Upscaling for a better understanding of climate links to ecosystems

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Dr. Nathan Mantua is currently the assistant director for University of Washington's Center for Science in the Earth System, and a full-time research scientist with the University Washington's Climate Impacts Group. His research includes efforts to understand the nature of climate variability, climate impacts on ecosystems, and how climate information can be used in resource management. Nate has worked at the University of Washington since 1995, and thinks that someday he would like to try his hand at the kind of blue-water field work that provides the data needed to untangle the mysteries of biophysical interactions in the Pacific. Nate has been involved with PICES serving as a member of the Study Group on Fisheries and Ecosystem Responses to Recent Regime Shifts in the North Pacific*.*

There are some obvious and major limitations in large-scale climate perspectives on biophysical interactions. Why might a vocal proponent for the importance of ENSO and the PDO for Pacific ecosystems (as I am!) believe this to be true? *First*, at the most fundamental level, all biophysical interactions must be local. A juvenile salmon in the northeast Pacific Ocean will only be influenced by an ENSO event if that tropical event somehow influences the physical or biotic environment experienced by that juvenile salmon. *Second*, large-scale climate indices generally do a poor job capturing the details of environmental changes at the scale of many (perhaps most) meaningful ecosystem interactions, and it is likely that the details of environmental events really do matter. This simple fact is by design: large-scale climate indices are developed to represent a one-dimensional perspective on large-scale aspects of climate variations, not to capture the details of local environmental changes. The PDO index, for example, is based on the monthly loadings of observed SST anomalies onto the leading EOF pattern identified in an analysis of monthly North Pacific SST variations from 1900-1993 (Zhang *et al*., *J. Climate*, 1997, 10, 1004; Mantua *et al*., *Bull. Am. Meteor. Soc.*, 1997, 78, 1069). As highlighted by Bond *et al*. (*Geophys. Res. Lett*., 2003, 30, 2183) and the commentary by McKinnell (*PICES Press*, 2004, 12, 16), the prominence of the PDO pattern varied over the period 1950-2003. In the 1990s, the PDO pattern was secondary in the total North Pacific SST variance it explained to that of the Victoria Pattern of SST variations (the 2nd EOF from an analysis of wintertime SSTs from the period 1950-2003 – see Bond *et al*. for details). In contrast, the environmental changes that influence biophysical interactions in marine ecosystems are likely to be multi-dimensional, possibly non-stationary in time, and with different elements of the key biophysical processes occurring over a variety of spatial and temporal scales.

This commentary on the limitations of large-scale climate perspectives does not aim to call for the removal of large-scale climate indices from Fishery Oceanography investigations. Instead, the objective here is to provide a climate scientist's perspective on analytical approaches for better understanding of the mechanisms for biophysical interactions, causes for local environmental and ecosystem variability, and ecosystem predictability.

A critical part of identifying and understanding the biophysical mechanisms underlying ecosystem changes is to match commensurate scales for the biotic and abiotic parameters of interest. One informative study of cross-scale issues is presented by Hallett *et al*. (Nature, 2004, 430, 71), wherein they report on investigations into the links between Soay Sheep population changes, local climate, and changes in the North Atlantic Oscillation (NAO) index. This collection of issues spans a vast range of spatial scales, from that of a small population of sheep (a few hundred animals) occupying a single catchment basin in the St. Kilda archipelago (spatial scales on the order of kms) to that of the NAO pattern that encompasses the entire North Atlantic sector. Over the period from 1985-2003, the NAO index is better correlated with Soay Sheep population variations than are indices tracking precipitation, winds, or temperatures from a meteorological station just 100 km distant. A closer inspection of the climate data reveals the source for this apparent paradox. The link between the NAO index and Soay Sheep comes with a range of different weather impacts on the limited food resources that sustain Soay Sheep in the winter season. In each case, local weather events influence wintertime mortality events for Soay Sheep; in some years it is extreme cold temperatures, in others it is high winds, and in others it is heavy precipitation events that appear as causal factors for Soay Sheep mortality events. The NAO index is modestly correlated with each of those factors, and it therefore offers a better correlation with Soay Sheep population numbers than any local one-dimensional weather index does. Important take home messages from this study are: (i) a one-dimensional view of climate (*e.g.*, temperature) is simply too narrow to identify and understand climate impacts on Soay Sheep; and (ii) that the NAO index, by itself, yields an incomplete picture for the causes of individual Soay Sheep mortality events.

