GLOBEC/PICES/ICES ECOFOR Workshop

by Emanuele Di Lorenzo, Arthur Miller, Shoshiro Minobe, Jacquelynne King, Marc Hufnagl and Chuck Greene

Motivations and goals

GLOBEC, PICES and ICES have advanced our understanding of the response mechanisms of the marine ecosystem lower trophic levels to climate variability. This improved knowledge allows us now to formulate climate-driven process models of low order (*e.g.*, low number of dimensions) to hindcast and forecast ecosystem species and indicators.

During 2011, PICES established two new working groups (WGs), WG 27 on *North Pacific Climate Variability and Change* and WG 28 on *Development of Ecosystem Indicators to Characterize Ecosystem Responses to Multiple Stressors*. While WG 27 is developing quantitative approaches to evaluate how large-scale climate variability and change impacts physical and biogeochemical variables (*e.g.*, sea surface temperature, ocean circulation, seasonal timing, nutrient fluxes, acidification, hypoxia, upwelling and mixing), WG 28 is developing ecosystem indicators that best characterize the ecosystem responses to these multiple stressors.

Several workshops have been conducted in recent years to advance the scientific basis for implementing forecasting models for ecosystem indicators (*e.g.*, FUTURE Workshop on "*Indicators of status and change within North Pacific marine ecosystems*", Honolulu, 2011; CINAR Workshop on "*Climate and ecosystem change in the NW Atlantic*", Woods Hole, 2011). Also, efforts like the Indicator of the Seas Project (IndiSeas), which was launched in 2005 under the auspices of the EUR-OCEANS Scientific Programme as a follow-up to the SCOR/IOC Working Group 119 on *Quantitative Ecosystem Indicators*, now provide us with more robust frameworks for isolating and selecting ecosystem indicators. However, examples of low order climate-driven process models that forecast ecosystem indicators are still rare.

The goal of the 2012 GLOBEC/PICES/ICES ECOFOR workshop (see the workshop banner below) is to begin a more systematic application of the previous knowledge from the GLOBEC/PICES and ICES programs to move beyond the simple correlation analyses between physical and biological variability, and to identify key processes that enable us to succinctly and quantifiably model the mechanisms underlying the relationships observed in physical-biological datasets, both in the North Pacific and North Atlantic. The process models developed for this goal include as few degrees of freedom as possible (not full complexity) to sufficiently capture and test specific mechanisms of the ecosystem response to climate forcing and of the internal population dynamics. The process models are developed and tested within statistically based frameworks (*e.g.*, Bayesian hierarchical models, linear inverse models, *etc*.) that allow formal quantification of the uncertainties in historical reconstructions and future predictions of targeted ecosystem variables. Ecosystem process models complement full-ecosystem complex models (*e.g.*, End-To-End, Atlantis, ROMS-NPZD-NEMURO, IBM) by (1) directly testing the understanding and (2) quantifying the role of specific mechanisms underlying the physical-biological linkages. Although process models by definition do not include a complete description of ecosystem function and cannot account for the multi-dimensional interactions, they avoid magnifying uncertainty stemming from processes that are not well understood and modeled in full-ecosystem complex models.

Here we provide a short overview of some of the process models and new hypotheses of physical-biological interactions discussed at ECOFOR-2012.

The process models

Process models use few indices of environmental forcing that represent selected and relevant physical processes (*e.g.*, advection, mesoscale eddies) to reconstruct existing time series of marine populations in the lower and higher trophic levels. The opening session of the workshop was devoted to introducing examples of diagnostic and predictive ecosystem process models of different degrees of complexity. Ten examples that were presented and discussed are available in the workshop report and on the workshop website at http://wg27.pices.int/ecofor. Here we report on two of the examples presented by young scientists (a graduate and undergraduate student) attending the workshop. These examples elucidate the application of process models for diagnosing (Example #1) and predicting (Example #2) marine populations.

