the resource systems on the ecological side (i.e., on population exchanges and changes in spatial pattern dynamics) could provide opportunities to explore additional options on the fishery management side. In addition, it was thought that some new ideas regarding mechanisms that could conceivably enable extremely rapid adaptive adjustments by marine populations might suggest ways to begin to understand how non-stationarities may be introduced into the processes that link fish populations to the environments that support them, and might also suggest some innovative adaptive management tactics that could conceivably develop into important new tools for managing both climatic and anthropogenic perturbations of fishery resource populations.

It was decided that, in general, the workshop focus would be on:

(1) identifying alternative conceptual frameworks and ideas that may better support fruitful interdisciplinary collaborations (particularly between climate scientists and fishery scientists of both the “ecological/biological” and “social science” types);
(2) exploring associated implications for innovative fisheries management approaches;
(3) considering potential applications of the comparative method as a means for effective multilateral research on climate/ecosystems/fisheries issues in the Pacific basin;
(4) exploring in this regard the potential utility of certain newly available technologies and methodologies.

2 *The workshop*

The Pacific Climate-Fisheries Workshop was held in Honolulu from November 14th to 17th, 2001, at the East-West Center of the University of Hawaii. As mentioned above, the primary sponsors were the International Research Institute for Climate Prediction (IRI), which is located at the Lamont-Doherty Earth Observatory of Columbia University and the International Pacific Research Center (IPRC) of the University of Hawaii. IRI was the primary organizer of the workshop while IPRC provided the venue and meeting arrangements. Also joining the effort as supporting co-sponsors of the workshop were the North Pacific Marine Science Organization (PICES), the new Center for Sustainable Fisheries (CSF) of the University of Miami, the GLOBEC International Project Office, and the IDYLE Project of the French Institut de Recherche pour le Développement (IRD). Other organizations providing support for attendees included the Intergovernmental Oceanographic Commission (IOC), the Food and Agriculture Organization of the United Nations (FAO), the NOAA Office of Global Programs, and the National Aeronautics and Space Administration (NASA). Forty-eight invited participants mainly from Pacific Rim and Pacific Island countries, but also from as far away as Germany, South Africa and the Seychelles, represented a good sampling of the best available international scientific expertise concerning climatic effects on fishery resource populations, fishing operations, and fishery-related economic and social issues. (Names and contact information of the invited participants are listed in Appendix 1.) An unusual aspect was the interaction of physical, biological, and social scientists at all levels of the discussions.

It was specifically intended that the emphasis in the workshop deliberations be on interdisciplinary (and also interregional) cross-education and cross-sharing of insights and ideas. Thus, the larger part of the workshop discussions took place in plenary sessions attended by all of the workshop participants. Discussions in these plenary sessions were chaired by Dr. Juergen Alheit, who has been longtime Chairman of the GLOBEC SPACC (Small Pelagic Fish and Climate Change) Project and the new Chairman of the GLOBEC "Focus 1" Working Group on Retrospective Studies. Dr. Alheit was specifically asked to come to Honolulu to serve as workshop Chairman, not only because of his demonstrated skill in running such meetings to the general satisfaction of all participants, but also to demonstrate the desire of the organizers to position this workshop and the scientific activities potentially resulting from it firmly within the International GLOBEC context. At the workshop, his skill in enforcing analytical focus with humor was appreciated by all.

In addition to plenary discussions, the workshop periodically broke up into separate, slightly less broadly multi-disciplinary "focus groups" for detailed discussions among specialists on particular topics of special interest to the particular group members. The focus groups were arranged as follows:

- Social Science Focus Group (Chair: M. Hamnett)
- Tuna Focus Group (Chair: R. Olson)
- Population Connectivity Focus Group (Chair: R. Cowen)
- Boundary Current Frontal Zone Focus Group (Chair: T. Sugimoto)
- Population-Ecosystem Ecology (Eco) Focus Group (Chair: R. Quinones)
- Climate Focus Group (Chair: A. Miller)

These groups initially met separately. However as the workshop progressed, most of the groups elected to combine in various combinations with other groups for joint discussions.

All sessions of the workshop, whether plenary or of focus groups, had designated rapporteurs. The notes recorded by the rapporteurs, some initial background documents prepared before the workshop by Andrew Bakun and Kenneth Broad, and summaries prepared by several of the focus group chairs form the primary basis for the following sections of this report. Several participants produced original contributions worthy of potential citation. Consequently, where a major section of the report essentially represents an original input prepared almost entirely (with minimal intervention by the editors) of an individual participant, this is indicated by the contributor's name in brackets next to the section title. In other cases, where one or more individuals made major contributions to a particular section, it is indicated in a footnote referenced on the section title. Respective affiliations of these cited individuals may be found in Appendix I. Andrew Bakun and Kenneth Broad, acting on behalf of IRI, with the input and assistance of Lorenz Magaard, Executive Associate Director of IPRC, were the primary planners and organizers of the workshop content and participation. Jerry Comcowich, of IPRC, coordinated operational arrangements in Honolulu, with the aid of Ellen Bahr and other IPRC administrative staff. Gisela Speidel, IPRC Public Relations Specialist, arranged interviews on the workshop with Honolulu newspapers[1]. Bakun and Broad acted as co-editors of this workshop report and are solely responsible for errors in representing the views of the participants.

3 *Adopted terminology*

In order to promote a truly fully-integrated discussion, the following terminology was proposed by the workshop organizers and distributed to participants several weeks before the workshop. The term *marine resource system (*MRS)* was proposed to refer to the entire composite system incorporating:

1. the fishery resource stock itself;
2. its regional marine ecosystem, including all components of its occupied

[1] The resulting articles can be read at the newspaper websites: "Climate could reveal secrets of fisheries" http://the.honoluluadvertiser.com/article/2001/Nov/18/ln/ln15a.html; "Experts examine how climate affects fisheries" http://starbulletin.com/2001/11/17/news/index.html. Dr. Speidel has also written a brief summary of the workshop for the IPRC Climate Volume 2, Number 1.

habitat and the entire trophic web within which it functions;

3. the characteristic seasonal climatology and the basic physical-chemical habitat structure (to which we expect the stock as well as the ecosystem to be "substantially" adaptively tuned);
4. the fishery (or fisheries) on the resource stock in question;
5. associated economic activities (including other, interacting uses of the regional marine ecosystem)and social values;
6. the relevant management framework and institutions;
7. the political context in which the management activities and the economic context operate.

Thus, the **MRS* was considered to be an intrinsically interlinked entity, with each element feeding back on other elements and no element being immune to such feedbacks from other elements. *A priori*, the **MRS* was not expected to be necessarily stationary in any way (in underlying mean state, in long-term trend, etc.). Further it was proposed that, for the workshop discussions, low-frequency (nonseasonal) climatic variability would be considered an external driving force acting on the **MRS*.

The more limited view that is often taken of a marine resource system was assigned the term *fish-habitat system (*fhs)*. This term was intended to refer to the subsystem of the **MRS* consisting of elements (1), (2), and (3).

4 General questions to be addressed

It was envisioned, and communicated to the participants, that the Honolulu Workshop would seek to identify potential research approaches to the following general questions:

(a)What are the effects of climate variability on the **MRS* (and can we potentially forecast these effects based on climate monitoring or forecasting)?

(b)What can climate variability tell us about the internal dynamics of the **MRS* (i.e., can we use climate variability as "experiments" to probe the mechanisms controlling the internal dynamics of the **MRS* – our lack of understanding of which upsets our ability to confidently answer question a)?

(c)What productive management actions could be enabled by significant scientific progress on specific aspects of questions a and b?

Moreover, it was emphasized that priority for discussion of particular aspects of questions a and b would be strongly determined by their potential relevance to question c (i.e., there would be less priority placed on discussing ways to develop the ability to say "the "steam roller is coming and you can't get out of way" than the ability to say "the steam roller is coming and here is what you can do (or try) in order to get out of the way").

5 Relevance for fisheries policy

It was recognized *a priori* that there are parallel trends in the discourse and development of fisheries regulatory mechanisms that focus on very different scales and embrace differing views on the centralization of management. These trajectories have implications for the potential uses of climate information for fisheries management (and fisheries related decision-making in general):

- On the one hand, there is an emphasis on *local level* involvement by multiple stakeholders in decisions regarding establishment of regulatory mechanisms. This emphasis is motivated by an increasing acceptance that without *co-management*, or *community management*, we are less likely to achieve regulatory compliance, anticipate socioeconomic feedbacks from various policies, or incorporate qualitative knowledge about the local ecosystem from long-time inhabitants (e.g., McCay and Acheson 1987, McCay and Svein 1996; Jentoft et al. 1998; Jentoft 2000, Hughey et al. 2000; Berkes et al. 2001).

- On the other hand, we are witnessing the development of an increasing number of *national* and *supranational* agreements – complex bilateral and multilateral treaties on the management of open ocean resources, of shared (straddling) stocks, and regarding ecosystem linkages between widely separated metapopulations (Ward et al. 2000). Underlying the establishment of such agreements is the acceptance that distant bodies of water, lands, and stocks of living resources are linked through large-scale oceanographic and biological processes, and activities in one locale may impact another.

Attention to the traditional approach of limiting the number of fish caught as determined by stock assessment models (i.e., Total Allowable Catch) has resulted in a large body of literature on the constraints and incentives for the adoption of different fishing restrictions. Further, there is extensive documentation of failures using these approaches due to social and ecological factors (e.g., McGoodwin 1990) Intractable limitations in data availability, assumptions of stationarity of living resources, assumptions of human behavior in open access situations, insufficient understanding of multi-species interaction, and climatic influences have been cited as factors that severely limit the efficacy of the many numerical approaches and the subsequent regulations based on model outputs.[2]

Alternative approaches that embrace the complexity, spatial heterogeneity, climatic influences, and data realities are gaining credence in the scientific community. These approaches emphasize an understanding of ecosystem interactions that can result in non-stationarity, and what some characterize as the chaotic nature of the abundance variations of many fish stocks (Bakun 2001). Such interactions are recognized to be important at multiple spatial (e.g., mesoscale events such as wind influenced larval survivability, and macroscale processes – basin wide asynchrony in species regime shifts) and temporal scales (i.e., days, seasonal to interannual, decadal). Of relevance are potential increases in our capability to monitor climatic and biological processes that may improve our ability to predict short term fluctuations in stock abundance. Meanwhile, awareness of fluctuations on longer timescales suggests the importance of understanding how the short-term fluctuations in abundance relate to longer term, more dramatic changes.

In summary, it appears that biological *and* human activities on multiple scales must be addressed. If we consider the implications of the change in approach to management on an ecosystem basis, we are led to consider alternative approaches to managing resources that force us to think about activities at a range of scales. From the policy perspective, certain key questions loosely guided much of the discussion during this workshop that is summarized further in the report:

- What is "the state of the art" in the current ability to predict fluctuations and movement of the major pelagic species in the Pacific on the *various time scales* (i.e., temporal and spatial resolution, forecast skill)?

- In what forms are this information available (i.e., probabilistic forecasts, hindcasting only) and to whom?

- How do we know when this information is "reliable enough" to be used in policymaking, or should we consider these only as hypothetical scenarios?

- How, if it all, is this information being used by policymakers, fishing groups, national governments, and other stakeholders in their decision-making?

[2] For (a controversial) overview of limits of numerical modeling in relation to fisheries management, see Wilson et al. (1994).

- Given current understanding and predictive capabilities, what are the potential uses of this information by the different stakeholders?

- How, if at all, is this knowledge being incorporated into agreements among fishing groups (from local to regional levels). How could it be better utilized?

- What are the constraints and incentives for the use of this information, and do they differ from the traditional ones identified in the literature?

- What are the potential unintended consequences of the introduction of or reliance on this information?

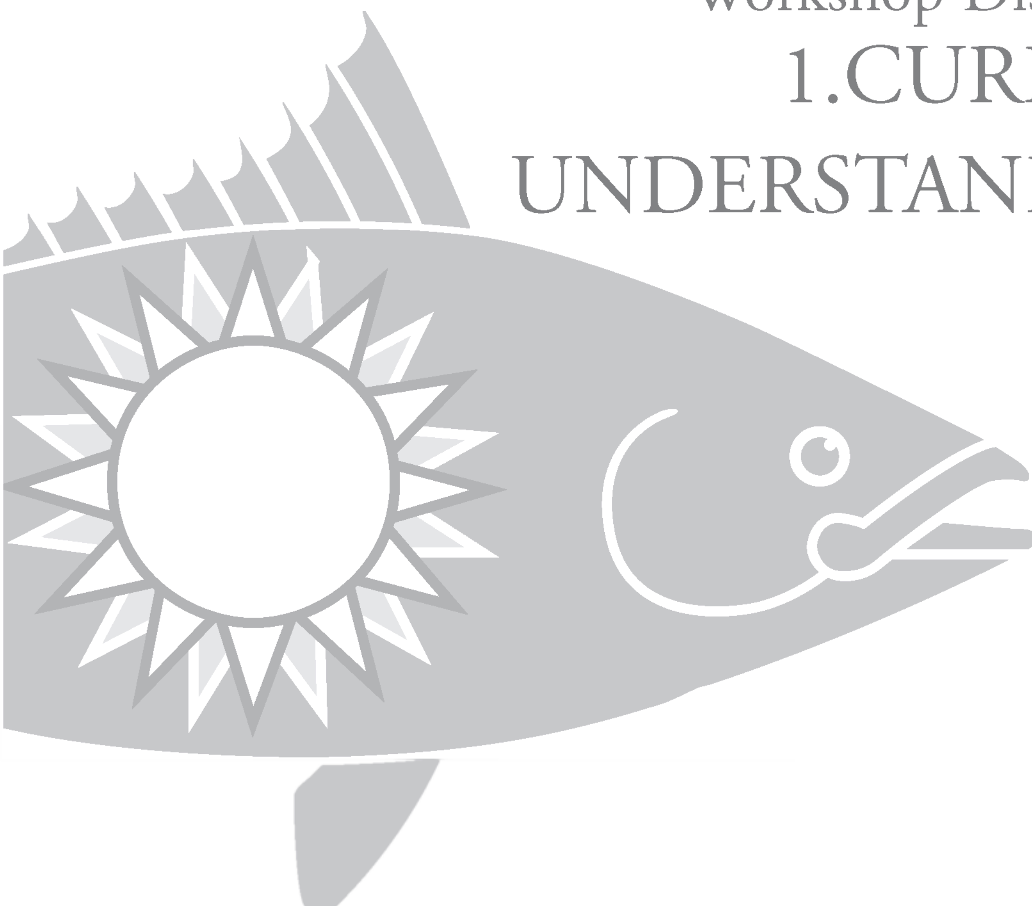
- What new tools and techniques are available that may influence current management of fisheries (e.g., egg pump, genetic marking)?

- How might this information be used to alter current management approaches?

- What are the relative trade-offs in investing in increasing observational capability of key indicators versus development of predictive models?

Workshop Discussions

1.CURRENT UNDERSTANDING



6 *Examples of currently-established climate-fisheries applications*

During the first plenary session, there was discussion of current uses of climate information for fisheries management. This provoked several participants to raise points that remained salient throughout the meeting, and also highlighted the varied (and often unanticipated) ways that climate information has been used to date. Several of the fisheries scientists noted the use of climate information (e.g., SST) in stock assessment (primarily to analyze catchability and estimate recruitment) and ecosystem models, emphasizing the point that climate information is not just of use to managers, but plays a crucial role in research as well. Other target audiences, or "end users" of climate information were mentioned, including members of the financial sector linked to fisheries, brokers of fish products, fleet and plant managers, and those who set fisheries regulations. Most examples were in the context of seasonal-to interannual variability (i.e., ENSO) versus longer timescale events. Many of the more detailed examples were drawn from the cases of small pelagics off the coast of S. America, tuna fisheries in Pacific small island states, and salmon in the NE Pacific. Below we highlight some of the main points from the discussion. *This section is NOT intended to be a review of the use of climate information in the fisheries sector, but to provide examples of the application of climate information that emerged in the workshop.*

Western S. America pelagics:

Peru and Chile have long been aware of the impact of climate variability, notably ENSO, on their marine ecosystem. During warm events there is both horizontal (southward) and vertical migration of small pelagics (the resource supporting one of the world's largest fishmeal industries), and during extreme warm events reproduction, and even survival, are seriously compromised (Barber and Chavez 1983, Arntz et al. 1985, Sharp and McLain 1993, Serra 1987, Serra 1991, Tarazona and Castillo 1999).[3] There are numerous examples of the use of climate forecasts by members of their fisheries sector (see Table 1 for examples of decisions that could be affected by climate information), some of which were anticipated by researchers prior to the dramatic advances in forecasting ENSO (Glantz 1979, 1986, Glantz and Thompson 1981, Walters 1989). For example, the oceanographic agency in Peru anticipates the need to increase sampling prior to an ENSO event, and budgets cruises accordingly; preemptive vedas (restricted fishing periods) to protect stressed stocks have been implemented during strong ENSO events, but are often cut short due to political pressure around election time, highlighting the inextricable role of national politics in affecting regulations. Similarly, restricting fishing of the shared stock of anchoveta on the border between Chile and Peru continues to remain politically hazardous, evoking nationalistic protests in both countries, with Peruvians arguing "why should we protect our fish if they are just going to be caught by the Chileans when they migrate southward" (for details concerning the use of various sorts of climate information by the fisheries sector in Peru during the 1997-98 El Niño, see Broad et al., in press, Carr and Broad 2000).

Given the scientific uncertainty of both the climate forecasts and the associated impacts on species (not all ENSO events have similar impacts on the ecosystem), fisheries regulators are faced with difficult options. One workshop participant involved with the 1997-98 ENSO gave the example of the dilemma faced by Peruvian regulators: when it was known that it was going to be an event of great magnitude, there were two seemingly equal logical management approaches: 1) to impose extreme conservation, with the societal result of unemployment, defaulted loans, and social unrest during an already depressed economic period, or 2) to allow heavy fishing since the fish may likely disappear (and not reproduce) due to the severity of the event, even with no fishing pressure. As might be expected, Peru took middle ground, alternating closed and "exploratory" fishing periods as pressure from the industry mounted.

[3] For an overview of the effects of the 1997-98 El Niño on physical mechanisms and biogeochemical cycles, see, e.g., McPhaden (1999) and Chavez et al. (1998).

Many banking decisions hinge on future expectations of ENSO events. Loan officers monitor forecasts on the internet as an aid in deciding whether to make a loan or not, assuming negative impacts of warm events on the pelagic fisheries. During the 1997-98 event, some Peruvian fishing firms were waiting for large loans and were alleged to have put pressure on the media and government scientific agencies to downplay the effects of El Niño, while another subset of the industry wanted to use El Niño as an excuse to have a state of emergency declared to reduce interest rates on existing loans, and to leverage refinancing packages. The fact that many financial investments (e.g., vessel and plant construction) are played out over multi-year time horizons reveals some of the difficulty in changing behavior, patterns of overinvestment, etc. with a short lead (3-6 month) ENSO forecast, and conversely, the potential for better understanding of longer term fluctuations to potentially influence such investment decisions.

Much of the debate over the intensity and timing of the 1997-98 El Niño played out in the media, who exhibited the tendency to sensationalize information to increase sales, often turning probabilistic statements by the scientific community into deterministic headlines. Conflicting messages reached the public, leading people to ignore the "noise". Again, this highlights the issue of communication of information in affecting societal decision-making.

The impact of El Niño on small pelagics receives the most attention. However both positive and negative impacts on species important to artisanal fisheries and to aquaculture (e.g., abundance of scallops) also occur (for details, see Tarazona and Castillo 1999). For example, the arrival of potentially valuable tropical species such as mahi mahi (dolphinfish) near shore provide an opportunity for small-scale fishers; however due to lack of capital to buy appropriate gear, or lack of export markets for the products, artisanal groups can not always take advantage of this opportunity. Further, during strong events such as 1997-98, tropical species may be so abundant, from Ecuador to Central Chile, that prices drop to such low levels that it is not worth the cost of fuel to catch the fish. And finally, to some regions, El Niño brings devastating floods, wave damage, and other infrastructure damage, reducing the ability to get products to market.

TABLE 1. Goals of actors in the Peruvian fishing sector and climate-related decisions (Broad et al. in press, *Climatic Change*)

GROUP	GOAL	DECISIONS
Industrial purse seine fishers and processors	Large industrial catch, Conglomerate profits	Build / Repair vessels, Change / Alter nets, Relocate fleet, Hire personnel, Layoff personnel, Install refrigeration system, Upgrade plant technology, Stop fishing, Stockpile products, Change product ratios (fishmeal vs. canning), Diversify into other industries
Artisanal fishers (net fishermen, purse seine (<30 gross registered tons), longline fisherman, trawlers, divers (shellfish and spearfishermen)	Large artisanal catch, Fishing tradition	Change fishing gear, Reject non-traditional gear, target new species, Change household production options (e.g., spouse works more), Negotiate five-mile limit with industry
Labor	High and full employment Adequate and stable income	Change household production options (e.g., children sent to work), Migration
Banks	Returns on investments	Accept or reject loan request, Refinance debt, Foreclose
Regulatory administrators and scientists	Sustainable fishery, Agency funding, job security, Prestige and consulting jobs	Establish closed seasons (*vedas*), Establish quotas, Gear restrictions / allowances, Increase enforcement, Increase sampling and observation, Permit / reject new licenses, Allow experimental fishing, Misrepresent skills / information
Conservation groups	Sustainable fishery	Support bans on fishing, Lobby for fleet size reduction
Politicians	Re-election, Overall welfare	Support regulatory measures, Support various constituencies (firm owners, labor)
Media	Sales (subscriptions, advertising)	Exaggerate impacts of El Niño, Attribute impacts to El Niño, Inject false certainty information
Foreign interests	Low-cost resource products (e.g., fishmeal), Debt repayment	Substitute protein source (soy), Structural adjustment policies

Tropical Pacific tuna:

The use of climate information as a gauge of tuna availability appears to be important for a number of actors in the small island states of the tropical Pacific region. For instance, the tendency for a general eastward shift of distributions of skipjack and yellowfin tuna during El Niño events (Lehodey et al. 1997) has obvious effects on the level of catches in the exclusive economic zones of Pacific island nations and results in important impacts on their economies. In addition, there are changes in schooling patterns, size, fat content, ratio of mixed species, and other characteristics, posing a challenge to those catching and processing these fish. Tuna are caught for commercial purposes by foreign vessels and for subsistence by locals in most small island states in the tropical Pacific region. There has been little study of the use of climate information by small-scale (subsistence) fishers, and only recently has there been study of the use of climate information by groups linked to the commercial industry, including national governments. We focus on the commercial industry below, drawing heavily on the recent work by Hamnett and Anderson (1998) who, through the Pacific ENSO Applications Center, work on the use of climate information with decision-makers in small island states of the Pacific.

One group that demonstrated a capability to quickly adapt to climate variability was the purse seine fleet. Accustomed to using advanced technology (i.e., satellite imagery, aircraft, FADs), some of the more experienced captains anticipated the spatial shift in resources due both to their own monitoring of conditions and to the climate forecasts issued by NOAA and other agencies. During the 1997-98 El Niño episode, however, this group encountered difficulty with the change in characteristics of the fish caught (size, flesh texture, fat content, etc.). This led to initial problems with "mushy tuna syndrome" until consultants were flown in from Hawaii to provide advice on modifying handling techniques. Other problems encountered by vessels included difficulty setting nets in "abnormal" current conditions, inability of equipment to handle the larger school sizes, and problems in catching the more deeply schooling fish. Processing plants also encountered initial difficulty due to the unusual characteristics of the fish, and had to modify equipment in response.

