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A model-based examination of multivariate physical modes in the Gulf of Alaska

A.J. Hermann[a,b,*], C. Ladd[b], W. Cheng[a,b], E.N. Curchitser[c], K. Hedstrom[d]

[a] Joint Institute for the Study of the Atmosphere and Ocean, University of Washington, Seattle, WA 98195, USA
[b] Ocean Environment Research Division, NOAA/PMEL, Seattle, WA 98115 USA
[c] Department of Environmental Sciences, Rutgers University, New Brunswick, NJ 08901, USA
[d] School of Fisheries and Ocean Sciences, Fairbanks, AK 99775, USA

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ABSTRACT

We use multivariate output from a hydrodynamic model of the Gulf of Alaska (GOA) to explore the covariance among its physical state and air/sea fluxes. We attempt to summarize this coupled variability using a limited set of patterns, and examine their correlation to three large-scale climate indices relevant to the Northeast Pacific. This analysis is focused on perturbations from monthly climatology of the following attributes of the GOA: sea surface temperature, sea surface height, mixed layer depth, sea surface salinity, latent heat flux, sensible heat flux, shortwave irradiance, net long wave irradiance, currents at 40 m depth, and wind stress. We identified two multivariate modes, both substantially correlated with the Pacific Decadal Oscillation (PDO) and Multivariate El Nino (MEI) indices on interannual timescales, which together account for ~30% of the total normalized variance of the perturbation time series. These two modes indicate the following covarying events during periods of positive PDO/MEI: (1) anomalously warm, wet and windy conditions (typically in winter), with elevated coastal SSH, followed 2–5 months later by (2) reduced cloud cover, with emerging shelf-break eddies. Similar modes are found when the analysis is performed separately on the eastern and western GOA; in general, modal amplitudes appear stronger in the western GOA.

1. Introduction

1.1. Overview of the GOA

The coastal Gulf of Alaska (GOA) supports major marine resources, and is governed by unique physical dynamics which include: substantial tidal mixing; strong eastern and western boundary currents; seasonal downwelling circulation; along-canyon transport; intermittent cross-shelf transport by eddies; upwelling via wind stress curl (Stabeno et al., 2004, 2016-a, 2016-b). Janout et al. (2010) described anomalous ocean cooling events in the GOA during 2006–2008, their formation by winter air-sea heat flux, and their modulation by runoff, winds, and other factors. Janout et al. (2013) elaborated on these findings with a climatological average heat budget at the northern head of the GOA, based on oceanographic and atmospheric data and reanalyses. They emphasized the importance of the Alaska Coastal Current (ACC) in replenishing the oceanic heat lost to the atmosphere each year in the GOA, and concluded that nearshore regions experience greater wintertime heat loss than the middle and outer shelves.

1.2. Goals of this analysis

Here we explore the physical dynamics of the GOA, including air-sea fluxes, as part of the Gulf of Alaska Integrated Ecosystem Research Program (GOAIERP). The GOAIERP is a vertically integrated field and modeling study of the physics, lower trophic level and fish dynamics of the GOA. The overarching goal of the program is to identify the primary physical and biological factors contributing to successful recruitment of five commercially and ecologically important groundfish species (Pacific cod, pollock, Pacific ocean perch, sablefish, and arrowtooth flounder). A primary hypothesis is that recruitment is largely determined by interannually-varying barriers to survival during early life stages – specifically, the “gauntlet” that larvae must overcome to reach juvenile nursery grounds. To help address this issue, we consider whether the physical dynamics of the GOA as a whole, or

* Corresponding author at: Pacific Marine Environmental Laboratory, 7600 Sand Point Way NE, Seattle, WA 98115, USA. Tel./fax: +1 206 526 6495.
E-mail address: albert.j.hermann@noaa.gov (A.J. Hermann).

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subregions thereof, can be broadly classified into a small number of spatiotemporal modes with strong interannual variance. We further consider whether such modes correlate to larger-scale patterns of the wider North Pacific.

To this end, using multivariate EOF analysis, we have examined a suite of physical variables from regional circulation model output (~10 km horizontal resolution), including air-sea flux of heat and momentum based on the atmospheric forcing fields and the evolving oceanic state. We examine the covariance structure of these fields, in order to summarize the combined physical state of the GOA using a limited set of spatial/temporal patterns. We compare the temporal evolution of those structures with the temporal amplitude of three large-scale atmospheric/oceanic patterns ("climate indices") that are generally considered to impact the GOA. Ultimately this may help GOA researchers to interpret the biological variability of the GOA, as the ecosystem experiences these coupled multivariate physical phenomena.

The large-scale patterns chosen for comparison were the Multivariate ENSO Index (MEI) (Wolter and Timlin 1993, 1998), the Pacific Decadal Oscillation (PDO) (Mantua et al., 1997) and the North Pacific Gyre Oscillation (NPGO) (Di Lorenzo et al., 2008). The spatial pattern of the PDO in particular has strong amplitude along the coastal Northeast Pacific (Mantua et al., 1997), and has been cited in numerous biological studies. In the GOA itself, many studies have suggested a link between the interannual variability of Sitka eddies and ENSO. Downwelling coastal Kelvin waves excited by ENSO (Melsom et al., 1999; Murray et al., 2001) as well as atmospheric teleconnections with the tropics (Melsom et al., 2003; Okkonen et al., 2001) contribute to interannual mesoscale variability in the eastern GOA (Hermann et al., 2009). The NPGO represents a simultaneous (positively correlated) variation of the subtropical gyre (which includes the California Current system) and the subpolar gyre (which includes the Alaska Current) of the Northeast Pacific. It has been shown to correlate with low-frequency fluctuations in salinity and nutrients at Line P (Di Lorenzo et al., 2009), which is located southeast ("upstream") of the GOA (see Fig. 1).

