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# Interdecadal Changes in Mesoscale Eddy Variance in the Gulf of Alaska Circulation: Possible 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 wind stresses from 1951–99. When the Aleutian Low strengthens after 1976–77, strong changes occur in the mean velocity of the Alaskan Stream and in its associated mesoscale eddy field. In contrast, the Alaska Current and the eddy flows in the eastern Gulf remain relatively 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 climate-driven mechanism, which has a characteristic east-west spatial asymmetry, may potentially help to explain changes in forage fish quality in diet diversity of Steller sea lions whose populations have declined precipitously since the mid-1970s in the western Gulf while remaining stable in the eastern Gulf.*

**RESUMÉ** [Traduit par la rédaction] *On étudie un changement sensible dans la circulation océanique dans le golfe d'Alaska survenu après le changement climatique de 1976–1977 à l'aide d'un modèle à équations primitives permettant les tourbillons, entraîné par les tensions du vent observées entre 1951 et 1999. Quand la dépression des Aléoutiennes se renforce après 1976–1977, d'importants changements se produisent dans la vitesse moyenne du courant d'Alaska et dans son champ de tourbillon de mésoéchelle. Par contre, le courant d'Alaska et les tourbillons turbulents dans l'est du golfe ne sont que peu modifiés après le changement. Comme les tourbillons de mésoéchelle représentent un mécanisme possible pour le transport d'eau de haute mer riche en nutriments vers la région productive de la plate-forme continentale, le flux d'énergie à travers le réseau trophique peut avoir été modifié par ce changement océanographique physique. Ce mécanisme régi par la climatologie, qui affiche une asymétrie spatiale est-ouest caractéristique, pourrait peut-être aider à expliquer les changements dans la qualité du poisson fourrage dans la diversité du régime alimentaire des lions de mer de Steller dont les populations ont abruptement décliné depuis le milieu des années 1970 dans l'ouest du golfe alors qu'elles restaient stables dans l'est du golfe.*

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## 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 north-westward along the eastern shelf-slope boundary, and the Alaskan Stream, which runs south-westward along the western shelf-slope boundary, both support an energetic open-ocean mesoscale cir-

ulation (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, 1981), 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

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open-ocean nutrient rich waters and shelf waters that contain iron (Okkonen et al., 2003; Stabeno et al., 2004; Strom, personal communication, 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 favoured over others. Indeed, one theory for the decline of the Steller sea lion populations in the western GoA in recent decades is that the diversity of their diets changed from being dominated by fatty fish (herring) to lean fish (pollock), which may have adversely affected their metabolism (Trites and Donnelly, 2003).

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 1970s and 1980s using available hydrographic data. But local timeseries 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 regarding the Steller sea lion decline. The first is the temporal issue, in that the western populations, living in and around Prince William Sound through the Aleutian Island chain, declined precipitously after the 1976–77 climate shift. Was this coincident 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 south-eastern 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 the 1976–77 climate shift? We address these questions in targeted numerical experiments in which we analyse 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 50°N with all straits through the Aleutian Islands closed. The topography is a smoothed version of the Smith and Sandwell (1997) dataset (Fig. 1). The horizontal resolution is approximately 0.25° longitude and 0.17° latitude, corresponding to approximately 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 the highest resolution in the upper 100 m. Vertical mixing is via the K profile parameterization (Large et al., 1994). Bottom drag is also included.

ROMS is configured with essentially the same subgrid-scale parameters that were used by Di Lorenzo et al. (2005) in successfully modelling the mechanism for generating the Haida eddy in the eastern GoA.

Open boundary conditions along the southern and south-western 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 freshwater fluxes are modelled 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 ten years. The model is then forced over the 1951–99 time period by monthly-mean wind stresses taken from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis. 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 expected to be 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 (Cummins and Mysak, 1988; 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 Fig. 2. EOF1 exhibits a sharp decadal-scale change in the late 1970s consistent with the 1976–77 climate shift of sea level pressure. Lagerloef (1995) also identified this pattern of variability, although it occurred as the second EOF in his analysis of the Comprehensive Ocean-Atmosphere Data Set (COADS) winds. It was also the dominant post-shift pattern found by Capotondi et al. (2005) who noted that it represents a weakening of the mean upwelling pattern of wind stress curl forcing in the north-eastern GoA, and strengthening to the south-west. EOF2 does not exhibit decadal-scale changes. Both EOFs contain substantial inter-annual variability, which may obscure signals on decadal timescales.