On a more macro scale, the individual island states are affected in diverse ways by the shift in spatial distribution of tuna, with some states being favored and others negatively affected by reductions in revenue for foreign fishing licenses and losses of labor in the processing plants (both of which account for a high percentage of the GDP and the basis for employment in some independent island states). Advanced warning of the 1997-98 El Niño allowed some governments to plan ahead for the changes in average revenue.

Taking a more regional perspective, participants pointed out the potential importance of the ways in which climate information may be utilized in multilateral fisheries management – namely by the newly established tuna commission for the western and central Pacific.[4] Under this regime, new institutional mechanisms will be developed to strengthen the scientific basis of tuna management (for example, in order to apply widely the precautionary approach). (See Tarte 2001 for political analysis of tuna management in this region). In this context it will be important to enhance knowledge of climate variability and its impact on the marine environment. Such information may also be useful for addressing economic and political issues within the Commission, such as the allocation of catch and effort quotas between member states. Tarte (2002) related the potential use of climate information to the particular situation in Fiji, where there has been controversy over the alleged illegal issue of fishing licenses by corrupt government officials. It has been suggested that the number of tuna licenses issued in the past year was four times that recommended as sustainable for the fishery in Fiji's exclusive economic zone (EEZ). Moreover, according to the Oceanic Fisheries Program of the Secretariat for the Pacific Community (SPC), there was serious under-reporting and under-estimating of catch and landings in Fiji, underscoring claims that the tuna fishery was in imminent danger of collapse.[5]

Tarte goes on to pose the question of what is a sustainable level of fishing activity in Fiji's exclusive economic zone? Determining this depends on a range of factors (not least the accuracy of catch and effort data). It also requires consideration of the possible impact of climate variation on stock levels. Policymakers in Fiji have suggested that Fiji has benefited from climatic changes that have caused tuna migrations through Fiji's EEZ to increase in recent years. Thus there was "immense potential" to exploit the tuna industry further by issuing more tuna licenses than were currently recommended.[6]

The above example points to the value and possible danger of the use of climate information in fisheries management decisions. It suggests that such information may be used by governments to issue more licenses, and by industry to catch more fish. As was noted in a 2000 workshop in Noumea,

[4] Information on multilateral treaties draws extensively on Tarte (2002).
[5] 'Fiji Fisheries in Bad Shape', *Pacific Magazine*, November 2001, pp.19-20.
[6] Statement by Fiji's Minister for Fisheries and Forests, *Fiji Times*, 28 November 2001, p.5.

"such responses are not necessarily helping with sustainable management"[7]. Therefore, in addition to more understanding of climate-fish linkages, there is a need to explore ways of integrating such information into a sustainable management strategy and to consider "institutional, socioeconomic and political questions".

North Pacific salmon:

The case of salmon in the North Pacific was also raised during the workshop as an example of the importance of shifts in the mean state of the ocean for understanding changes in biological productivity. This case has been studied from the biophysical perspective (e.g., Beamish et al. 1997, 1999) as well as from a policy perspective, bringing into relief several important points that remain to be adopted by policymakers. Pacific salmon catches in Alaska have varied inversely with catches from the U.S. West Coast during the past 70 years and appear to be related to climate forcing associated with the Pacific Decadal Oscillation (Hare et al. 1999, Mantua et al. 1997). Miller (1996, 2000), applying a game theory model, has related these shifts in productivity and catch to ongoing treaty negotiations, and the breakdown in cooperation between the US and Canada in setting harvest allocations under the Pacific Salmon Treaty. Miller emphasizes that institutional factors will determine the extent to which the management of such resources can adapt effectively to climate variability or long-term climate change.

Salmon also provide an example of the potential use of seasonal-to-interannual climate information for managing complex ecosystems. Pulwarty and Redmond (1997) analyze the use of climate information in the management of the Columbia River system, which attempts to balance hydropower production with salmon restoration and multiple stakeholder groups. Despite some clear potential uses for seasonal forecasts in reducing uncertainty, their study found that the "complexity of the management environment, the lack of well-defined linkages among potential users and forecasters, and the lack of supplementary background information relating to the forecasts pose substantial barriers to future use of forecasts".

The above three cases are not intended to address all uses of climate information in the fisheries sector, but merely to highlight the many actors, overlapping scales, conflicting goals, and potential unintended consequences that may be impacted by introducing climate information into society. These cases cover a wide geographical, cultural, and ecosystem range, and represent some of the most detailed analyses of the actual and potential use of various sorts of climate information available to date. There remains promise, by most researchers' accounts, for pursuing individual applications of climate information in these and similar cases.

7 *Climate variability affecting fish stocks and fisheries* [Art Miller, Raghu Murtugudde and Frank Schwing]

Climate changes in physical oceanographic variables have been clearly linked with oceanic ecosystem changes on many temporal and spatial scales. This physical forcing is especially obvious on seasonal (and shorter) timescales where variations in sea-surface temperature (SST) and upwelling, for example, strongly control productivity, growth and migration. This forcing is also prominently evident on interannual timescales associated with El Niño and La Niña episodes, when tropical ecosystems are directly affected by the severely altered oceanic conditions or when eastern Pacific boundary ecosystems are remotely forced by the concomitant oceanic and atmospheric teleconnections. On longer timescales, such as those associated with decadal regime shifts there is still a high degree of uncertainty concerning the mechanisms that are involved when changes in physical oceanographic conditions influence ocean biology (e.g., Alheit and Bernal 1993, Miller and Schneider 2000, Hare et al. 2000).

The mechanisms by which physical forcing affects oceanic ecosystems range from those associated with the smallest scales of dissipation, turbulent mixing

[7] Report on Workshop on Inter-annual Climate Variability and Pelagic Fisheries, International Research Institute for Climate Prediction, New Caledonia, 6-24 November, 2000, p.20.

and diffusion, to those acting on the mesoscale associated with fronts, eddies, and upwelling, to those operating on the basin scale associated with gyres, El Niño, and the thermohaline convective circulation (Denman et al. 1996). The regional and local manifestations of this physical forcing on the biology can occur instantaneously or with a time delay. Climate forcing apparently acts to modulate the complicated ecosystem in both linear and non-linear ways.

The most important physical oceanographic variables that influence biology are thought to be sea surface temperature (SST), mixed-layer depth (MLD), thermocline depth, upwelling strength, upper-ocean current fields and sea ice. SST, which is strongly correlated to atmospheric sea level pressure, is the best observed oceanic physical variable over climate timescales. Partly for this reason, studies often attempt to link SST changes to ecosystem changes. But the direct influence of SST on ecosystems is obscured by the fact that many physical processes cause SST to change (e.g., direct surface heating, horizontal current advection, upwelling, changes in mixing) so that SST anomalies can be symptomatic rather than causal.

The oceanic MLD, in concert with the nutricline and photic zone depths, can influence primary production by affecting new nutrient availability and the average light intensity to which individual autotrophs are exposed. Primary production in the subtropics tends to be limited by nutrients, in contrast to the subpolar regions where light tends to be the limiting factor. Long-term changes in thermocline depth along boundaries can directly influence the preferred habitats of benthic fauna or change the characteristics of mesoscale eddy and filament formation to fundamentally affect upwelling processes and near-surface nutrient enrichment.

7.1 Biological sensitivities and links to the physics

These physical environmental changes occurring in the ocean affect viruses, bacterioplankton, phytoplankton, and so on up to whales. Correlations between these physical variables and long-term changes in ecosystems have routinely been identified, but the specific mechanisms involved are usually unclear. There are a number of reasons for this: the ecosystem can be contemporaneously influenced by many physical variables; the ecosystem can be very sensitive to the seasonal timing of the anomalous physical forcing; and the ecosystem can generate intrinsic variability on climate time scales. Determining baseline levels of "biological noise" in the absence of altered climatic conditions would be an important achievement. But limited observations of both the physics and biology also confound these various interpretations. Consequently, only the generalized influences of large-scale physical forcing rather than precise linkages are normally invoked in explaining decadal ecosystem variations.

Long-term decreases in macrozooplankton in the Southern California Bight and California Current System have drawn considerable attention as being fundamental to the health of the entire ecosystem and have been hypothesized as being indicative of global warming influences (Roemmich and McGowan 1995). The long time series of the California Cooperative Fisheries Investigations (CalCOFI) surveys gives a unique long-term perspective to physical forcing of biological systems on decadal timescales. Long-term warming of the CalCOFI region is often cited as a determinant of decreased productivity through weaker upwelling; however, data-based estimates of upwelling changes are found to be opposite to that expectation.

The grand challenge is to understand the mechanisms of the responses to these instantaneous and delayed physical environmental changes and the various modes of significant feedback through the trophic web. The basin-scale nature of climate change appears to organize patterns of response in fishery resource populations. For example, salmon stocks in Alaska tend to vary in phase with each other but out of phase with salmon stocks of the U.S. Pacific Northwest (Mantua et al. 1997). Similarly, basin-wide correlations and anti-correlations occur between geographically disparate sardine and anchovy populations (Schwartzlose et al. 1999).

Many ideas have been advanced to explain these linkages, including direct influences of temperature anomalies on fish migration routes and concomitant predation factors, the influence of regional zooplankton productivity differences on feeding conditions and early life history effects on populations.

The problems inherent in relying on catch data are rather obvious. Catchability, migration, and recruitment can all be aliased and misinterpreted one for another. For example, the warming in the tropical

Atlantic during 1983 was initially assumed to have caused loss of fisheries whereas later analysis indicated that the catchability was simply low due to a deeper thermocline and resulting lower position of the tuna in the water column.

Another challenge is to separate effects of life cycle changes due to climate impact from changes due to migration. The former could be related to environmental changes that affect such things as ocean triad configurations (see Section 10.2) while the latter may simply be the response of the adult populations to changes in location of preferred conditions (temperatures, prey concentrations, etc.). Seasonal to interannual variability in the fishery resource populations of different regions or of different species in the same region may appear uncorrelated due to their adaptations to respond to the expected local large amplitude environmental changes such as El Niño or the migration of the fronts or the variability in the upwelling. However, regime shifts or relatively small amplitude changes that persist for extended periods appear to produce synchronous responses in regions far removed from each other and among unrelated and non-competitive species.

7.2 *Predictability issues and needed future work*

At this stage, appropriate diagnosis is generally more important than forecasting. However, in some cases, predictable components of the physical ocean system can be identified. For example, a portion of the variance of SST in the region off the coast of Japan (Figure 2) can be predicted with significant skill at one-to-three year lead times (Schneider and Miller, 2001). Determining the influence of these subtle and complicated physical changes on ecosystem dynamics holds promise for predicting ecosystem changes as well.

State-of-the-art tools such as general circulation models (GCMs), individual based models (IBMs), and trophodynamic (nitrate-phytoplankton-zooplankton-detritus, NPZD) models can be employed together with data mining and retrospective analyses of all available data to better understand the variability seen in fisheries. It is paramount to be able to properly downscale from the large-scale climatic indices to their impacts on triads, fronts, eastern and western boundary currents, and coastal upwellings. Coupled operational general circulation (OGCM) primary production models exist that can be forced with fairly reliable "reanalyses" winds and fluxes and combined with ocean reanalysis products to quantify the variability of the subtropical/subarctic gyres, transports in the eastern and western boundary currents, thermocline depths, etc.

8 *Regime shifts* [8]

Over the past decade and a half, earlier beliefs in an essential stability of marine ecosystems have been largely displaced by a growing appreciation of the importance of large-amplitude low-frequency variability occurring in many regions of the world's oceans. For example, Venrick et al. (1989) reported a doubling of depth-integrated chlorophyll in the subtropical North Pacific starting in the mid-1970s. Brodeur and Ware (1992, 1995) indicated a doubling of biomass of zooplankton and of pelagic fish and squid in the subarctic North Pacific in the 1980s compared to the late 1950s to early 1960s period. Roemmich and McGowan (1995) reported a 70% decrease in zooplankton biomass in the California Current since the 1950s, along with corresponding drastic declines in certain seabird species. A very sharp 60%-70% decline in zooplankton biomass off Peru in the mid-1970s, following the collapse of the anchoveta was also reported (Carrasco and Lozano 1989, Loeb and Rojas 1988, Alheit and Bernal 1993). Remarkably, a significant component of this mode of variability appears, at least in the period of the 1970s and 1980s, to have been synchronized over very large spatial scales (Kawasaki 1983, Lluch-Belda et al. 1989, 1992). Accordingly, some manner of linkage via large-scale climatic (atmospheric) teleconnections would appear to be a logical necessity.

This mode of low frequency variability seems often to take on the appearance of periods of relative

8 Alec MacCall, Jeff Polovina, and Skip McKinnell made important contributions to this section.

stability over time scales of one to several decades which are interspersed by comparatively sudden "regime shifts". These *regime shifts* tend to be characterized by radical expansions or contractions of occupied habitat of important populations and/or by replacement of one dominant species of fish by another. The question of how to properly account for regime shifts in fisheries management and endangered species protection has become a major issue.

A shift that occurred around 1976 has received the most attention because it is strongly evident in a very wide variety of biological and physical measurements (Ebbesmeyer et al. 1991, Graham 1994, Trenberth and Hurrell 1994, Miller et al. 1994, Polovina et al. 1994, Parrish et al. 2000, Hare et al. 2000) Previous regimes and transitions showed a variety of phase relationships, whereas the 1976 event was nearly synchronous. Also, the evidence for most of the earlier transitions is less quantitative, and may be subject to other plausible explanations, for instance, development of canning technology in the rise of earlier sardine fisheries.

Some other proposed regime shifts include:

- the early 1940s off the West Coast of North America,
- the late 1960s in the Humbolt system,
- the late 1980s in the Humbolt system, off Japan and in parts of the North Pacific,
- the late 1990s off the West Coast of North America.[9]

We may be using the term "regime shift" rather loosely. For example, many biological changes associated with the late 1980s event are evident, but the underlying physical changes are not as clear.

The properties of regime shifts may provide insight into their underlying mechanisms. In contrast to ENSO events (i.e., both El Niño and La Niña), which are relatively transient, regimes are long-term phenomena. The transitions or shifts between regimes include changes on a variety of time scales, nonlinear effects and phase relationships. However the general character is a bimodal tendency[10] in which the mean is a relatively rare condition. Much of the evidence for changes in regimes is biological, and the differential responses of various species may allow a natural classification system. Even if some biological changes result from a redistribution in space, rather than a change in abundance, that redistribution may be a valid indicator of a change in underlying physical and biological conditions. Small changes in the timing of physical events and conditions relative to the seasonality of fish spawning could be a sensitive mechanism of physical-biological interaction. A gradual change in physics can result in a sudden shift in the biological system.

In describing the patterns of regime shifts, it is hard to judge when an event actually starts. It is well known that matching time series can be arbitrary and easily produces spurious relationships, but that approach continues to be used in describing patterns of shifts. The nature of biological control, whether top-down or bottom-up, may also influence the order of events. The actual physical or biological trigger may be hard to see. This may be further complicated by the influence of pre-existing conditions, for example, it has been hypothesized that the recent growth of the sardine population off California started during a period of "biological opportunity" and was released by a physical change (of course the key to understanding is to identify the nature of the "opportunity" and the "change"). In some cases, classical predator-prey phase relationships are apparent, but are subject to alternative explanations and could be misleading.

Atmospheric interactions tend toward wide-scale synchronicity (e.g., north and south of the Equator), but deep ocean mechanisms allow long lag times (e.g. on east and west sides of the Pacific). ENSO events contribute a large portion of the variance in physical and biological measurements, and we might be able to interpret regime-scale events more clearly if the ENSO-related phenomena could be filtered out. Shifts in winds can cause large changes in coastal circulation and patterns of primary and secondary productivity. Although we are not able to model food chain effects satisfactorily, both the Humbolt Current and California Current systems have demonstrated severe decreases in primary and

9 Evidence is not yet complete.

10 Actually, it remains to be determined whether the character of regimes is bimodal or polymodal, as our detailed observational base is short, and long-term qualitative historical indicators such as sardine presence and absence tend to be binary.

secondary productivity since the early 1970s. Because of the complexity of these physical and biological systems, it would appear important to use multiple variables to define regimes and regime shifts.

The emphasis we have placed on a few popular and highly visible indicator species such as sardines and anchovies may be misleading. Other species, such as horse mackerel off South America, may be experiencing large regime-related changes in abundance, but our monitoring is inadequate. Even the sardine-anchovy system does not necessarily behave similarly in different systems. In the Humbolt system, both anchoveta and sardine show large and inverse variability. In the Japan and California system, sardines fluctuate strongly, but anchovies are much less variable. Fisheries can further complicate the interpretation of biological shifts. Intense harvesting can change the abundances of both target species and species that function as predators, prey and competitors. However, fishing will not influence the physical system. The relative effects of fishing and climate have been difficult to separate in the relatively short history of quantitative data, but resolution should become easier as the time series of observations is extended, and with increased opportunities for inter-system comparisons.

The recent apparent regime shift in 1998/99 has had dramatic effects on coastal zooplankton communities (Mackas et al. 2001). Coastwide increases in juvenile salmon abundance were first identified in 1999 at the Coastal Ocean/Salmon Ecosystem event in Nanaimo (Peterson and McKinnell 2000a) and have persisted through 2000 (McKinnell 2001) and in 2001, newspaper headlines such as "Salmon returning to area rivers in record numbers" were not uncommon.

8.1 Regime-like variations in Pacific salmon stocks

Attention was focused on climate and Pacific salmon issues by Beamish and Bouillon (1993) when they reported the coherence of low frequency, large amplitude variation in catches of sockeye, pink, and chum salmon around the Pacific Rim. The feeding migration of these three species, along with steelhead trout, occur in the oceanic waters of the North Pacific Ocean whereas coho and particularly chinook salmon tend to occupy coastal areas to a greater extent. Beamish & Boullion reported that dramatic increases in the abundance of sockeye, pink, and chum salmon, particularly in Alaska and Japan, were coincident with the 1976/77 climate regime shift (Ebbesmeyer et al. 1991). Remarkably, just as dramatic increases in sockeye, pink, and chum salmon were first reported on basin-wide scales in the early 1990s, the catches of chinook and coho salmon, and steelhead trout declined dramatically in the southern parts of their range in North America such that many individual populations were listed as Endangered Species in the United States. In Canada, some salmon fisheries that had continued for over 100 years were closed as a conservation measure for the first time (McKinnell et al. 2001b).

The fisheries management response to these abrupt declines was not immediate, in part because their view (and the view of many scientists) was that marine survival of salmon was a stochastic process, rather than an autocorrelated regime-like process. Fisheries on coho salmon, for example, continued at high exploitation rates even when salmon generations would not have replaced themselves even in the absence of fishing (Bradford and Irvine 2000).

8.2 Indicators of a regime shift

In current practice, the population trends of quickly responding pelagic fish species such as anchovy tend to be watched for indications of regime shift. For example in the Humboldt Current system, the anchovy is considered to be a primary indicator, particularly when the several anchovy stocks distributed from northern Peru to southern Chile exhibit simultaneous changes in abundance trends. When this happens, other species such as the common sardine (*Strangomera bentincki*), that tend like the anchovy to be favored in cool periods in this system, seem to vary simultaneously and synchronously. Where two primary small pelagic species seem to fluctuate out of phase (e.g., sardines and anchovies), the earliest indication may be gleaned from the population dynamics of the subdominant (suppressed) species, as the subdominant species sometimes has begun to increase toward eventual dominance while the currently dominant species was still abundant (Schwartzlose et al. 1999).

Changes in the geography of habitat utilized by small pelagic fish stocks, particularly reproductive habitat, tend to accompany major abundance trends.

Consequently, such changes might be a valuable early indicator for a regime shift. Egg pump surveys (Checkley et al. 2000) would provide a good way to monitor the distribution of current reproductive habitat and therefore to perhaps spot incipient regime shifts.

Another potential regime shift indicator proposed in the workshop discussions was surface chlorophyll measured from satellite, which has the distinct advantage of being data that is readily available. However, there was considerable controversy concerning the utility of surface chlorophyll for identifying regime shifts. It has been difficult to find clear relationships between variations in chlorophyll and in fisheries. For example, the four major eastern boundary current systems around the world have very similar chlorophyll biomass levels, but the fish production that they typically support differs by as much as 20 fold or more. Certainly, the use of satellite remotely sensed chlorophyll has proved useful to identify convergent fronts, to monitor the interannual dynamics of these fronts, and to explain aspects of the movement of albacore in the North Pacific (Polovina et al. 2001). However this application doesn't link chlorophyl biomass changes to fish dynamics, but rather uses the fact that sharp chlorophyll gradients may be a proxy indicator for a convergent surface front.

Zooplankton species composition appears to be a sensitive indicator of water mass changes that may be key elements in marine ecosystem regime shifts. Examples of changes in zooplankton volume and species composition have been associated with low frequency changes in the California Current and between the density of certain Atlantic zooplankton species and the North Atlantic Oscillation. Attention may need to be paid to the zooplankton size structure since effects on higher trophic levels (i.e. fish) may be size-specific.

There was considerable debate at the workshop about what may constitute a regime shift. For example, it was mentioned that in recent years there has been a significant change in zooplankton species composition off Oregon, which is likely a response to an increase in the southward transport of Transition Zone waters. Some participants felt that this southward movement of the Transition Zone pelagic ecosystem represented a regime shift while others felt that to qualify as a regime shift, the changes must go beyond mere spatial movements of water masses and their entrained planktonic communities.

In any case, it was generally agreed that to qualify as a regime shift, there must be organized changes in a variety of biological and environmental characteristics. Thus, an appropriate single index of regime probably must be substantially multi-dimensional and multivariate. An example of a multivariate approach was the use of 100 physical and biological time series to identify 1977 and 1989 regime shifts in the Northeast Pacific (Hare and Mantua 2000).

9 *Population connectivity* [11]

Processes driving variability in fish populations (and fisheries) operate on a variety of spatial and temporal scales. It appears that current conceptual models regarding "fisheries" and "climate" may tend to emphasize the time domain while under-representing the spatial domain. Such models might benefit from broadening the focus to include spatial dynamics, of which population "connectivity" is a key element.

There are at least four levels of connectivity that might be important.

