Workshop on "*Identifying Mechanisms Linking Physical Climate and Ecosystem Change: Observed Indices, Hypothesized Processes, and "Data Dreams" for the Future*"

by Ryan R. Rykaczewski and Emanuele Di Lorenzo

Climate variability and change are now recognized as significant factors influencing population fluctuations of living marine resources. However, distilling complex climate–ecosystem interactions into key, testable hypotheses remains a challenge. Living components of marine ecosystems, particularly upper-trophic-level populations, commonly display variability at low temporal frequencies (*e.g.*, decadal and multi-decadal). Understanding such low-frequency variability is facilitated by a combination of historical observations and mechanistic models that represent physical–biological interactions. Time series of sufficient length may permit multiple observations of the relatively infrequent changes in the system, and models that represent influential interactions allow simulation of poorly resolved, low-frequency events. Increased understanding of the key physical–biological processes through which climate influences marine ecosystems can improve observational and modeling approaches and will promote incorporation of physical data into management strategies. Simplified process models may prove more effective for these efforts than full-complexity models, which are typically associated with multiple sources of uncertainty. The development of such reduced complexity climate-driven ecosystem models relies on: (1) identifying mechanisms controlling the response of the marine ecosystem to climate forcing, (2) isolating the climate forcing functions that are relevant to the specific ecosystem that is studied, and (3) linking these climate forcing functions to the dynamics of large and regional scale climate variability (Fig. 1).

This desire to better identify and represent key climate–ecosystem interactions motivated the GLOBEC/PICES/ICES

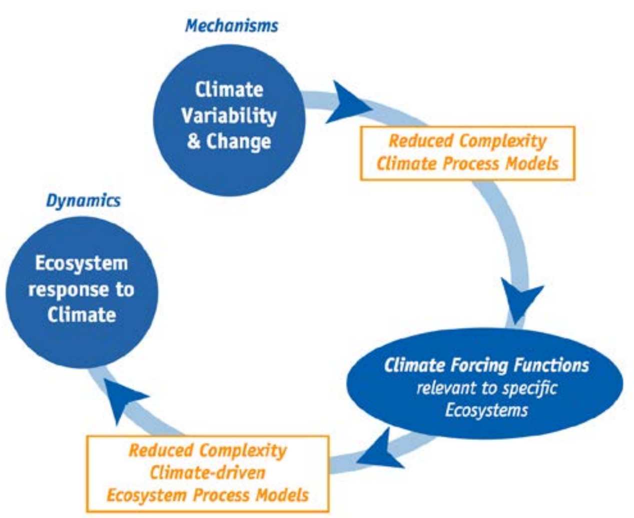

Fig. 1 Conceptual diagram illustrating the development of climate-driven ecosystem process models.

Workshop on "*Forecasting ecosystem indicators with process-based models*" (ECOFOR). The workshop was organized by the PICES Working Group on *North Pacific Climate Variability and Change* (WG 27) and was held at Friday Harbor Laboratories (Washington State, USA) in September 2012. The goal of the ECOFOR workshop was to begin a more systematic application of previous knowledge to identify key processes enabling modeling of the mechanisms underlying physical–biological relationships in the North Pacific and North Atlantic. Physical and biological oceanographers, ecologists, climate scientists, and a mathematician were included among the PICES and ICES participants (see PICES Press Vol. 21, No. 1). Two major results from this workshop were: (1) recognition of the community's continuing enthusiasm for the exchange of concepts between physical and biological ocean scientists, and (2) realization that although immense progress has been made over the past several years, understanding of key mechanisms underlying ecosystem variability in both North Atlantic and Pacific basins remains in a stage of development. Succinct description of physical–biological interactions has often been limited by the paucity of relevant observations of sufficient length and resolution and so, many mechanistic descriptions persist as early hypotheses.