## 3 Results

The model develops a mean circulation consistent with previous observational analyses (e.g., Reed, 1984), exhibiting a strong Alaskan Stream along the western boundary and an Alaska Current along the eastern boundary (Fig. 3a). The circulation also exhibits energetic current variability in general agreement with observations (e.g., Reed and Schumacher, 1984; Thomson and Gower, 1998; Stabeno et al., 2004) and previous modelling studies (e.g., Cummins and Mysak, 1988). This variability is primarily associated with a mesoscale eddy field concentrated around the regions of strong currents where model eddies develop as meanders of the Alaskan Stream and Alaska Current, which are then advected by background mean currents or propagate westward into the interior (Fig. 3a). The model eddies have spatial and temporal scales comparable to those observed by satellite

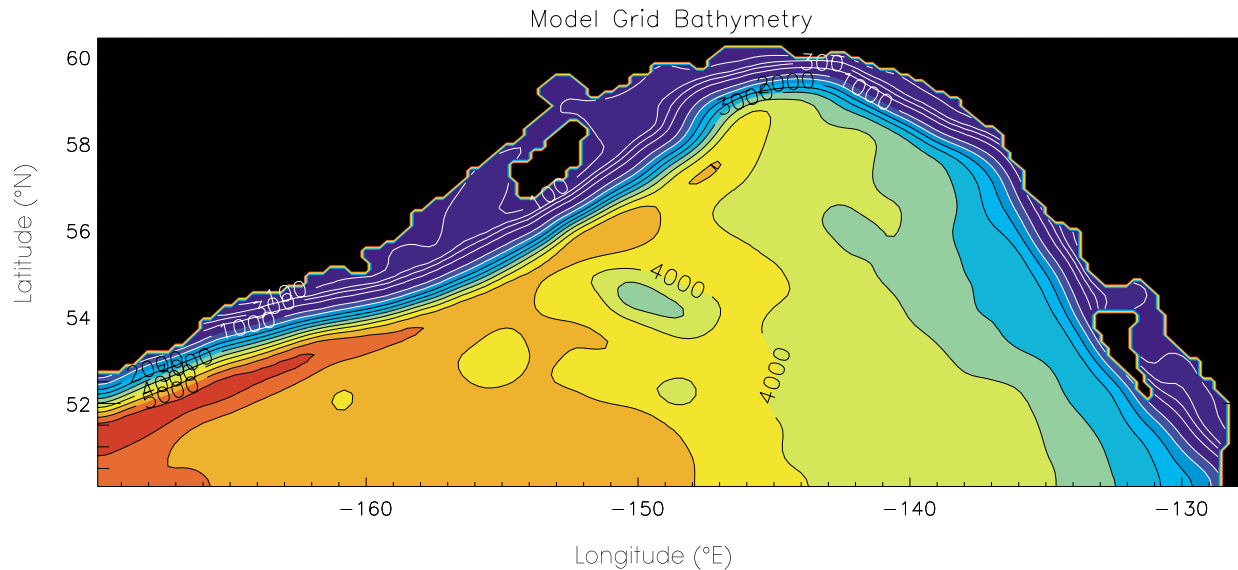


Fig. 1 Bathymetry of the ocean model. Contour interval is 500 m, except for additional contours at 100 m, 200 m, and 300 m.

altimeters (Fig. 3b). Transient wind forcing also plays a role in the current variability by producing additional anomalies with broader spatial scale than those generated by instability processes.

The analysis of the model hindcasts focuses on horizontal surface velocity fields since these are the most sensitive indicators 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 Fig. 2 and allowing for a two-year adjustment timescale after the shift (Deser et al., 1999). The results are not sensitive to the exact choice of epoch dates.

