Interdecadal changes in mesoscale eddy variance in the Gulf of Alaska circulation: Implications for the Steller sea lion decline

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Abstract. A distinct change in the ocean circulation of the Gulf of Alaska after the 1976-77 climate shift is studied in an eddy-permitting primitive equation model forced by observed windstresses from 1951-1999. After the Aleutian Low strengthens, mean velocities of the Alaskan Stream increase northeast of Kodiak Island and decrease southwest of it. Mesoscale eddy variance likewise increases to the northeast of Kodiak and weakens to the southwest. Mean and eddy flows in the eastern Gulf remain unchanged after the shift. Since mesoscale eddies provide a possible mechanism for transporting nutrient-rich open-ocean waters to the productive shelf region, the flow of energy through the food web may have been altered by this physical oceanographic change. This mechanism may explain the changes in forage fish quality in diet diversity of Steller sea lions whose populations have declined precipitously since the mid-1970’s in the western Gulf while remaining stable in the eastern Gulf.

1. Introduction

The Gulf of Alaska (GoA) supports a rich and diverse ecosystem. The mechanisms by which the physical environment affects the productivity of the biological system are complicated and poorly understood [Francis et al., 1998]. The Alaska Current and the Alaskan Stream both support an energetic open-ocean mesoscale circulation [Kelly et al., 1993; Bograd et al., 1999; Hermann et al., 2002]. The open ocean interior is generally an upwelling region, while the coastal regions, through which the Alaska Coastal Current meanders [Royer, 1982], are generally downwelling. Even so, primary productivity is highest in the coastal regions, possibly due to poorly understood cross-shelf mixing processes involving mesoscale eddy variability of open-ocean nutrient rich waters and shelf waters that contain iron [Okkonen et al., 2003; Stabeno et al., 2004; Strom et al., 2004].

Long-term changes in the way that mesoscale eddies mix these open-ocean and nearshore water masses may profoundly influence the flow of energy up the food web. If primary production is altered by changed nutrient fluxes to the euphotic zone, then different species may be favored. Indeed, one theory for the decline of the Steller sea lion (SSL) populations in the western GoA in recent decades is that their diet diversity changed from being dominated with fatty fish (herring) to lean fish (pollock), which may have adversely affected their metabolism [Trites and Donnelly, 2002].
Long-term changes in mesoscale eddies, however, have not been identified in the GoA due to limited observations. Local timeseries of cross-shelf hydrographic surveys may alias mesoscale eddies. We therefore turn to a numerical model of the GoA to determine if changes in mesoscale eddy variance may have occurred in response to the strengthening of the Aleutian Low after the 1976-77 climate shift [Miller et al., 1994].

Our objective is to address two unexplained issues about the SSL decline. The first is the temporal issue: western populations, living in and around Prince William Sound through the Aleutian Island chain, declined precipitously after 1976-77. Was this coincident with a strong change in mean and eddy ocean circulation in this region? The second is the spatial issue: eastern populations, living in and around southeastern Alaska and British Columbia, remained stable over this period. Is there a strong east-west asymmetry in the GoA ocean circulation changes that occurred after 1976-77? We address these questions in targeted numerical experiments simulating changes in eddy statistics occurring after the climate shift.

2. Ocean model hindcasts

We use the Regional Ocean Modeling System (ROMS), which is a generalized sigma-coordinate, hydrostatic, primitive equation model with a free surface [Moore et al., 2004]. The model domain is the GoA north of 50°N with closed straits through the Aleutian Islands (Figure 1). The resolution is 0.25° longitude and 0.17° latitude, roughly 15 km in the central basin, with twenty layers concentrated in the upper 100m. We invoke implicit high-order lateral friction [Shchepetkin and McWilliams, 1998] and KPP vertical mixing.

Open boundary conditions follow the procedure of Marchesiello et al. [2001], which combines a relaxation to Levitus climatology on inflow with a radiation condition on outflow. SST and surface salinity are relaxed to seasonal cycle climatologies.

The model is spun-up with climatological winds for 10 years, then forced over the 1951-1999 period by monthly-mean wind stresses taken from the NCEP/NCAR re-analysis. No other anomalous forcing in surface fluxes or boundary conditions is included.

