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Interannual variability of the Gulf of Alaska eddy field

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[1] Regions of high eddy kinetic energy (EKE) in the Gulf of Alaska (GOA), calculated from altimetry data, denote formation regions and translation pathways for eddies. High EKE is observed along the shelf break in winter and spring with lower values in summer and autumn. Three regions of high EKE are examined in detail. In the eastern GOA, particularly high EKE occurred in 1998. In the northwestern GOA, eddies were observed quasi-annually between 1999 and 2004, but were less frequent prior to that time (or in 2005 and 2006). Eddies northeast of Kodiak Island have been implicated in high offshelf chlorophyll concentrations observed from ocean color satellites. Correlations between EKE and chlorophyll concentration are significant there suggesting that EKE may be valuable for predicting phytoplankton blooms in this region. **Citation:** Ladd, C. (2007), Interannual variability of the Gulf of Alaska eddy field, *Geophys. Res. Lett.*, *34*, L11605, doi:10.1029/2007GL029478.

1. Introduction

[2] Gulf of Alaska (GOA) eddies originate in three formation regions. Yakutat eddies are formed off the relatively wide (~100 km) shelf south of Yakutat, Alaska (Figure 1) and translate around the GOA staying close to the shelf break [*Gower*, 1989; *Gower and Tabata*, 1993; *Ladd et al.*, 2005]. Sitka eddies are formed farther south, off the narrower (~25 km) shelf near Sitka, Alaska [*Tabata*, 1982]. Sitka eddies follow one of two paths, either along the shelf break like Yakutat eddies, or westward into the basin [*Crawford et al.*, 2000; *Ladd et al.*, 2005, 2007]. Haida eddies form off the southern tip of the Queen Charlotte Islands from the outflow from Hecate Strait [*Crawford*, 2002; *Crawford et al.*, 2002; *Di Lorenzo et al.*, 2005]. Haida eddies typically move westward. All of these eddies exhibit anticyclonic rotation and diameters of approximately 200 km.

[3] GOA eddies influence the biology of the region from phytoplankton [*Brickley and Thomas*, 2004; *Crawford et al.*, 2005; *Okkonen et al.*, 2003] to zooplankton [*Batten and Crawford*, 2005; *Mackas and Galbraith*, 2002; *Mackas et al.*, 2005] to upper trophic levels [*Ream et al.*, 2005]. Thus, investigating variability in the mesoscale physical system has implications for understanding variability in the ecosystem.

[4] Many mechanisms can contribute to the influence of eddies on phytoplankton distributions. In early spring, the shelf-derived eddy core waters contain plentiful macronutrients and iron [*Johnson et al.*, 2005]. Later in the spring and summer, drawdown of macronutrients has been observed in the GOA [*Chierici et al.*, 2005; *Johnson et al.*, 2005; *Whitney et al.*, 2005]. In the fall, storms can mix iron and macronutrients to the surface from deeper eddy core waters [*Crawford and Whitney*, 1999; *Johnson et al.*, 2005]. Fall storms can also remove surface water from eddies, removing kinetic energy in the process. To spin up new surface water, potential energy is converted to kinetic energy, requiring relaxation of the suppressed isopycnals and moving nutrients upward in the water column [*Mackas et al.*, 2005]. Fall storms can also vertically redistribute phytoplankton in the water column resulting in an apparent increase in chlorophyll observed by satellite (W. R. Crawford et al., Eddy transport into a cyclonic gyre: An example in the Gulf of Alaska, submitted to *Progress in Oceanography*, 2007, hereinafter referred to as Crawford et al., submitted manuscript, 2007).

[5] Sea level anomalies (SLA) from satellite altimeters can be used to identify and track eddies [e.g., *Matthews et al.*, 1992; *Meyers and Basu*, 1999]. In this paper, we use over a decade of high quality altimetry data to investigate eddy variability in the GOA. In addition, nine years of SeaWiFS chlorophyll concentration data allow an analysis of the influence of eddies on chlorophyll distributions.