Figure 4 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 south-westward along the western shelf-slope boundary of the domain. The Alaska Current is also evident before and after the shift, flowing north-westward along the eastern shelf-slope boundary of the GoA. After the shift, however, the Alaskan Stream is strengthened considerably in the north-west part of the GoA (north of 56°N) and weakened in the south-western domain (south of 55°N). The strengthening is so intense in the north-west basin that what appears to be an eddy-driven inertial recirculation occurs south-eastwards of the Alaskan Stream. This surface countercurrent is probably unrealistically large, although moderate countercurrents have been noted previously in several observational studies (Reed, 1984; Royer and Emery, 1987; Bograd et al., 1999). The strength of this model countercurrent is likely to be controlled by the magnitude and form of the lateral and bottom frictional parametrizations invoked in the simulations (Shchepetkin and McWilliams, 1998; Marchesiello et al. 2003; Hermann and Stabeno, 1996). Assessing this sensitivity will require further study, but is not vital to the basic results found in this paper.

This increase in the strength of the Alaskan Stream after the climate shift is not consistent with a simple “time-dependent Sverdrup” response to the altered Ekman pumping pattern associated with the wind stress-curl structure of Fig. 2b. Integrating the Ekman pumping from the eastern boundary of the Gulf to the western boundary results in a streamfunction pattern that predicts a weakening of the Stream. An early attempt by Reed et al. (1980) to apply this simple theory to observed interannual changes in transport of the Alaskan Stream also failed. This failure 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 winds as previously shown by Lagerloef (1995) and Cummins and Lagerloef (2002) when modelling observations of dynamic height and pycnocline depth in the Gulf, and by Capotondi et al. (2005) when diagnosing a coarse resolution primitive equation model of the GoA. Instead, a local, static ‘thermocline heave’ response to the Ekman pumping pattern of Fig. 2b sets up a broad-scale tilt in the pycnocline. North-westward geostrophic flow that impinges on the western boundary is associated with this large-scale pycnocline gradient which drives the increase (not decrease) in the Alaskan Stream (Capotondi et al., 2005).

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 distribution of the mesoscale eddy variance. Figure 5 shows the variance of monthly-mean anomalous surface currents for the two epochs along with the difference in variance after the climate shift. Before the shift, mesoscale eddy variance is highest south-east of Kodiak Island and along the Alaskan Stream to the south-west of Kodiak. After the shift, mesoscale eddy variance increases sharply in the north-western GoA and decreases precipitously to the south and west of Kodiak Island.