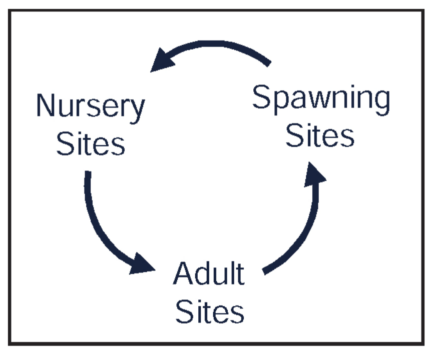


FIGURE 1.
*Connectivity **within** populations.*

(1) *Connectivity **within populations**.* Many marine species use separate locations for spawning, larval development, juvenile feeding, and adult feeding. Such complex life histories require successful connections between spatially segregated locations to "close" the life-cycle and successfully produce subsequent generations (Fig. 1). Fishing pressure and/or climate could potentially affect any of these

[11] This section reports "Connectivity" Focus Group deliberations involving Robert Cowen (chairman), Suam Kim, Simon Thorrold, Ian Perry, Mary-Elena Carr and was prepared by Jeff Shima (Focus Group rapporteur)

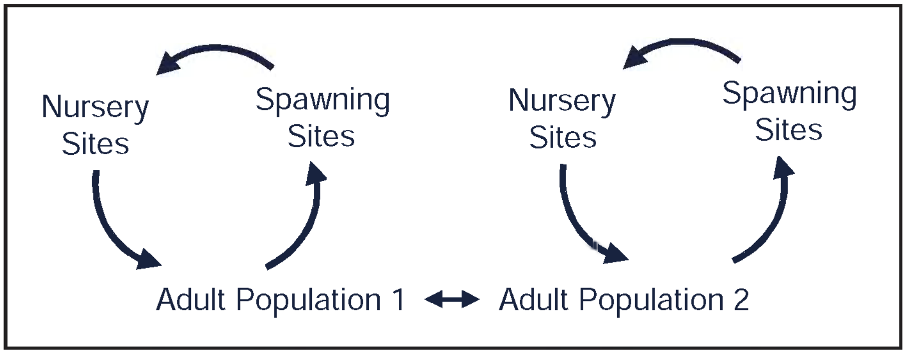


*FIGURE 2. Connectivity **among** populations.*

critical linkages. Climatic shifts, for example, could disrupt connectivity within populations through alterations of ocean circulation patterns. In addition, more localized impacts resulting from climatic shifts (e.g., changes in upwelling regimes at adult sites; changes in terrestrial runoff at estuarine nursery sites) and/or fishing practices (e.g., overfishing at adult sites; by-catch of undersized individuals at nursery sites) may break the "flow" of individuals between sites.

Pertinent in this respect is the potential role of "fish culture" (i.e., learned behavior) in maintaining patterns of connectivity or isolation. Cod, groupers, and herring (Hay et al. 2001) were cited as possible examples, whereby older individuals might indicate to younger generations the routes to particularly fruitful feeding/spawning grounds. We discussed how intensive size-selective fisheries could remove these individuals leading to a breakdown in historical migration routes, and by implication, use of historical feeding/spawning grounds. For species where "culture" might play an important role, we also discussed how an increase in the relative abundance of young (i.e., naïve) individuals might result in a greater "sampling" of the environment, leading to populations more equipped to track optima in changing climatic regimes.

(2) *Connectivity **among** populations.*

Marine species with complex life histories may have separate populations (or stocks) that share a common location during one portion of their life-history (e.g., shared larval-, juvenile-, or adult feeding habitat), with continued reproductive isolation maintained by some mechanism (e.g., natal homing; Thorrold et al. 2001). Consequently, genetically distinct populations may be directly connected with one another at some stage of their life-cycle, facilitating competitive interactions and/or related responses to spatially discrete fisheries/climate disturbances. Examples of such

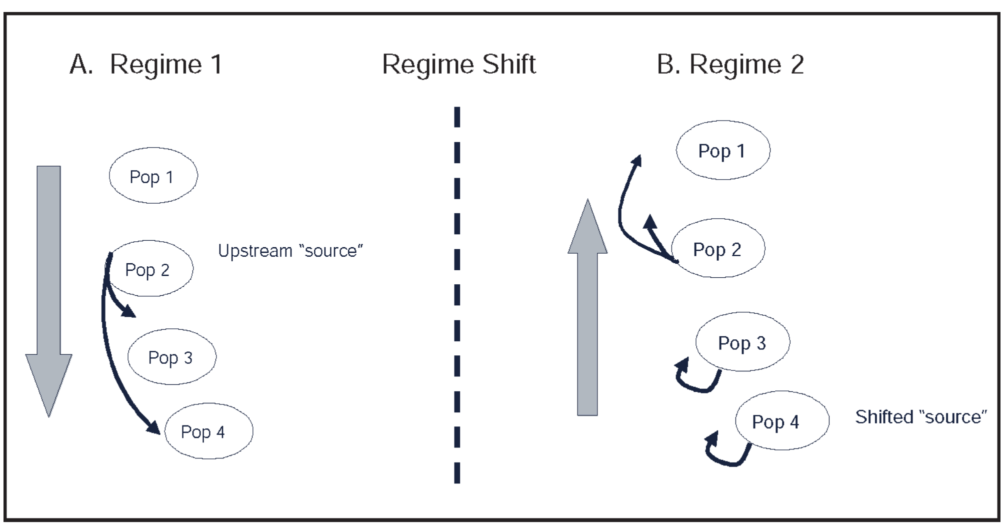


*FIGURE 3. Connectivity **between** populations. Panel A indicates "normal" regime with southward current and an upstream source of propagules. Panel B depicts potential alteration in connectivity resulting from a shifted hydrodynamic regime.*

connectivity *among* populations include stocks of Atlantic herring, which mix as adults in the North-West Atlantic, but retain discrete spawning locations.

(3) *Connectivity* ***between populations.***
Many marine populations may be composed of discrete subunits (i.e., local populations) connected by a dispersal phase (typically the larval phase but can include migratory juvenile or adult stages). Such a grouping of local populations may be best thought of as a "metapopulation" (sensu Hanski 1991). A metapopulation may exhibit dynamics that diverge substantially from a well-mixed stock, highlighting the importance of considering spatially explicit dynamics for species where a metapopulation framework may be representative. The nature of the connections between local populations constituting the metapopulation is likely to be influenced by hydrographic conditions, which may affect transport and/or survival and successful recruitment (Fig.3). Changes in hydrodynamic conditions (potentially stemming from climatic regime shifts) may alter patterns of connectivity between local populations (e.g., Cowen et al. 2000). Similarly, changes in the reproductive output of any source stock (through localized fishing of adults, or climatic shifts that alter local primary productivity, etc.), may influence the "flow" of individuals between local populations.

(4) *Ecosystem Connectivity.*
Although local marine populations may be reproductively isolated from one another (i.e., genetically distinct), they may not fluctuate independently from one another because of a shared resource base (e.g., primary production depleted by one stock may not reach another stock) or a shared predator/fishery (e.g., predators/fisheries may switch to another stock depending upon the dynamics of a focal stock). The nature of these shared ecosystem connections may act to synchronize dynamics of demographically disconnected populations. Climate/hydrodynamic shifts could therefore influence separate populations through actions upon predator/fishery behavior or dynamics, and/or via effects on a shared resource base, independent of any potential effects on direct (i.e., demographic) population connectivity.

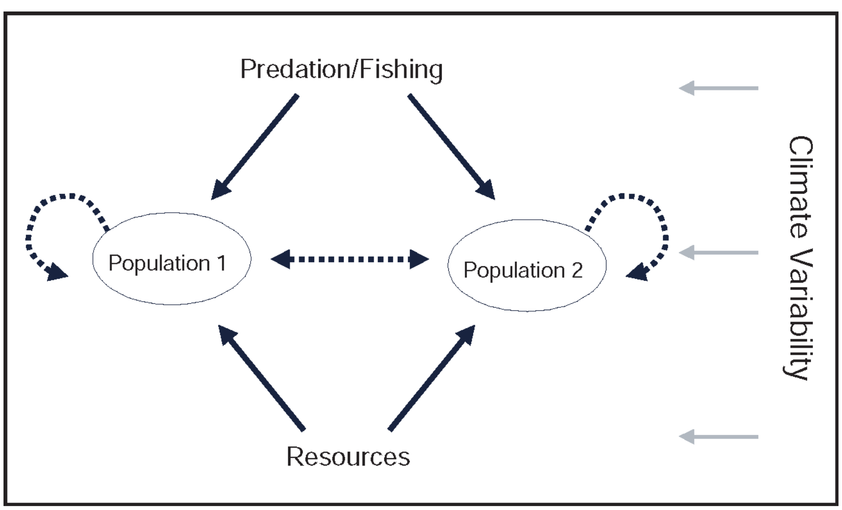


FIGURE 4. Ecosystem Connectivity. Reproductively isolated local populations may be indirectly connected via a shared resource (i.e., "bottom-up connectivity") or a shared predator or fishery (i.e.,"top-down connectivity"). Climatic shifts may affect any of these ecosystem levels.

10 *Available integrative concepts in fishery resource ecology*

There are several available schematic constructions that serve to integrate a number of processes to capture an aspect of the perceived reality of marine ecosystem operation within an easily recognized conceptual "package". These serve as a useful communicative "shorthand" among colleagues working in fisheries oceanography, facilitating efficient discussion by encapsulating a relatively complex set of processes and interactions in a single jargon-type terminology. It may be useful here to identify and describe several of the most prominent of these.

10.1 The "optimal environmental window"

Within the last fifteen years, effective nonlinear methods of empirical analysis have been introduced to marine ecology and fisheries science (Mendelssohn and Cury 1987, Mendelssohn and Mendo 1987). These methods were applied by Cury and Roy (1989) to the Peruvian anchoveta, the California sardine, the Moroccan sardine, and the Senegalese and Ivoirian sardinellas. The result was a consistently domed-shaped relationship (Fig. 5) where reproductive success appeared highest at an intermediate wind intensity and decreased at both higher and lower intensities.

Over the past several decades, empirical analyses of the relationships between local wind effects and recruitment variability in different eastern ocean pelagic fish populations often yielded differing and, therefore, rather unsatisfying results. In view of the results of Cury and Roy, it is no mystery that the previous results may have been inconsistent. In cases in which most of the data may have been on the "left flank" (low wind speed side) of the optimal environmental window, a positive relationship with wind speed would be found. Conversely, if most of the data were on the "right flank" (high wind speed side), an inverse relationship with wind speed would be found. If the data were rather evenly distributed across both flanks of the window, linear methods could pick up no relationship at all.

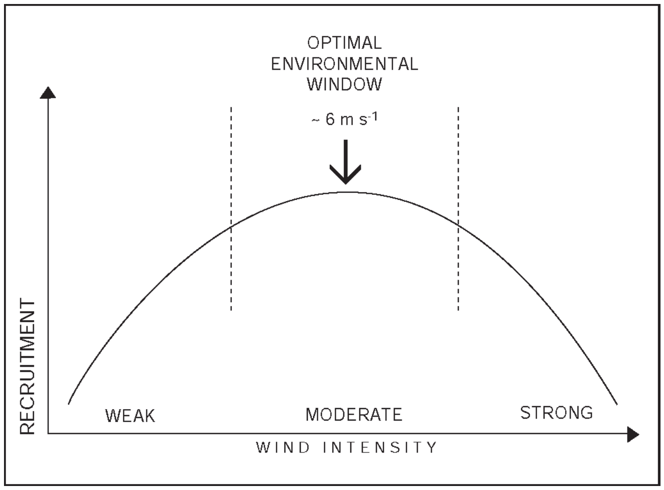


FIGURE 5. The optimal environmental window (Cury and Roy 1989) where reproductive success (recruitment) is highest at an intermediate wind intensity level and declines at both higher and lower intensity levels.

Expansion of Cury's and Roy's analysis to additional stocks or data sets has consistently yielded the same characteristic "window" feature such that maximum recruitment corresponded to an intermediate wind intensity level during the larval period. These include California anchovy (Cury et al. 1995), a new series of recruitment estimates for the Moroccan sardine (Kifani 1991, Roy et al. 1991), an analysis of pre-1945 data for the California sardine (Ware and Thomson 1991), and the Chilean sardine (Serra et al.1998). Various studies associated with the elaboration and interpretation are reported in the “CEOS volume” (Durand et al. 1998).

Constructing an interpretation of the optimal environmental window result is quite straightforward. It readily conforms to, and incorporates, several prominent current hypotheses concerning variability in larval survival. The control on the "right flank", i.e., the "high wind" side, could come about either through (1) excessive offshore transport leading to offshore loss of pelagic larvae from the favorable coastal habitat (e.g. 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 1975, 1978) 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. 1994). An obvious explanation for 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".

10.2 Ocean triads

Comparative studies of fish habitat climatology have tended to identify three major classes of physical 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.

This set of types of processes has been called the "fundamental triad" underlying reproductive habitat suitability by Bakun (1996). Ocean zones where the triad elements coexist in configurations that are evidently favorable for population growth of locally reproducing species are sometimes called “ocean triads” (Bakun 1998).

The importance of *enrichment* processes is widely recognized and appreciated. Perhaps less widely appreciated is the importance of *concentration* processes. For small organisms, such as fish larvae, 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 (e.g., Fig. 6) 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. Such interfaces tend either to be maintained by, and/or to maintain, mechanisms of concentration (Bakun 1996). Ocean fronts (Fig. 6) 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 may be too subtle to be directly sensed by pelagic organisms operating 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.

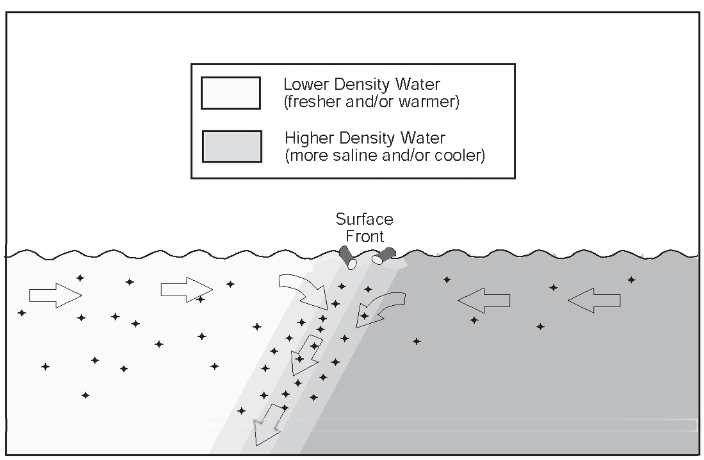


FIGURE 6. Schematic diagram of a front between waters of differing density. Arrows indicate density-driven flows associated with the front. "Particle" symbols indicate planktonic organisms capable of resisting vertical displacement. (Scales are distorted: vertical scale greatly expanded relative to horizontal; particles greatly magnified; surface waves not to scale, etc.) After Bakun (1996).

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

The third element 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 resources. Consequently, fish populations tend to spawn in locations and seasons that minimize such losses (Parrish et al. 1981, Sinclair 1988).

A set of examples of favorable ocean triad configurations for eastern ocean coastal upwelling systems can be found in Bakun (1998), and for a semi-enclosed sea in Agostini and Bakun (2002). Other examples are described in Bakun (1996).

10.3 MacCall’s basin model

A particularly fully-elaborated theoretical construction is MacCall’s (1990) “basin model” conceptualization (Fig. 7), where the favorability of the habitat for population growth and maintenance at each location is plotted on a diagram on a scale that increases downwards, visually tracing out a “basin”. Density-related unfavorable factors (crowding, competition for food, etc.) oppose the accumulation of all the fish in the most favorable location (the “deepest” point in the basin”). In fact, the model postulates that

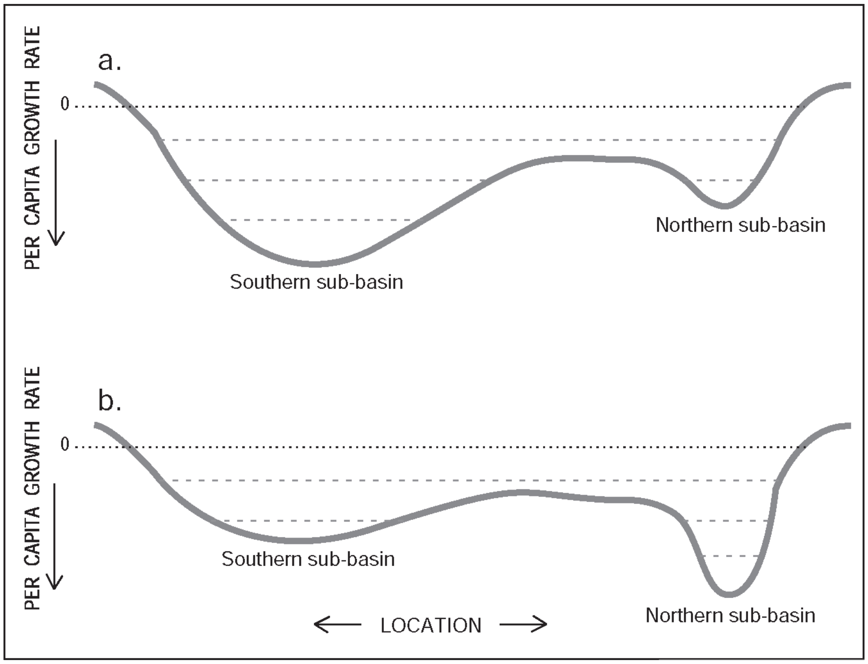


FIGURE 7. Schematic diagrams based on MacCall's "basin model" concept of density-dependent habitat suitability (MacCall, 1990). The area circumscribed by the intersection of each dashed horizontal line with the basin floor is functionally related to total population size. The line corresponding to zero population growth implies the "carrying capacity" of the habitat. The habitat suitability and corresponding steady-state population density are implied by the depth of the basin at any location. (a) Before a climatic shift. (b) Following a climatic shift.

the fish will spread themselves through the habitat in such a way that reduced density counteracts the effects of poorer habitat, such that all the fish have equal net benefit regardless of their position, a condition called an "ideal free distribution" in ecological theory. MacCall does not provide a mechanism as to how the fish might accomplish such an equitable allocation of habitat space in any particular instance but proposes that such a distribution can be approached if fish have a tendency to follow gradients of perceived improvement in habitat favorability. The characterization is probably apt in a long-term mean sense and might in any particular instance be considered as a most probable distribution of biomass concentration. In the long-term mean case, one could imagine individuals of a population as being analogous to molecules of a liquid, which would fill the "basin" up to a given level, with the number of molecules (individuals) at any horizontal location being proportional to the depth (habitat favorability) of the basin at that location.

Thus in Fig.7a, a high biomass phase might be visualized as filling the basin up to one of the upper dashed lines, where the best habitat and therefore the greatest density of individuals would be located in the deeper southern sub-basin, but the population level is high enough so that some of the population overflows the intermediate "shallows" in habitat suitability, to fill up the secondary northern sub-basin. This signifies the habitat expansion that tends to accompany higher biomass phases of sardines and other small coastal pelagic species. Then if the population were to decline sufficiently (e.g., to a level below the level of the shallow area between the two sub-basins) the population may be entirely confined to the deeper sub-basin. As long as the basic mean environmental configuration (i.e., the basin topography) remains unchanged, the population distribution will continue to cycle through essentially the same pattern of geographical expansion and contraction.

However, if a climate shift altered the underlying basin topography (e.g., if the northern sub-basin became deeper than the southern one as indicated in Fig. 7b) the population could actually shift its location in a low biomass phase to become concentrated in area of the northern sub-basin.

10.4 "Member-vagrant" concept

Sinclair (1988) presented an elegant treatment of the role of local retention of early life stages by physical ocean structural features in maintaining marine populations. He referred to the individuals retained as "members" and those lost to the local population as "vagrants". Sinclair's essay has done much to call attention to the essential linkages of ocean hydrodynamics to marine population dynamics, particularly to the fact that it is only the "member" portion of the surviving offspring that are important to year-to-year population variation, and to the essential question of degree of "openness" or "closed-ness" of a local population segment. Thus the term "member-vagrant" has come to connote a specific class of extremely important issues in the climate-fisheries research area.

10.5 "Match-mismatch" hypothesis

Cushing (1971, 1975, 1990) has popularized the idea that year class success in relatively high-latitude systems, because of the short growing seasons for phytoplankton production, may be crucially dependent on the timing of spawning with respect to the timing of availability of sufficient concentrations of larval food particles (e.g., copepod nauplii), with years with a good "match" yielding good reproductive success and strong year classes, and years of substantial mismatch resulting in poor reproductive success and weak year classes. Because of the very important effect of temperature on rates of biological development, interannual temperature variations are important elements of this way of thinking about population variation. Likewise, because the establishment of water column stability tends to be what determines the onset of the spring phytoplankton bloom in sub-polar systems, incidence of late winter or early spring storms may also be extremely important to annual recruitment strength.

Cushing mainly focused his attention on North Atlantic herring, but the idea obviously may be applicable to a number of different types of species of higher latitudes, including cod, haddock, flounder, etc. (e.g., Brander and Hurley 1992, Fortier et al. 1995, Gotceitas et al. 1996, Brander et al. 2001) and also animals other than fishes. For example, Bertram et al. (2001) showed that early spring warming results in early arousal from diapause in *Neocalanus cristatus*. When the plankton grow and return to depth in diapause early, they are not available to the important planktivorous bird, Cassin's auklet, and as a consequence there is reproductive failure in the auklet.

10.6 "Lasker windows"

Although the idea has been in a state of relative eclipse in recent years following the decline of the IOC-FAO International Recruitment Program and the ascendancy of the GLOBEC Program, Lasker's (1975, 1978) *stable ocean hypothesis* was a major factor in structuring fisheries-oceanographic research in the 1980s and early 1990s. In a remarkable series of laboratory experiments and field investigations, Reuben Lasker and his colleagues concluded that fine-scale patches of highly concentrated food particles were necessary for successful first feeding of anchovy larvae off Southern California, and that storm events could destroy this fine scale structure, leading to recruitment failure. Bakun and Parrish (1980) noted that it is probably not the average mixing intensity that is crucial, but the existence of adequate temporal "windows" during which the production of turbulent mixing energy remains low for a long enough period for concentrated food particle strata to accumulate and for larvae to accomplish successful "first-feeding". For example, if five full days may be required following a storm-related mixing event in order to form sufficiently concentrated food strata to prevent larval starvation, any calm period five days or less in duration would have no influence in increasing survival of a year class. It is only on the sixth day and the succeeding days of continued calm that larvae may pass through this critical "first feeding" survival window. And as soon as another mixing event took place, the process would have to begin again with the necessity of another unbroken five-day string before any more larvae could be successful in avoiding starvation.

Following this idea, Peterman and Bradford (1987) succeeded in empirically relating interyear variability in larval anchovy mortality rate off California to frequency of calm periods of sufficient duration for fine scale strata of food organisms to form. Such calm periods have been called variously "Lasker windows", "Lasker events", "Lasker gates", etc.

Following Pauly (1989), one can define a "Lasker {x,y} window" as representing a full day in which the wind speed did not exceed "x" m s^{-1}, which directly follows an unbroken sequence of at least "y" preceding days with wind speeds not exceeding the same "x" m s^{-1} limit. This allows a rational parameterization of crucial variability occurring on shorter scales than the time increment (e.g., a full spawning season) used in analysis. Such a parameterization, which refers specifically to a defined set of mechanisms, represents an advance over using mere averages as proxies for aggregate effects of shorter-scale variability. Peterman and Bradford (1987) chose 10 m s^{-1} for the wind speed limit in applying the Lasker window approach in their study of California anchovy. Mendelssohn and Mendo (1987) chose a lesser wind speed limit of 5 m s^{-1} for their study of Peruvian anchoveta.

One should note that "Lasker windows" represent a physical effect that passively *allows* concentrations of food particle distributions to build up and persist, as opposed, for example, to the process of active concentration by the physical process of convergence in frontal formations. In this case the active concentrating agent is biological, produced either by active swarming behavior or by *in situ* growth. Existence of the physical event (i.e., a sufficient Lasker window) permits the biological process to be effective.