2. Data and Methods

[6] The "ref merged SLA" data set (available at http://www.jason.oceanobs.com) consists of merged data from two satellite missions, Topex/Poseidon and ERS, followed by Jason-1 and Envisat. This data set has stable sampling in time [*Collecte Localisation Satellites*, 2006]. The mapped altimetry data set includes one map every 7 days with a 1/3° spatial resolution on a Mercator grid [*Ducet et al.*, 2000; *Le Traon and Dibarboure*, 1999].

[7] Eddy kinetic energy (EKE) calculated from SLA can be used as a measure of mesoscale variability. Assuming geostrophy, the EKE (per unit mass) is estimated from the SLA data η' as:

$$EKE = \frac{1}{2}\left[\langle U_g'^2\rangle + \langle V_g'^2\rangle\right],$$

$$U_g' = -\frac{g}{f}\frac{\Delta\eta'}{\Delta y},\ V_g' = \frac{g}{f}\frac{\Delta\eta'}{\Delta x},$$

where U_g' and V_g' are the geostrophic velocity anomalies, f is the Coriolis parameter, and $\langle\ \rangle$ denotes the time average [*Ducet et al.*, 2000].

[8] SeaWiFS monthly time series of chlorophyll concentration were obtained from the Ocean Biology Processing

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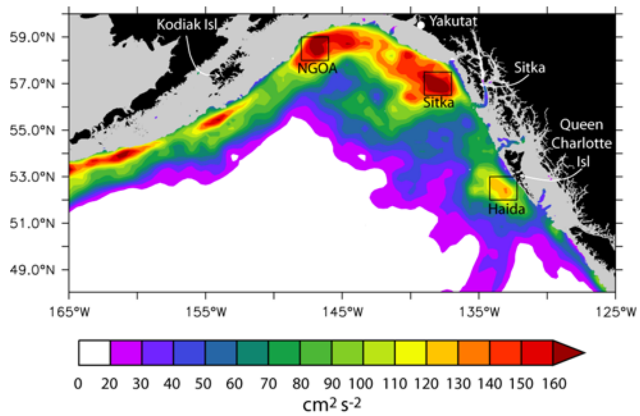

Figure 1. Mean EKE (cm^2 s^{-2}). Gray region is shelf (<300 m depth).

Group (OBPG; available at http://reason.gsfc.nasa.gov/OPS/Giovanni/ocean.seawifs.shtml).

3. Results

3.1. Eddy Kinetic Energy

[9] The mean EKE in the GOA shows high values around the boundaries associated with the Alaska Current and the Alaskan Stream, the eastern and western boundary currents of the eastern subarctic gyre, respectively (Figure 1). High EKE associated with the Alaskan Stream on the western side of the basin is tightly confined to the shelf break while that on the eastern side of the basin shows tongues of high EKE extending westward into the basin. This study focuses on three regions (Figure 1) of relatively high EKE: the Haida region (134.2–132.2°W, 52–53°N), the Sitka region (139–137°W, 56.5–57.5°N), and the region northeast of Kodiak Island which we will call the Northern GOA (or NGOA) region (148–146°W, 58–59°N). Note that the Sitka and Haida regions are eddy formation regions while the NGOA region is a region through which eddies formed in the eastern GOA travel. Thus high EKE in the Sitka and Haida regions generally implies strong eddy formation. High EKE in the NGOA region may be due to strong eddy formation in the eastern GOA or it may be due to a change in translation pathways.

[10] A local maximum EKE >200 cm^2 s^{-2} near 57°N, 138°W denotes the region of Sitka eddy formation first described by *Tabata* [1982]. A tongue of high EKE extends southwest from this region. A continuous band of moderately high EKE values (>120 cm^2 s^{-2}) extends from the Sitka eddy formation region northwestward along the shelf-break to the NGOA region where another region of high EKE (>180 cm^2 s^{-2}) occurs. Eddies in the NGOA region originate as either Sitka eddies following the northwestward path or as Yakutat eddies [*Ladd et al.*, 2005].