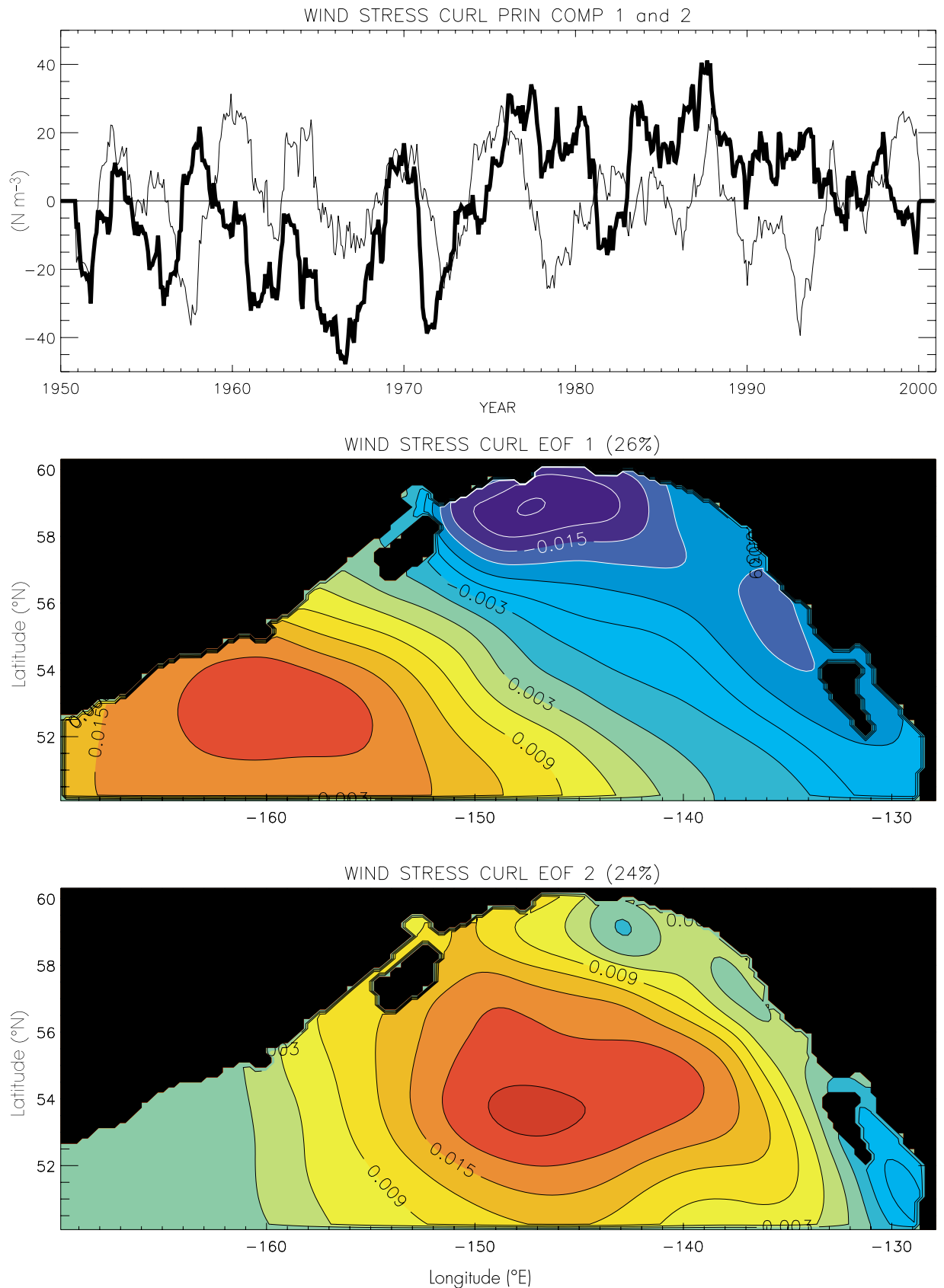


Fig. 2 Principal components (top) of the first (thick) and second (thin) empirical orthogonal functions of the wind stress curl over the 1951–99 period from the NCEP/NCAR reanalysis. After computing the EOFs from monthly mean fields, the PCs were smoothed with a 2-year running mean filter. EOF1 (middle) and EOF2 (bottom) of the wind stress curl, explain 26% and 24% of the monthly mean variance, respectively. Values are scaled by  $10^{10}$ .