Example #1: Diagnosing North Atlantic Right Whales

by E. Meyer-Gutbrod, C. Greene and A. Pershing

Erin Meyer-Gutbrod (elg82@cornell.edu) is a third-year PhD student in the Earth and Atmospheric Sciences Department at Cornell University (USA) working with Dr. Charles Greene. She is interested in the population dynamics of endangered cetacean populations, with a special focus on the effects of environmental drivers on reproduction rates. She will use this research to define benchmarks in prey abundance that support the population growth of right whales in the North Atlantic and Southern Resident killer whales in the North Pacific. Erin is currently supported by the National Defense Science and Engineering Graduate fellowship.

The North Atlantic right whale, *Eubalaena glacialis*, has previously suffered declining populations due to the high rate of anthropogenic mortalities and low rate of reproduction. Numbering fewer than 500 individuals, the North Atlantic right whale is listed as critically endangered. The long calving intervals that hallmark low reproduction may be driven by nutritional deficiencies in adult females resulting from low prey availability. The abundance of *Calanus finmarchicus* in the Gulf of Maine and Western Scotian Shelf, a primary nutritional source for North Atlantic right whales, has been shown to respond to climate forcing from the Arctic as well as within the North Atlantic Basin. Given the critical state of the right whale population, it is vital to determine how changing climate and the corresponding changes in prey abundance will affect the future of the species.

A new demographic model has been built to incorporate changes in prey availability in the prediction of right whale calving intervals. Using a time series of calving events and viable cows from 1980–2005, we developed a deterministic matrix population model to estimate the distribution of cows among three reproductive stages: resting, pregnancy and nursing (Fig. 1). The probabilities of transitioning between reproductive stages are estimated as logistic functions of the *Calanus finmarchicus* abundance index as determined from 26 years of Continuous Plankton Recorder (CPR) survey data from the Gulf of Maine. The CPR data can be divided into separate indices representing a time series of bimonthly values in five key regions in the right whale feeding habitat: Gulf of Maine, Cape Cod Bay, Western Gulf of Maine, Eastern Gulf of Maine and Scotian Shelf. With this data resolution, we can determine the signature of the prey region and season that can be incorporated into the model to best fit the observed calving series. This exercise allows us to infer which feeding areas and times contribute significantly to successful right whale reproduction.

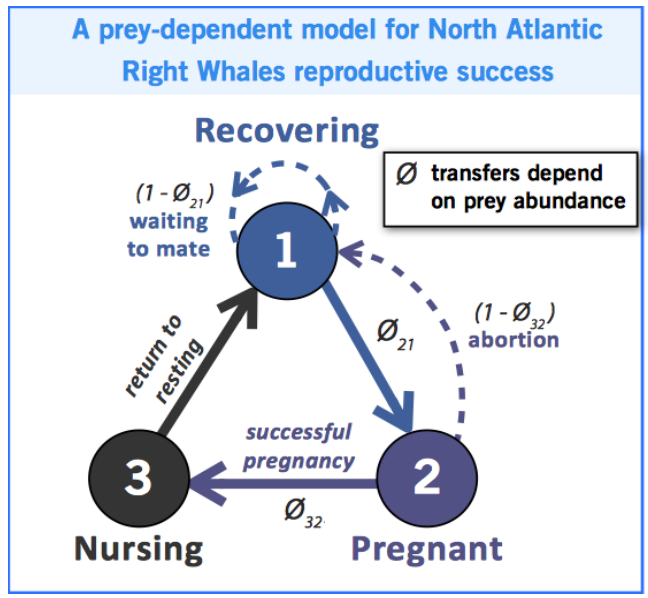

Fig. 1 A three-stage model of the right whale reproduction cycle. The recovery stage (1) is a period of time when a female is recuperating from previous pregnancies or waiting for ideal conditions for impregnation. The pregnant stage (2) lasts approximately one year, given that the pregnancy is not prematurely terminated. If an abortion occurs, the cow will return to the recovery stage (1). If the pregnancy is successful, the cow will move into the nursing stage (3). The nursing stage can last between 8 months and a year, after which the female enters the recovery stage (1) again.