In spite of the limitations provided by the NAO perspective alone, the relative risk for observing different dimensions of Soay Islands weather can be directly quantified by direct comparisons of the NAO index and Soay Islands temperature, precipitation, and wind data. Thus an understanding for NAO predictability, and the NAO link to the environmental changes of interest, offers a direct avenue for quantifying the predictability for multiple dimensions of the St. Kilda archipelago's climate. Establishing this causal chain across scales of space and time is necessary for understanding and quantifying the predictability of NAO-related Soay Sheep mortality events.

This improved understanding for climate impacts on Soay Sheep populations has come with what I would describe as an upscaling perspective on North Atlantic climate and Soay Islands biophysical interactions. In this case, upscaling refers to a study design that begins with local ecosystem measures of interest (sheep mortality records) and local weather records of interest (St. Kilda precipitation, temperature, and wind data). The mechanisms of the key biophysical interactions are established and quantified with no consideration at all for the possible links to the NAO. Yet important links to NAO variability, which is strongly suggested through the direct correlations between the NAO index and the Soay Sheep population data, becomes much more understandable by establishing the NAO influence on the local environmental parameters of interest.

The time-space scale diagram shown in Figure 1 highlights the fact that the Soay Sheep and NAO index example is quite similar to the kinds of spatial scales involved in many fishery oceanography studies aimed at linking regional ecosystem indices to large-scale climate indices. Soay Sheep populations are confined to small catchment basins (spatial scales ranging from 10's of meters to 10's of kms), and the time scales for mortality events range from hours to days. In contrast, the NAO pattern captures variations in North Atlantic sector SLPs from 100's to 1000's kms, and the NAO index varies across time scales ranging from intra-seasonal to inter-decadal (*e.g.*, see Hurrell *et al*. 2003, *Geophys. Monogr. Ser*., 134, 1).

Logerwell *et al*. (*Fish. Oceanog*., 2003, 12, 554) used an upscaling approach to develop a simple model for understanding and predicting annual variations in Oregon coho salmon marine survival variations with environmental data. The environmental model for Oregon coho survival uses 3 "local" environmental predictors: wintertime SST at a single location on the Oregon coast (a proxy for early spring water column stratification), the date of the spring transition based on coastal winds from 42ºN-48ºN and coastal sea level at Neah Bay, WA, and springtime sea level anomalies at Neah Bay, WA (a proxy for alongshore transport and coastal upwelling). Training this model on marine survival data from 1970-2001 yields a high degree of explanatory power (R^2=0.75). In contrast, direct correlations between annual indices for ENSO and PDO yield a much weaker explanatory power (R^2 = 0.008 for the Niño3.4 SST index; R^2=0.07 for the PDO index). So unlike the Soay Sheep and NAO example, the Oregon coho example is one in which the locally and regionally measured aspects of the environment offer much stronger correlations with the ecological time series of interest than one finds with a focus on only the basin-scale ENSO and PDO indices.

Time and Space Scales of Oceanic Processes

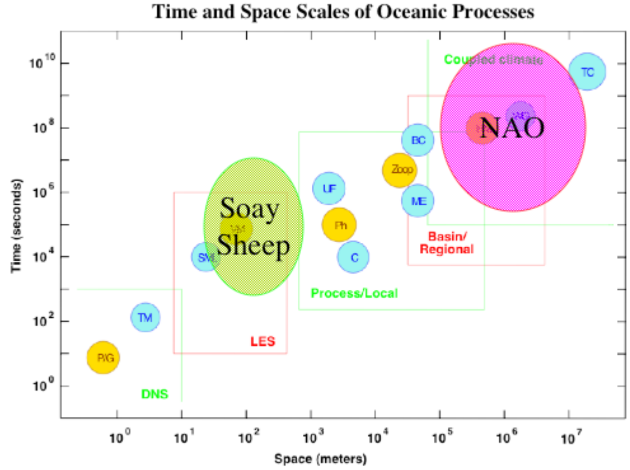

Fig. 1 Space-time schematic highlighting some of the physical and biological processes important to fisheries oceanography studies and the relative positions of the Soay Sheep populations and NAO pattern. Physical processes (in blue) include: turbulent mixing (TM), surface mixed layer processes (SML), upwelling fronts (UF), convection (C), boundary currents (BC), mesoscale eddies (ME), and the thermohaline circulation (TC). Biological processes (in yellow) are: predation/grazing (P/G), vertical migration (VM), horizontal migration (HM), and the natural scales of aggregation for phytoplankton (Ph) and zooplankton (Zoop). The rectangular boxes in green and red show the approximate space/time scales covered by five classes of ocean and/or ocean/atmosphere models: Coupled climate, Basin/regional, Process-oriented/Local, Large-eddy simulation (LES) and Direct numerical simulation (DNS). After Mantua et al.*, 2002,* Oceanography*, 15, 75.*

Generally speaking, I believe that we should expect that custom-tailored environmental predictors would outperform large-scale climate indices in their ability to explain and predict ecosystem variations indexed by measurements at spatial scales smaller than 1000's of km.