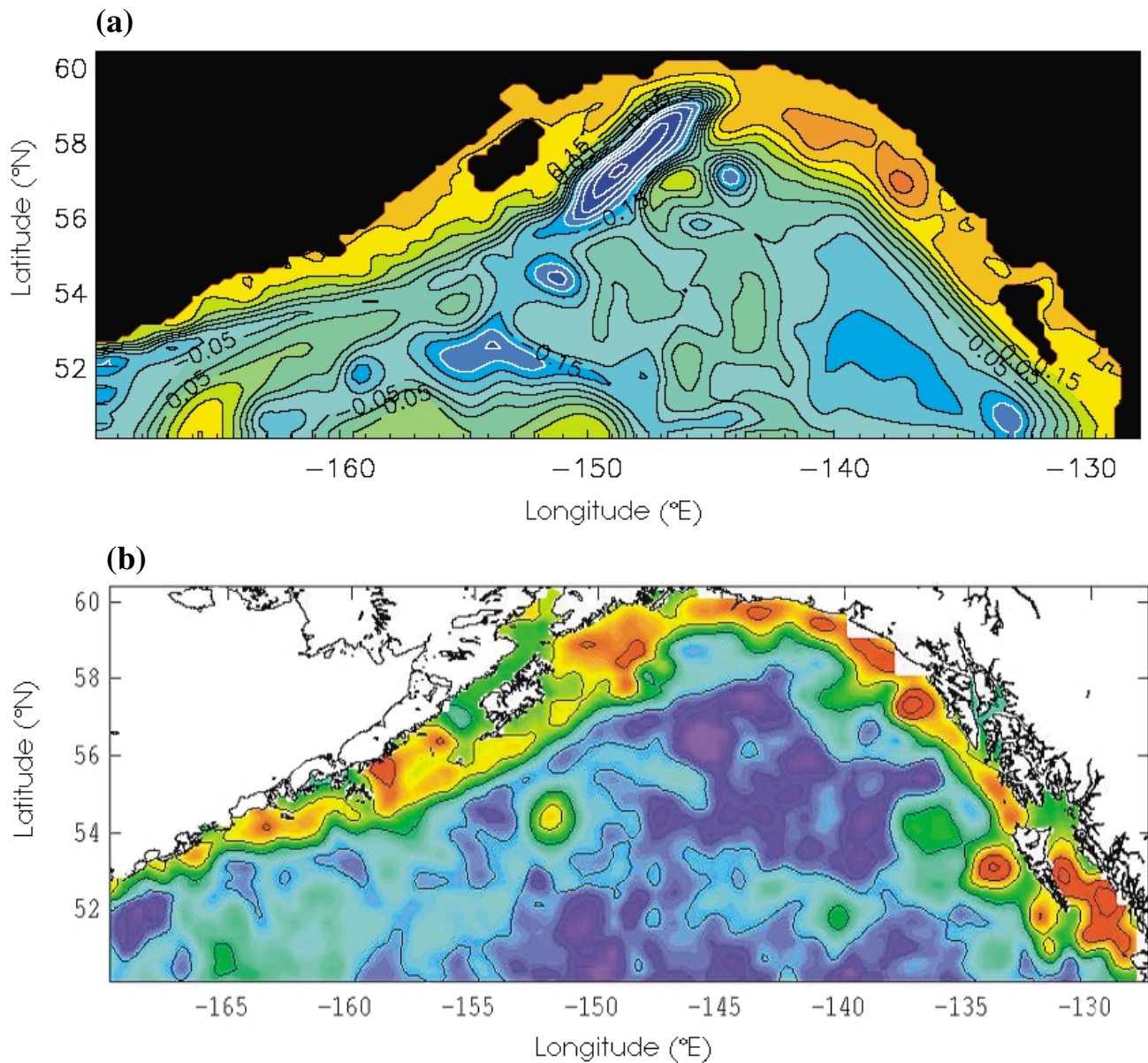


Fig. 3 (a) Instantaneous map of model sea level during the late 1970s showing the typical spatial scales of mesoscale variability that develop as meanders of strong currents of the Alaskan Stream and the Alaska Current. CI = 5 cm (b) Map of TOPEX/ERS observed sea level during the late 1990s showing its comparability in spatial scale to model sea level eddies. CI = 5 cm.

The bulk of the variability in the surface currents is not due to direct atmospheric forcing, but rather to flow instabilities. To demonstrate this, we executed two additional model runs with only seasonal cycle winds. One was forced for ten years with monthly-mean seasonal cycle winds based on the 1971–76 (six-year) average. The other was forced for ten years by the 1977–82 average. The averaged mean currents and velocity anomaly variance plots of these two runs are very similar to Figs 4 and 5, respectively, except for a basin-wide increase in variance in the anomalous-wind forced runs. It is clear that the distribution of velocity variance along the western boundary is controlled by the eddies, not by the anomalous winds. The mean flows of the Alaska Current in the eastern GoA (Fig. 4), in contrast, are nearly unchanged after the shift. Likewise, the anom-

alous surface velocity variance is only weakly altered, being reduced slightly compared to pre-shift conditions (Fig. 5). 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 GoA that exhibit an east–west spatial asymmetry after the 1976–77 climate shift. The increase in the strength of the Aleutian Low drives a more energetic Alaskan Stream and eddy circulation in the north-west GoA and a weaker circulation in the south-west GoA. In the eastern GoA, in contrast, the Alaska Current and