The best fit prey-dependent reproduction model yields a significantly more precise calving time series than a prey-independent model, which strengthens the hypothesis that prey abundance drives reproduction. The prey-dependent model suggests that high winter prey levels in the Scotian Shelf and Cape Cod Bay may be especially good predictors of favorable breeding seasons.

Although the 1990s were characterised by long calving intervals and low reproduction rates which correspond with depressed copepod abundances, a regime shift occurring at the new millennium has led to increased abundances of *Calanus finmarchicus*, similar to the levels seen in the 1980s. Reflecting this increase in prey availability, the right whale calving rate experienced a sustained boom from

2001 to present. Although the inflated calving rate can be partially explained by an increase in viable cows attributed to slow population growth over the past two decades, it is likely that increased prey abundances are driving the shorter calving intervals for each cow and improving reproductive efficiency. Future work will be performed to determine whether the regions and seasons of copepod occurrence that drive right whale reproduction are distinct in the three decadal regimes recently witnessed in the North Atlantic.

Example #2: Predicting Alaskan sablefish recruitment
by A. Smith, K. Shotwell, M. Stachura and E. Di Lorenzo

Andrew Smith (andrewwsmith@gatech.edu) is a fourth-year undergraduate student majoring in Earth and Atmiospheric Sciences at the Georgia Institute of Technology (USA). He is currently conducting research on the topics of climate and marine ecosystem dynamics with Dr. Emanuele Di Lorenzo and of climate and monsoon variability with Dr. Peter Webster.

In the Gulf of Alaska, strong downwelling events (*e.g.*, the winter following the 1997 El Niño) drive high sea level along the coastal Gulf of Alaska. The high sea level and the resulting intensification of the Alaskan coastal current and Alaskan Stream excite the generation of strong anticyclonic eddies that entrain coastal waters rich in nutrients and iron. In the eastern Gulf, these eddies tend to generate at very predictable locations (*e.g.*, the Sitka and Haida eddies) and to persist for several years in the Gulf once they migrate away from the coastal waters.

Oceanographic surveys of these Alaskan large anticyclonic eddies have shown that the eddy regions are potentially very favorable environments for marine populations because of the richness in nutrients and because of the ability of these eddies to sustain secondary circulations that fuel primary production. Observations also suggest that these eddies have an impact on larval fish assemblages, which may change depending on the age and formation location of the eddy (Atwood *et al*. 2010). Alaska sablefish (*Anoplopoma fimbria*) is a commercially valuable slope-spawning groundfish species with highly variable recruitment (Hanselman *et al*. 2012). Larvae of these fish have also been observed in these eddy formation regions (Atwood *et al*. 2010), and it has been hypothesized that their cross-shelf transport may be influenced by the strength of the eddies (Shotwell *et al*. In press).

These concepts led a group of scientists from Georgia Tech and the Alaska Fisheries Science Center (Dr. Shotwell *et al*., AFSC, NMFS, NOAA) to explore the hypothesis that higher sablefish recruitment is related to the strength of these large anticyclonic eddies. Although we do not have sufficient data to fully test this concept and understand the exact dynamics linking eddies to the sablefish life cycle, we have explored a simple predictive model of sablefish recruitment based on the intensity of the large Alaskan anticyclones. A regional eddy-resolving ocean model hindcast (ROMS) from 1950–2008 was used to generate an index of anticyclonic eddy strength. More specifically, because the dominant anticyclonic eddy in the northern Gulf is the Sitka Eddy, an index of its strength was produced by averaging the winter sea surface height anomaly (SSHa) from the ROMS eddy-resolving model in the formation region of the Sitka Eddy (see Fig. 2). The comparison of the Sitka Eddy index with the sablefish recruitment time series shows significant positive correlation (R = 0.45) and lends support to the hypothesis that sablefish recruitment is highest in years when Sitka eddies are stronger. Although further analysis and observations are required to develop and test the mechanistic link between this large anticyclone and sablefish recruitment dynamics, this work is an example of using data from an eddy-resolving model hindcast to generate a regional physical index to hindcast and forecast recruitment data, which is typically not available until several years later when young adult sablefish become vulnerable to surveys and the fishery.