[11] Mean EKE >130 cm^2 s^{-2} at the south end of the Queen Charlotte Islands denotes the formation region for the Haida eddy [*Crawford et al.*, 2002]. Tongues of high EKE extend from this region northwestward and southwestward into the basin. These two pathways are consistent with pathways previously observed for Haida eddies [*Whitney and Robert*, 2002]. A region of low EKE (<100 cm^2 s^{-2}) separates the Haida region from the Sitka region, suggesting that Haida eddies do not regularly move along the shelf break past the north end of the Queen Charlotte Islands.

[12] In all three regions, the climatological annual cycle calculated from the altimetry record is maximum in March and minimum in November (Figure 2). Maximum coastal downwelling occurs in December/January (Upwelling index, 2003, Pacific Fisheries Environmental Laboratory, Pacific Grove, Calif., available at http://www.pfeg.noaa.gov/products/PFEL/modeled/indices/upwelling/NA/data_download.html). Thus, maximum EKE occurs as the downwelling winds start to weaken. The strong downwelling favorable winds during December/January drive a coastal current flowing toward the northwest with associated cross-shelf density gradient and storage of potential energy. As the downwelling favorable winds weaken, periods of upwelling favorable winds become more likely. These wind events allow the potential energy of the coastal current to be transferred to kinetic energy of baroclinic instabilities. This

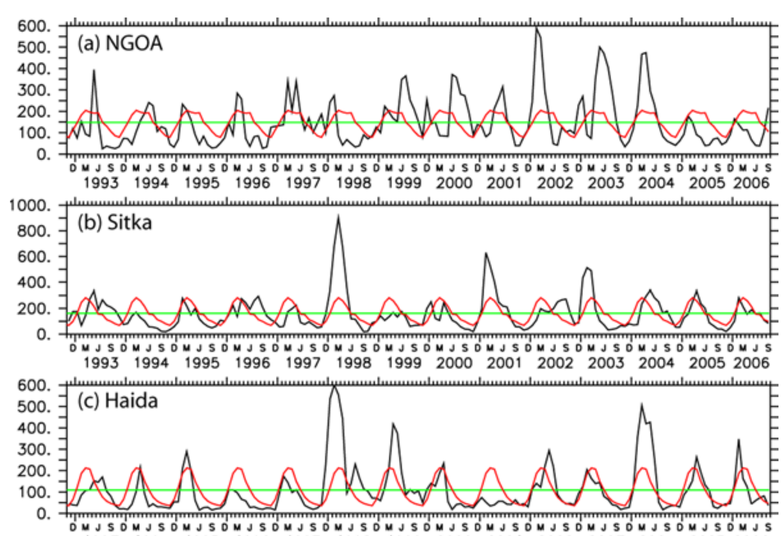

Figure 2. Time series of monthly averaged (black), monthly climatological (red), and mean (green) EKE (cm^2 s^{-2}) averaged over the three boxes shown in Figure 1. (a) NGOA, (b) Sitka, and (c) Haida.