Wind stress curl (WSC) is expected to be the most important forcing function for the large-scale variability of the GoA circulation [Kelly et al., 1993]. The first empirical orthogonal function (EOF) and principal component (PC) of WSC (Figure 2) exhibits a sharp decadal-scale change in 1976-77 consistent with the climate shift. Lagerloef [1995] identified this pattern, although it occurred as the 2nd EOF in his analysis of COADS winds. It was also the dominant post-shift pattern found by Capotondi et al. [2004] (C04) who noted it represents a weakening of the mean upwelling pattern of WSC forcing in the northeastern GoA, and strengthening to the southwest. PC2 (Figure 2) of EOF2 exhibits prominent interannual variations like PC1, but no decadal-scale changes.

3. Results

Horizontal surface velocity provides a sensitive indicator of circulation changes. Consider ten-year epochs around the 1976-77 climate shift. The periods 1967-76 and 1979-88 are chosen as representative of pre- and post-shift conditions based on PC1 of WSC and allowing a two-year adjustment
timescale after the shift. The results are not sensitive to the exact choice of epoch dates.

Figure 3 shows the mean surface currents for the two epochs. Before and after the shift, the Alaskan Stream is clearly present and flows southwestward along the western shelf-slope boundary of the domain. The Alaska Current is also evident before and after the shift, flowing northwestward along the eastern shelf-slope boundary of the GoA. After the shift, however, the Stream is strengthened considerably in the northwest part of the GoA (north of 56° N) and weakened in the southwestern domain (south of 55° N). The strengthening is so intense in the northwest basin that what appears to be an eddy-driven inertial recirculation occurs seaward of the Stream. This countercurrent is probably unrealistically large due to the weak friction in the model, but is not vital to the basic results found in this paper.

This increase in strength of the Stream after the climate shift is not a Sverdrup response to the WSC pattern of Figure 2b, which would predict a weakening of the Stream. This is because Rossby wave adjustment is required to equilibrate the steady-state Sverdrup solution. Yet Rossby waves do not appear to play an important role in the GoA in the observed response to fluctuating interannual winds \cite{Cummins and Lagerloef, 2002}, in coarse resolution models \cite{C04} or in this eddy-permitting model. Instead, a broad, static ‘thermocline heave’ response to the WSC pattern of Fig. 2b drives northwestward geostrophic flow that impinges on the western boundary and drives the increase in the Stream \cite{C04}.

This change in the strength of the Stream over decadal timescales would be expected to alter the stability properties of the flow field and change the mesoscale eddy variance distribution. Figure 4 shows the variance of monthly-mean anomalous surface currents for the two epochs. Before the shift, mesoscale eddy variance is highest southeast of Kodiak Island and along the Stream to the southwest. After the shift, mesoscale eddy variance increases sharply in the northwestern GoA and decreases sharply to the south and west of Kodiak Island.

Mesoscale eddies, not fluctuating wind-forced currents, are responsible for these velocity variance changes. To demonstrate this, we executed two additional 10-yr model runs with only seasonal cycle winds, computed from the 1976-77 and 1977-82 6-yr periods. The mean currents and velocity anomaly variance of these two runs are very similar to their counterparts of Figures 3 and 4, except for a basin-wide decrease in variance from the lack of anomalous winds.

The mean flows of the Alaska Current in the eastern GoA (Figure 3), in contrast, are nearly unchanged after the shift. Likewise, the anomalous surface velocity variance is only weakly altered, being reduced slightly compared to pre-shift conditions (Figure 4). Hence, an east-west asymmetry occurs in the GoA circulation response to the altered Aleutian Low.

4. Discussion

An eddy-permitting ocean model hindcast reveals distinct changes in the circulation of the Gulf of Alaska after the 1976-77 climate shift. The strengthening of the Aleutian Low drives a more energetic mean and eddy circulation in the northwest GoA and a weakened circulation south and west of Kodiak Island. In the eastern GoA, the Alaska Current remains relatively unchanged after the shift.

These novel results offer a possible explanation for the mechanism behind climate-forced changes in the oceanic ecosystem that may have affected the food supply for the
Steller sea lion populations that declined precipitously in the western GoA beginning in the late 1970’s [Benson and Trites, 2002]. Mesoscale eddies around the Alaskan Stream mix open-ocean waters, which are rich in nutrients like nitrate, with near-coastal waters, which include iron. If the distribution and amount of cross-shelf mixing is altered for extended periods, as found here in a hindcast, then the structure of the food chain may be altered, affecting the distributions of herring and pollock [Hinckley et al., 2001]. This change is visible in dietary changes of SSL populations over the same time period, from higher quality fish (e.g., herring) to lower quality fish (e.g., pollock). The less fatty diet has been hypothesized to weaken the ability of SSLs to nurture healthy offspring [Rosen and Trites, 2000].