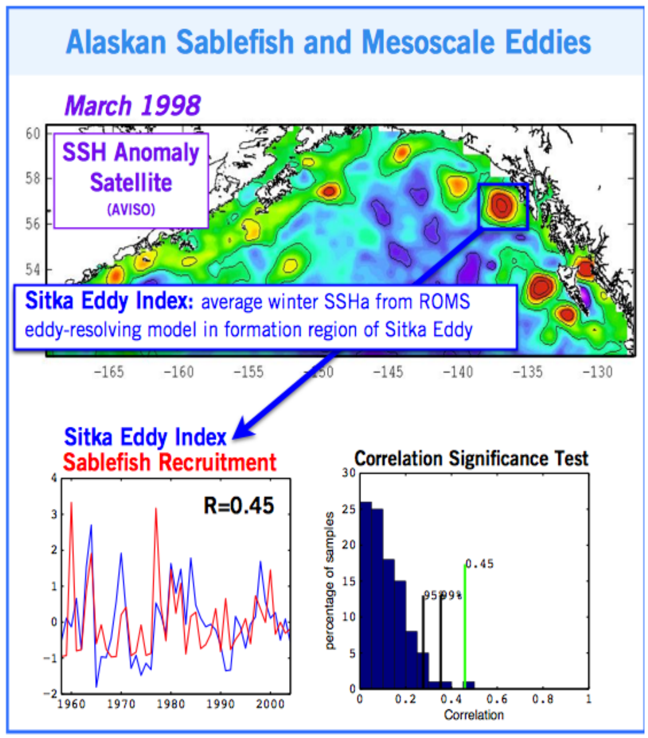

Fig. 2 Top panel shows large anticyclone eddies (e.g., Sitka Eddy) that follow the strong downwelling event associated with El Niño forcing in 1997–1998. A time series of the Sitka Eddy intensity reconstructed with high-resolution ocean model hindcast tracks correlating closely with the sablefish recruitment time series (bottom panel). Given that the recruitment data are not available in real time, the physically derived index could be exploited for prediction of sablefish recruits several years in advance.

New hypotheses linking climate modes to ecosystem response

Identifying large-scale climate patterns enables us to capture large fractions of the field variability (*e.g.*, sea surface temperature, sea level pressure) with a small number of spatial patterns and associated time series – this is often done with data compression techniques like Empirical Orthogonal Function (EOF) and/or Principal Component Analysis (PC). Population dynamics are sometimes better correlated with large-scale climate indices rather than with local weather. This may be explained by the fact that one-dimensional views of the local climate (*e.g.*, temperature, rain-fall) are often too narrow to capture the climate impacts on ecosystems, which typically involve many dimensions.

