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 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 diets 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 oceanic environment of 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, which runs northwestward along the eastern shelf-slope boundary, and the Alaskan Stream, which runs southwestward along the western shelf-slope boundary, both support an energetic open-ocean mesoscale circulation [Kelly et al., 1993; Bograd et al., 1999; Hermann et al., 2002]. Among the interesting aspects of the large-scale circulation of the GoA is that 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 mixing by mesoscale eddy variability of open-ocean nutrient rich waters with shelf waters that contain iron [Okkonen et al., 2003; Stabeno 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 an increase or decrease in nutrient fluxes to the euphotic zone, then different species may be favored over others. Indeed, one theory for the decline of the Steller sea lion populations in the western Gulf of Alaska in recent decades is that their food source changed from fatty
fish (herring) to lean fish (pollock), which may have adversely affected their metabolism [Trites and Donnelly, 2002].

Long-term changes in mesoscale eddy variance, however, have never been identified in the GoA due largely to limited observations. Lagerloef [1995] identified broad-scale changes in the circulation throughout the 1970’s and 1980’s using available hydrographic data. But local time series of cross-shelf hydrographic surveys may alias mesoscale eddies. Hence, we turn to a numerical model of the GoA circulation 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., 1994a].

Our objective is to address two unexplained key issues about the Steller sea lion decline. The first is the temporal issue, in that the western populations, living in and around Prince William Sound though the Aleutian Island chain, declined precipitously after the 1976-77 climate shift. Was this co-incident with a strong change in ocean circulation and associated mesoscale variability in this region? The second is the spatial issue, in that the eastern populations, living in and around southeastern Alaska and British Columbia, remained stable over this same time period. Is there a strong east-west asymmetry in the GoA ocean circulation changes that occurred after 1976-77 climate shift? We address these questions in targeted numerical experiments in which we analyze the runs for changes in eddy statistics that occurred 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 restricted to the GoA north of 50N with all straits through the Aleutian Islands closed. The topography is a smoothed version of the Smith and Sandwell [1997] dataset (Figure 1). The horizontal resolution is approximately 0.25° longitude and 0.17° latitude, corresponding to roughly 15 km resolution in the central basin. Horizontal friction is treated implicitly in the differencing scheme, where it occurs as a high-order lateral friction [Shchepetkin and McWilliams, 1998]. The vertical resolution is twenty generalized sigma-coordinate levels, with highest resolution in the upper 100m. Vertical mixing is via the K profile parameterization [Large et al., 1994].

Open boundary conditions along the southern and southwestern boundaries follow the procedure of Marchesiello et al. [2001], which combines a relaxation to Levitus climatology on inflow with a radiation condition on outflow. Surface heat fluxes and surface fresh water fluxes are modeled as a relaxation to the climatological seasonal cycle of sea-surface temperature and salinity, respectively.

The model is first spun-up with climatological winds for 10 years. The model is then forced over the 1950-1999 time 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. The model run therefore can only be examined for dynamic adjustment to the wind stress changes, which is the dominant large-scale forcing function for the GoA.

Wind stress curl is expected to be the most important forcing function for the large-scale variability of the GoA circulation [Kelly et al., 1993]. The first and second empirical orthogonal functions (EOFs) and principal components (PCs)
of wind stress curl in the model domain are shown in Figure 2. EOF1 exhibits a sharp decadal-scale change in the late 1970’s consistent with the 1976-77 climate shift of sea level pressure. Lagerloef [1995] also identified this pattern of variability, 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] who noted it represents a strengthening of the mean pattern of wind stress curl forcing. EOF2 does not exhibit decadal-scale changes. Both EOFs contain substantial interannual variability, which may obscure signals on decadal timescales.

3. Results

The analysis of the model hindcasts focuses on horizontal surface velocity fields since these are the most sensitive indicator of changes in the GoA circulation. It is especially illuminating to 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 wind-stress curl of Figure 2 and allowing a two-year adjustment timescale after the shift [Deser et al., 1999]. The results are not sensitive to exact choice of epoch dates.