10.7 The "school trap"

During the collapse of the California sardine population in the 1940s and 1950s, pure schools became less frequent and sardines were found mixed with anchovy or chub mackerel (Radovich 1979). During the period of very low abundance in the late 1960s, the only California sardines ever reported were observed in very small numbers entrained within schools of much more numerous jack mackerel of similar size. Likewise, off Peru, large sardines have been found in mixed schools with horse mackerel and chub mackerel of similar size, whereas smaller sardines have been observed nearer the coast mixed with anchoveta (Jordán et al. 1978).The existence of mixed-species fish schools appears to underscore the extreme strength of the schooling imperative (Bakun and Cury 1999). Associated larger than optimal school size distributions and extreme reluctance of individuals to voluntarily leave a school may lead to lowered levels of resources available to individuals. Related mechanisms may account for observed features of density-dependent somatic growth, density-dependent habitat selection and species alternations in small pelagic fishes[12].

An interesting point brought out by Bakun and Cury is the possibility of adverse effects on a minority species operating within schools of a more abundant species. For example, because sardines are known to be more migratory than anchovies, and presumably therefore better adapted for sustained strong efficient swimming, anchovies entrained in sardine schools may find themselves needing to swim harder than their level of optimal efficiency just to keep up. Because sardines are able to effectively filter much smaller food particles, these entrained anchovies may experience difficulties in capturing sufficient food in many of the areas through which a sardine-dominated school might elect to traverse. Thus the school trap could be a factor in the fact that population oscillations of anchovies and sardines tend to be in opposite phase, almost never in modern fishery experience reaching high levels of biomass at the same time.

11 *Potential implications of rapidly-evolving adaptive response mechanisms*

Bakun (2001, 2002a) has elaborated a premise that (1) durable adaptive responses may be evolving within fish populations on much more rapid time scales (~10 – 50 years) than possible via classical genetics-based Darwinian evolution and (2) if so, there are major implications for the way we may view fish population dynamics. For example, any degree of understanding of the adaptive mechanisms involved, or even a well-founded belief that such mechanisms are operating, could conceivably open up a broad range of new considerations for adaptive management responses, design of mitigation actions, and foresight as to the nature and course of climatic or

[12] A. Bakun, P. Cury, P. Fréon, C. Roy (under revision) The "school trap"–The price to pay for remaining together.

anthropogenic impacts. It was, in fact, suggested that such rapidly-evolving response processes operating within exploited resource populations could cause some conventional fishery management responses to be absolutely the wrong ones (e.g., serving to trap and maintain the populations within low-productivity phases) and that moreover, unless the mechanisms involved are understood, it may be very difficult to ever sort out, understand, and adequately allow for, the interacting effects of low frequency climate variability. One particular aspect of the school-mix feedback mechanism is that it could conceivably be an important element of regime shifts occurring in marine ecosystems. Another is that the mechanism could provide a process by which mobile fish populations might alter their customary zones of operation so as to withdraw away from areas of major fisheries.

The author of these ideas, Andrew Bakun, being one of the organizers of the workshop, distributed an extract from Bakun (2002a) to the invited participants prior to the workshop in order to try to motivate discussion on this class of issues. Workshop participants generally agreed that there is clear evidence that fisheries pressure can act to alter population characteristics such as age and size of first reproduction, sex ratio, etc. It was also agreed that it is rather clear that what may have seemed to be population collapses, have been so in reality. Participants were generally unaware of situations where stock abundance had been essentially maintained, while only the distribution had changed. While many felt a need for a paradigm shift in fisheries thinking, most tended to agree that more evidence is needed before the premise that adaptive responses may be evolving within fish populations under strong selective pressures (especially fisheries as a selective pressure) and that these responses are passed on to succeeding generations.

Most were more comfortable with more conventional ideas of direct adaptive responses to changes in environmental conditions that, rather than representing the type of rapidly-evolving response envisioned by Bakun (2001, 2002a), would seem to be innate elements of the animals basic physiology, or behavioral responses that are ingrained in the species by very long time-scale biological (Darwinian) evolution. For example, Alec MacCall reported an observed adaptive response of sardines in that they increase egg production when food availability is high, which is likely a direct physiological response to the individual's excess available energy for elaborating reproductive products.

As another example, it was noted that during calm winters previous to the climatic regime change that occurred about 1976, the Japanese sardine, which was in a low population phase at the time, had the habit of spawning in bays during late winter. After 1976, intense monsoon forcing associated with harsh winters may have caused deep mixing of the bays, making them non-suitable for adult feeding or for survival of offspring, thereby causing the populations to move out of the bays. It was in this period, when the earlier adapted strategy may have become non-viable, that the sardine population underwent its dramatic expansion. Thus vertical stability has been hypothesized as the agent for switching the sardines between the two phases of population abundance, yielding the apparent paradox of a change to poor environmental conditions in an adaptively-selected reproductive habitat leading to a massive population increase (some participants were dubious). The process by which the population was moved out of the bays in a durable manner was not specified. One possibility is that each generation of the fish went back and tested the suitability of the bays and each time found them lacking. Otherwise, some sort of rapidly-evolving adaptive response mechanism would seem to have been required to keep new year classes of the population, which tend to be segregated in separate schools because of size differences, from re-entering the bays.

In general, the feeling among workshop participants was that there may be inadequate data to directly resolve the school-mix feedback issue. However, some felt that there might be ways that the "school mix-feedback" hypothesis could be tested empirically using otolith microchemistry to identify relative abundance of individuals with differing "affinities" for a particular region. This approach might be most applicable to species that exhibit specific behavioral attributes (e.g., natal homing). Some participants were of the opinion that the hypothesis seems too focused on a simple predator-prey interaction; for example, the existence of replacement mechanisms among species at the ecosystem level, including changes from vertebrate to invertebrate dominance or changes from a "chitinous" to a "gelatinous" food web, emphasize the importance of considering more complex multispecies interactions than a simple predator-prey interaction. In any case, in order to test the school-mix feedback" hypothesis, very explicit definition of its assumptions and critical mechanisms and processes to be falsified are necessary. However, under time constraints of this workshop, deeper examination of this issue was not possible.

However, the discussion produced a clear recognition of the fact that we are always limited by data and that the practitioners of fisheries oceanography need to allocate more energy to synthesis efforts to generate testable hypothesis about the mechanisms and processes involved in the relation between climate and fisheries variability. We are in need of new ideas that can break the conceptual deadlock and produce real progress.

Workshop Discussions

2. FUTURE DIRECTIONS

12 *Applications to real world needs* [13]

Although the application of knowledge of climate and societal interactions is a relatively young field, there have been enough lessons gleaned from recent use of climate information in parallel cases (e.g., technology transfer) that can be brought to the table when considering how current and future information could be used in the fisheries sector (see examples of constraints and opportunities related to the use of climate information in other sectors in Agrawala and Broad 2002, Barrett 1998, Broad and Agrawala 2000, Glantz 1986, 1995, 1996, Hansen 2001, Letson et al. 2001, Mjelde et al. 1988, Mjelde and Keplinger 1998, Orlove and Tosteson 1998, Pulwarty and Redmond 1997, Pfaff et al. 1999, Rayner et al. 1999, Roncoli 2000, Sarewitz et al. 2000, Stern and Easterling 1999). The attention of the "social science" focus group (which included anthropologists, political scientists, biological and physical scientists with experience in climate forecast applications, a FAO fisheries specialist, and a US government economist involved in fisheries management) was on addressing the issue of what decisions could potentially be enabled, or enhanced, by significant scientific progress on understanding the effects of climate variability on the marine resources system. Several themes emerged early in the discussion and remained central throughout the meeting. These included:

(a) definitional issues regarding relevant decision-makers who could potentially use climate information;

(b) distinguishing timescales of importance and identifying key decisions made on those timescales;

(c) recognition of the importance of communication of probabilistic scientific information;

(d) the risk of unintended consequences of the use of climate information.

Current and potential understanding of the linkage between climate and fisheries on multiple timescales is theoretically relevant to many of the groups that make up the "fisheries sector". For example, in addition to the scientists who make recommendations on regulations and the managers themselves, we must consider the financial decision-makers (e.g., bankers who make loans), plant owners and labor, industrial and artisanal fishers, and even their families who make household-level decisions based on expectations of the coming season(s) catch. Central to the discussion was the point that it is not only fisheries managers who can, and will, use the latest available scientific information for regulatory purposes. Thus, these other groups should be considered as integral to the communication process from the start.

In the current dialogue concerning use of climate information, there remains division over what are the critical timescales for various fisheries management decisions. Again, if we define this issue broadly, as discussed above, based on current knowledge of reactions to information by the different actors, different timescales have implications for different decisions:

Synoptic:
Improvements in real-time observational capabilities tend to favor the industry versus the regulators. Industry is usually on the cutting edge of developing/adapting new technologies and are already adept at using satellite information to choose optimal fishing grounds. General regulations, on the other hand, are difficult to change in response to synoptic scale information because of insufficient lead time to make changes in the regulatory process. However, improvements in sampling devices (i.e., egg pump counter) and satellite tracking devices could be used for finer grain management and enforcement decisions in near real-time, especially once an event is underway.

Seasonal-to-interannual:
This has been the timescale of greatest focus to date in terms of application of forecast, in large part because of our understanding of the physical mechanisms that enable the ability to predict of one of the main drivers of seasonal climate variability, the El Niño-Southern Oscillation (ENSO). ENSO has direct

[13] Guillermo Podesta made important contributions to the preparation of this section.

impacts on some commercially important species (e.g., Peruvian anchoveta, tropical Pacific tuna populations). While forecasts of ENSO events have some skill with up to 6 months lead time, there remain problems with implementing major changes in fisheries within this time frame for a number of reasons: the industrial sector (including vessels, fishmeal plants, canneries, etc.) is usually heavily indebted, with investments that are calculated to be paid off over multiple years. Again, only when the timing of the investment happens to coincide with relevant information about upcoming conditions that may affect the coming seasons could a decision-maker make good use of information (e.g., give a loan/don't give a loan; buy a new engine or not, etc.). Otherwise, lenders (i.e., banks) and borrowers (i.e., firms) are locked into a pattern with a different temporal scale than ENSO-like events; artisanal (small scale) fishing groups tend to lack the capital to switch apparatus or the skills to temporarily switch professions given the short lead time; current forecasts have difficulty predicting the magnitude and duration of events, and each event is associated with different impacts on the living marine resources.

Decadal-interdecadal (regime shifts):
Much of the meeting focused son the issue of large scale fluctuations in major fisheries populations. Such occurrences have obvious dramatic implications for the human populations that depend on these resources. However, given our level of understanding of such shifts, the realistic potential for this information to affect fisheries-related decisions are not clear. We are still unable to answer basic questions necessary for societal decision-making, for example, "are we in the rise, peak, or decline phase of a fluctuation?" or "how can we tell a regime shift from other sorts of variability?", or "what is the relationship between interdecadal variability and events that occur on other timescales?". This does not imply, however, that we "throw the baby out with the bathwater" – from a societal perspective; understanding these shifts is arguably a key factor to reducing what is increasingly agreed to be the central problem in global fisheries – overcapitalization of the industry. As mentioned above, many of the decisions leading to overcapitalization (e.g., lending practices) are not going to be solved/reversed with short-term climate information, but in theory, more rational decisions could be made by groups ranging from government planners to plant laborers if there were a sense of what the next few years could hold.

There was general consensus in the group that there needed to be a more systematic study of the range of actors and decisions made on the various timescales. Drawing on experiences from the application of climate information in the agricultural and water management sectors, one product that was identified as likely to be useful for our understanding of the potential of different sorts of climate information was a "decision calendar" (see Pulwarty and Melis, 2001, for an example of a case study that bridges timescales and demands of multiple stakeholders). This product would include key decisions by the different actors, key periods when these decisions are made, the lead times, and the type of information necessary for influencing the decision. Such a product is a first step for (a) identifying points of insertion of climate information of all types/timescales, (b) identifying unintended consequences of poor forecasts, and (c) identifying which groups might be favored or hurt by the introduction of climate information into the decision-making process.

Considering the issue of application of scientific knowledge brings up the question of when is the science good enough to "go public"? Of course, there is not a clear benchmark, and ultimately, applying scientific knowledge becomes an iterative learning process based on successes and failures. Past lessons have led to the realization that effort must be put on the communication process, as decision-makers interpret probabilistic information in a variety of ways based on the societal and individual characteristics from which they operate. Thus a bank manager accustomed to dealing with the uncertainty associated with financial forecasts may be better suited to use probabilistic climate information than a vessel captain who must maintain a high degree of certainty in actions that affect the safety of the crew would be. This may necessitate different sorts of approaches/products/education for different decision-makers within the same sector – a time consuming and costly endeavor that the scientific community may not be able to undertake.

As with all sorts of applications of new information and technology transfer, there is a risk of potential unintended consequences of introducing new information into a social system. Unintended outcomes may result from erroneous information, misunderstanding of information, malicious use of information, or a range of exogenous factors outside the control of the decision-maker. Further, given our relative lack of understanding of many aspects of *regime shifts*, the scientific community may risk losing legitimacy by promoting the use of what information we have to fisheries managers and other decision-makers, thereby reducing the chances of being taken seriously in the future. Finally, rational decisions by individuals may not result in an outcome that is good for a collective group. For example, detailed knowledge of migratory patterns of some species in response to climatic trends may allow more advanced planning of fleet location, gear needs, etc., thus leading to increased, even more efficient extraction and an ensuing drop in prices (good for the consumer, bad for the fishing industry). Fisheries that lack enforcement (e.g., tuna outside of the EEZ) may be especially vulnerable. Differential understanding of information during the 1997-98 El Niño in parts of S. America demonstrated how benefits may accrue unequally, and how probabilistic information can be subject to alternative, and often self-serving, interpretations (see for example, Broad et al. in press).

13 *Role of comparative studies*

The great biologist, Ernst Mayr has called the experimental method and the comparative method “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 some reasonable degree of confidence. The experimental method, wherein experimental controls are imposed that allow the scientist to systematically vary conditions of interest while holding other factors constant, is perhaps the most direct approach to assembling the needed suite of realizations. But climatic linkages to marine ecosystems and to associated human economic and cultural activities are hardly amenable to experimental controls.

Fortunately, the comparative method presents an available alternative. For example, Mayr (ibid.) credits the comparative method for nearly all of the revolutionary advances in evolutionary biology, which likewise involves scales (mostly temporal in that case) that can not be encompassed by the usual experimental approaches. 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 naturally existing conditions and phenomena. That is, different sets of geographical settings, encompassing a range of natural variability in the conditions and mechanisms, replace controlled experimental "treatments".

Of the available integrative concepts enumerated in Section 10, the optimal environment window, ocean triads, school trap and the member-vagrant results are clear examples of products of application of the comparative method. In addition, the basin model, while perhaps fundamentally a theoretical (intellectual) concept, was obviously framed on the basis of MacCall’s early knowledge of the similar patterns of correspondence between population abundance and extent of occupied habitat in the California and Peru-Humboldt regional systems.

13.1 Time series analysis: the application of the comparative method in the temporal domain

Of course, one may look for independent realizations of a process in time as well as in space. Thus time series analysis is essentially another mode of application of the comparative method where the separate realizations required for drawing valid inferences are separated by time rather than space. Essential to the application of most common methodologies for drawing scientific inference via time series analysis is the requirement for stationarity of the basic mechanism being investigated. This works well in physics and chemistry, and in biology for mechanisms acting at the molecular level. But organisms and groups of organisms have abilities to adapt habits and behaviors, which may introduce important nonstationarities into the operation of environmental – biological linkage mechanisms (as discussed in Section 11). Since fitting of models and empirical functions to data series based on an assumption of stationarity has become such a basic element of fisheries science, a major challenge appears to be to find ways to ensure that stationarity assumptions are appropriate when we use them. Another may be to find ways to validly utilize the comparative method in the time domain to investigate the nonstationary processes and mechanisms that are intrinsic to biological systems.

Another problem is the fact that in 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. 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. 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.

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.), than a 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.

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. Consequently, without the discipline of a single *a priori* choice, such as linearity, the problem of spurious fits becomes even worse than usual.

13.2 Inter-regional comparative time-series analysis

In such circumstances, requiring comparative interregional consistency in functional form may offer a useful alternative. In order to help relieve the problems introduced by the very short time series of annual data points normally available for fisheries-environmental research, Bakun (1985) suggested arraying empirical models, derived on similar bases from different similarly-structured regional ecosystems, and attempting to recognize informative patterns among model parameters. Cury and Roy (1989) took up this idea and added the additional aspect of non-linear analysis methodologies. The result was the famous, domed-shaped, "optimal environmental window" relationship (Fig. 5, Section 10.1). This finding, and its follow-on extensions (see Durand et al. 1998) represents the most consistent empirical "environment-population dynamics" result that we have in fishery science. It has provided tangible empirical support for concepts (e.g., the *ocean triads* idea) that had been emerging inferentially over the previous decade. Most importantly, the fact that the local wind emerges consistently as the factor yielding the *a priori*-expected dome-shaped response makes it rather clear that the global climatic signals that seem to be imposing large-scale marine population synchrony are, in the case of eastern-ocean coastal upwelling ecosystems, most probably transmitted primarily by the action of the local wind on the sea surface.

14 *Role of modeling* [14]

Modeling has become an essential component of integrated ocean research efforts. Models provide the basic "bookkeeping" for testing how well what we believe we understand about the controlling mechanisms operating within a system of interest indeed adds up, based on the observed "inputs" to the system, to what is actually observed in terms of "outputs". Thus they are an essential discipline enforced upon our scientific credulity in situations where the system may be sufficiently complex that one cannot easily encompass mentally all the significant details of its operation. This is particularly true where the processes in the system have feedback linkages or where nonlinearities may be involved. And we know that marine ecosystem processes are rife with interlinking feedbacks and nonlinearities.

However, one must always keep in mind the famous "garbage in, garbage out" warning. A model's results do not represent any new factual knowledge generated internally to the model itself, but are only the direct reflection of the knowledge, insights, and assumptions that went into the model's formulation. This is a fact that must be emphasized in fisheries science, where model outputs representing the results of fairly arbitrary assumptions, have come to be viewed, in a situation where real objective reality has been hard to come by, as acceptable substitutes for actual reality.

But, with this admonition in mind, it is undeniable that process-oriented models, which are normally executed on computers, are extremely useful components of a scientific investigation. Model studies tend to be very inexpensive compared, for example, to at-sea operations. They are an extremely economical way to identify data requirements, and to develop hypotheses that may be amenable to testing. They can be run in simulation mode to help clarify and communicate ideas and to identify key junctures in the system. For example, one may use different models with the same forcing to understand how the outcomes may differ based solely on the different model formulations. A computer laboratory, based on a set of models, may provide a virtual environment that can be used to follow an experimental approach and to run controlled experiments (i.e., altering the wind forcing, the currents at the boundary, the sea floor topography, the nutrient composition of the water, mortality of larvae, etc.). In this way, computer models can be used to complement field studies.

Currently, biological models tend to not be very useful in a predictive sense because they are, as yet, not very good. And the degree of uncertainty increases as the results are compounded through the various levels of an ecosystem. But lack of skill in specific prediction does not necessarily connote lack of utility (consider, for example, the current situation in El Niño prediction, where a number of different models are used to assemble a current prognosis; the fact that a particular model may perform well in one situation but "miss" widely in another does not in any way mean that what we have learned about the evolution of and precursors to El Niño episodes is not extremely valuable in a very practical sense). Arraying together the outcomes of runs of similarly formulated models applied to different regional situations and attempting to rationalize informative patterns of correspondence and non-correspondence in these results may be a productive methodology for pursuing inferences and insights via the comparative method (thus seeking to make any models developed "transportable" to different regional situations is a very good idea).

The problem of "down-scaling" from global atmospheric models or basin-scale ocean models, to regional (e.g., "coastal band" models, etc.) capable of resolving mesoscale features is an important one. The response of the open ocean to major climatic signals or events such as ENSO, PDO (*Pacific Decadal Oscillation*, Mantua et al. 1997) and NAO (*North Atlantic Oscillation*, Hurrell and van Loon 1997) is extensively studied and documented[15]. While these studies have considerable implications for understanding large-scale climate dynamics of the earth, their regional manifestation and especially their consequences at smaller scales such as the scale of the ocean's continental shelves remain poorly documented and understood. Climate and oceanographic basin scale analyses are often based on spatially smoothed datasets

[14] Claude Roy and Frank Schwing made important contributions to the preparation of this section.

[15] It is notable that some global climate models (e.g. Timmermann *et al.* 1999) predict an increase in the amplitude and frequency of ENSO evacents in the equatorial Pacific due to atmospheric accumulation of greenhouse gases.

or on large-scale models, with a resolution too coarse to resolve the mesoscale structures such as upwelling that occurs over the continental shelf. As a consequence, these analyses tend to submerge indications of the coastal response within those of the adjacent larger-scale oceanic environment. For example, an analysis of SST and wind along the coastal shelf off West Africa indicated that the link between ENSO and this part of the Atlantic ocean is far stronger than previously thought (Roy and Reason, 2001).

Surprisingly, the impact of large-scale climate variability on the ecology of coastal ecosystems is quite often better known than the impact on the coastal marine physical components. For example, there is a abundant literature on the impact of the 1982-1983 and 1997-1998 El Niño episodes on the marine biota and resources of California and Peru but much less is known on the El Niño impact on the local physical processes (see for example, the volume "Pacific Climate Variability and Marine Ecosystems Impacts" (McKinnell et al. 2001a)).

A comparative research focus on the impact of the dominant large-scale climatic signals on coastal ecosystems might be particularly relevant from a socio-economic perspective. A good candidate for a pilot study would be the eastern boundary regions of the Pacific and Atlantic oceans where atmospheric forcing plays a dominant role in controlling key ecosystem processes such as coastal upwelling. It could start by investigating the local signature of the major climatic signals in atmospheric forcing fields as well as at the oceanic boundaries of the coastal regions. This can be done using historical time series as well as output from basin-scale atmospheric and oceanic models. A next step would be to implement higher-resolution regional-scale coastal models over the continental shelf. These models, forced at their boundaries by atmospheric and oceanic signal may provide particularly efficient tools for exploring the response of the dynamics and structure of coastal ecosystems to major basin-scale (or global) climatic signals (Penven et al. 2001, Marchesiello et al. 2002).

15 *Sardine regimes and mesoscale structure (an integrative hypothesis) [Alec MacCall]*

An Hypothesis Explaining Biological Regimes in Sardine-producing Pacific Boundary Current Systems (South America, North America and Japan): Implications of Alternating Modes of Slow, Meandering Flow and Fast Linear Flow in the Offshore Region

Introduction and acknowledgement

Because this hypothesis is the product of a workshop and draws on ideas contributed by a long list of excellent scientists, it seems appropriate to begin rather than end with some acknowledgments. The following hypothesis was developed while participating in the Boundary Current - Frontal Systems Working Group at the Pacific Climate and Fisheries Workshop, held November 14-17, 2001 at the East-West Center, University of Hawaii. Especially notable is the contribution of Takashige Sugimoto, who originally described most aspects of this hypothesis for the Japanese ecosystem. The contribution I made was to generalize and extend his hypothesis to the other Pacific boundary current systems. Don Olson provided an oceanographer's insight as to how flow conditions in these three systems might be linked. Other scientists who were not at the workshop (e.g., Richard Parrish of the Pacific Fisheries Environmental Laboratory, Pacific Grove, Paul Smith of the Southwest Fisheries Science Center, La Jolla, and Daniel Lluch-Belda of the Centro Interdisciplinario de Ciencias Marinas, La Paz) have nonetheless contributed significantly to development of the hypothesis. Finally, a major acknowledgement goes to Andrew Bakun, who not only convened this workshop, but also provided the foundation for these ideas through his extensive work on the oceanography of pelagic fish reproduction.