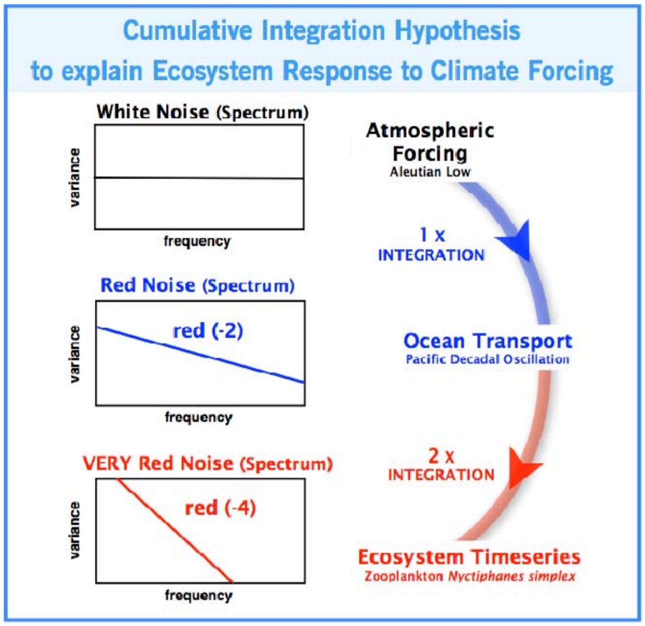

Fig. 3 Random white noise atmospheric variability (e.g., Aleutian Low) has been shown to drive oceanic responses (e.g., changes in ocean transport) that are captured by specific climate modes (e.g., PDO). The integration of the atmospheric forcing by the climate modes leads to a red noise ocean spectrum – that time series with enhanced low frequency variability compared to the high frequency. Marine populations (e.g., zooplankton in the California Current) that are forced by changes in ocean conditions can integrate the white noise atmospheric forcing a second time and lead to time series that exhibit even stronger low-frequency variability and apparent state changes – a very red noise spectrum. This cumulative integrations hypothesis of environmental forcing may explain the long-term regime-like transitions observed in marine populations and serve as a null-hypothesis to assess the level of significance in ocean ecosystems.

A new approach for exploring and explaining the relationship between climate modes and low-frequency changes in ecosystem time series was proposed by Di Lorenzo and Ohman (PNAS, in press) and discussed by the group. The underlying hypothesis behind this approach is based on cumulative integrations of white noise atmospheric forcing, which can generate marine population responses that are characterised by strong transitions and prolonged apparent state changes (see Fig. 3 and caption for a more detailed description). The applicability and success of this model was shown with a 60-year-long observed time series of zooplankton in the California Current, where changes in transport associated with the PDO (1x integration of atmospheric forcing) drive changes in zooplankton abundance (2x integration of atmospheric forcing). Although this approach and example for the California Current are promising, it is important (as noted by the group) that the magnitude of the forcing and response are tested more quantitatively using available observations. The effects of cumulative integrations of environmental and climate forcing on time series of marine populations (*e.g.*, zooplankton and fish) naturally lead to potentially strong and prolonged apparent state transitions that must be carefully considered when searching for apparent nonlinear responses and climate change signatures in marine ecosystems.

Recommendation for PICES and ICES

A major challenge towards developing and testing new hypotheses of the physical-biological linkages is the need to (1) identify/develop targeted observational and modelling datasets that can be used with process models and (2) better understand the regional physical forcing dynamics associated with the large-scale climate variability and change. To this end, the workshop recommended the development of a web-based repository of relevant climate forcing indices (from observations and models) along with a comprehensive explanation of their regional impacts and dynamics. This activity is already ongoing within PICES WG 27 but may also be considered within ICES for the activities of the new joint PICES/ICES Section (Strategic Initiative) on *Climate Change Effects on Marine Ecosystems* (http://www.pices.int/members/sections/CCME-S.aspx).

The workshop also identified two priorities for successfully developing hindcast/forecast ecosystem process-based models:

1. Maintain and improve the collaboration and exchange between marine ecosystem scientists, physical oceanographers, and climate scientists. This dialog is the foundation for developing better and new hypotheses linking ecosystem response to climate forcing.
2. Identify and develop targeted observational and modelling datasets that are required to test the new hypotheses using the process models.

All the material and documents of the ECOFOR workshop have been organised on the PICES WG 27 website at http://wg27.pices.int/ecofor/. The website also contains the presentation files and summary for each of the presenters.

The group and social events

A group of 28 international scientists and 5 graduate students attended the workshop. As in every good workshop, social events and team building activities are essential to develop the necessary trust that leads to successful collaborations. In this regard, the Friday Harbor setting was an ideal location to promote interactions among the participants. The evenings began with a wine reception at an ocean view dining terrace and ended at sundown with fireside chats. There was also a whale-watching excursion with sack lunch on the second day of the workshop (see photos).

People in order of appearance (top to bottom): Sanae Chiba, Julie Keister, Louis Botsford, Matt Newman, Michael Alexander, Shoshiro Minobe, Nick Bond, Tony Koslow, Mark Hufnagl, Ryan Rykaczewski and Steve Bograd.