Given these issues and the ongoing interest identified at the ECOFOR workshop, members of WG 27 convened a theme session at the 2013 ICES Annual Science Conference and a workshop at the 2013 PICES Annual Meeting (ICES session M: and PICES W2). The goal of these events was to promote and expand discussion regarding modeling physical forcing of ecosystem variability. The ICES theme session and PICES workshop shared the title: "*Identifying mechanisms linking physical climate and ecosystem change: Observed indices, hypothesized processes, and "data dreams" for the future*." Workshop convenors encouraged contributions which sought to identify and model key processes explaining mechanisms underlying the correlative relationships in physical–biological datasets. Convenors also hoped to solicit ideas and new hypotheses concerning mechanisms of physical–biological interactions that can be tested by establishing novel long-term observational strategies or by developing creative modeling datasets.

The quantity of abstract submissions and attendance at the PICES workshop exceeded our expectations. A full day was allocated for 14 oral presentations (including four invited speakers) and a poster. Of note was the extensive range of scales and approaches, indicative of the broad interest across the PICES and ICES communities. The four invited speakers offered examples of the scales over which the mechanisms of climate–ecosystem interactions are examined. At the relatively small spatial and temporal scale, invited speaker Dr. Hans Pörtner (Germany) discussed recent findings regarding organismal capacity to respond to multiple stressors in a climate context. He introduced the concept of oxygen- and capacity-dependent thermal tolerance: while thermal stressors appear to be the dominant factor influencing biogeographical ranges, phenology, and species composition, this thermal tolerance may be narrowed by oxygen and CO_2 stress. Dr. Pörtner highlighted the need to understand the molecular adjustments in species' eco-physiological responses to climate-related stressors, as these are the fundamental scales that structure direct organism responses to changes in climate-related variables.

On the other end of the spatial spectrum, invited speaker Dr. Jürgen Alheit (Germany) discussed evidence of basin-scale climate forcing (related to the Atlantic Multi-decadal Oscillation) of small pelagic fish in the northeast Atlantic. He noted that variability in commercially harvested fish populations of both the North Pacific and North Atlantic may be associated with expansion and contraction of the subpolar gyres, advocating for further investigation of gyre size as a potential integrative indicator of large-scale ecosystem changes.

Between these basin-scale and organismal-scale perspectives, the workshop's two other invited speakers presented case studies demonstrating mechanisms of climate–ecosystem relationships at mesoscale to regional scales. Dr. Bryan Black (USA) presented results of a study detailing the sensitivity of northeastern Pacific ecosystem productivity (both in the marine and in the adjacent terrestrial environments) to atmospheric conditions; specifically wintertime upwelling events. In addition to contemporary fisheries, seabird, and atmospheric observations, this project utilized tree-ring records, rockfish otoliths, and geoduck shells to examine interannual climate–ecosystem interactions over the last six centuries (Fig. 2). Dr. Carolina Parada (Chile) discussed a dynamical model-based investigation of the potential impact of mesoscale and submesoscale hydrographic features on the distribution and biophysical conditions experienced by larval and juvenile walleye pollock in the Gulf of Alaska. She also emphasized the uncertainties associated with modeling pollock survival, as data concerning temporal changes in the predator field are few, currently limiting the ability to accurately estimate recruitment variability.

A number of speakers also utilized more conceptual and numerical methods to explore the mechanisms of climate–ecosystem interactions. Select examples of this approach were the presentations by Drs. Emanuele Di Lorenzo and Kenneth Denman. Dr. Di Lorenzo (USA) numerically simulated biological responses to climate variability and demonstrated the tendency of populations to fluctuate in phase with a global-scale climate pattern, even when this pattern has a relatively minor influence on the factors that directly affect marine populations. Dr. Denman (Canada) presented results of simulations examining the responses of a population's phenotypic composition to variability and trends in climate factors. A synthesis of some key findings from the PICES workshop and ICES theme session is highlighted in Box 1.

