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Iron limitation impact on eddy-induced ecosystem variability in the coastal Gulf of Alaska☆

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ABSTRACT

A data assimilative, coupled physical–biological model for the northwestern coastal Gulf of Alaska (CGOA) is used to characterize lower trophic level ecosystem response to eddy variability at the shelfbreak over a 5-year period (1998–2002). The ocean circulation component is an implementation of the Regional Ocean Modeling System (ROMS), the lower trophic level ecosystem component is a six-compartment Nutrient-Phytoplankton-Zooplankton-Detritus (NPZD) model with iron limitation, and the data assimilation component is the adjoint-based, four-dimensional variational (4D-Var) system available in ROMS. Assimilated observations consist of weekly satellite sea surface height and temperature, as well as bimonthly *in situ* temperature and salinity measurements. Overall, the model results are in agreement with earlier observational studies, and confirm that eddy-induced cross-shelf transport of biological properties can potentially enhance phytoplankton concentrations in the basin by: (1) alleviating iron limitation on phytoplankton growth by transporting iron-rich shelf waters offshore, and (2) transporting elevated shelf phytoplankton concentrations offshore. Simulated nutrient anomalies during eddy events indicate a substantial increase in dissolved iron concentrations in near-surface waters, thereby suggesting that eddy-induced offshore transport of iron-rich shelf waters is the dominant mechanism regulating locally-generated offshore production in the CGOA high nutrient-low chlorophyll (HNLC) region during eddy events. In fact, for the period 1998–2002, the model results predict that approximately two thirds of the eddy-induced production in the Yakutat/ Sitka “eddy corridor” is associated with locally-generated production resulting from alleviated iron limitation conditions on phytoplankton growth. The remaining third can be attributed to eddy-induced offshore export of chlorophyll concentrations of shelf origin.
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1. Introduction

Despite being subjected to predominantly downwelling-favorable winds, the northwestern coastal Gulf of Alaska (CGOA; from ca. 142° to 162° W, along the Alaskan Peninsula) (Fig. 1, left panel) has a highly productive shelf, and supports rich and diverse marine resources. As such, the region has been designated by the U.S. GLOBEC (Global Ocean Ecosystem Dynamics) program as a study site to investigate the potential impact of global climate change on ecosystem dynamics and fisheries. In contrast, the Alaska Gyre interior is generally referred to as a high nutrient-low chlorophyll (HNLC) region because severe iron limitation on phytoplankton growth maintains low levels of primary production despite elevated macro-nutrient (nitrate, silicate) concentrations (Martin and Fitzwater, 1988). Since shelf waters are iron-rich from river input and sediment resuspension (Stabeno et al., 2004), physical mechanisms contributing to offshore transport are critically important for supplying shelf iron to HNLC basin waters and alleviate growth limitation on phytoplankton.

In the CGOA, cross-shelf exchange of physical and biological properties is seasonally modulated by anticyclonic mesoscale eddies which propagate southwestward along the shelfbreak, (Crawford et al., 2007; Okkonen et al., 2003). These anticyclonic eddies typically form during winter either on the relatively broad shelf south of Yakutat, Alaska, or further south and east of the CGOA on the relatively narrow shelf off Sitka, Alaska. While Yakutat eddies propagate southwestward along the CGOA shelfbreak (Ladd et al., 2005a), Sitka eddies have been observed to follow two distinct paths: either they propagate westward into the interior of Alaska Gyre, or they propagate along the shelfbreak following a path similar to that of Yakutat eddies (Crawford et al., 2000). Both eddy types are anticyclonic, baroclinic features with horizontal scales in the range of 100 to 200 km, and positive sea surface height anomaly signatures of 0.1 to 0.4 m. Forcing by atmospheric planetary waves, relaxation in downwelling wind conditions, and interactions between the Alaskan Current and bottom topography (Swaters and Mysak, 1985; Thomson and Gower, 1998) have been suggested as potential formation mechanisms for Sitka and Yakutat eddies. Years of

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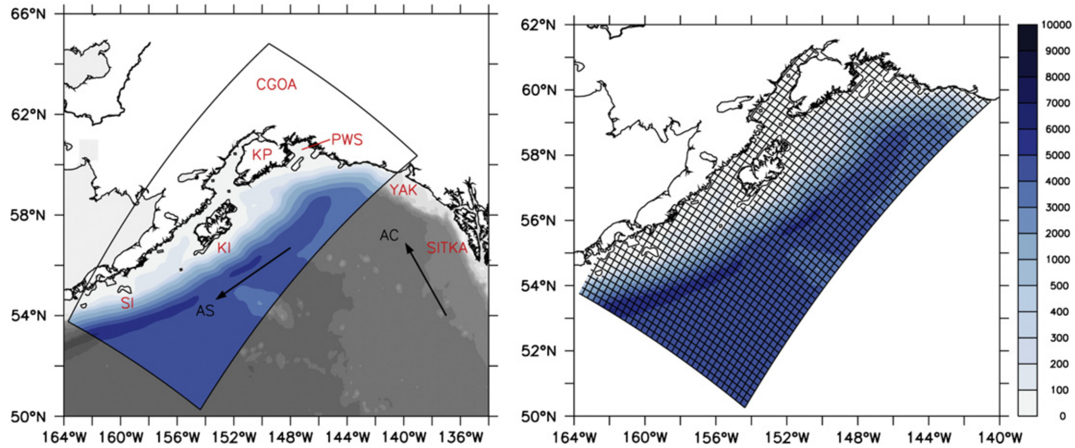

Fig. 1. CGOA geographical map and model domain. Left: map of the Gulf of Alaska superimposed with the region covered by the CGOA model (black outline) and, for reference, the geographical locations of Sitka, Yakutat (YAK), Prince Williams Sound (PWS), Kenai Peninsula (KP), Kodiak Island (KI), and Shumagin Islands (SI); also indicated is the direction of the two dominant boundary currents, the Alaska Current (AC) and the Alaskan Stream (AS). Right: CGOA model domain and computational grid (subsampled by a factor of two for clarity). Bottom topography (m; colorscale) is indicated in both panels.

intensified downwelling-favorable wind conditions are also known to result in increased eddy activity in the CGOA (Henson and Thomas, 2008; Okkonen et al., 2001).