Future activities in 2013

As an outcome of the 2012 ECOFOR workshop, a theme session at the 2013 ICES Annual Science Conference in Reykjavík, Iceland, and a workshop at the 2013 PICES Annual Meeting in Nanaimo, Canada, were proposed and accepted. These two events share the same scientific focus and title, "*Identifying mechanisms linking physical climate and ecosystem change: Observed indices, hypothesized processes, and* "*data dreams*" *for the future*", in order to collect inputs from both the PICES and ICES scientists. While the ICES session's goal is to collect information and examples of relevant science ongoing in the ICES community on the topic of process modelling, the PICES workshop is aimed more at promoting and expanding the ECOFOR discussions. The PICES workshop format will be a mixture of talks and group discussions that aim at enriching the exchange of ideas and concepts between physical and biological ocean scientists. The ultimate goal of these events is to deliver (1) a set of new hypotheses of the mechanisms of marine ecosystem responses to climate forcing and (2) a description of the observational and modelling datasets required to test these hypotheses using process models.

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Dr. Shoshiro Minobe (minobe@mail.sci.hokudai.ac.jp) is a Professor at the Graduate School of Sciences, Hokkaido University, Sapporo, Japan. His overall interest is to understand the ocean's role in the earth's climate system. Shoshiro is working on decadal climate variability over the North Pacific, ocean–atmosphere interactions, and recently biogeochemistry data analysis. In PICES, he co-chairs Working Group 27 on North Pacific Climate Variability and Change.

Dr. Arthur (Art) Miller (ajmiller@ucsd.edu) is a Research Oceanographer, Senior Lecturer in Climate Sciences, and Director of the Climate, Atmospheric Science, and Physical Oceanography (CASPO) Division at the Scripps Institution of Oceanography, University of California, San Diego (USA). His research interests include ocean modeling, coupled ocean–atmosphere modeling, ocean data assimilation, and climate forcing of marine ecosystems.

Dr. Jacquelynne King (Jackie.King@dfo-mpo.gc.ca) is a Research Scientist at the Pacific Biological Station (Fisheries and Oceans Canada) and an Adjunct Professor at the University of British Columbia. She received her PhD in Limnology from the University of Toronto in 1997 and began her career in marine ecology as a Post Doctoral Fellow studying North Pacific regime shifts. Her current research includes climate change impacts on marine ecosystems and methods of incorporating climate variability into stock assessment advice. She is also Program Head of the Canadian Pacific Shark Research Lab. Within PICES, Jackie was the Chairman of the Study Group on Fisheries and Ecosystem Responses to Recent Regime Shifts, a member of the Climate Forcing and Marine Ecosystem Response Task Team and Working Group 16 on Climate Change, Shifts in Fish Production, and Fisheries Management. She is currently a member of the FIS Committee, the Section on Climate Change Effects on Marine Ecosystems, Working Group 27 on North Pacific Climate Variability and Change, and FUTURE AP-COVE.

Dr. Marc Hufnagl (Marc.Hufnagl@uni-hamburg.de) is a Junior Professor in Fisheries Science and Modelling, University of Hamburg, Germany. His research interests include modeling behaviour physiology and drift of marine invertebrates, ecosystem models, analyzing climate effects on ecosystems, fish and fisheries, life cycle modeling, population dynamics and lifecycle of the brown shrimp Crangon crangon, and selective Tidal Stream Transport (STT).

Dr. Chuck Greene (chg2@cornell.edu) is a Professor in the Department of Earth and Atmospheric Sciences and Director of the Ocean Resources and Ecosystems Program at Cornell University. He received his PhD in Oceanography from the University of Washington and spent a year as a postdoctoral fellow at the Woods Hole Oceanographic Institution prior to joining the faculty at Cornell. His research interests range from the ecological dynamics of marine animal populations to the effects of global climate change on ocean ecosystems. Chuck combines his research and educational interests in ocean science and technology by promoting innovative training opportunities for undergraduate and graduate students. Since 1993, he has organized 18 courses in marine bioacoustics that have trained over 250 students from 30 different countries. He also supervises the Cornell-WHOI Masters of Engineering Program in Ocean Science and Technology.