Figure 3 shows the mean surface currents for the two epochs along with the difference field. Both 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 Alaskan 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 southeastward of the Alaskan Stream. The increase in the strength of the Alaskan Stream is consistent with coarse resolution model results of Capotondi et al. [2004].

This increase in the strength of the Alaskan Stream after the climate shift is not consistent with a Sverdrup response to the wind stress-curl pattern of Fig. 1a, which would predict a weakening of the Stream. This is because Rossby wave adjustment is required to equilibrate the Sverdrup solution. Yet Rossby waves are not observed to occur in the GoA in response to fluctuating interannual winds in nature (Cummins and Lagerloef, 2000), in coarse resolution models (Capotondi et al.) or in the present eddy-permitting model. Instead, a broad, static thermocline heave response to the curl pattern in Fig. 1a drives northwestward geostrophic flow that impinges on the western boundary and drives the increase (not decrease) in the Alaskan Stream (Capotondi et al.).

This change in the mean strength of the Alaskan 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 monthly-mean anomalous surface current velocity variance for the two epochs along with the difference in variance after the climate shift. Before the shift, mesoscale eddy variance is highest southeast of Kodiak Island and along the Alaskan Stream to the southwest of Kodiak. After the shift, mesoscale eddy variance increases sharply in the northwestern GoA and decreases precipitously to the south and west of Kodiak Island. The consequences of this change will include altering the cross-shelf/slope mixing of water masses of the open ocean and shelf regions.
To demonstrate that mesoscale eddies rather than fluctuating wind-forced currents are responsible for these velocity variance changes, we executed two additional 10-year model runs. One was forced for 10 years with monthly-mean seasonal cycle winds based on the 1970-76 (6-yr) average. The other was forced for 10 years by the 1977-82 (6-yr) average. The averaged mean currents and velocity anomaly variance plots of these two runs are very similar, respectively, to Figures 3 and 4, except for a basin-wide increase in variance in the anomalous-wind forced runs. It is clear that the distribution of velocity variance is controlled by the eddies, not the 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 increase in the strength of the Aleutian Low drives a more energetic mean and eddy circulation in the northwest GoA. In the western GoA, south and west of Kodiak Island, however, the mean and eddy circulation is weaker. In the eastern GoA, the Alaska Current remains relatively unchanged after the shift.

These novel results offer a possible explanation for 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]. The mesoscale eddy fields around the Alaskan Stream mix open-ocean waters, which tend to be rich in basic nutrients like nitrate, with near-coastal waters, which tend to include the limiting nutrient iron. If the amount of mixing is altered for extended time periods, as found here in an ocean hindcast, then the structure of the food chain may be altered. This may be a possible mechanism for the change in distributions of herring and pollock population [Hinckley et al., 2001]. This change is visible in dietary changes of Steller sea lion populations over the same time period, from high quality fish (e.g., herring) to low quality fish (e.g., pollock). The less fatty pollock-based diet has been hypothesized to weaken the ability of these animals to nurture healthy offspring [Rosen and Trites, 2000].

While these modeling results are suggestive, they are not conclusive. A lack of sufficiently dense space-time sampling of ocean hydrography prohibits a definitive data analysis that may support these modeling results [Stabeno and Hermann, 1996]. However, Lagerloef [1995] estimated dynamic height from CTD and XBT data acquired from 1968-1990 and found a preponderance of low (high) dynamic height in the 1970’s (1980’s) across the northeastern GoA (see his Figure 5). This is broadly consistent with a static response to the Ekman pumping pattern of EOF1. It also agrees with the model results of Capotondi et al. (2004) who showed thermocline deepening (increased dynamic height) across the northeastern GoA after the climate shift. The limited data analysis of Lagerloef [1995], in fact, suggested that the Alaskan Stream weakened north of 55° N after the shift, which apparently contradicts our model results. While we are presently re-assessing the data analysis procedure, used by Lagerloef to determine if the sparseness of data in the
coastal regions may have inadvertently allowed the objective analysis contours to close around broadscale open-ocean features, forming spurious boundary layers that turn the presumptive flow in the wrong direction. Indeed, the open-ocean interior flows of the Lagerloef analysis have many consistencies with the model solutions. Moreover, one would intuitively expect a strengthening of the boundary currents after increasing the mean amplitude of the wind stress curl. Coarse resolution models [Capotondi et al., 2004; Miller et al., 1994b] give dynamical support to this dynamical intuition.