15.1 Outline of the flow-based hypothesis

The major sardine-producing systems have two distinct pelagic habitats, a nearshore coastal habitat and an offshore boundary current habitat. The characteristic long-term patterns of biological variability in these systems are associated with inter-decadally alternating strong and weak modes of boundary current flow and related reproduction-related physics of the nearshore and offshore habitats, and from habitat switching by the larger species (i.e., sardines, but not anchovies) to utilize the offshore habitat when conditions are favorable. Under conditions of slow, meandering boundary current flow, retention of eggs and larvae spawned in the offshore habitat is greater than under conditions of fast, straight flow.

15.2 Fish behavior: habitat switching

Some species such as anchovies (*Engraulis* spp.) and juvenile coho salmon (smolts of Oncorhynchus kisutch) are restricted to the coastal habitat, probably because of their small size and limited swimming ability. Other generally larger species such as sardines (*Sardinops* spp.), mackerel (*Scomber japonicus*) and horse mackerel (*Trachurus* spp.) are able to utilize both nearshore and offshore habitats, and switch between nearshore and offshore habitats according to their relative favorability for feeding and reproduction. The evidence for habitat switching by populations of the larger pelagic species varies among geographic regions. During their recent increase of sardine abundance in the Japanese system, the population clearly expanded into far offshore regions associated with the Kuroshio Current (Wada and Kashiwai 1989). In the California Current, the far offshore region has not been well sampled even by the CalCOFI ichthyoplankton surveys, especially after the regime shift of 1976. Importantly, sardine eggs were collected 200 to 300 miles off California and Oregon in early ichthyoplankton surveys conducted in 1931 and 1939 during the earlier period of high sardine productivity (Smith 1990). In the early 1990s, the Russian trawler *Novodrutsk* conducted exploratory fishing for *Trachurus* 200 miles off the California coast and found unexpected abundances of *Sardinops* and *Scomber* in those offshore waters (D. Abramenkoff, NMFS La Jolla, personal communication). Recent sardine egg surveys using the Continuous Underway Fish Egg Sampler provide improved offshore monitoring (Checkley et al. 2000), but frequently fail to reach the offshore edge of the distribution.

Bakun's (1996) "fundamental triad" of enrichment, concentration and retention provides a framework for evaluating the suitability of inshore and offshore habitats. The role of enrichment in this hypothesis is unresolved, and may vary among systems (see below), but the meandering patterns associated with weaker boundary current flow have clear implications for concentration and retention. Of the elements of the triad, variability in larval retention is by far the most important aspect of this hypothesis.

15.3 Physical and biological oceanography

The offshore boundary current tends to exhibit two alternative modes:

1. A fast transport mode, in which the current is relatively straight (reduced motion perpendicular to the main flow).

2. A slow transport mode, in which the current meanders (increased motion perpendicular to the main flow) and has complicated structure, a relatively large frontal area, and greater tendency to form persistent mesoscale eddies.

Note that temperature anomalies associated with flow strength are governed by the source water temperature: The slow, meandering mode is associated with warming in the California and Peru Currents which have high latitude sources, but a slowing of the Kuroshio system produces a cooling because of its tropical source. In the eastern Pacific systems, the slow meandering mode characteristic of warm regimes may also occur during El Niño events embedded within cool regimes (e.g., the El Niño of 1957-58 off California, during which sardines experienced two years of good reproduction in a decade that otherwise showed consistent recruitment failures). It is hypothesized that with the exception of El Niño perturbations, these boundary currents tend to stay in the same flow mode for periods of many years, and then switch suddenly to the opposite mode in a so-called "regime shift".

Logerwell and Smith (2001) have shown that offshore mesoscale eddies in the California Current are associated with significantly elevated densities of sardine larvae. Logerwell et al. (2001) modeled the spatial bio-energetics of such an offshore eddy, and concluded that they are likely to be a significant source of sardine recruitment. An important unanswered question is whether the hypothesized decreased current velocity and increased meandering associated with the slow-flow current is sufficient to improve retention of sardine larvae, or whether the flow must form persistent eddies with closed circulation and well-developed structure for sardine populations to increase. In either case, the extent of meandering and/or eddy formation is presumed to be enhanced during periods of weaker boundary current flow.

Modes of boundary current flow exhibit regional variations that may explain regional differences in nutrient patterns. Richard Parrish (NMFS Pacific Fisheries Environmental Laboratory, personal communication) has shown that the post-1976 slow mode of the California Current drew nutrient-poor water from the equatorward side of the North Pacific transition zone, whereas the pre-1976 fast mode drew richer water from a higher latitude. Parrish's mechanism helps explain the post-1976 decline in plankton volumes seen in the California Current (Roemmich and McGowan 1995); a similar mechanism in the southern hemisphere could explain the parallel decline in plankton abundance off Peru reported by Carrasco and Lozano (1989). Plankton volumes should be interpreted with caution, as they include gelatinous forms and do not necessarily reflect trends in abundance of zooplankton that would serve as forage (Smith 1985). In contrast to the eastern Pacific systems, the slow-flow mode of the Kuroshio system may experience an enrichment due to increased intrusion of nutrient-rich Oyashio Current water, as happened during the mid-1980s, ending suddenly in1988 (Sugimoto et al. 2001).

Differences in nearshore oceanography associated with these flow modes is less clear. In the Eastern Pacific systems, coastal upwelling and nutrient enrichment may be somewhat stronger during fast flow modes, but substantial coastal upwelling also occurs during slow flow modes. However, the reduction in nutrients and the deeper thermocline depths associated with the warm, slow flow mode in the Eastern Pacific systems may reduce nutrient enrichment associated with coastal upwelling under those conditions. The convoluted island and shoreline topography of the Japanese coastal ecosystem contrasts strongly with the linear, exposed coastline of the Eastern Pacific systems, and may provide resident fishes with good nearshore egg and larval retention during periods of fast Kuroshio Current flow.

15.4 Synchrony and teleconnections

At the decadal scale, a general synchrony of regime shifts in the various Pacific coastal boundary currents has been observed (Kawasaki 1983, 1989), but at finer time scales this synchrony is only approximate. Interdecadal variability in intensity of the major North and South Pacific gyres appears to be linked through hemispheric and global atmospheric circulation so that changes of intensity of both gyres are approximately in phase. In the recent record, the major unexplained departure from synchrony is the apparent time lag of about one decade in the California Current relative to the Japanese and Peruvian systems (MacCall 1996).

Trachurus benefits from attaining a larger size before individuals migrate to the cold and energetically demanding offshore and high latitude waters. A detailed demographic comparison of life-histories and habitat preferences for these characteristic boundary current species would be useful. There may be an opportunity for more detailed predictability of abundance fluctuations in the full list of pelagic species, and not only sardines and anchovies.

15.5 Concluding thoughts

In previous efforts to understand "the regime problem" (e.g., Schwartzlose et al. 1999) we have been distracted by temperature relationships evident in the eastern Pacific systems (i.e., warm conditions favor sardine productivity), and have tended to think of the Japanese system (in which cold conditions are associated with sardine productivity) as being different, and requiring a different explanation. By acknowledging that temperature anomalies are primarily the result of flow patterns, and that reproductively important aspects of species ecology and life history are more closely associated with properties of the flow itself, this hypothesis unifies our understanding of the three major boundary current systems in the Pacific.

We have also been distracted by habitat selection theories such as the basin model (MacCall 1990) and the ideal free distribution selection (Wada and Kashiwai 1989). These models suggested that the offshore expansion of the sardine spawning grounds (considered as "effect") is in response to the increase in abundance (considered as "cause"). This new flow-based hypothesis reverses the interpretation of cause and effect, so that the improvement of offshore spawning habitat (now the "cause") leads to improved reproduction and increased abundance (now the "effect"). However, the flow-based hypothesis is not exclusive of the previous habitat selection theories, and there may well be habitat selection effects within the nearshore and offshore systems. This is consistent with the geographic expansion of sardine spawning within the southern California Bight during the increasing abundances of the late 1980s (Barnes et al. 1992, Smith 1990). MacCall's basin model may be best suited to the anchovy (for which it was originally developed), the species that is least able to switch between nearshore and offshore habitats.

Table 2. Comparison of Pacific Ocean coastal ecosystem properties under weak and strong modes of boundary current flow.

Mode of current flow	Weak, slow flow	Strong, fast flow
Coastal sea level	Higher	Lower
Water motion	Enhanced meandering	Reduced meandering
Frontal area	Increased	Decreased
Offshore larval retention	Favorable	Unfavorable
Temperature anomaly		
Eastern Pacific	Warm	Cool
Japan	Cool	Warm
Nutrient supply		
Eastern Pacific	Reduced (lower lat. source)	Enhanced (higher lat. source)
Japan	Enhanced (Oyashio intrusion)	Reduced
Sardine abundance	Increased	Decreased
Anchovy abundance		
California	Slight decrease	Slight increase
Peru/Chile	Strong decrease	Strong increase
Japan	Slight decrease	Slight increase

16 *Climate and tuna fisheries* [16]

Tunas are particularly valuable fishery resources, supporting highly capitalized, technologically advanced fishing operations and important international trade (a single large bluefin tuna in prime condition for sashimi preparation may sell for US$40,000 or more in the Tokyo fish market). They are a diverse group of fishes; for example, comparing the biology of frigate and bullet tunas (*Auxis* spp.) with that of Atlantic bluefin tuna (*Thunnus thynnus*) encompasses a broad r-k continuum. In recent years, the annual world catch of the four main tropical tuna species (skipjack, yellowfin, bigeye, albacore) approached 4 million tones, with two thirds of the catch coming from the Pacific (Lehodey 2002).

ENSO fluctuations appear to have major effects on Pacific tuna populations, both on distributions and migrations (Lehodey et al. 1997) and on recruitment strength and population abundance (Fournier et al. 1998). The effect of El Niño episodes appears to be positive on skipjack recruitment and negative on albacore recruitment, resulting in a negative correlation in recruitment between these two species. This is reflected in an interdecadal (regime-scale) out-of-phase relationship between the two species, with albacore recruitment appearing to decline to a lower average level after the 1976 climatic shift (see Section 9) to a more El Niño-dominated phase of the Pacific Decadal Oscillation, while skipjack recruitment generally increased (Lehodey 2002).

Regime-type fluctuations also seem to occur in tuna populations. For example, it appears that the yellowfin population has experienced two different recruitment regimes (1975-1984 and 1985-1999), the second being higher than the first. The two recruitment regimes correspond to two regimes in biomass, the higher recruitment regime producing greater biomasses.

A summary of current needs in tuna research is presented in the document "Research Implications of Adopting the Precautionary Approach to Management of Tuna Fisheries" (FAO 2001). Quoting from the executive summary of that document: "*There is a growing acknowledgement worldwide that abiotic and biotic environmental changes significantly affect the distributions, and perhaps also the productivity, of various tunas. Thus it is important to determine the nature and extent of the impact of climate variability upon the pelagic ecosystems and the tuna stocks. This natural variability should be taken into account as an additional source of uncertainty in stock assessment and management.*"

The discussions in the tuna focus group at the Honolulu workshop revealed a number of salient points concerning climate-fisheries research issues. Clearly, there is a need to learn more about the habitat preferences of tunas, (i.e., more research is needed on the behavior and physiology of individual fish). Are habitat preferences stationary or plastic? The effects of climate change on tunas depend on the fact that tunas are mobile. Climate effects are, therefore, more complex than for sedentary fishes. The environment and the status of the population mitigate rates, timing, and routes of migration or movement. For example, albacore migrate from the west to the east following fronts. Usage of the fronts may depend on the productivity of the fronts. Different age-classes may have different migration behaviors.

Temperature and forage are considered to be important determinants of tuna movements. Not much is known about the relationships between tunas and their forage as a whole, and the effect of climate on trophic processes such as ecological transfer from primary production to the middle trophic levels is an important topic of research. The lengths of food chains leading to tunas probably vary over large regions (e.g., western vs. eastern Pacific). Data on variability trends in the forage base are not available. Physics plays a role in concentrating prey and making it available to the predators (for example, the concentration of prey in the upper mixed layer by a shoaling thermocline).

It is important that a clear distinction be made between catchability and availability of tunas, and the effects of physical processes on catchability. In the western Pacific, changes in the vertical thermal structure associated with ENSO fluctuations (i.e., shallower thermocline during El Niño events) seem to have only a minor influence on the skipjack catchability but

[16] Bob Olson and Patrick Lehodey made important contributions to the preparation of this section.

increase the catchability of yellowfin by surface gear (pole and line and purse seine). However, for tuna longlining in the tropical Pacific the MLD is known to change the catchability of fishing gear (Lu *et al.* 1998, Lu *et al.* 2001).

Situations exist which may lend themselves to testing hypotheses regarding rapidly evolving mechanisms. For example, sometimes when the fish are small schools of tunas are composed of two or more species. Since different species grow at different rates, these fish will be of slightly different ages when schooling together. Yet at that particular ontogenetic stage they are sharing a common behavior by schooling together. This aspect of tuna schooling behavior might be used to design experiments to test hypotheses.

Although spawning by yellowfin tuna in the eastern Pacific appears to be quite widespread (Schaefer 1998), rather specific spawning sites are thought to exist for this species in the Atlantic (an example is the Gulf of Guinea in the first quarter of each year). This site fidelity may provide a source to study school-mix feedback mechanisms reminiscent of the albacore example provided by Bakun (2001). Tagging studies and size composition analysis of the catch might be useful tools for this purpose.

Floating objects and seamounts are known to aggregate tunas. In the eastern Pacific, prior to 1982 the only floating objects utilized by purse seine vessels were natural logs. After 1982, artificial fish aggregating devices (FADs) began to be used by the purse-seine fishery to attract tunas, markedly increasing the catchability of smaller yellowfin and bigeye. Thus, a larger proportion of the total catch originated from floating-object sets after 1982 than before 1982. There is a possibility that this aspect of the fishery might have altered the yellowfin and bigeye populations by removing fish that may have been predisposed to aggregating at floating objects versus fish that might be more likely to school in unassociated or dolphin-associated schools. It was suggested at the workshop that fisheries data stratified before and after 1982 might provide a tool to elucidate rapidly-evolving adaptations in yellowfin and bigeye populations related to changes in fisheries selectivity.

There is a need to use fisheries-independent sampling platforms to study tunas and to test hypotheses generated by spatial models (e.g., Lehodey 2001). Research is constrained by data generated by the commercial fisheries alone. Researchers generally have access to data about the fish only in the locations where the fisheries are operating; nothing is known about the growth rates (for example) of tunas in other areas. Some regions are predicted by models to contain good habitat for certain tunas, but this cannot be validated because the fisheries may not operate in those areas during those seasons. Fisheries-independent sampling platforms might include experimental longline vessels and dedicated purse-seine vessels.

An important problem is the fact that ecosystem models adapted to an ecosystem-management approach are still at an early stage of development. Such an approach implies the integration of spatio-temporal and multi-population dynamics and the consideration of interactions among populations of different species and between populations and their physical and biological environment. The modeling of such a complex system is certainly a challenge, requiring combining two viewpoints which are most often pursued separately by separate groups of scientists (i.e., population dynamicists focused on temporal variations in population abundance and fisheries oceanographers/ecologists who have generally, in the case of tunas, centered on species distribution).

Due to the extended distributions and migrational habits and capabilities of large oceanic pelagic fishes, there have in the past been problems in confidently knowing even if the populations are varying at all, much less knowing how much they are varying, and even less knowing why they may be varying. Incorporation of statistical functions, i.e. likelihood functions, in population dynamics models with multiple types and sources of data (catch-effort, length frequencies, tagging) now produce much better estimates of population abundance indices (recruitment, biomass). The reliability of these series is believed to be increasing, while at the same time suggesting larger fluctuations that what is predicted from classical virtual population (VPA) analysis, and blind tests show that these models can predict real trends within a range of error less than 10-20%. Although there is no way to produce direct confirmation of these estimates, the correlation between fluctuation of abundance indices with climate indices constitutes an indirect validation. Another indirect validation is the correspondence of biomass and recruitment estimates based on statistical models to those derived from models (such as SEPODYM, Lehodey 2001) that are constrained only by environmental variables.

The design, rationale, and preliminary findings associated with the GLOBEC-OFCCP project (see Section 17, below), were presented at the workshop in plenary session by Patrick Lehodey. This presentation excited much interest and favorable comment. Early results of an integrated physical-ecosystem model in which forage dynamics are simulated in an underlying advective-diffusive ocean model linked to phytoplankton, zooplankton, forage, and tuna components are promising. The model has been successful in explaining ~50% of the variance in spatially-disaggregated catch distribution (monthly one-degree squares) of Pacific skipjack catch between 1972 and 1992 (Lehodey 2001b). Specifically, it successfully models interannual variability associated with El Niño events, as well as a lower frequency shift at about 1976 (see Section 9, above) toward lower albacore and higher skipjack catches. The sources of the modeled variability are ENSO-related effects on physical factors (advection and temperature) and biological productivity (primary and secondary production) in two spawning regions.

This work stimulated discussion about the desirability of including major modeling efforts to address the primary issues not only concerning tuna but in terms of Pacific climate and fisheries in general. It also brought out the fact that there are some interesting unexplained issues, such as why yellowfin and skipjack tuna populations seem to have fluctuated in opposite phase with respect to El Niño episodes, that may offer potentially productive entry points into the general tuna/climate research problem. It also made it clear that the comparative method, applied interregionally on a global basis, might be a particularly economical and efficient way to acquire real insights into key aspects of the operation of the climate/ecosystem/tuna systems.

This led to the suggestion for a global "umbrella"-type project directed at large oceanic pelagic fish resources, which would operate somewhat analogously to the GLOBEC SPACC project focusing on small pelagic fish resources of ocean boundary regions and peripheral seas and which likewise relies heavily on the comparative approach. This project, code-named "CLIOTOP" (see Section 18, below), of which the OFCCP project in the tropical Pacific would be a cornerstone, would ideally be developed within the International GLOBEC context.

17 *OFCCP – A proposal for a GLOBEC Pacific regional project [Patrick Lehodey]*

The Oceanic Fisheries and Climate Change project (OFCCP GLOBEC) has been designed to systematically investigate the potential effects of climate change on the productivity and distribution of oceanic tuna stocks and fisheries in the Pacific Ocean with the goal of predicting short- to long-term changes and impacts related to climate variability and global warming.

During the last decade, considerable progress has been achieved in the development of physical and biogeochemical 3D numerical ocean models. Biologists have also developed a diverse range of modeling approaches that reflects both the complexity of marine ecosystems and interests in the study and exploitation of the ocean. Studies of physiology and behaviour of higher pelagic predators like tuna or salmon led to elaboration of energetics and individual-based (IBM) models (Dagorn and Freon 1999, Kirby et al. 2000). The science of fisheries stock assessment has shown significant progress in the recent years; for example, the integration of statistical functions allowing extraction from multiple sources of data the best estimates for population dynamics (Fournier et al. 1998). At larger scale, the community and its food web appear increasingly complex. Their mathematical descriptions require several levels of simplification, for example using functional groups of species or using a size spectrum in which larger organisms feed on smaller ones. Combinations of these different approaches may also be possible. For instance, the model SEPODYM (Bertignac et al. 1998, Lehodey et al. 1998, Lehodey 2001b) combines a production model for the forage functional group with an age-structured population model of tuna predator species and their multi-fisheries. The dynamics of forage and predators are constrained only by environmental variables (temperature, oxygen, oceanic currents, and primary production) that can be predicted from coupled physical-biogeochemical models. Therefore, it now seems possible, using these different modeling approaches, to explore the underlying mechanisms by which climate–induced environmental variability affects the pelagic ecosystem and tuna populations.

17.1 Project description

The ultimate goal of the project is to conduct simulations with ecosystem models that include the main tuna species, using an input data set predicted under a scenario of climate change induced by greenhouse warming as defined by the Intergovernmental Panel on Climate Change (IPCC). This should lead to the first tentative understanding of how greenhouse warming will affect, at the ocean and global scales, the abundance and productivity of marine populations in the pelagic ecosystem, focusing on the major exploited species and fisheries, by a real coupling between atmospheric, oceanic, chemical and biological processes. Potential feedbacks from the changes in the pelagic ecosystem, and socio-economical consequences will be investigated to propose adaptation measures for the future. However, analyses of simulations based on retrospective series of oceanic and fishing data sets are necessary intermediate steps to increase the reliability in the predictive capacity of the models. In particular, realistic prediction by the models of changes and fluctuations observed at short (e.g., ENSO) and decadal (e.g., Pacific Decadal Oscillation, PDO) time scales in the ocean ecosystem and the tuna populations are necessary before prediction based on the global warming projection are incorporated. In addition, diverse studies are needed to improve the parameterization (e.g., energy transfer from primary to secondary production), the modeling of key processes (e.g., recruitment, movements, and feeding), and to validate the results of the simulations. Four major components have been identified to achieve these objectives.

17.2 Monitoring the upper trophic levels of the pelagic ecosystem

The past decade has generated significant progress in understanding ocean processes and the coupling of ocean and atmosphere in regulating Earth's climate. These accomplishments were made possible by the concurrent development of new technology and instrumentation, as well as substantial progress in numerical modeling (ocean general circulation models and new conceptual models of lower trophic level food webs). Despite the increase complexity when considering all the pelagic ecosystem, a similar approach, closely associating observation and modeling, seems the most appropriate to investigate the dynamics of upper trophic levels (from macroplankton to higher predators). However, while there has been substantial progress in acoustical technology or individual electronic tracking devices, the instrumentation allowing large-scale and long-term recording of key upper trophic components is still missing. One of these key components is the micronekton for which there is relatively little information. Comparatively, there is much more information on large pelagics (the predators of the micronekton) that are usually valuable exploited species. The fisheries for these species provide key information (catch, size) allowing population dynamics models to predict the population biomass, and eventually their spatial distribution, especially where large-scale tagging programs have been carried out for these valuable species. Therefore, while climate change concerns as well as recent ecosystem-based management requirements necessitate rapid development of numerical ecosystem models, we have only a very preliminary idea of the biology, ecology and dynamics of the intermediate key components of the pelagic food web. Indeed, there are not even enough observations to produce a mean spatial distribution of the micronekton biomass at the scale of ocean basins.

It is proposed in the present project to use existing technologies, and also to develop new instrumentation for monitoring the upper trophic levels of the pelagic ecosystem. Observation will combine both extensive studies at the ocean basin-scale and intensive studies in some sub-areas and key sites. Extensive studies aim at building ocean data sets for micronekton biomass and large pelagics biomass or individual records, using acoustic (micronekton biomass), sonar (tuna biomass), and electronic tracking (individuals) devices. Intensive studies will focus on important processes and behavior (e.g., prey-predator interaction, habitat, schooling and aggregation of tunas, reproduction, composition and dynamics of micronekton, etc). In addition, at each scale of observation there will be a corresponding modeling development, e.g., large-scale ecosystem, population models or individual-based models. Observations will be used to parameterize and improve the models. Eventually, models could provide real-time prediction for operational activities at sea, and help in the validation of dynamic processes or hypotheses arising from model simulations.