Since the CGOA region is dominated by downwelling-favorable winds, anticyclonic eddies have a profound impact on lower trophic level ecosystem processes by contributing to nutrient replenishment on the shelf through cross-shelf transport (Ladd et al., 2005b). For instance, *in situ* observations linked increased nutrient concentrations with the presence of a shelfbreak eddy in May 1999 (Childers et al., 2005). Eddy-induced cross-shelf transport can also regulate primary production at the shelfbreak and in the basin by transporting iron-rich shelf waters into the Alaska Gyre HNLC region. As such, Sitka and Yakutat eddies play an important role in shaping phytoplankton community structure in the CGOA by controlling the cross-shelf concentration gradients of limiting nutrients (Strom et al., 2006). Other mechanisms contributing to cross-shelf transport of nutrients in the CGOA include surface Ekman transport, topographic steering, tidal mixing, and relaxation of downwelling conditions (Whitney et al., 2005), as well as mesoscale variability associated with the intrinsic dynamics of the southwestward-flowing Alaskan Stream (Combes et al., 2009).

While much has been learnt about Sitka and Yakutat eddies and their contribution to cross-shelf exchange of physical and biological properties from observational studies, little is known about the actual role played by iron limitation during eddy events, and about the importance of locally-generated additional production in the HNLC region (as a result of eddy-induced offshore iron transport) compared to that of shelf production being advected offshore by the eddy circulation. The objective of the present study is therefore to use results from a data assimilative, coupled physical–biological model for the CGOA to characterize the spatial and temporal lower trophic level ecosystem response to mesoscale eddy variability. Of particular interest are: (1) anomalies in velocity, temperature, and salinity fields during eddy events, (2) anomalies in dissolved nitrogen, dissolved iron, and phytoplankton concentrations during eddy events, and (3) relative contributions of eddy-induced offshore transport of shelf phytoplankton vs. locally-generated production in HNLC region associated with eddy-induced offshore transport of iron-rich shelf waters.

The ocean circulation component for the CGOA is an implementation of the Regional Ocean Modeling System (ROMS; Haidvogel et al., 2000; Shchepetkin and McWilliams, 2005), and the lower trophic level ecosystem component is provided by a six-compartment Nutrient-Phytoplankton-Zooplankton-Detritus (NPZD) model (Franks, 2002, Powell et al. 2006) with iron limitation (Fiechter et al., 2009). The data assimilation method is the adjoint-based, four-dimensional variational (4D-Var) system available in ROMS (Moore et al., 2011; Powell et al., 2008). The coupled ROMS-NPZD model configuration has been used previously without data assimilation to characterize interannual ecosystem variability and iron limitation on phytoplankton growth in the CGOA (Fiechter et al., 2009). Assimilation of remotely-sensed and *in situ* physical observations into the coupled model significantly improved the accuracy with which the model reproduced oceanic mesoscale variability along the CGOA shelfbreak, leading to substantial improvements to the biological response predicted by the lower trophic level ecosystem model (Fiechter et al., 2011). An overview of the data-assimilative, coupled ROMS-NPZD model is given in Section 2, mode-data comparisons are presented in Section 3, eddy-induced physical and biological variability is described in Section 4, and a discussion is provided in Section 5.

2. Data assimilative, coupled physical–biological model

2.1. Regional ocean circulation model

The ocean circulation model for the northwestern CGOA is an implementation of ROMS, and the domain encompasses a region ranging geographically from ca. 50 to 62° N and 140 to 164° W (Fig. 1, left panel). ROMS is a hydrostatic, primitive equation model that uses a terrain-following vertical coordinate and a split-mode technique to efficiently solve for the baroclinic and barotropic components of the circulation. The ocean circulation model is driven on all open boundaries by monthly-averaged fields from the Northeast Pacific (NEP) ROMS simulations of Curchitser et al. (2005), which provide realistic transport values and temperature and salinity profiles for the Alaskan Stream entering and exiting the CGOA domain near 59° N, 142° W and 54° N, 162° W, respectively. Surface forcing for the CGOA model is derived from the datasets for Common Ocean-Ice Reference Experiments (CORE2; Large and Yeager, 2008), which consist of 6-hourly winds, air temperatures, sea level pressure and specific humidity; daily short-wave and downwelling long-wave radiation; and monthly precipitation. Short wave radiation is needed to compute vertical turbulence profiles in the ocean circulation model, as well as phytoplankton growth in the ecosystem model. The sensible, latent, and longwave components of the surface fluxes are derived from CORE2 using a bulk flux formulation (Fairall et al., 1996; Liu et al., 1979). Freshwater input from river discharge is imposed as a line source at the coast, and explicitly accounts for seasonal variations (Royer, 1982). The CGOA model grid has a horizontal resolution of about 11 km and 42 non-uniform vertical levels, with clustering near the surface (Fig. 1, right panel). A horizontal resolution of 10 km may not fully resolve small-scale flow-topography interactions or ACC frontal dynamics on the

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