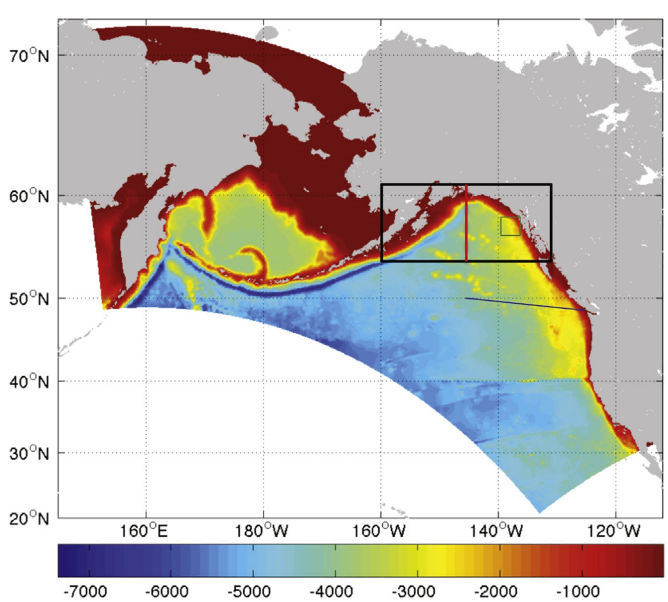

Fig. 1. ROMS-NEP numerical model domain with bathymetry (shaded, m). Full Gulf of Alaska domain used for statistical analysis is shown by black line. The red line denotes separator (at 145 W) between east and west subsections used for analysis. Blue line indicates location of hydrographic line P. Green box indicates the domain of the EKE analysis (56.5–58 N, 139–136 W). Figure modified from Danielson et al. (2011).

Table 1
Variables used in the statistical analysis.

Category	Variable name	Description	Units
Ocean scalars			
	SSH	sea surface height	m
	SST	Sea surface temperature	°C
	SSS	Sea surface salinity	psu
	SBLD	Mixed layer depth	m
Heat flux			
	LATEN	Latent heat flux	$W\,m^{-2}$
	SENSI	Sensible heat flux	$W\,m^{-2}$
	LW	Net longwave heat flux	$W\,m^{-2}$
	SW	Shortwave heat flux	$W\,m^{-2}$
Wind stress			
	USTRESS	Eastward wind stress	$N\,m^{-2}$
	VSTRESS	Northward wind stress	$N\,m^{-2}$
Ocean velocity			
	U	Eastward 40 m velocity	$m\,s^{-1}$
	V	Northward 40 m velocity	$m\,s^{-1}$

Our analysis is focused on perturbations from monthly climatology of the following attributes of the GOA: sea surface temperature, sea surface height, mixed layer depth, sea surface salinity, latent heat flux, sensible heat flux, shortwave irradiance, net long wave irradiance, currents at 40 m depth, and wind stress (see Table 1). Some of these variables are available directly from observations for limited time periods and location, or derivable from observations using bulk flux algorithms, as in Janout et al. (2013). However, our multivariate analysis requires a self-consistent, uniformly gridded set of atmospheric and oceanic properties at scales finer than those typically available from global ocean reanalyses, and ideally spanning multiple decades for all variables. Lacking ready access to a fine-scale, multidecadal, data-assimilating, two-way coupled air-sea simulation for the GOA, we instead utilized output from a regional model with ~10 km horizontal resolution spanning the GOA, driven by a global atmospheric reanalysis. We recognize that this approach excludes both direct feedback of the ocean on the atmosphere, and likewise excludes mesoscale atmospheric features such as gap winds which have been shown to impact GOA circulation (Ladd and Cheng, 2016; Ladd et al., 2016). Despite these shortcomings, our chosen method benefits from a consistent oceanic hindcast at sufficiently fine scale to resolve most of the energetic features of the GOA, including: the Alaska Current/Alaskan Stream system, the Alaskan Coastal Current, and the formation and detachment of shelf-break eddies at ~200 km scale (Stabeno et al., 2004). Impacts of the specific model configuration on our results are discussed further in Section 4.

2. Methods

2.1. The hydrodynamic model

We performed the multivariate analysis on output from an existing regional model spanning the GOA during 1970-2005 (Fig. 1). This model is an implementation of the Regional Ocean Modeling System (ROMS) for the Northeast Pacific (NEP-5) described by Danielson et al. (2011). ROMS is a sigma-coordinate model with curvilinear horizontal coordinates; a description of basic features and implementation can be found in Haidvogel et al. (2008) and Shchepetkin and McWilliams (2005). The NEP-5 grid has approximately 10 km horizontal resolution, with 60 vertical levels. Fine-scale bathymetry is based on ETOPO5 and supplementary datasets as described in Danielson et al. (2011); smoothing of that bathymetry was utilized for numerical stability. Any regions shallower than 10 m were set to be 10 m deep.