17.3 Food web structure in pelagic ecosystems

Production at higher trophic levels (usually exploited species) depends on the production at lower levels (bottom-up control) and may be modulated by the physical forcing and the structure of the marine food webs. Ecological concepts suggest for instance that the structure of the food web can be controlled by the biodiversity within the system and/or by higher predators (top-down control). However, concerning pelagic ecosystems, there is very little observation to illustrate such controls. In association with the data collected by the monitoring component of this project, it is essential for modeling the pelagic ecosystem to identify the functional groups, how energy and matter flow through these groups and how they are affected by physical and biological changes as well as by human activities (fisheries).

Two kinds of analyses will be helpful in this task: a classical approach based on the study of stomach contents to establish the prey-predator interactions, and the more recent isotope-ratio approach, that appears a promising way for describing the energy transfer through the food web (Rau et al. 1983, Fry 1988). The success of these approaches also relies on the multiplicity of studies in different regions of the ocean(s) and in different periods of time. The comparative study necessitates developing standardized protocols, reference databases and controlled laboratory experiments. Retrospective analyses based on the numerous diet studies published or still in archives of many institutes should be also encouraged. Information obtained from these studies and from the monitoring will be used in individual energetics models (IBM), mass-balance models (ECOPATH-ECOSIM) and spatial ecosystem models (SEPODYM).

17.4 Modeling from ocean basin to individual scale

Close association between observation and modeling has been a permanent guide in conceptualization of this project. Recognizing the diversity of space-time scales processes overlapping in pelagic ecosystem dynamics, a second key idea is that a general framework is needed to integrate studies at different time and space scales with potential connections between them. Therefore, at each scale the models and sources of data collected in the studies of the first two components are indicated. There is a large range of models represented in the project covering global to individual scales. At global or basin scales, predictions from three different coupled physical-biogeochemical models will be used over the period 1950-present. The global model will also provide predictions for the next century using a scenario of greenhouse warming. These predictions will be used to run the ecosystem models of upper trophic levels on which the economical and social analyses rely. At least one of the physical-biogeochemical models should provide prediction at high resolution in one or a few identified sub-regions (first step for a nested model approach) where intensive process studies are conducted. A similar approach will be investigated for the spatial ecosystem models. This would allow connections between large and small scales (low and high frequencies) processes and testing the mechanisms that control the system when moving from one scale (frequency) to the other.

17.5 Socio-economical impacts

The interannual climate variability due to ENSO events has important socio-economic impacts on the tuna fishery and the industry at the global scale that in turn may affect the tuna populations (e.g., higher/ lower catch) and the pelagic ecosystem (by-catch, interaction between species, top-down effects). Several causes drive the fluctuations of tuna stocks and catches. While economic rather than biological reasons limit (today) the catch increase of the most productive tuna species (skipjack) in the Pacific, the intense fishing effort on the highly valuable bluefin tuna, perhaps combined with environmental forcing, has led to a decline in this population from the 1960s to the 1980s. Interactions amongst species and between the multiple and diverse fisheries, as well as potential cascade effects in the ecosystem raise important questions for management with potential strong socio-economic repercussions.

Based on an existing spatial model (Chakravorty 1997, Chakravorty and Sibert 1999, Chakravorty and Nemoto 2001) developed for investigating optimal spatial allocation of fishing effort, new studies will include climate variability to obtain information on alternative scenarios regarding the interannual as well as spatial variability of fish stocks. A key issue will be in classifying alternative scenarios of climate change that could be translated into the spatial and temporal distribution of fish species, as well as their movement. Other issues that will need to be modeled include multiple fleets with different efficiency characteristics, and the presence of fishing vessels from multiple political jurisdictions, that will imply different costs of fishing through differences in material and labor costs. The presence of multiple countries will allow the use of strategic behavioral models. For instance, Nash Equilibria could be calculated for regions that are subject to fishing by multiple countries. These results could be compared to optimal outcomes under single ownership of the fishery and the impacts of feasible management measures could be simulated.

Investigations of these interactions and effects occurring with ENSO would help to assess the vulnerability and impacts in a scenario of global warming, and to eventually propose adaptations and/or mitigation measures for the future.

18 *CLIOTOP — A proposed global comparative research effort on large oceanic pelagic fisheries [Olivier Maury]*

In the current context of very strong fishing pressure, climatic variability and potential climate change, understanding, modeling and eventually forecasting the dynamics of open ocean ecosystems associated with apex predators is becoming crucially important. Adequately responding to this major challenge will require major improvements of our knowledge concerning the processes involved in offshore ecosystem dynamics at various scales and complexity levels.

The Honolulu Climate-Fisheries Workshop provided very stimulating prospective discussions on these issues. One important outcome is the idea that time has come to organize on a global scale a comparative study of open sea pelagic ecosystem/climate coupling to identify interaction processes. An international cooperative research effort, code-named the CLIOTOP (CLimate Impacts on open Ocean TOp Predators) project, was proposed.

Indeed, there is now a remarkable correspondence between the scales at which oceanographers, climatologists and biogeochemists are developing state-of-the-art physical (OGCM, ect.) and biological/ecosystem (e.g., "nutrient-phytoplankton-zooplankton (NPZ)) models and the basin scales at which open ocean apex predator populations may operate. But due to the large extent and complexity of the considered ecosystems, adequate observational and experimental approaches are very difficult to implement and most often must be restrained to local regional phenomena and special cases. As a consequence, our ability to analyze and understand observed phenomenon in terms of causal processes and mechanisms is seriously compromised.

The process of generalizing those available local observations and findings may be facilitated by the large-scale comparative approach (see Section 14, above) that would be the core of the CLIOTOP project framework. Such an international project would facilitate the sharing of ideas and information among a large number of independent research projects pursuing GLOBEC-type approaches involving observation and modeling in a variety of open ocean regions and over a range of species. This could provide the basis for informative applications of the comparative method, which would benefit all the collaborating parties (i.e., the whole, in such a case, being much more than the sum of the parts).

It is clear that such sharing of information and experience among regional programs has yielded great dividends at relatively minor cost in the progression of international comparative research projects addressing small pelagic fish systems that has occurred over the past 15 years (i.e., first the IOC-FAO Sardine-Anchovy Recruitment Project (SARP), then the NOAA-IRD-ICLARM Climate and Eastern Ocean Systems (CEOS) Project, and finally the current GLOBEC Small Pelagics and Climate Change (SPACC) Project). The experience and insights gained by these projects could probably allow us even to shorten the process of setting up an efficient "open sea" project.

In analogy to SPACC, the proposed CLIOTOP program could be an "umbrella"-type program covering various independent and potentially collaborating regional projects[17] in the three oceans[18]. There is indeed a very large, multi-national community of marine ecologists, fishery scientists, climate scientists and oceanographers that is highly interested in such a large-scale "open sea" project. The CLIOTOP project would serve to promote and facilitate information flow and exchange of ideas among various projects and institutions throughout the world. It would organize meetings for comparative analysis and informative pattern recognition and would facilitate publication of reports focused on this problem area. It would be organized around scientific questions focusing on processes and mechanisms, the ultimate goal being to improve our predictive capabilities concerning the operation of open ocean ecosystems in a global change context.

Studying the dynamics of large pelagic ecosystems in such a climatic change perspective involves several fields ranging from climate modeling and oceanography to population biology and ecology, fishery science and socio-economics. Given the complex nature of its foci, an "open sea" GLOBEC program should strongly encourage the co-operation and exchanges with other IGBP programs such as SOLAS, GAIM and JGOFS as well as World Climate Research Project (WCRP) programs such as CLIVAR. Being able to make use of the tools and expertise provided by those international programs is a crucial need for such a future "open sea" project.

A collective intent letter has been written to the GLOBEC Scientific Steering Committee and signed by a number of individual scientists involved in the discussions which have followed the meeting (Dr. Juergen Alheit, Baltic Sea Research Institute, Germany; Dr. Andrew Bakun, IRI, USA; Dr. Robert Cowen, RSMAS/MBF, USA; Dr. Jean-Marc Fromentin, IFREMER, France; Dr. Patrick Lehodey, SPC, New Caledonia; Dr. Olivier Maury, IRD, Seychelles; Dr. Arthur J. Miller, Scripps Institution of Oceanography, USA; Dr. Raghu Murtugudde, ESSIC, USA; Dr. Ian Perry, Fisheries and Oceans, Canada; Dr. Jeffrey Polovina, NMFS Hawaii, USA; Dr. Claude Roy, IRD, South Africa). Its purpose is to propose to the GLOBEC-SSC the adoption of CLIOTOP as new International GLOBEC project.

19 *Potential utility of a multilateral comparative retrospective data analysis effort* [19]

Climate is often implicated as the driving force in many of the large-scale shifts in marine ecosystems. Evidence for climate-induced ecosystem changes on decadal scales has been accumulating. This evidence has been gained mostly from local retrospective studies and, where a comparative approach among a number of similar systems has been possible, the results have proven quite significant (e.g. the *optimal environmental window* result discussed in Sections 10.1 and 13.2).

However, there always has been a serious problem of spurious correlations in fisheries-environmental science. There are several reasons for this[20]:

1. The lack of abundant degrees of freedom available in time series (available data series tend to be too short to contain sufficient realizations of the important variations of interest);

2. The pertinent data series also tend to contain substantial autocorrelation

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17 **Proposed initial CLIOTOP pilot projects:**
- the **OFCCP** project (Oceanic Fisheries and Climate Change in the Pacific; contact: P. Lehodey, SPC, Nouméa)
- the **RSMAS** billfish project on billfish early life history (contact: R.K. Cowen, CSF, Miami)
- the **STROMBOLI/MERCATOR** Atlantic bluefin tuna project (contact J.M. Fromentin, Ifremer, Sète).
- the **THETIS** project (Thons tropicaux: Environnement, sTratégies d'exploitation et Interactions biotiques dans les écoSystèmazes hauturiers; contact: F. Marsac, IRD la Réunion; O. Maury, IRD Seychelles),
- the **TUNABAL** project (Bluefin Tuna Eggs and Larval Study in the Azores ; contact ; A. Garcia, COM, Malaga).

18 As in the case of SPACC, the CLIOTOP project would rely mostly on interregional applications of the comparative method, whereas its member projects might be involved with actual field operations, data acquisition or modelling exercises. At this very preliminary stage, five pilot research projects have already been identified and could potentially be involved in CLIOTOP.

19 Ian Perry made important contributions to the preparation of this section.

20 For further elaboration and examples, see Section 11.1 in Bakun 1996.

(which further reduces degrees of freedom);

3. An inability to realistically estimate significance levels of an empirical finding in a situation where we almost never are made aware of the "failures", only of the "successes".

Item 3 may be the most problematic. For example, (case a) if a single researcher were to search through twenty different combinations of data series, and found one that met a significance criterion of $p<0.05$, this is clearly no more than what he could expect to find merely by chance in twenty such tries with different series of random numbers. If he then published this relationship as a significant finding, we might consider that individual to be either naive or cynically dishonest. However, if (case b) each of twenty different researchers (each entirely independently of one another, each basing the test on a logical a *priori* hypothesis, etc.) tested a different one of the same group of data sets, and one of them found the same significant relationship, which he then published, we would certainly consider this to be proper. However, since the others who did not find relationships would not publish that fact (no journal welcomes papers reporting studies that did not yield significant results), the real result of case (b) is identical to that of case (a). Thus, unless we know the potential distribution from which an empirical result is drawn, it is impossible to judge its true significance.

Thus it may be time to take the process out of the hands of individuals and, as a community, simply assemble the largest available number of potentially pertinent data series from a variety of regional environmental settings, species types, etc., assemble them into a large data base, and simply "grind out" the inter-series data structures with shear "raw" modern computer power. Then we would have the distributions of successes and failures so that we can realistically judge the true significance of our findings.

The important point is that one might hope to use variations in climate, in particular as manifested in different regions of the world's oceans, as natural experiments to understand how these systems respond to climate variability. Moreover, in addition to conventional tests for linear predictors, etc., one might be able to perform informative *meta analyses* (tests on distributions of tests). An example (Bakun 2002b) of a potential test for the existence of life-cycle length dependent adaptive response mechanisms (such as school-mix feedback, see Section 11), was distributed to workshop participants prior to the meeting.

Discussion at the workshop, and ultimately consensus, centered about the utility of conducting these types of comparisons solely on a global basis. Much useful information and understanding can be gained by conducting these analyses on regional scales, as well as on global scales. Much of the immediate forcing to fish populations occurs through local processes, for example upwelling, and the local manifestations of these forcing processes may differ among locations. Such local instances of forcing may be connected over very large scales by "teleconnections", through which the characteristics of the local process may be altered or subsumed by the teleconnection process. There is, however, a great need to do both types of analyses: comparisons at the local/regional level, and on a global basis.

In addition to purely statistical comparisons of fish populations and climate variables, there is a need to develop a model-based approach. Using models, such as coupled physical-biological models, to define a framework for the analyses would help increase understanding of the processes or mechanisms underlying the statistical relationships. Models permit tools from different disciplines to be combined, and help to define and to improve the questions being asked of the data. Models also enable more sophisticated questions to be asked, and tested, about the linkages between climate and fisheries than is possible with purely statistically-based analyses. Models permit the incorporation of additional data (e.g., the NCEP reanalyses of atmospheric data, into the comparisons). Model output might also be considered as data for input into the fisheries comparisons, e.g. as for difficult-to-observe variables such as sub-surface water properties, or primary production. Models can help to alleviate problems with statistical significance by narrowing the range of explanatory variables used in the climate – fisheries comparisons.

Another approach, which can be thought of as intermediate between the statistical and modeling approaches and between the local and global comparison scales, is to look for coherent regional-scale climate structures or perturbations, and look to see if there are relationships among fish populations to these regional physical systems. An example is the apparent coherent physical manifestation of the climate system in the North Pacific, that is reflected in the Pacific Decadal Oscillation Index (PDO) (Mantua et al. 1997). Finding relationships and building understanding of the mechanisms linking such regional-scale climate features to responses by fish populations (and their marine ecosystems) may be easier because connections at these scales may have the least amount of "filtering" compared to widely-dispersed systems which are connected through indirect teleconnections.

Teleconnections, however, are potentially still important, and they are important to understand in the context of responses of the *MRS to global changes. Most progress has perhaps been made on the study of global teleconnections of fluctuations of small pelagic fishes (e.g. Schwarztlose et al. 1999). Whether small pelagic fishes are more susceptible to global climate changes because they live pelagically and have short life-spans, or whether they are the only group that has been investigated in a coherent manner, is unclear. Other species groups need to be investigated for global synchrony, and compared with the patterns of small pelagic fishes to understand the potentially different responses by species with different life-history strategies.

In summary, there is an urgent need for understanding climate–fish–fisheries connections by making comparisons between populations within species, and between different species groups, at spatial scales larger than local. These comparisons ultimately need to be done on a global scale, but valuable understanding can be gained by working from regional to global scales. Regional analyses should strive to identify coherent structures or processes in the physical climate system to which fish populations may respond, and then look for differences in reactions among these populations or species to similar forcing events. At global scales, analyses need to look for large-scale coherent responses that may be synchronized by as-yet poorly understood teleconnection processes. For both scales of analyses, a combination of statistical and model-based approaches are recommended to both provide new data sets and test mechanistic understanding. The analysis may require some degree of coordination and/or central planning so that numbers of significant and non-significant tests can be recorded, and relationships that might not be significant individually but which may be significant in aggregate can be recognized. "Knotty" issues such as the proprietary nature of data and the mechanics of (and incentives for) making data accessible to the broad community would need to be addressed.

20 *Proposed formulation of a Pacific regional climate-fisheries project*

The Pacific Ocean appears to offer several distinct advantages for studying climate-scale effects on fisheries and fishery resource populations:

1. Interyear variability dominates in the Pacific regional ecosystems to a much greater degree than in the systems of other oceans and seas. Moreover, the first-order mechanisms behind the largest component of this variability, ENSO, are relatively well understood;

2. There appears also to exist in the Pacific a strong component of rather coherent interdecadal variability (the Pacific Decadal Oscillation), at least in the northern part of the ocean basin;

3. The fish communities on the two sides of the Pacific, and in both the northern and southern hemispheres, seem to be composed of similar species complexes (for example, in strong contrast to the situation in the much smaller Atlantic Ocean, a single species of sardine, *Sardinops sagax*, appears to be a dominant component in all four widely-distant quadrants of the Pacific: Californian, Peru-Humboldt, Japanese and Australian.) This would appear to facilitate effective application of the comparative method.

4. The fact that many of the most important fishery resource stocks appear to be varying in a degree of synchrony on interdecadal time scales indicates that much of the potential feedback complexity in trophic and other ecosystem linkages must be operating somewhat in the background and that the dominant mechanisms must be acting rather simply and directly on the resource populations themselves and be driven by basin-scale climatic teleconnections;

5. There are available some prominent enigmas that appear to defy understanding according to the conventional conceptual framework. These might turn out to be extremely useful entry points to the process of identifying and addressing the missing pieces in our current understanding. These enigmatic issues include:

(a) Why is the Peru-Humboldt Current ecosystem able to produce so much greater tonnage of fish in comparison to other similar eastern ocean upwelling systems?

(b) Why do sardines, which are a species obviously adapted to highly productive ocean conditions (upwelling areas, etc.) appear to do better, at least in the eastern Pacific, during El Niño episodes since these are characterized by abruptly lowered primary productivity?

(c) How is it that fisheries can apparently fluctuate in phase even though they exist in very different types of ecosystems that appear to respond very differently to common large-scale forcing?

6. The Pacific Ocean's great distances and associate separations of regions, markets, cultural traditions, states of economic and technological development, etc., may render the Pacific regions particularly amenable to applications of the comparative method to socio-economic aspects of climate-fisheries research and research applications.

Accordingly, in addition to the proposed new OFCCP and CLIOTOP efforts to be focused particularly on tunas and other large oceanic pelagic fishes, it was proposed at the workshop in Honolulu that a regional project focusing more broadly on various resource stocks, important ecosystem components, and fisheries of the Pacific region might offer an avenue to some substantial progress within the general climate-fisheries research area. This idea attracted considerable interest and discussion.

It appears that a first step might be to undertake a full assessment of the degree of climate/ ocean synchrony in the Pacific Ocean, including whether anomalies of a nature that might affect fisheries in the southern and northern hemispheres are in or out of phase. One of the challenges may be to develop effective proxies for climatic data in the South Pacific, which has traditionally been poorly observed.

Among hypotheses that have been developed are:

1. Bakun's (2001, 2002a) rapid adaptive/ behavioral responses (e.g. school - mix feedback) model (See Section 11)
2. Cushing's (1971, 1975, 1990) match/ mismatch hypothesis, e.g., peaks of abundance of fish larvae and their prey (zooplankton) in phase or not (See Section 10.5.)
3. Lehodey's advection and larval food/ predator ratio model which combines food web forcing with spatial and temporal dynamics (See Section 17)
4. MacCall's advection / retention e.g. mesoscale variability model (See Section 15)
5. Gargett's (1997) Optimal Stability Window hypothesis that relates Pacific salmon survival to regime-like variations in water column stability.
6. The possibility that shifts in food particle size spectra, perhaps in response to changes in relative importance of the "microbial loop", might shift favorability between filter-feeding species with different gillraker mesh size (sardines having much finer filtering capabilities than do anchovies (Louw et al. 1998)).

Recognizing that there were too many participants at the workshop to effectively propose and adopt, in the limited time available, an appropriate framework for such a major Pacific-scale project, the workshop participants agreed to request that PICES, IRI and IPRC consult among one another on development of such a framework. It was suggested that the PICES North Pacific Transitional Areas Symposium, to be held in La Paz, Mexico, on 23-25 April, 2002, might be a possible venue for such a consultation.

21 *Useful application of current state of scientific understanding*

Many workshop participants emphasized the need to achieve a balance in approaches to acquiring and applying understanding of climate-fisheries interactions, with an important first step being improved communication between the fisheries and climate research communities. Over the last few years, there has been much interest from the climate community in demonstrating the predictive capability gleaned from the last few decades of work. Simultaneously the biological community is moving away from forecasting of single species dynamics toward understanding multiple species interaction through ecosystem models. Such fisheries research will necessitate close interaction with the climate community on projects involving hindcasting, modeling studies, and reanalysis studies within the biological community.

Participants were also keenly aware that multiple economic, political, cultural, and environmental factors interact to affect the sustainability of fisheries. Better understanding of climate's role on living marine resources will not be the "silver bullet" that reverses the many years of overcapitalization and lack of enforcement that characterize global fisheries. However the group was enthusiastic about the potential for the use of various sorts of climate information to better inform decisions, ranging from the negotiation of multilateral treaties to the private sector's long-term investment strategies to optimal design of observational programs, that may help to alleviate some of these chronic problems. As with all sorts of scientific information and technological breakthroughs, care must be taken to pay proper attention to issues of communication of this knowledge, involving stakeholders in the process from the start.

The science, of course, will never be perfect and one challenge addressed at the workshop was to consider how strongly, and in what circumstances, to promote the use of climate information in addressing real-world fisheries issues given our current state of scientific knowledge and understanding. While there was much optimism that we may be close to significant conceptual and scientific breakthroughs, the above discussion has focused in large part on the current limitations of our knowledge. A concept that was raised was that of "foreseeability", referring to the fact that even if we cannot predict exactly what is going to happen, based on experience and existing data, decision makers should be able to anticipate likely occurrences (and thus may be accountable for not taking action). Bearing these issues in mind, there was agreement that there are activities and products that would be useful to pursue given even our current state of somewhat limited scientific understanding. These include:

"Picking low-lying fruit"

In certain areas of the world (e.g., many Pacific Island states, coastal Peru), fisheries systems, including the human dimensions, react relatively consistently to certain predictable climate events such as El Niño. Thus, we are at a stage to focus on these areas for direct application of climate information. Such activities should be pursued (however, keeping in mind the potential unintended consequences discussed above).

Decision calendars/maps

For areas where we believe there is a discernible climate impact or trend, we need to study in detail the decisions and their required lead times that may be affected by introducing this knowledge. Such socioeconomic research takes time and should proceed in parallel with the ecologically-oriented research. Local knowledge should be incorporated, as there are clear examples where the biological system may give indications of coming environmental events prior to those ensuing from physical/dynamical forecasts.

Knowledge products

Although we may not have definitive answers to give managers and other key actors in fisheries, particularly with respect to longer timescales, the group was of the opinion that we should strive for a participatory approach, beginning with basic education about the current state of the knowledge for relevant decision-makers, including those in the financial sector. There was emphasis that we must be transparent in representing the limitations of our knowledge in order to avoid a backlash and loss of legitimacy. While we may not be able to predict regime shifts, knowledge by actors within the fisheries sector that dramatic fluctuations can occur may help proactive planning and serve as additional impetus to an adaptive management approach.

Impacts maps

Drawing on experience in other spheres involving climate patterns and their impacts, it was suggested that spatial maps and corresponding time series of the climatic/oceanographic patterns in the Pacific Ocean associated with the known large-scale patterns of biological variations and fisheries impacts would be a useful product for the research and public education communities. The idea is to provide a conceptual framework for organizing the data so that one might conveniently juxtapose environmental factors and expected impacts by species, fishery, and other variables.