A lack of dense space-time sampling of ocean hydrography prohibits a definitive data analysis to test these modeling results. However, Lagerloef [1995] estimated dynamic height from CTD and XBT data from 1968-1990 and found a preponderance of low (high) dynamic height in the 1970’s (1980’s) across the northeastern GoA (his Figure 5). This is consistent with a static response to Ekman pumping pattern EOF1 and with the model results of CO4 that show thermocline deepening (increased dynamic height) across the northeastern GoA after the climate shift. While Lagerloef [1995] inferred that the Stream weakened north of 55°N after the shift, mass-conserving and dynamically consistent models [Figure 3; CO4; Miller et al., 1994] give dynamical support for an increase in strength of the Stream after the shift.

The surface countercurrent seaward of the Stream, which intensifies after the shift, is an interesting component of the hindcast. While there is no consensus in the literature whether this is a real feature, there are many indications that it is. Reed [1984] and Royer and Emery [1987] present hydrographic sections with dynamic height calculations across the shelf-slope system south of the Aleutians that suggest a countercurrent. Bograd et al. [1999] find a similar indication in surface drifters. The model countercurrent clearly follows the topography of the Aleutian trench, which agrees with the observed topographic location of the countercurrent [Onishi and Otani, 1999]. A Pacific-wide, coarser resolution, ROMS run [Shchepetkin, private communication, 2004] also shows a mean countercurrent following the topographic slopes of the trench, indicating that it is not an artifact of our open boundary conditions. The eddy-driven inertial recirculation in the northwest GoA after the shift is likely to be stronger than observed, possibly due to weak implicit friction.

WSC is the dominant forcing function for large-scale flows of the GoA, so our contention that wind stress will largely control the circulation changes after the shift is credible. Yet several forcing effects were not considered in this simulation. No changes to the open boundary condition or closed straits were allowed. These inflows may especially alter the Alaska Current, through interannual changes of interior flows [Strub and James, 2003] and coastally trapped disturbances [Melsom et al., 2003]. No changes in surface heat flux or fresh water flux were included, which may affect upper ocean stability properties. Long-term changes in runoff may affect the Alaska Coastal Current [Royer, 1982]. How these effects influence and interact with the open-ocean eddy variations will require additional experimentation [Hermann et al., 2002]. Higher resolution models will determine the robustness of these results, since the 15 km resolution is comparable to the GoA deformation radius (10-18km).

The model results are nonetheless plausible and dynamically consistent with changes in atmospheric
circulation that followed the 1976-77 climate. A better understanding of how the ocean ecosystem responds to these physical circulation changes is perhaps the greatest challenge. As observations of the physical-biological system increase, our ability to model the past changes in the system will grow. Our results here are a step towards that goal.

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Figure 1. Bathymetry of the ocean model. CI: 500m, plus contours at 100m, 200m, 300m.
Figure 2. PCs (top) of the first (thick) and second (dash) EOFs of the WSC over 1951-1999. After computing EOFs from monthly mean fields, PC’s smoothed with 2-year running mean. EOF1 (bottom) and EOF2 (not shown) of the WSC, explain 26% and 24% of the monthly mean variance, respectively. CI: 0.003, scaled by 10^{10}. 

Figure 2. PCs (top) of the first (thick) and second (dash) EOFs of the WSC over 1951-1999. After computing EOFs from monthly mean fields, PC’s smoothed with 2-year running mean. EOF1 (bottom) and EOF2 (not shown) of the WSC, explain 26% and 24% of the monthly mean variance, respectively. CI: 0.003, scaled by 10^{10}.
Figure 3. Mean surface currents for 10-year epochs 1967-1976 (top), 1979-1988 (middle), and difference between epochs (bottom). Every 6th grid point receives an arrow, if >5cm/s. CI: 10cm/s.
Figure 4. Variance of anomalous monthly mean surface currents for 10-year epochs 1967-1976 (top), 1979-1988 (middle), and difference between epochs (bottom). Anomalies defined with respect to the monthly mean seasonal cycle of the respective 10-year epoch. CI: 100 cm$^2$/s$^2$. 

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