The occurrence of a mean surface northeastward countercurrent seaward of the Alaskan Stream, which intensifies after the shift, is another interesting component of the model solution. While there is no consensus in the literature whether this is a real feature of the GoA circulation, 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 seaward countercurrent. 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 seaward countercurrent. Bograd et al. [1999] find a similar indication in their surface drifter analysis. Lastly, the countercurrent in the model also clearly follows the topographic contours of the southeastern slope of the Aleutian trench, which agrees with the observed topographic location of the countercurrent location found by Onishi and Otani [1999]. A Pacific-wide, but 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 the open-boundary conditions of this regional model. The eddy-driven inertial recirculation in the northwest GoA after the shift is likely to be stronger than observed, possibly a consequence of the rather weak frictional parameters in this class of ocean model [Shchepetkin and McWilliams, 1998].

Wind stress curl is thought to be the dominant forcing function for the large-scale flows of the GoA, so our contention that wind stress will largely control the circulation changes after the shift is likely correct. However, several other forcing effects were not considered in this simulation. First, no changes to the open-ocean boundary condition were allowed in the southern boundary or along the numerous straits in the Aleutian Island chain. These inflows may alter the broad-scale flows to some degree, especially in the region of the Alaska Current, which has been linked to interannual changes of interior flows [Strub and James, 2003] and poleward propagating coastally trapped disturbances [Strub and James, 2002; Melsom et al., 2003]. Second, no changes in the surface heat fluxes or fresh water fluxes were included. Buoyancy fluxes may affect the upper water column stability properties, which may affect mesoscale eddy formation. Long-term changes in streamflow runoff may affect the Alaska Coastal Current, which is largely forced by the mean runoff [Royer, 1982]. How these changes might influence and interact with the open-ocean eddy variations is not apparent and will require additional experimentation [Hermann and Stabeno, 1996; Okkonen et al., 2001]. Lastly, the resolution of the model is only 16km, which is good compared to coarse resolution models but poor compared to the internal deformation radius in the GoA. Higher resolution models need to be examined to determine if these results are robust [Hermann et al., 2002].

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

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Figure 1. Bathymetry of the ocean model. Contour interval is 500m, except for additional contours at 100m, 200m, and 300m.
Figure 2. Principal components (top) of the first (thick) and second (thin) empirical orthogonal functions of the wind stress curl over the 1951-1999 period from the NCEP/NCAR re-analysis. After computing the EOFs from monthly mean fields, the PC’s were smoothed with a 2-year running mean filter. EOF1 (middle) and EOF2 (bottom) of the wind stress curl, explain 26% and 24% of the monthly mean variance, respectively. Values are scaled by $10^{10}$.
Figure 3. Mean surface currents for the 10-year epochs 1967-1976 (top) and 1979-1988 (middle), and the difference between the two epochs (bottom). Currents less than 5 cm/s do not receive a vector, and only every 6th grid point receives an arrow. Magnitude of the current is contoured at 10 cm/s intervals.
Figure 4. Variance of the anomalous monthly mean surface currents for the 10-year epochs 1967-1976 (top) and 1979-1988 (middle), and the difference between the two epochs (bottom). Anomalies are defined with respect to the monthly mean seasonal cycle of the respective 10-year epoch. Variance of the current is contoured at 100cm²/s² intervals.