A common challenge acknowledged at the conclusion of the workshop concerns the difficulty in describing the mechanisms through which variability in lower-trophic-level populations influences populations of higher-trophic-levels. Comprehensive model description of multi-dimensional interactions among populations and the changing physics of their environment is impractical, and thus the desire to concisely represent key relationships with simplified

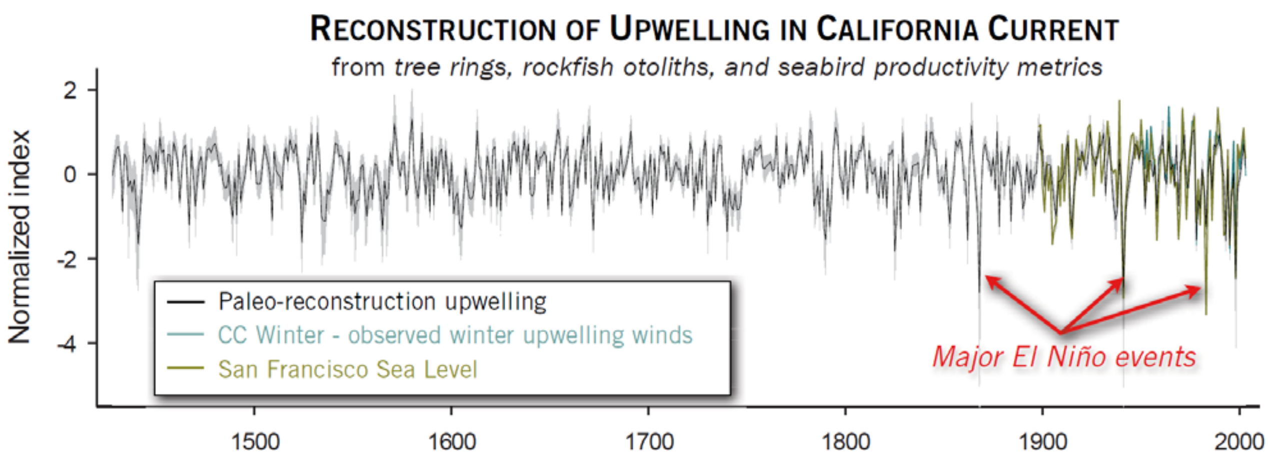

Fig. 2 A 600-year reconstruction of winter climate in the central California Current derived from tree-ring data. CC winter, the target of the reconstruction, is the leading principal component of winter (Jan–Mar) Northern Oscillation Index (a measure of the North Pacific High), winter upwelling index averaged across 36°N and 39°N, and winter sea level at San Francisco. Gray shading indicates 95% confidence intervals. Note that the reconstruction is dominated by high-frequency variability and that the four most extreme negative values all occurred during major El Niño events (i.e., 1868, 1941, 1983, and 1998). Dr. Black's presentation, as well as those of the other workshop speakers, is available on the PICES website at http://www.pices.int/publications/presentations/PICES-2013/2013-W2/2013-W2.aspx.

Box 1. Synthesis of the main findings of the PICES workshop and ICES theme session

1. Sensitivity of ecosystem to physical drivers changes with season

During different months of the season, different physical drivers become important in driving ecosystem variability. Therefore, using regional indices that track the seasonal sensitivity of the ecosystem leads to better predictions than using climate indices. In future studies it is critical to examine whether IPCC class models can resolve the dynamics of the regional forcing functions.

2. Lower-trophic levels variability tracks regional and local physical forcing

Ecosystem properties of lower-trophic levels (*e.g.*, nutrient fluxes and primary productivity) are typically sensitive to few environmental drivers and often track indices of climate variability that are regionally or locally defined. These regionally defined indices allow capture of the local scale environmental variability as well as the impacts of large-scale climate variability.

3. Higher-trophic levels integrate multiple forcings and track large-scale climate modes

Ecosystem functions of higher-trophic levels (*e.g.*, fishes) are typically sensitive to multiple stressors. Hence, higher-trophic levels have the ability to integrate multiple sources of environmental variability and exhibit the tendency to align their variability with that of the large-scale climate modes, which capture the shared, low-frequency variance among the different environmental forcings.