References

Agrawala, S. and K. Broad. 2002. Technology transfer perspective on climate forecast applications. Research in Science and Technology Studies 13, 45-69.

Alheit, J. and P. Bernal. 1993. Effects of physical and biological changes on the biomass yield of the Humboldt Current ecosystem. p. 53-68. In: K. Sherman, L. M. Alexander, and B. Gold (eds.) Large Marine Ecosystems—Stress, Mitigation, and Sustainability. American Association for the Advancement of Science.

Arntz, W. E., A. Landa and J. Tarazona. 1985. El Niño: Su impacto en la fauna marina. Bol. Inst. Mar., vol. ext., Perú-Callao, 222 pp.

Bakun, A. 1996. Patterns in the Ocean: Ocean Processes and Marine Population Dynamics. University of California Sea Grant, San Diego, California, USA, in cooperation with Centro de Investigaciones Biológicas de Noroeste, La Paz, Baja California Sur, Mexico. 323 pp.

Bakun, A. 1998. Ocean Triads and Radical Interdecadal Stock Variability: Bane and Boon for Fishery Management Science. pp. 331-358. In: T.J. Pitcher, P.J.B. Hart and D. Pauly (eds.) Reinventing Fisheries Management. Kluwer Academic Publishers, Dordrecht, Netherlands.

Bakun, A. 2001. 'School-mix feedback': a different way to think about low frequency variability in large mobile fish populations. Prog. Oceanogr. 49, 485-511.

Bakun A. 2002a. Seeking an expanded suite of management tools: implications of rapidly-evolving adaptive response mechanisms (such as "school-mix feedback"). In: N. Erhardt (ed.) Proceedings of the World Conference on Sustainable Fisheries. Center for Sustainable Fisheries, Univ. Miami (in review).

Bakun A. 2002b. An empirical test for the existence of a generation-time-dependent mechanism for rapid adaptive response of fish populations to variations in ocean climate, predation or fishery exploitation. pp. 2-4. In: C.D. Van der Lingen, C. Roy, P. Fréon, M. Barange, L. Castro, L. Gutierrez, L. Nykjaer and F. Shillington (eds.) Report of a GLOBEC-SPACC/IDYLE/ENVIFISH workshop on spatial approaches to the dynamics of coastal pelagic resources and their environment in upwelling areas. GLOBEC Rep. 16.

Bakun, A. and P. Cury. 1999. The "school trap": a mechanism promoting large-amplitude out-of-phase population oscillations of small pelagic fish species. Ecol. Letters 2, 349-351.

Bakun, A. and R. Parrish. 1980. Environmental inputs to fishery population models for eastern boundary currents. pp. 67-104. In: G.D. Sharp (ed.) Workshop on the effects of environmental variation on the survival of larval pelagic fishes. IOC Workshop Rep. 28., Intergovernmental Oceanographic Commission, UNESCO, Paris. 323p.

Barber, R. T. and F. P. Chavez. 1983. Biological consequences of El Niño. Science 222, 1203-1210.

Barnes, T., L. Jacobson, A. MacCall, and P. Wolf. 1992. Recent population trends and abundance estimates for the Pacific sardine (*Sardinops sagax*). Calif. Coop. Oceanic Fish. Invest. Rep. 33, 60-75.

Barrett, C. B. 1998. The Value of Imperfect ENSO Forecast Information: Discussion. Amer. J. Agricul. Econ. 80 (5), 1109-1112.

Beamish, R. J., and D. R. Bouillon. 1993. Pacific salmon production trends in relation to climate. Can. J. Fish. Aquat. Sci. 50, 1002-1016.

Beamish, R. J., C. E. M. Neville, et al. 1997. Production of Fraser River sockeye salmon (Oncorhynchus nerka) in relation to decadal-scale changes in the climate and the ocean. Can. J. of Fish. Aquat. Sci. 54, 543-554.

Beamish, R.J., D.J. Noakes, G.A. MacFarlane, L. Klyashtorin, V.V. Ivanov and V. Kurashov. 1999. The regime concept and natural trends in the production of Pacific salmon. Can. J. of Fish. Aquat. Sci. 56, 516-526.

Berkes, F., R. Mahon, P. McConney, R. Pollnac and R. Pomeroy. 2001. Managing Small-Scale Fisheries. Alternative Directions and Methods. International Development Research Centre, Canada. 320p.

Bertram, D.F., D.L. Mackas and S.M. McKinnell. 2001. The seasonal cycle revisited: interannual variation and ecosystem consequences, pp. 283-307 In: S.M. McKinnell, R.D. Brodeur, K. Hanawa, A.B. Hollowed, J.J. Polovina and C.-I. Zhang (eds.) Pacific Climate Variability and Marine Ecosystem Impacts. Prog. Oceanogr. 49.

Bradford, M. J., and J.R. Irvine. 2000. Land use, fishing, climate change, and the decline of Thompson River, British Columbia, coho salmon. Can. J. Fish. Aquat. Sci. 57, 13-16.

Brander, K.M. and P.C.F. Hurley. 1992. Distribution of early-stage Atlantic cod, (*Gadus morhua*), haddock (*Melanogrammus aegelfinus*) and witch flounder (*Glyptocephalus cynoglossus*) eggs on the Scotian Shelf: A reappraisal of evidence on the coupling of cod spawning and plankton production. Can. J. Fish. Aquat. Sci. 49, 238-251.

Brander, K.M., R.R. Dickson and J.G. Shepherd. 2001. Modelling the timing of plankton production and its effect on recruitment of cod (*Gadus morhua*). ICES J. Mar. Sci. 58, 962-966.

Broad, K., and S. Agrawala. 2000. The Ethiopia famine: Uses and limits of seasonal climate forecasts. Science 289, 1693-1694.

Broad, Kenneth, Alex Pfaff, and Michael H. Glantz (in press) Effective & Equitable Dissemination of Seasonal-to-Interannual Climate Forecasts: policy implications from the Peruvian fishery during El Niño 1997-98. Climatic Change.

Brodeur, R.D., and D.M. Ware. 1992. Long-term variability in zooplankton biomass in the subarctic Pacific Ocean. Fish. Oceanogr. 1, 32-38.

Brodeur, R.D., and D.M. Ware. 1995. Interdecadal variability in distribution and catch rates of epipelagic necton in the North Pacific Ocean. pp. 329-356. In Beamish, R.J., ed. Climate Change and Northern Fish Populations. Can. Spec. Publ. Fish. Aquat. Sci. 121.

Carr, M.-E. and K. Broad. 2000. Satellites, Society, and the Peruvian fisheries during the 1997-98 El Niño. pp. 171-191. In: D. Halpern (ed.) Satellites, Oceanography and Society. Elsevier Science, Amsterdam.

Carrasco, S. and O. Lozano. 1989. Seasonal and long-term variations of zooplankton volumes in the Peruvian Sea, 1964-1987. pp. 82-85. In: Pauly, D., P. Muck, J. Mendo, and I. Tsukayama, Eds. The Peruvian upwelling ecosystem: dynamics and interactions. ICLARM Conference Proceedings 18, 438p.

Chakravorty, U. 1997. "Optimal regulation of the Hawaii pelagic fishery: Proposal," Pelagic Fisheries Research Program, 1997-2002.

Chakravorty, U. and K. Nemoto. 2001. Modeling the effects of area closure and tax policies: A spatial-temporal model of the Hawaii longline fishery. Marine Resource Economics 15, 179-204.

Chakravorty, U. and J. Sibert, eds. 1999. Ocean-Scale Management of Pelagic Fisheries: Economic and Regulatory Issues, Joint Institute of Marine and Atmospheric Research Contribution 99-321, 102 pp.

Checkley, D., R. Dotson and D. Griffith. 2000. Continuous, underway sampling of eggs of Pacific sardine (*Sardinops sagax*) and northern anchovy (*Engraulis mordax*) in spring 1996 and 1997 off southern and central California. Deep-Sea Res. II 47, 1139-1155.

Cowen R., K.M.M. Lwiza, S. Sponaugle C.B. Paris and D.B. Olson. 2000. Connectivity of marine populations: open or closed? Science 287, 857-859.

Cury, P., and C. Roy. 1989. Optimal environmental window and pelagic fish recruitment success in upwelling areas. Can. J. Fish. Aquat. Sci. 46, 670-680.

Cury, P., C. Roy, R. Mendelssohn, A. Bakun, D.M. Husby, and R.H. Parrish. 1995. Moderate is better: nonlinear climatic effect on California anchovy (Engraulis mordax). pp. 417-424. In: R.J. Beamish (ed.). Climate Change and Northern Fish Populations. Can. Spec. Publ. Fish. Aquat. Sci. 121. 739 pp.

Cushing, D.H. 1969. Upwelling and fish production. FAO Fish. Tech. Pap. 84. 40pp.

Cushing, D.H. 1971. The dependence of recruitment on parent stock in different groups of fishes. J. Cons. int. Explor. Mer. 33, 340-362.

Cushing, D.H. 1975. Marine Ecology and Fisheries. Cambridge University Press, Cambridge. 278p.

Cushing, D.H. 1990. Plankton production and year-class strength in fish populations: an update of the match/mismatch hypothesis. Adv. Mar. Biol. 26, 249-293.

Dagorn, L. and P. Freon. 1999. Tropical tuna associated with floating objects: a simulation study of the meeting point hypothesis. Can. J. Fish. Aquat. Sci. 56, 984-993.

Durand, M.-H., P. Cury, R. Mendelssohn, C. Roy, A. Bakun and D. Pauly (eds.) 1998. Global Versus Local Changes in Upwelling Systems. ORSTOM Editions, Paris. 594 pp.

Ebbesmeyer, C.C., D.R. Cayan, D.R. McLain, F.H. Nichols, D.H. Peterson, and K.T. Redmond, 1991. 1976 step in the Pacific climate: forty environmental changes between 1968-1975 and 1977-1984. In: J. Betancourt and V.L. Tharp (eds.) Proc. 7th Annual Pacific Climate Workshop. Calif. Dept Water Resources, Interagency Ecol. Stud. Prog. Tech. Rep. 26, 129-141.

FAO. 2001. Research implications of adopting the precautionary approach to management of tuna fisheries. FAO Fish. Circ. 963. 88 pp.

Fortier, L., D. Ponton and M. Gilbert. 1995. The match/mismatch hypothesis and the feeding success of fish larvae in ice-covered southeastern Hudson Bay. Mar. Ecol. Prog. Ser. 120, 11-27.

Fournier,D.A., J. Hampton and J.R. Sibert. 1998. MULTIFAN-CL: a length-based, age-structured model for fisheries stock assessment, with appliacation to South Pacific albacore, *Thunnus alalunga*. Can. J. Fish. Aquat. Sci. 55, 2105-2116.

Fry, B. 1988. Food web structure on Georges Bank from stable C, N, and S isotopic compositions. Limnol. Oceanogr. 33, 1182-1190.

Gargett, A.E. 1997. The optimal stability 'window': a mechanism underlying decadal fluctuations in North Pacific salmon stocks? Fish. Oceangr. 6, 109-117.

Glantz, M.H. 1979. Science, politics, and economics of the Peruvian anchovy fishery. Marine Policy, July, 1979, 201-210.

Glantz, M.H. 1986. Man, state, and fisheries: An inquiry into some societal constraints that affect fisheries management. Ocean Development and International Law 17, 191-270.

Glantz, M.H. (ed.) 1995. Usable Science II: The Potential Use and Misuse of El Niño Information in North America. NCAR, 260 pp.

Glantz, M.H. 1996 (2001). Currents of Change: El Niño's impact on climate and society. Cambridge Univ. Press, 194 pp.

Glantz, M.H. and J.D. Thompson (eds.) 1981. Resource Management and Environmental Uncertainty: Lessons from Coastal Upwelling Fisheries. John Wiley and Sons, New York.

Gotceitas, V., V. Puvanendran, L.L. Leader and J.A. Brown. 1996. An experimental investigation of the 'match/mismatch' hypothesis using larval Atlantic cod. Mar. Ecol. Prog. Ser. 130, 29-37.

Graham, N.E. 1994. Decadal-scale climate variability in the 1970s and 1980s: observations and model results. Climate Dyn. 10, 135 162.

Hamnett, M.P. and C.L. Anderson C.L. 1998. Impact of Climate Variability on Pelagic Fisheries in the Pacific Islands. NOAA Office of Global Programs Progress Report, April 1998. Social Science Research Institute, Univ. Hawaii.

Hansen, J. W. (ed.) 2001. Forthcoming: Special Issue on Applying Seasonal Climate Prediction to Agriculture. Agricultural Systems.

Hanski I. 1991. Metapopulation dynamics: a brief history and conceptual domain. Biological J. Linn. Soc. 42, 3-16.

Hare, S. R. and N. J. Mantua. 2000. Empirical evidence for North Pacific regime shifts in 1977 and 1989. Prog. Oceanogr. 7, 103-145.

Hare, S. R., N. J. Mantua and R.C. Francis. 1999. Inverse production regimes: Alaska and West Coast Pacific salmon. Fisheries 24, 6-14.

Hare, S.R., S. Minobe, W.S. Wooster, and S. McKinnell. 2000. An introduction to the PICES symposium on the nature and impacts of North Pacific climate regime shifts. Prog. Oceanogr. 47, 99-102.

Hay, D.E., P.B. McCarter, and K.S. Daniel. 2001. Tagging of Pacific herring *Clupea pallasi* from 1936-1992: a review with comments on homing, geographic fidelity, and straying. Can. J. Fish. Aquat. Sci. 58, 1356-1370.

Hughey, KFD, R. Cullen and G.N. Kerr. 2000. Stakeholder groups in fisheries management. Marine Policy 24, 119-127.

Hurrell, J. W. and H. van Loon. 1997. Decadal variations in climate associated with the North Atlantic oscillation. Climatic Change 36, 301-326.

Jordán, R., J. Csirke and I. Tsukayama. 1978. Situacion de los recursos anchoveta, sardina, jurel y caballa al Junio 1978. Instituto del Mar del Peru, Informe No. 56. 32 p.

Jentoft, S. 2000. The community: A missing link of fisheries management. Marine Policy 24, 53-59.

Jentoft, S., B. J. McCay and D. C. Wilson. 1998. Social theory and fisheries management. Marine Policy 22, 423-436.

Kawasaki, T. 1983. Why do some pelagic fishes have wide fluctuations in their numbers? Biological basis of fluctuation from the viewpoint of evolutionary ecology. pp. 1065-1080 In: Sharp, G. D. and J. Csirke (eds.). Proceedings of the Expert Consultation to Examine Changes in Abundance and Species of Neritic Fish Resources. San Jose, Costa Rica, 18-29 April, 1983. FAO Fish. Rep. 291(2,3).

Kawasaki, T. 1989. Long-term variability in the pelagic fish populations. pp.47-60 In: T. Kawasaki, S. Tanaka, Y. Toba and A. Taniguchi (eds.), Long-term variability of pelagic fish populations and their environment. 402p.

Kifani, S. 1991. Approaches spatio-temporelle des relations hydroclimat-dynamique des espèces pélagiques en région d'upwelling: cas de la sardine du stock central marocain. Thèse de Doctorat, Spécialité Océanographie halieutique. Univ. Bret. Occid. 290 pp.

Kirby, D.S., O. Fiksen and P.J.B. Hart. 2000. A dynamic optimisation model for the behaviour of tunas at ocean fronts. Fish. Oceanogr. 9, 328-342.

Lasker, R. 1975. Field criteria for survival of anchovy larvae: the relation between inshore chlorophyll maximum layers and successful first feeding. Fish. Bull. U.S. 73, 453-462.

Lasker, R. 1978. The relation between oceanographic conditions and larval anchovy food in the California Current: Identification of the factors leading to recruitment failure. Rapp. P.-v. Réun. Cons. int. Explor. Mer. 173, 212-230.

Lasker, R. 1981a. Factors contributing to variable recruitment of the northern anchovy (*Engraulis mordax*) in the California Current: Contrasting years 1975 through 1978. Rapp. P.-v. Réun. Cons. int. Explor. Mer. 178, 375-388.

Lasker, R. 1981b. The role of a stable ocean in larval fish survival and subsequent recruitment. p. 80-87. In: R. Lasker (ed.) Marine Fish Larvae: morphology, Ecology and Relation to Fisheries. Univ. Washington Press, Seattle. 131pp.

Legendre, L., and S. Demers. 1985. Auxiliary energy, ergoclines and aquatic biological production. Naturaliste can. Rev. Écol. Syst. 112, 5-14.

Lehodey, P. 2001. Sepodym skipjack analysis. 14th Standing Committee on Tuna and Billfish. Secretariat of the Pacific Community,Noumea, New Caledonia. Working Paper SKJ-2. 24 pp. (**http://www.spc.int/OceanFish/Html/TEB/Env/SKJ2.pdf**)

Lehodey, P. 2002. Impacts of the El Niño Southern Oscillation on tuna populations and fisheries. FAO, Rome. In press. (**http://www.spc.int/OceanFish/Html/TEB/Env/FAO_Paper.pdf**)

Lehodey, P., M. Bertignac, J. Hampton, A. Lewis, A. and J. Picaut. 1997. El Nino Southern Oscillation and tuna in the western Pacific. Nature 389, 715-718.

Lehodey, P., J-M. Andre, M. Bertignac, J. Hampton, A. Stoens, C. Menkes, L. Memery and N. Grima. 1998. Predicting skipjack tuna forage distributions in the equatorial Pacific using a coupled dynamical bio-geochemical model. Fish. Oceanogr. 7, 317-325.

Letson, D., I. Llovet, et al. 2001. User perspectives of climate forecasts: Crop producers in Pergamino, Argentina. Climate Res. 19, 57-67.

Lluch-Belda, D., R.J.M. Crawford, T. Kawasaki, A.D. MacCall, R.H. Parrish, R.A. Schwartzlose and P.E. Smith. 1989. World-wide fluctuations of sardine and anchovy stocks: the regime problem. S. Afr. J. mar. Sci. 8, 195-205.

Lluch-Belda, D., R.A. Schwartzlose, R. Serra, R.H. Parrish, T. Kawasaki, D. Hedgecock, and R.J.M. Crawford. 1992. Sardine and anchovy regime fluctuations of abundance in four regions of the world oceans: a workshop report. Fish. Oceanogr. 1, 339-347.

Loeb, V.J. and O. Rojas. 1988. Interannual variation of ichthyoplankton composition and abundance relations off northern Chile, 1964-83. Fish. Bull. U.S. 86 1-14.

Logerwell, E. and P. Smith. 2001. Mesoscale eddies and survival of late stage Pacific sardine (*Sardinops sagax*) larvae. Fish. Oceanogr. 10, 13-25.

Logerwell, E., B. Lavaniegos, and P. Smith. 2001. Spatially-explicit bioenergetics of Pacific sardine in the Southern California Bight: are mesoscale eddies areas of exceptional prerecruit production? Prog. Oceanog. 49, 391-406.

Louw, G.G., C.D.van der Lingen and M.J. Gibbons. 1998. Differential feeding by sardine *Sardinops sagax* and anchovy *Engraulis capensis* recruits in mixed shoals. S. Afr. J. mar. Sci. 19, 227-232.

Lu, H.-J., K.-T. Lee, and C.-H. Liao. 1998. On the relationship between El Niño/Southern Oscillation and South Pacific albacore. Fish. Res. 39, 1-7.

Lu, H.-J., K.-T. Lee, H.-L. Lin, and C.-H. Liao. 2001. Spatio-temporal distribution of yellowfin tuna, Thunnus albacares, and bigeye tuna, Thunnus obesus, in the tropical Pacific Ocean in relation to large temperature fluctuation during ENSO episodes. Fish. Sci. 67, 1046-1052.

MacCall, A.D. 1990. Dynamic Geography of Marine Fish Populations. University Washington Sea Grant Program, Seattle.158 pp.

MacCall, Alec D. 1996. Patterns of low frequency variability in fish populations of the California Current. Calif. Coop. Oceanic Fish. Invest. Rep. 37, 100-110.

Mackas, D.L., R.E Thomson and M. Galbraith. 2001. Changes in the zooplankton community of the British Columbia continental margin, 1985-1999, and their covariation with oceanographic conditions. Can. J. Fish. Aquat. Sci. 58, 685-702.

MacKenzie, B.R., T.J. Miller, S. Cyr and W.C. Leggett. 1994. Evidence for a dome-shaped relationship between turbulence and larval fish ingestion rates. Limnol. Oceanogr. 39, 1790-1799.

Mantua, N., S. Hare, Y. Zhang, J. Wallace, R. Francis. 1997. A Pacific interdecadal climate oscillation with impacts on salmon production. Bull. Am. Meteor. Soc. 78, 1069-1079.

Marchesiello P., J.C. McWilliams and A. Shchepetkin. 2002. Equilibrium structure and dynamics of the California Current System. J. Phys. Oceanogr. In press.

Mayr, E. 1982. The Growth of Biological Thought. Harvard Univ. Press, Cambridge, Mass. 974 pp.

McCay, B.J. and J. Acheson, 1987. The Question of the Commons: The Culture and Ecology of Communal Resources. Univ. Arizona Press. Tucson.

McCay, B.J. and Svein, J. 1996. From the bottom up: participatory issues in fisheries management. Society and Natural Resources 9, 237-250.

McGoodwin, J.R., 1990. Crisis in the World's Fisheries. Stanford Univ. Press.

McKinnell, S.M. 2001. 2001 coastal ocean/salmon ecosystem event. PICES Press Vol. 9 (2), 26-27.

McKinnell, S.M., R.D Brodeur, K. Hanawa, , A.B. Hollowed, J.J. Polovina and C.-I. Zhang (eds.) 2001a. Pacific Climate Variability and Marine Ecosystem Impacts. Prog. Oceanogr. 49. 639 pp.

McKinnell, S.M., C.C. Wood, D.T. Rutherford, K.D. Hyatt and D.W Welch. 2001b. The demise of Owikeno Lake sockeye salmon. N. Amer. J. Fish. Manage. 21, 774-791.

Mendelssohn, R., and P. Cury. 1987. Forecasting a fortnightly abundance index of the Ivoirian coastal pelagic species and associated environmental conditions. Can. J. Fish. Aquat. Sci. 44, 408-421.

Mendelssohn, R., and J. Mendo. 1987. Exploratory analysis of anchoveta recruitment off Peru and related environmental series. pp. 294-306. In: D. Pauly and I. Tsukayama (eds.) The Peruvian Anchoveta and Its Upwelling Ecosystem: Three Decades of Change. ICLARM Studies and Reviews 15. Instituto del Mar del Peru (IMARPE), Callao, Peru; Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ), GmbH, Eschborn, Federal Republic of Germany; and International Center for Living Aquatic Resources Management (ICLARM), Manila, Philippines. 351pp.

Miller, A. J., and N. Schneider. 2000. Interdecadal climate regime dynamics in the North Pacific Ocean: Theories, observations and ecosystem impacts. Progr. Oceanogr. 47, 355-379.

Miller, A.J., D.C. Cayan, T.P. Barnett, N.E. Graham, and J.M. Oberhuber. 1994. Interdecadal variability of the Pacific Ocean: model response to observed heat flux and wind stress anomalies. Clim. Dyn. 9, 287 302.