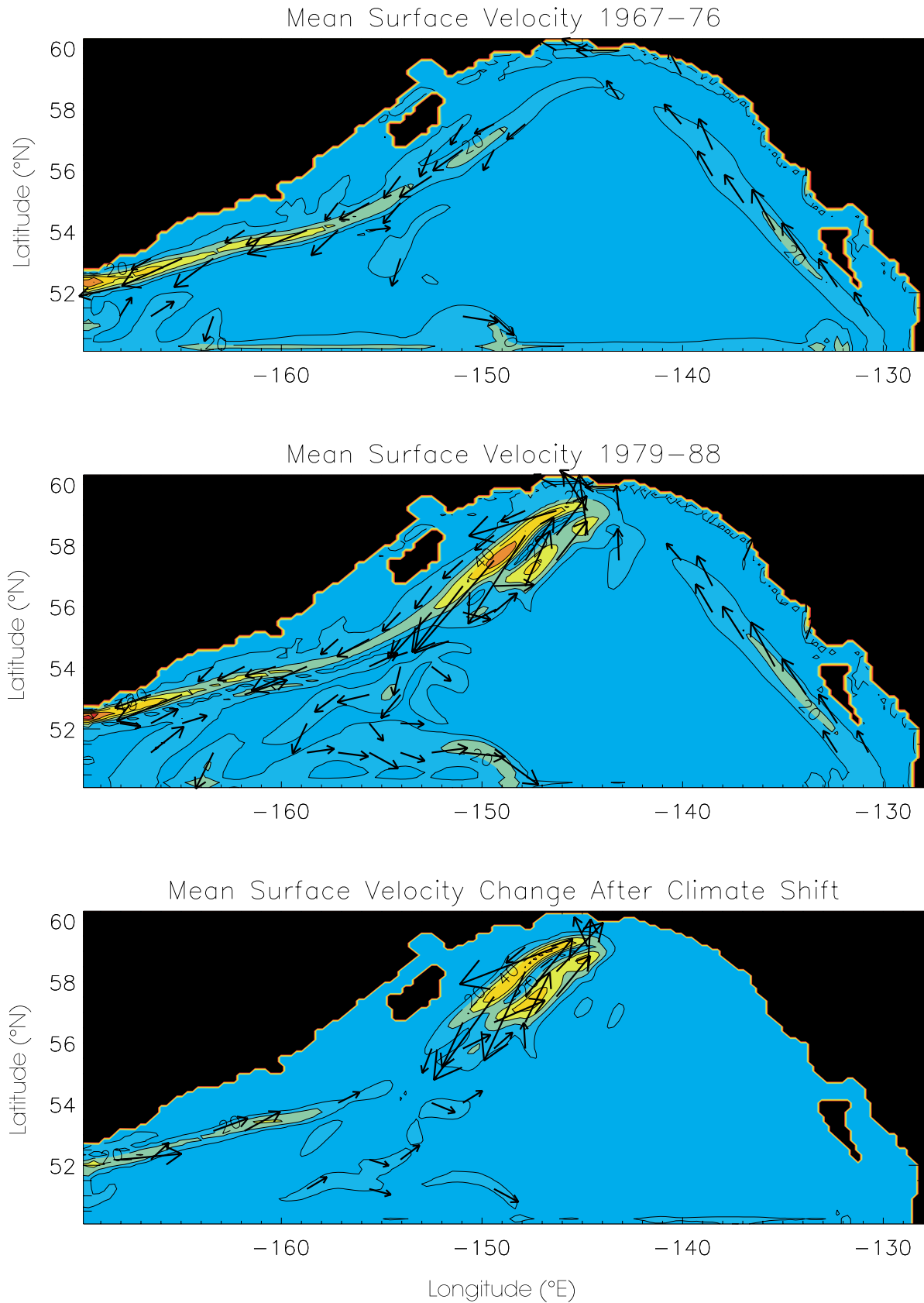


Fig. 4 Mean surface currents for the 10-year epochs 1967–76 (top) and 1979–88 (middle), and the difference between the two epochs (bottom). Currents less than  $5 \text{ cm s}^{-1}$  do not receive a vector, and only every sixth grid point receives an arrow. Magnitude of the current is contoured at  $10 \text{ cm s}^{-1}$  intervals.

