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North Pacific basin-scale differences in lower and higher trophic level marine ecosystem responses to climate impacts using a nutrient-phytoplankton–zooplankton model coupled to a fish bioenergetics model

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ABSTRACT

We present a modeling approach where we use one common model formulation of a 11 state variable lower trophic level model that includes two groups of phytoplankton, three groups of zooplankton, and representations of nitrogen and silicate embedded in a three-dimensional ocean general circulation model (OGCM) and forced with a common climate forcing. Results are applied to a fish bioenergetics model for two geographically distinct ocean regions off Japan including the Oyashio, mixed, and Kuroshio subregions and off California including the subarctic, transition and subtropical subregions. The model is applied to two fish species (Pacific saury: *Cololabis saira* and Pacific herring: *Clupea harengus pallasii*) with different life histories in each region and the influence of three different “regime shift” periods was explored. With this approach, we narrow the observed biological response and model dynamics to reflect local conditions and eliminate differences related to the model formulations in each region. In general, the trend in temperature was negatively correlated with trends in the zooplankton community. Out-of-phase herring growth trends were observed between the Japan and California regions ($r = -0.259$, $p = 0.02$). In-phase growth trends between herring and saury were observed at the California region ($r = 0.61$, $p < 0.01$). We did note some evidence of a basin-scale PDO mode response. During 1980–1985, simulated saury and herring in both regions showed a consistent increase in weight-at-age. In the Oyashio subregion, temperature decreased and all three zooplankton groups increased beginning around 1980. The same pattern of a decrease in temperature and an increase in zooplankton densities was observed between 1980 and 1985 in the subarctic subregion of California. Results are discussed in the context of ecosystem-based fisheries management.

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1. Introduction

The response of marine ecosystems to climate change is one of the most significant sampling and modeling challenges presently faced by the ocean research community (deYoung et al., 2004). Although many important marine ecosystems worldwide are being intensely studied, the mechanisms by which climate change leads to ecosystem responses are not fully understood. Providing mechanistic understanding is especially critical when trying to assess the impacts of climate change on target populations at the basin-scale.

In the North Pacific Ocean, physical and ecological variability often have a coherent basin-wide expression owing to the global processes that drive them, e.g., ENSO, PDO, etc. (King, 2005). Despite the recognition that the basin-scale oceanic system is forced by climate, the upper ocean response and consequent changes in ecosystem structure are localized depending on modulation by specific local expressions of physical and biological attributes.

Significant and coherent changes in the state of the ocean, across large geographic areas such as the whole North Pacific basin, should be manifested in regional marine ecosystems if long-term changes in climate variability influence ecosystem productivity. Indeed, broad scale physical and biological changes have been noted throughout the North Pacific basin. Around 1977, population abundance, productivity and distribution, across all trophic levels in ecosystems throughout the North Pacific underwent rapid changes (Hare and Mantua, 2000). In the eastern Pacific, coherent changes were observed in fish stocks and recruitment patterns (Hollowed and Wooster, 1992, 1995; Beamish and Bouillon, 1993; Hare et al., 1999; McFarlane et al., 2000; King, 2005) and zooplankton biomass, timing and community composition in the northeastern Pacific gyre (Brodeur and Ware, 1992; Mackas et al., 1998, 2001). In the western Pacific, similar observations of coherent decadal scale variability patterns in the winter Kuroshio/Oyashio current ecosystems have been made in plankton biomass (Sugimoto and Tadokoro, 1998), winter abundance of large copepods (Nakata and Hidaka, 2003), and fish abundance and fisheries CPUE for sardine, mackerel, and Pacific saury (Yatsu and Ueno, 2004).

A widely used index for decadal changes in the state of the North Pacific Ocean is the Pacific Decadal Oscillation index (PDO). The PDO tracks the dominant spatial pattern of sea surface temperature variation across the North Pacific and the major low frequency changes in North Pacific climate. Shifts in the PDO are often used to delineate different regime periods (Mantua et al., 1997). It has been well established that in the North Pacific climate regime shifts took place in 1977, 1989, and 1998 (King, 2005). The climate shift that occurred in the late 1970s was associated with an abrupt transition from a negative to a positive phase of the PDO. This pattern resulted in anomalously warm waters along the west coast of North America, and cooler waters in the western North Pacific (Mantua et al., 1997; Yasunaka and Hanawa, 2002). Prior to 1989, the main mode of variation was in an east–west pattern and it is referred to as the classic PDO mode. Since 1989, a different north–south pattern has emerged, often referred to as the Victoria mode (Bond et al., 2003). Further information

on the characteristics of the classic PDO and Victoria modes can be found in Mantua et al. (1997), Minobe (1997), Hare and Mantua (2000) and Bond et al. (2003). As discussed by King (2005), the most noteworthy feature of this collection of observations is that observed changes in the marine ecosystems are evident on the scale of the whole North Pacific, and that the changes persist on time-scales of a decade or longer.

Despite a substantive observational database, we still lack quantitative knowledge of how major oceanic ecosystems respond to North Pacific climate variability. Understanding the processes that regulate marine ecosystems is essential to assessing and predicting impacts of climate variability on marine biota and on the human communities that depend on them. Unfortunately, the observational records are short relative to the time scale of regime shifts, as well as spatially incomplete, and hence it is not certain if modes observed during this century are regular in structure, intensity, and timing. Moreover, these patterns cannot be observed in isolation. Andrew C. Revkin, science and environmental writer for the New York Times, proposed the analogy of pointillist paintings with being able to see patterns in nature “the picture is revealed only when a large number of points are regarded as a whole” (Revkin, 2006).

Simulation modeling serves as a tool for quantitatively synthesizing our current knowledge and is well suited to exploring long-term ecosystem response to climate change over broad regions. However, models only represent a caricature of the complexity of the real world (Libralato et al., 2006). Nonetheless, simulation experiments allow exploration of questions and hypotheses that are difficult to address with limited field data. Use of a single model, or multiple models developed to be comparable, enables a more straightforward comparison of predicted responses among different species and among regions. Often, such comparisons of predictions are confounded by differences in responses being inseparable from true biological differences or because different models were applied by different investigators to the species and regions of interest.

Using modeling approaches and data sets described in this issue (Kishi et al., 2007; Ito et al., 2007; Megrey et al., 2007; Rose et al., 2007b), our study focuses on two highly productive, economically important and dynamically distinct ecosystems of the North Pacific at similar latitudes: the California Current System (CCS) and the Kuroshio/Oyashio extension current System (KOS). The CCS extends along the west coast of North America from British Columbia, Canada to northern Baja California, Mexico. The KOS is a swift ocean current extending from the coast of Japan to the central North Pacific, forming the West Wind Drift Current, which bifurcates as it reaches the west coast of the North American continent. The southern arm of the bifurcation forms the CCS. We have focused on the CCS and KOS regions as key response locations to Pacific decadal climate variability, for the reasons discussed above.

Our objective is to present the results of a simulation model of the growth response of Pacific herring (*Clupea harengus pallasi*) and Pacific saury (*Cololabis saira*) to long-term climate changes in the KOS (we term Japan) in the western Pacific and the CCS (we term California) in the eastern Pacific (Fig. 1). We use a nutrient-phytoplankton–zooplankton lower trophic level (LTL) model, NEMURO (Kishi et al., 2007) embedded in a

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