4. Changes in large-scale and regional scale circulation play a dominant role in driving ecosystem variability

Changes in large-scale and regional scale circulation play a dominant role in driving ecosystem variability both at the lower and higher trophic levels. Resolving the circulation dynamics with regional climate models is key to allow a proper understanding of how coastal ecosystems respond to climate forcing. It will be important in the future to develop adequate data archives of ocean currents and advection pathways that can be used offline by ecosystem scientists to test hypotheses regarding ecosystem responses to environmental oceanic forcing. These data archives will likely be assembled using the output of regional scale model hindcasts. It was also pointed out the resolving eddies at the regional scale is critical, but introduces a stochastic component in the variability associated with the degree of intrinsic nature of the eddy-scale circulation. Future eddy-resolving models will need to perform an ensemble hindcast in order to separate the fraction of variance that is deterministically forced vs. the internal variance.

5. Spatial dimension is key for understanding the links between physical variability and ecosystem response

As we develop reduced-complexity models of the marine ecosystem responses to climate forcing, it will be critical to incorporate the spatial dimension (*e.g*., associated with species distributions). This topic has already emerged from the Section on *Climate Change Impacts on Marine Ecosystem* (S-CCME) and is currently an important topic of research and discussion. Although several talks showed examples of how the spatial dimension plays an important role, no systematic approach was presented to incorporate the spatial dimension in reduced-complexity models. During the discussion, a Linear Inverse Model methodology was suggested as one approach to model the spatial dimension of fish distribution in the context of a changing climate.

process models is warranted. However, such efforts must recognize that important ecological responses to anthropogenic climate change (*e.g.*, species invasions and replacements) may not be represented accurately in simplified process models. Either explicit acknowledgment of these ecological issues as caveats of the approach or attempts to include such issues in future process models of long-term ecosystem changes should be considered in future discussions.

Further recommendations from the workshop include future workshops that might narrow the focus of discussion while maintaining the exchange of information between physical and biological oceanographers. The advertised scope of the workshop attracted participants from diverse groups within the PICES and ICES communities and brought together experts in physical and biological oceanography and fisheries management. However, the wide-ranging subjects of the presentations and limited time available constrained the further distillation of available hypotheses into a key subset of mechanisms describing climate impacts of marine ecosystems. The entrainment of increasingly diverse and numerous participants acted to broaden, rather than focus, our discussions. The workshop provided a forum for the presentation of mechanisms relating climate and higher trophic levels at a wide range of scales, but we are still faced with the challenge of applying a more systematic approach to represent these underlying relationships using models of reduced complexity. One proposed strategy for future workshops may be to divide participants into smaller groups for more focused discussions emphasizing climate–ecosystem variability at a specific scale (*e.g.*, mesoscale, regional, or global scale; interannual to centennial scale) or via general mechanistic categories (*e.g.*, trophic interactions, ecophysiology, genotypic and phenotypic responses, or species distributions). However, collaboration among physical and biological ocean scientists and recognition of interacting spatial and temporal scales must be maintained.

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Dr. Emanuele (Manu) Di Lorenzo (edl@gatech.edu) is a Professor of Ocean and Climate Dynamics in the School of Earth and Atmospheric Sciences, Georgia Institute of Technology (USA). His research interests and experience span a wide range of topics from physical oceanography to ocean climate and marine ecosystems. More specific focus is on dynamics of basin and regional ocean circulation, inverse modeling, Pacific low-frequency variability, and impacts of large-scale climate variability on marine ecosystem dynamics (http://www.oces.us). In PICES, Manu co-chairs the Working Group on North Pacific Climate Variability and Change, leads the Study Group on Social-Ecological-Environmental Systems (SG-SEES), and is a member of the FUTURE Advisory Panel on Climate, Oceanographic Variability and Ecosystems (AP-COVE). He also serves on the US Comparative Analysis of Marine Ecosystem (CAMEO) Science Steering Committee.