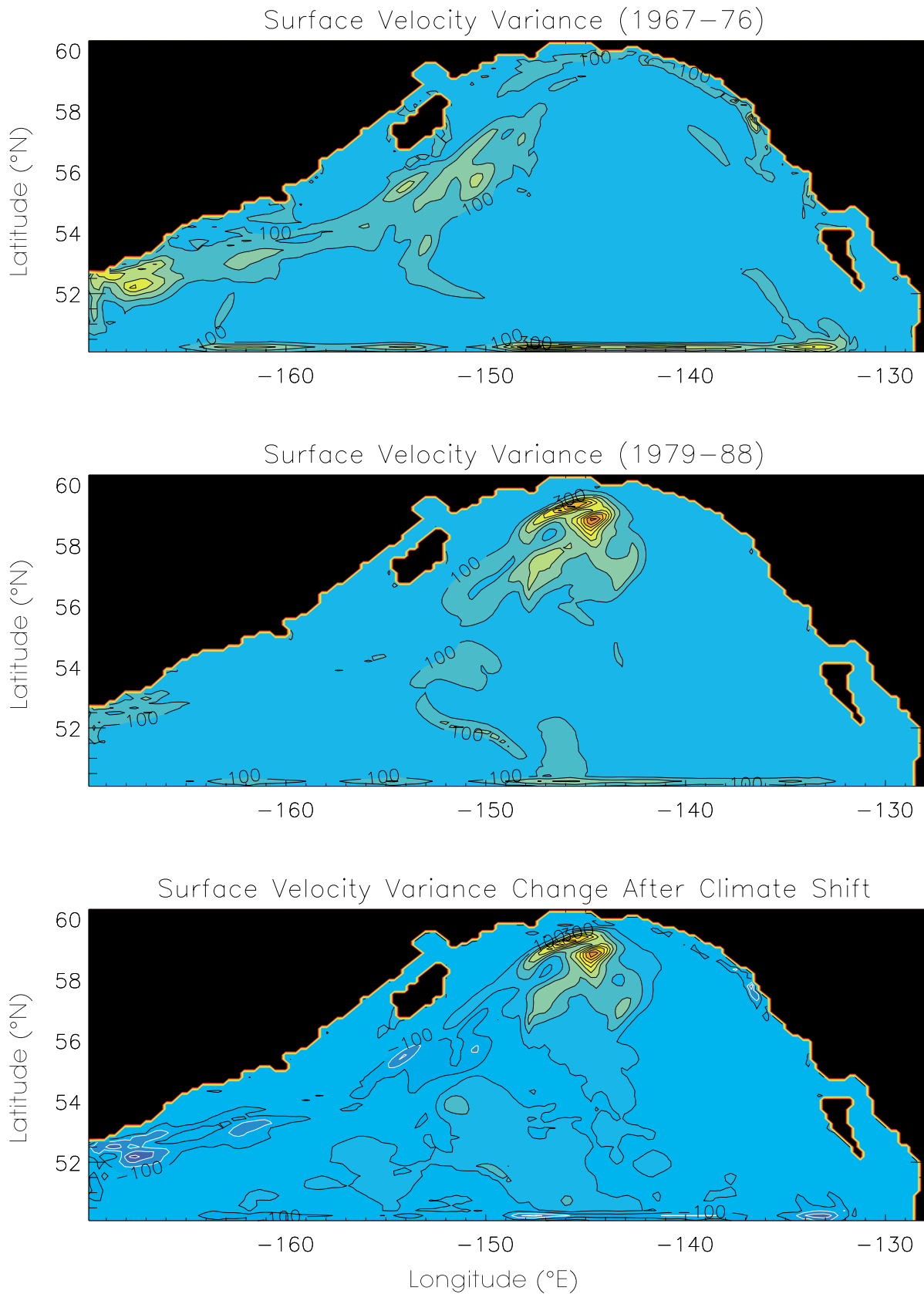


Fig. 5 Variance of the anomalous monthly mean surface currents for the 10-year epochs 1967–76 (top) and 1979–88 (middle), and the difference between the two epochs (bottom). Anomalies are defined with respect to the monthly mean seasonal cycle of the respective 10-year epoch. Variance of the current is contoured at  $100 \text{ cm}^2 \text{ s}^{-2}$  intervals.

its associated eddy field remain relatively unchanged after the shift.

