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Climate to fish: Synthesizing field work, data and models in a 39-year retrospective analysis of seasonal processes on the eastern Bering Sea shelf and slope

Ivonne Ortiz[a,*], Kerim Aydin[b], Albert J. Hermann[a,j], Georgina A. Gibson[c], André E. Punt[d], Francis K. Wiese[e], Lisa B. Eisner[b], Nissa Ferm[b], Troy W. Buckley[b], Elizabeth A. Moffitt[f], James N. Ianelli[b], James Murphy[g], Michael Dalton[b], Wei Cheng[a,j], Muyin Wang[a,j], Kate Hedstrom[h], Nicholas A. Bond[a,j], Enrique N. Curchitser[i], Charlotte Boyd[d]

[a] *Joint Institute for the Study of the Atmosphere and Ocean, University of Washington, Seattle, WA 98195, USA*
[b] *Alaska Fisheries Science Center, NOAA, 7600 Sand Point Way N.E., Building 4, Seattle, WA 98115, USA*
[c] *International Arctic Research Center, University of Alaska Fairbanks, Fairbanks, AK 99775, USA*
[d] *School of Aquatic and Fishery Sciences, University of Washington, Seattle, WA 98195-5020, USA*
[e] *Stantec Consulting Services Inc., 725 E Fireweed Lane, Anchorage, AK 99503, USA*
[f] *Sea Star Scientific Editing, Seattle, WA 98115, USA*
[g] *Center for Studies in Demography and Ecology, University of Washington, Seattle, WA 98195-3412, USA*
[h] *Institute of Marine Science, University of Alaska, Fairbanks, AK 99775, USA*
[i] *Department of Environmental Sciences, Rutgers University, New Brunswick, NJ 08901, USA*
[j] *Pacific Marine Environmental Laboratory, NOAA, 7600 Sandpoint Way NE, Building 3, Seattle, WA 98115, USA*

A R T I C L E I N F O

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A B S T R A C T

We combined field data and the output from a climate-to-fish coupled biophysical model to calculate weekly climatologies and 1971–2009 time series of physical and biological drivers for 16 distinct regions of the eastern Bering Sea shelf and slope. We focus on spatial trends and physical-biological interactions as a framework to compare model output to localized or season-specific observations. Data on pollock (≥ 8 cm) diet were used to evaluate energy flows and zooplankton dynamics predicted by the model. Model validation shows good agreement to sea-ice cover albeit with a one month delay in ice retreat. Likewise, the timing of spring phytoplankton blooms in the model were delayed approximately one month in the south and extend further into summer, but the relative timing between the spring and fall bloom peaks was consistent with observations. Ice-related primary producers may shift the timing of the spring bloom maximum biomass earlier in years when sea ice was still present after mid-March in the southern regions. Including the effects of explicit, dynamic fish predation on zooplankton in the model shifts the seasonal spring peak and distribution of zooplankton later in the year relative to simulations with implicit predation dependent only on zooplankton biomass and temperature; the former capturing the dynamic demand on zooplankton prey by fish. Pollock diets based on stomach samples collected in late fall and winter from 1982–2013 show overwintering euphausiids and small pollock as key prey items in the outer and southern Bering Sea shelf; a characteristic not currently present in the model.

The model captured two large-scale gradients, supported by field data, characterizing the overall dynamics: 1) inshore to off-shelf physical and biological differences with a gradient in inter-annual variability from higher frequency inshore to lower frequency offshore; and 2) latitudinal gradients in the timing of events. The combined effects of length of day, bathymetry, and tides, which are consistent from year to year, and the two large-scale gradients, characterize the environment on which regional differences were based and restrict their inter-annual and seasonal variability. Thus, the relative timing and sequence of events remained consistent within regions. The combination of model outputs and observational data revealed specific ecosystem processes: (1) The spatial progression in the timing, peaks and sequence of events over the shelf is driven by wind, sea ice, and stratification and creates a seasonal expansion and contraction of the warmer pelagic and bottom habitat suitable to pollock. (2) The seasonal warming of air temperature and the spring-summer expansion of the warm pelagic and bottom habitats influence the ice retreat and the associated ice edge and open water spring blooms, as well as subsequent

* Corresponding author. Fax: +1 206 526 6723.
E-mail address: ivonne@u.washington.edu (I. Ortiz).

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production/abundance of copepods and euphausiids. (3) These warmer conditions favor pelagic energy flows to pollock (≥ 10 cm) and allow their distribution to expand shoreward and northward along the shelf break. (4) The fall-winter expansion of the seasonal ice cover drives the contraction of warmer waters towards the outer and southwest shelf and favors benthic energy flows over most of the shelf. There, fall blooms allow for additional lipid storage by large copepods and euphausiids that sink close to the bottom where they either go into diapause or have a restricted diel migration over winter. (5) During these cold months, the preferred pollock habitat shifts and contracts towards the outer and southwest shelf where their increased density and reduced prey availability leads to winter pollock cannibalism and consumption of overwintering euphausiids. Our project highlights the benefits of linking continuous and long-term field work with the development and implementation of highly complex models. In the face of uncertainty, simulations such as these, tightly coupled to field programs, will be instrumental as testbeds for process exploration and management evaluation, increasing their relevance for future fisheries and ecosystem management and strategic planning.