Miller, K.A. 1996. Salmon stock variability and the political economy of the Pacific Salmon Treaty. Contemporary Economic Policy 14(3), 112-129.

Miller, K.A. 2000. Pacific salmon fisheries: Climate, information and adaptation in a conflict-ridden context. Climatic Change 45, 37-61.

Mjelde, James W. and K. Keplinger 1998. Using the Southern Oscillation to Forecast Texas Winter Wheat and Sorghum Crop Yields. J. Climate 11, 54-60.

Mjelde, J.W, H.S.J. Hill, and J. F. Griffiths. 1988. A review of current evidence on climate forecasts and their economic effects in agriculture. Amer. J. Agri. Econ. 80, 1089-1095.

Orlove, B.S. and J. Tosteson. 1998. The application of aeasonal to interannual climate forecasts based on El Niño-Southern Oscillation (ENSO) events: Lessons from Australia, Brazil, Ethiopia, Peru, and Zimbabwe. Institute of International Studies, University of California, Berkeley, WP 99-3.

Parrish, R.H., C. S. Nelson, and A. Bakun. 1981. Transport mechanisms and reproductive success of fishes in the California Current. Biol. Oceanogr. 1, 175-203.

Parrish, R.H., F.B. Schwing, and R. Mendelssohn. 2000. Mid-latitude wind stress: the energy source for climatic shifts in the North Pacific Ocean. Fish. Oceanogr. 9, 224-238.

Pauly, D. 1989. An eponym for Reuben Lasker. Fish. Bull. U.S. 87, 383-384.

Penven P., C. Roy, G.B. Brundrit, A. Colin de Verdière, P. Fréon, A.S. Johnson, J. R.E. Lutjeharms and F.A. Shillington. 2001. A regional hydrodynamic model of upwelling in the Southern Benguela. S. Afr. J. Sci. 97, 472-475.

Peterman, R.M., and M. J. Bradford. 1987. Wind speed and mortality rate of a marine fish, the northern anchovy (*Engraulis mordax*). Science 235, 354-356.

Peterson, W.T. and S.M. McKinnell. 2000. Ocean ecology of juvenile salmonids along the North American coast. PICES Press 8 (2), 25-26.

Pfaff, A., K. Broad and M. H. Glantz. 1999. Who benefits from climate forecasts? Nature 397, 645-646

Polovina, J.J, E. Howell, D.R. Kobayashi and M.P. Seki. 2001. The transition zone chlorophyll front, a dynamic global feature defining migration and forage habitat for marine resources. Prog. Oceanogr. 49, 469-483.

Polovina, J.J., G.T. Mitchum, N.E. Graham, M.P. Craig, E.E. DeMartini and E.N. Flint. 1994. Physical and biological consequences of a climate event in the central North Pacific. Fish. Oceanogr. 3, 15-21.

Pulwarty, R.S. and T.S. Melis. 2001. Climate extremes and adaptive management on the Colorado River: Lessons from the 1997-1998 ENSO event. J. Environ. Manag. 63, 307-324.

Pulwarty, R.S., and K.T. Redmond. 1997. Climate and Salmon Restoration in the Columbia River Basin: The Role and Usability of Seasonal Forecasts. Bull. Amer. Meteor. Soc. 78, 381-397.

Radovitch, J. 1979. Managing pelagic schooling prey species. In: Predator-Prey Systems in Fisheries Management. Sport Fishing Institute, Washington, D.C.

Rayner, S., M. Houk, et al., 1999. Institutional Issues in Adoption of Probabilistic Climate Variation Among US Water Managers. Society for Applied Anthropology 1999 Annual Meeting: Constructing Common Ground: Human and Environmental Imperatives, April 21-25, Tucson, AZ.

Roemmich, D., and J. A. McGowan. 1995. Climatic warming and the decline of zooplankton in the California Current. Science 267, 1324-1326.

Roncoli, C. (ed.) 2000. Anthropology and climate change: Challenges and contributions. Practicing Anthropology 22 (4 -special issue).

Rothschild, B.J. and T.R. Osborn. 1988. The effects of turbulence on planktonic contact rates. J. Plankton Res. 10, 465-474.

Roy, C. and C. Reason. 1991. ENSO related modulation of coastal upwelling in the eastern Atlantic. pp. 245-256. In McKinnell, S.M., R.D Brodeur, K. Hanawa, A.B. Hollowed, J.J. Polovina and C.-I. Zhang (eds.) Pacific Climate Variability and Marine Ecosystem Impacts. Prog. Oceanogr. 49.

Roy, C., P. Cury and S. Kifani, 1991. Optimal environmental window and pelagic fish reproductive strategies in upwelling areas. International Symposium on Benguela Trophic Functioning, Resource Utilization from an Ecosystem Perspective, Cape Town, South Africa, 8-13 Sep 1991.

Sarewitz, D., R.A. Pielke Jr. and R. Byerly Jr. (eds.) 2000. Prediction: Science, Decision Making, and the Future of Nature, Island Press, Washington, DC.

Schaefer, K.M. 1998. Reproductive biology of yellowfin tuna (Thunnus albacares) in the eastern Pacific Ocean. Bull. Inter-Am. Trop. Tuna Comm. 21(5), 201-272.

Schneider, N. and A.J. Miller. 2001. Predicting western North Pacific Ocean climate. J. Climate, 14, 3997-4002.

Schwartzlose, R., J. Alheit, A. Bakun, T. Baumgartner, R. Cloete, R. Crawford, W. Fletcher, Y. Green-Ruiz, E. Hagen, T. Kawasaki, D. Lluch-Belda, S. Lluch-Cota, A. MacCall, Y. Matsuura, M. Nevarez-Martinez, R. Parrish, C. Roy, R. Serra, K. Shust, and M. Ward, and J. Zuzunaga. 1999. Worldwide large-scale fluctuations of sardine and anchovy populations. S. Afr. J. Mar. Sci. 21, 289-347.

Serra, R. 1987. Impact of the 1982-83 ENSO on the Southeastern Pacific fisheries, with an emphasis on Chilean fisheries. pp. 24-29. In M. Glantz, R. Katz and M. Krenz (eds.) Climate Crisis: The Societal Impacts Associated with the 1982-83 Worldwide Climate Anomalies. NCAR/ESIG, Boulder, Colorado, 105 pp.

Serra, R. 1991. Long - term variability of the Chilean sardine. pp 165-172. In: T. Kawasaki, S. Tanaka, Y. Toba and A. Taniguchi (eds.) Proceedings of the International Symposium on the Long - Term Variability of Pelagic Fish Populations and their Environment. Pergamon Press, New York.

Serra, R., P. Cury and C. Roy. 1998. The recruitment of the Chilean sardine and the optimal environmental window. pp. 267-274. In: M. Durand, P. Cury, R. Mendelssohn, C. Roy, A. Bakun, D. Pauly (eds.) Global versus local changes in upwelling systems. ORSTOM Editions, Paris, 585 pp.

Sharp, G.D. and D.R. McLain. 1993. Fisheries, El Niño-Southern Oscillation and upper-ocean temperature records: An eastern Pacific example. Oceanography 6, 13-22.

Sinclair, M. 1988. Marine Populations. An essay on population regulation and speciation. Washington Sea Grant Program. Univ. Washington Press, Seattle and London. 252 p.

Smith, P.E. 1985. A case history of an anti-El Niño to El Niño transition on plankton and nekton distribution and abundances. pp 121-142 .In: W.S. Wooster and D.L. Fluharty (eds.) El Niño North: Niño Effects in the Eastern Subarctic Pacific Ocean. Washington Sea Grant Program, Univ. of Washington, Seattle.

Smith, P. 1990. Monitoring interannual changes in spawning area of Pacific sardine (*Sardinops sagax*). Calif. Coop. Oceanic Fish. Invest. Rep. 31, 145-151.

Steele, J.H. 1974. The stucture of marine ecosystems. Harvard Univ. Press, Cambridge, Mass. 128 p.

Stern, P.C., and W.E. Easterling. 1999. Making Climate Forecasts Matter. National Academy Press, 175 pp.

Sugimoto, T., S. Kimura and K. Tadokoro. 2001. Impact of El Niño events and climate regime shift on living resources in the western North Pacific. Prog. Oceanog. 49, 113-127.

Sverdrup, H.U. 1953. On conditions for vernal blooming of phytoplankton. J. Cons. int. Explor. Mer 18, 287-295.

Tarte, S. 2001. The international politics of tuna management in the Western and Central Pacific. Conference on People and the Sea, Amsterdam, 30 August – 2 September, 2001.

Tarte, S. 2002. Report on Pacific Climate and Fisheries Workshop, Honolulu, Hawaii, 14-17 November, 2001. Department of History/ Politics, University of the South Pacific, Suva, FIJI.

Tarazona, J. and E. Castillo. 1999. El Niño 1997-98 y su impacto sobre los ecosistemas marino y terrestre. Revista Peruana de Biología, Volumen Extraordinario, December 1999.

Thorrold, S.R., C. Latkoczy, P.K. Swart and C.M. Jones. 2001. Natal homing in a marine fish metapopulation. Science 291, 297-299.

Timmermann, A., J. Oberhuber, A. Bacher, M. Esch, M. Latif, and E. Roeckner. 1999. Increased El Niño frequency in a climate model forced by future greenhouse warming. Nature 398, 694-697.

Trenberth, K.E. and J.W. Hurrell. 1994. Decadal atmospheric-ocean variations in the Pacific. Clim. Dyn. 9, 303 319.

Venrick, E.L., J.A. McGowan, D.R. Cayan and T.L. Hayward. 1987. Climate and chlorophyl a: long-term trends in the Central North Pacific Ocean. Science 238, 70-72.

Walters, C.J. 1989. Value of short-term forecasts of recruitment for harvest management. Can. J. Fish. Aquat. Sci. 46, 1969-1976.

Wada, T. and M. Kashiwai. 1989. Changes in growth and feeding ground of Japanese sardine with fluctuation in stock abundance. pp.181-190 In: T. Kawasaki, S. Tanaka, Y. Toba and A. Taniguchi (eds.), Long-term variability of pelagic fish populations and their environment. 402p.

Ward, P., B. Kearney and N. Tsirbas, 2000. Science arrangements for the regional management of tuna fisheries. Marine Policy 24, 93-108.

Ware, D.M., and R.E. Thomson. 1991. Link between long-term variability in upwelling and fish production in the northeast Pacific Ocean. Can. J. Fish. Aquat. Sci. 48, 2296-2306.

Appendix 1.
List of Participants

Vera Agostini
School of Aquatic and Fishery Sciences
Box 355020
University of Washington
Seattle, WA 98190
tel: (206) 221-5461
vagostin@u.washington.edu

Jürgen Alheit
Baltic Sea Research Institute
Seestr. 15
18119 Warnemünde
Germany
tel: +49-381-5197 208
fax: +49-381-5197 440
juergen.alheit@io-warnemuende.de

Andrew Bakun
IRI-The International Research Institute
for Climate Prediction
NEW ADDRESS (after 1 July, 2002)
Center for Sustainable Fisheries
University of Miami, RSMAS
4600 Rickenbacker Causeway
Miami, FL 33149
abakun@rsmas.miami.edu

Kenneth Broad
Research Asst. Professor,
Div. of Marine Affairs & Policy
University of Miami, RSMAS
4600 Rickenbacker Causeway
Miami, FL 33133
tel: 305 361-4851
fax: 305 361-4862
kbroad@rsmas.miami.edu

Mary-Elena Carr
Jet Propulsion Laboratory MS 300-323
4800 Oak Grove Dr.
Pasadena, CA 91101-8099
tel: (818) 354-5097
fax: (818) 393-6720
mec@pacific.jpl.nasa.gov

Dave Checkley, Jr.
Scripps Institution of Oceanography
La Jolla, CA 92093-0218 USA
tel: +01 (858) 534-4228
fax: +01 (858) 822-0562
dcheckley@ucsd.edu

Robert Cowen
Director, Center for Sustainable
Fisheries (CSF)
University of Miami, RSMAS
4600 Rickenbacker Causeway
Miami, FL 33149
tel: 305 361-4023
rcowen@rsmas.miami.edu

Jerome M. Comcowich
IPRC -
International Pacific Research Center
University of Hawaii
2525 Correa Road
Honolulu, HI 96822
comco@soest.hawaii.edu

Jorge Csirke
Chief,
Marine Resources Service (FIRM)
FAO
Vialle delle Terme di Caracalla
00100 Rome, Italy
tel. +39 06 570 56506
fax. +39 06 570 53020
Jorge.Csirke@fao.org

Dave Gilbert
National Institute of Water &
Atmospheric Research Ltd
P.O. Box 14-901
Wellington
New Zealand
Email: d.gilbert@niwa.cri.nz
tel: +64-4-386 0537
fax: +64-4-386 0574
Home telephone: +64-4-568 5360

Michael Glantz
Senior Scientist
ESIG/NCAR
Box 3000
Boulder, CO 80307
glantz@ucar.edu

Safwan Hadi, Dr.
Departemen Geofisika dan Meteorologi
Institut Teknologi Bandung
Jl. Ganesha 10
Bandung 40132
Indonesia
tel: 62-22-250-0409
fax: 62-22-253-4139
e-mail: safwan@geoph.itb.ac.id

Michael Hamnett
Pacific Basin Development Council
Suite 1075
Honolulu, HI 96813-5214
tel: (808) 596-7229
fax: (808) 596-7249
hamnett@hawaii.edu

Toshio Katsukawa
Ocean Research Institute,
University of Tokyo
1-15-1 Minamidai, Nakano-ku,
Tokyo 164-8639, Japan
tel: +81 3 5351 6511
fax: +81 3 5351 6506
katsukawa@0orcu-tokyo.ac.jp

Hak Gyoon Kim
Director,
Marine Environment, Oceanography
& Harmful Algal Bloom Research
Department
National Fisheries Research and
Development Institute (NFRDI)
408-1 Shirang-ri, Kijang-up Kijang-gun,
Busan 619-902, Korea
hgkim@haema.nfrda.re.kr

Jin-Yeong Kim
National Fisheries Research &
Development Institute
408-1, Sirang-Ri
Gijang-Eup
Guang-Gun
Busan 619-902, Korea
tel: (051) 720-2270
fax: (051) 720-2277
jiykim@nfrdi.re.kr

Suam Kim
Dept. of Marine Biology
Pukyong National University
599-1 Daeyeon3 - Dong Nam-Gu
Pusan 608-737, Korea
tel (051) 620-6268
fax (051) 620-6268
suamkim@pknu.ac.kr

R. Michael Laurs
Director, Honolulu Laboratory
Southwest Fisheries Science Center
National Marine Fisheries Service
(NOAA)
2570 Dole Street
Honolulu, HI 96822-2396
tel: 808-983-5300
fax: 808-983-2902
Mike.Laurs@noaa.gov

Patrick Lehodey
Senior Fisheries Scientist
Oceanic Fisheries Programme
Secretariat of the Pacific Community
BP D5
98848, Noumea cedex
New Caledonia
tel: (687) 26 20 00
fax: (687) 26 38 18
patrickl@spc.int
web: http://www.spc.int/oceanfish/

Salvador E. Lluch-Cota
Centro de Investigaciones Biologicas del
Noroeste, S.C.
PO Box 128
La Paz, BCS
Mexico 23000
[Courier delivery:
Centro de Investigaciones Biologicas del
Noroeste, S.C.
Km 0.5 Acceso a la Telefonica s/n
El Conchalito
23096 La Paz, B.C.S. CR-23001
Mexico]
tel: (52-112)53633 ext 3432
fax: (52-112)32756
slluch@cibnor.mx

Hsueh-Jung Lu
Department of Fisheries Science
National Taiwan Ocean University
2, Pei-Ning Road, Keelung, Taiwan
20224, R.O.C.
tel: +886-2-2462-2192 ext.5033
fax: +886-2-2463-2659
hjlu@mail.ntou.edu.tw or
hjlu@ms1.hinet.net

Lorenz Magaard
IPRC -
International Pacific Research Center
University of Hawaii
2525 Correa Road
Honolulu, HI 96822
tel: (808) 956-7509
fax: (808) 956-5035
lorenz@hawaii.edu

Alec MacCall
Fishery Biologist
Santa Cruz Laboratory
National Marine Fisheries Service
110 Shaffer Rd.
Santa Cruz, CA 95060 z
tel: (831) 420-3950
fax: (831) 420-3977
Alec.MacCall@noaa.gov

John Marra
Lamont-Doherty Earth Observatory of
Columbia University
61 Route 9W
Palisades, NY 10964-8000
tel: 1-845-365-8891
fax: 1-845-365-8150
marra@ldeo.columbia.edu

Olivier Maury
IRD
(Institut de Recherche pour le
Développement)
SFA BP 570
Victoria, Iles Seychelles
maury@ird.fr or omaury@sfa.sc
tel & fax: (248) 22 47 42

Jay McCreary
Director, IPRC - International Pacific
Research Center
University of Hawaii
2525 Correa Road
Honolulu, HI 96822
jay@musashimaru.soest.hawaii.edu

Skip McKinnell
Assistant Executive Secretary
North Pacific Marine Science
Organization
c/o Institute of Ocean Sciences
P.O. Box 6000
Sidney, B.C., Canada
V8L 4B2
tel: 1-250-363-6826
fax: 1-250-363-6827
mckinnell@pices.int

Arthur J. Miller
Research Oceanographer
Scripps Institution of Oceanography
Nierenberg Hall, Room 439
University of California, San Diego
La Jolla, CA 92093-0224
tel: (858) 534-8033
fax: (858) 534-8561
ajmiller@ucsd.edu
http://meteora.ucsd.edu/~miller

Raghu Murtugudde
CSS Bldg, Room 2201
Univ of MD, Collge Park, MD 20742
tel: (301) 314-2622
ragu@vinsanto.essic.umd.edu

I-Hsun Ni
Department of Environmental Biology
& Fishery Science
National Taiwan Ocean University
2, Pei-Ning Road, Keelung, Taiwan,
R.O.C.
tel: (886-2) 2463-2341
fax: (886-2) 2462-2192 ext 5013
niih@mail.ntou.edu.tw

Donald Olson
Univ. of Miami, RSMAS
4600 Rickenbacker Cswy.
Miami, FL 33149
tel: 305 361 4074
fax: 305 361- 4696
dolson@rsmas.miami.edu

Robert J. Olson
Inter-American Tropical
Tuna Commission
8604 La Jolla Shores Drive
La Jolla, CA 92037-1508
tel: (858) 546-7160
fax: (858) 546-7133
rolson@iattc.org

Ian Perry
Fisheries & Oceans Canada
Pacific Biological Station
3190 Hammond Bay Road
Nanaimo, B.C. V9R 5K6
Canada
tel: (250) 756-7137
fax: (250) 756-7053
perryi@pac.dfo-mpo.gc.ca

Guillermo Podesta
University of Miami, RSMAS
4600 Rickenbacker Causeway
Miami, FL 33149
gpodesta@rsmas.miami.edu

Jeffrey J. Polovina
Honolulu Laboratory
Southwest Fisheries Science Center
National Marine Fisheries Service
(NOAA)
2570 Dole Street
Honolulu, HI 96822-2396
tel: 808-983-5300
fax: 808-983-2902
Jeffrey.Polovina@noaa.gov

Renato Quinones
Department of Oceanography
University of Concepcion
Casilla 160-C, Concepcion
Chile
tel: +56-41-203861
fax: +56-41-256571
rquinone@udec.cl

Ruben Rodriguez-Sanchez
CICIMAR
Apdo. Post. 592
La Paz, B.C.S.
23000, Mexico
street address:
Playa El Conchalito s/n
La Paz, Baja California Sur
23000, Mexico
tels: (52-612) 253-44 / 253-66/ 303-50
fax: (52-612) 253-22
rrodrig@ipn.mx

Claude Roy
IRD (France)
French-South African IDYLE Project
Dept. of Oceanography
University of Cape Town
Rondebosch 7701
South Africa
D6UR9C@mail.uct.ac.za

Rodolfo Serra
Instituto de Fomento Pesquero
Division de Evaluacion de Pesquerias
Casilla 8-V, Valparaiso
Chile
tel: +56-32-212-630
fax: +56-32-213-178
rserra@ifop.cl

Frank Schwing
Pacific Fisheries
Environmental Laboratory
1352 Lighthouse Avenue
Pacific Grove, CA 93950-2097
tel: (831) 648-8515
fax: (831) 648-8440
fschwing@upwell.pfeg.noaa.gov

Eileen Shea
The East-West Center, Burns Hall 2062
University of Hawaii
1601 East-West Road
Honolulu, HI USA 96848-1601
tel: 808-944-7253
fax: 808-944-7376
SheaE@EastWestCenter.org

Jeffrey Shima
Biological Sciences
Victoria University
PO Box 600
Wellington
New Zealand
tel: +64 4 463 6494
fax: +64 4 463 5331
Jeffrey.Shima@vuw.ac.nz

Takashige Sugimoto
Ocean Research Institute,
University of Tokyo
1-15-1 Minamidai, Nakano-ku,
Tokyo 164-8639, Japan
tel: +81 3 5351 6511
fax: +81 3 5351 6506
sugimoto@ori.u-tokyo.ac.jp

Kazuaki Tadokoro
Frontier Research System for
Global Change
31173-25 Showa-machi
Kanazawa-ku, Yokohama-city
Kanagawa 236-0001, Japan
tel: +81-45-778-5602
fax: +81-45-778-5602
denden@jamstec.go.jp

Sandra Tarte
Department of History/Politics
University of the South Pacific
tel: 679 212577
fax: 679 301 487
tarte_S@usp.ac.fj

Simon Thorrold
Biology Department MS # 35
Woods Hole Oceanographic Institution
Woods Hole, MA 02543
tel: 1 508 289-3366 (Office)
1 508 289-2985 (Lab)
fax: 1 508 457-2158
sthorrold@whoi.edu

Sidney Thurston
Associate Program Director,
Austral-Asia Region
NOAA Office of Global Programs
Level 14, Hibiya Central Building
1-2-9 Nishi-Shimbashi Minato-ku
Minato-Ku
Tokyo 105-0003, Japan
tel: 813-5532-7249
fax: 813-5532-7373
Thurston@ogp.noaa.cov

Neil Ward
IRI-The International Research Institute
for Climate Prediction
101 Monell Bldg.
Lamont-Doherty Earth Observatory,
Columbia University
Palisades, NY 10964-8000
tel: (845) 680-4446
fax: (845) 680-4864
nward@iri.ldeo.columbia.edu

Chang Ik Zhang
Permanent address:
Dept. of Marine Production Mgmt.
College of Fisheries Sciences
Pukyong National University
599-1 Diamonding, Nam-go
Pusan 608-737, Korea
tel: (82-51) 620-6124
fax: (82-51) 628-8145
cizhang@dolphin.pknu.ac.kr
Current address:
Visiting Fisheries Scientist
Alaska Fisheries Science Center
NMFS/NOAA
BIN C15700; Bldg. 4
7600 Sand Point Way, NE
Seattle, WA 98115-0070
tel: 206-526-4250
fax: 206-526-6723
Chang.Zhang@noaa.gov

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INTERNATIONAL RESEARCH INSTITUTE
FOR CLIMATE PREDICTION
Columbia Earth Institute
61 Route 9W
Palisades, NY 10964-8000 USA
Phone: 845-680-4468
Fax: 845-680-4866
http://iri.columbia.edu