These novel results offer a possible explanation for the mechanisms 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 1970s yet remained stable in the eastern GoA (Benson and Trites, 2002). The mesoscale eddy fields that develop as meanders of the Alaskan Stream can mix open-ocean waters, which tend to be rich in basic nutrients such as nitrate, with near-coastal waters, which tend to include the limiting nutrient iron (Strom, personal communication, 2004). If the distribution and amount of cross-shelf 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). Other effects of the altered physical system on the ecosystem could include changes in advection of larvae, prey or predators by horizontal currents and changes in open-ocean Ekman pumping and coastal upwelling that affect nutrient availability. Detailed hindcast simulation of the ecosystem response (e.g., Haigh et al., 2001; Chai et al., 2003) will be required to sort out all these possible effects.

While these modelling 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 modelling results (Stabeno and Hermann, 1996). However, Lagerloef (1995) estimated dynamic height from CTD and XBT data acquired from 1968–90 and found a preponderance of low (high) dynamic height in the 1970s (1980s) across the north-eastern GoA (see his Fig. 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. (2005) that show thermocline deepening (increased dynamic height) across the north-eastern GoA after the climate shift. While Lagerloef (1995) suggested that the Alaskan Stream weakened north of 55°N after the shift, we are presently reassessing his data analysis procedure. Sparseness of data in the coastal regions may have inadvertently allowed the objective analysis contours to close around broad-scale open-ocean features, forming spurious boundary layers that turn the presumptive boundary flows in the wrong direction. Mass-conserving and dynamically consistent coarse resolution models (Capotondi et al., 2005; Miller et al., 1994b) also give additional dynamical support for an increase in strength of the Alaskan Stream after the shift.

The occurrence of a mean surface north-eastward 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 as to

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. Bograd et al. (1999) find a similar indication in their analysis of surface drifters. The countercurrent in the model also clearly follows the topographic contours of the south-eastern slope of the Aleutian trench, which agrees with the observed topographic location of the countercurrent found by Onishi and Otani (1999). A Pacific-wide, but coarser resolution, ROMS run (Shchepetkin, personal communication, 2004) also shows a mean countercurrent following the topographic slopes of the trench, indicating that it is not an artefact of the open-boundary conditions of this regional model. The eddy-driven inertial recirculation in the north-west GoA after the shift is likely to be stronger than observed, which is 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 (Cummins and Mysak, 1988), so our contention that wind stress will largely control the circulation changes after the shift is likely correct. However, the results will then be dependent on the quality of the NCEP wind product, which appears to be good in regions away from the coast (Ladd and Bond, 2002; Auad et al., 2001). Downscaling the NCEP coastal winds would be useful because they may excite coastally trapped disturbances (e.g., Kelvin waves, shelf waves) that can affect the stability properties of the mean currents and consequent eddy field (Melsom et al., 1999).

In addition, several other forcing effects were not considered in this simulation. Firstly, no long-term changes to the open-ocean radiation/relaxation boundary conditions were allowed along the southern boundaries or along the numerous straits in the Aleutian Island chain that were closed in the model framework. 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 driven by tropically forced oceanic and atmospheric teleconnections (Strub and James, 2002; Melsom et al., 1999, 2003). This remote oceanic forcing could be especially important in generating long-term changes in the Alaska Current and its associated eddy field, which exhibited no significant interdecadal changes in the present simulations. Secondly, 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, 1981). 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 16 km, which is good compared to coarse resolution



models but only comparable to the internal deformation radius in the GoA, which ranges from 16–18 km in the open ocean GoA (Chelton et al., 1998) to 10 km over some shelf regions. Higher resolution models that test the sensitivity of solutions to changes in frictional parametrizations, topographic smoothing, inflow conditions, radiation boundary conditions and surface forcing need to be examined to determine the robustness of our results.

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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