1. Introduction

The volume and value of fisheries in the eastern Bering Sea (EBS) was over a billion pounds and 1.4 billion US dollars in product value in 2014 (Fissel et al., 2015). Large and numerous populations of seabirds and marine mammals are present and utilize this area for feeding and reproduction (Friday et al., 2012; Allen and Angliss, 2012; Denlinger, 2006). The EBS has experienced shifts in the physical environment in response to the 2000-2005 warm years (Stabeno et al., 2007), including changes to circulation (Stabeno et al., 2010; Danielson et al., 2012), the extent and duration of seasonal ice coverage and subsequent variability in bottom temperatures, stratification and mixed layer depth (Hunt et al., 2011; Stabeno et al., 2012a). These physical factors affect biological productivity (Hunt et al., 2011; Stabeno et al., 2012b), fish, seabird and marine mammal distributions (Friday et al., 2013; Hollowed et al., 2012; Hunt et al., 2014; Kotwicki et al., 2005; Mueter and Litzow, 2008; Ressler et al., 2014), predator–prey interactions (Livingston and Methot, 1998; Boldt et al., 2012; Hunt et al., 2014), and survival rates and reproductive success (Heintz et al., 2013; Hunt et al., this issue).

Climate variability, and in particular climate change under the global warming background (IPCC, 2007, 2013), impacts abundance, distribution, and the commercial catch of marine resources and has thus been recognized as one of the main challenges to sustainable fisheries (Brander, 2013; Salinger, 2013). Tools that resource management agencies have employed to understand the impact of climate change on the abundance, distribution and species composition of marine resources and fisheries include, but are not limited to, spatial models, single- and multi-species stock projections with environmental forcing and/or predator/prey interactions, and spatially-explicit ecosystem models (Hollowed et al., 2011, 2013). Diverse management measures have been implemented as part of an Ecosystem Approach to Fisheries Management (EAFM) for the Alaskan groundfish fisheries for over 15 years (Witherell et al., 2000). The general framework of the ecosystem assessment has evolved from that described by Livingston et al. (2005), to the current selected suite of physical-, biological- and fisheries-related ecosystem indicators that provide the core information for an annual ecosystem report card and ecosystem assessment chapter (e.g. Zador, 2015). A multi-model approach that includes multi-species models/reference points and ecosystem models, is used to simulate future ecosystem status and policy options (Jurado-Molina et al., 2005; Ianelli et al., this issue; Moffitt et al., this issue).

End-to-end models, which incorporate processes from climate to fish at various levels of complexity, have proliferated in recent years, and have become increasingly relevant as they improved to include human dimensions, climate impacts, and processes at multiple spatial and temporal scales (Travers et al., 2007; Rose et al., 2010; Punt et al., this issue). As a result, end-to-end models that include downscaled earth systems models coupled to lower trophic level models are starting to be more commonly applied to address fisheries-management concerns – especially those models that include key fish groups (Travers et al., 2009; Kishi et al., 2011; Rose et al., 2015; Travers et al., 2014a, 2014b). End-to-end models have also been recognized as effective strategic tools and are considered essential to EAFM (Fulton, 2010; Fulton et al., 2014). Despite these advances, active research continues on refining our understanding of the linkages between climate variability and marine resources as mediated by oceanography and phytoplankton/zooplankton productivity.

As part of the Bering Sea Project, a large scale, multi-disciplinary, and multi-institutional ecosystem research program (Wiese et al., 2012), we developed (and coupled) ~10-km resolution models of the physics, lower trophic levels and key fish species in the Bering Sea. The Regional Ocean Model System (ROMS) applied to the Bering Sea (Bering10K) provides information such as currents, temperature, ice thickness and snow cover to the lower trophic level Nutrients-Phytoplankton-Zooplankton (NPZ) model developed under the Bering Ecosystem Study (BEST; ARCUS, 2004, 2005). The BESTNPZ model provides phytoplankton and ice-algae density estimates that were used to attenuate light in the Bering10K-ROMS model, thus establishing a two-way feedback between oceanography and lower trophic levels. In turn, the BESTNPZ model provides the zooplankton prey fields (euphausiids [Order Euphausiacea, krill], and small and large copepods [*Neocalanus* sp., *Calanus marshallae*, respectively]) to the Forage and Euphausiids Abundance in Space and Time (FEAST) fish model. Two-way feedback therein is enabled by applying the fish predation on zooplankton from the FEAST model to the zooplankton biomass in the BESTNPZ model. The spatially-explicit fisheries removals are included by sector, gear, and species (Fig. 1). The dual objectives for the coupled regional Bering10K-ROMS-BESTNPZ-FEAST models were to: 1) investigate biophysical processes and climate impacts; and 2) aid fisheries management by addressing both bottom-up and top-down forcing mechanisms on fish stocks and ecosystems (Wiese et al., 2012).

Here we describe the Bering10K-ROMS-BESTNPZ-FEAST model, and the physical and biological data used for comparison with, and validation of, the model output. We then present the weekly climatologies of physical and biological characteristics from a 1971-2009 hindcast of the model and highlight seasonal process in 16 distinct regions in the EBS shelf and slope. Finally, we present modeled monthly climatologies and length-based feeding habits of walleye pollock (*Gadus chalcogrammus* formerly known as *Theragra chalcogramma*, Page et al., 2013 and hereafter, pollock), based on stomach data collected from 1982 to 2013, and consider