In spite of scale mismatches between many climate and ecosystem indices, there are at least two good reasons to keep one eye trained on large-scale climate patterns, while the other eye focuses on the local and regional environment. *First* is the issue of predictions. The predictability for large-scale climate variations is often well researched and quantified. In the case of ENSO variability, prediction tools have been developed for over 15 years and are now used to make regularly updated forecasts for lead-times up to one year into the future. The ENSO prediction effort serves as the foundation for modern climate predictions for the extratropical North Pacific and North America, and ENSO forecasts can be used for making skillful one-year lead time PDO index forecasts (Newman *et al*. 2003, *J. Climate*, 16, 3853). *Second*, carefully developed climate indices can greatly simplify large numbers of environmental time series into a small set of meaningful large-scale climate indices. This has been common practice for nearly a century in the Pacific starting with the groundbreaking work of Sir Gilbert Walker (*e.g*., Walker and Bliss, 1932, *Mem. R. Meteorol. Soc*. 4, 53). Because there are repeatable, physically meaningful and robust spatial patterns of variability in the atmosphere and ocean, substantial fractions of the climate system's total variance can often be described with a small set of climate indices. As shown by Bond *et al*., about 48% of the North Pacific's winter-to-winter SST variance from 1950-2003 is accounted for by just two patterns of variability (30% by the PDO pattern, and 18% by the Victoria Pattern). So at the spatial scale of the entire North Pacific basin, and the temporal scales of interannual to inter-decadal variability, these two indices represent a very economical means for describing past variations in North Pacific SST.

Finally, I offer yet another cautionary note on the use and utility of large-scale climate indices like those tracking variability in the PDO and Victoria SST patterns. These large-scale climate indices do not represent the actual measured value of SST at any single grid-point in the North Pacific for any particular day, week, month, season, or year. To recover the variability of SST at a single location off the coast of Oregon, for instance, one might require ten different large-scale patterns to recapture 90% of the actual variability. Such a "reconstruction" would be ridiculous if the actual data series for the location of interest is readily available.

Closing thoughts:

- A detailed understanding for the mechanisms giving rise to biophysical interactions is necessary for understanding the potential predictability of ecosystem changes.
- Large-scale climate perspectives are valuable for providing a better understanding for the long-term history of environmental and ecosystem changes.
- Once the local biophysical interactions are understood, links with large-scale climate patterns provide an avenue for quantifying the predictability of future ecosystem changes. The ability to predict ENSO variability at lead times of ~ 1 year, combined with the strong tendency for year-to-year persistence in the PDO pattern, offer two potentially valuable guidelines for predicting future large-scale climate conditions relevant to many regions and ecosystems in the North Pacific.
- In order to evaluate the possible ecosystem impacts of long-term climate changes, such as those associated with human-caused global warming, some kind of model for local biophysical impacts must be developed, and key parameters must be upscaled to the coarse spatial-scale information that is typically provided in future climate scenarios.
- Empirical studies that identify biophysical impacts from just a few decades of historical data are likely to undersample many dimensions of potentially important biophysical interactions. It is likely that such models will fail when confronted with future environmental and/or ecosystem conditions that are significantly different from those contained within the ranges of the training data.

PICES Interns

PICES offers special thanks to Mr. Gong-Gu Back (National Oceanographic Research Institute, Ministry of Maritime Affairs and Fisheries, Seoul, Korea), who will complete his internship at the Secretariat at the end of January and will returned to Korea.

We are pleased to announce that Mr. Jin-Yong Lee from the Korea Ocean Research & Development Institute (KORDI), Ansan, Korea, joined the Secretariat last November as the new PICES intern. You will have a chance to meet Jin at the upcoming "Climate variability and sub-Arctic marine ecosystems" Symposium to be held May 16-20, 2005, in Victoria, Canada. Now he is mainly involved in preparing the 2004 PICES Annual Report.