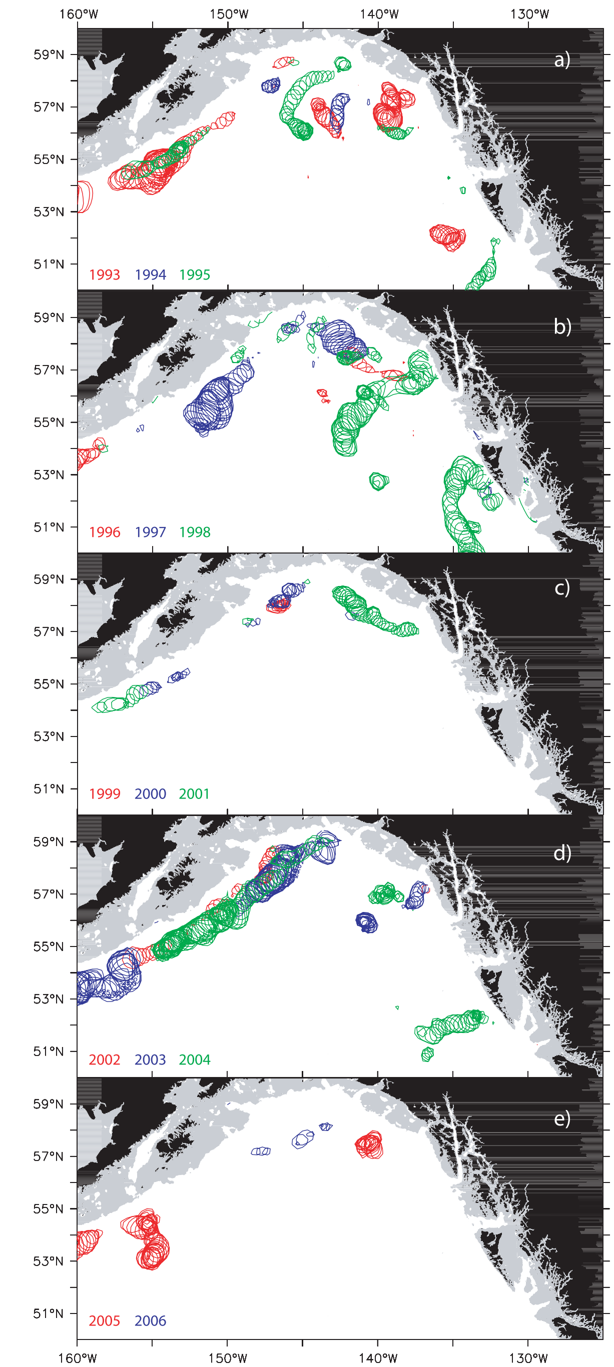

Figure 3. (a–e) Contours of 25 cm SLA colored by the years indicated. The year 2006 includes data through May.

mechanism was invoked as the formation mechanism for a train of eddies observed along the eastern GOA in March 1995 [*Thomson and Gower*, 1998]. Other mechanisms are also likely to contribute to eddy formation in the GOA.

[13] The highest EKE in the Sitka and Haida regions occurred in early 1998 (Figure 2). The strongest (over almost 60 years) winter coastal downwelling index at 57°N, 137°W also occurred in winter 1998 (Upwelling index, Pacific Fisheries Environmental Laboratory, Pacific Grove, Calif., available at http://www.pfeg.noaa.gov/products/PFEL/modeled/indices/upwelling/NA/data_download.html). Formation of the strong 1998 eddies has been attributed to the influence of the 1997/98 El Niño [*Crawford et al.*, 2002; *Melsom et al.*, 1999], although the relative influence of oceanic versus atmospheric teleconnections is unclear. EKE was also particularly high in March 2001 in the Sitka region, another year with anomalously strong winter downwelling. In the Haida region, high EKE was also observed in 1999 and 2004, a La Niña year and a weak El Niño year respectively.

[14] In the NGOA region (an eddy transit region, not a formation region), EKE was higher during the years 1999–2004. In 1993–1998, annually averaged EKE anomaly in the NGOA region was negative in 5 out of 6 years while in 1999–2004, the anomaly was positive in 5 out of 6 years. The cyclonic circulation of the Alaska gyre intensified around 1999, with an increase in geostrophic velocities in the Alaskan Current of $\sim$2 cm s^{-1} [*Volkov and van Aken*, 2005]. The translation of eddies is determined by a combination of planetary wave dynamics (β effect), topographic Rossby wave dynamics, and advection. Eddies would tend to move westward due to the β effect, while both topographic Rossby wave dynamics and the mean current would tend to move Sitka eddies toward the northwest along the shelf-break. Because Sitka eddies exhibit both paths, the relative strength of the forces toward the west versus toward the northwest are likely similar. Thus, an increase in current velocities in 1999 may have been enough to allow the northwestward path to dominate, allowing more Sitka eddies to reach the NGOA region.

[15] The location of major eddies and their pathways are shown by the 25 cm SLA contours (Figure 3). By showing only eddies with SLA larger than 25 cm, many smaller eddies are missed and some eddies appear and disappear as their magnitude becomes less than the threshold. However, the 25 cm threshold presents a clean picture of eddies and their pathways.

[16] Prior to 1999, many eddies were observed in the center of the GOA north of $\sim$55°N (Figures 3a and 3b). The large, long-lived 1998 Sitka and Haida eddies are particularly notable for their southward paths (Figure 3b). After 1999, most of the eddies remained close to the shelf break with very little activity in the central gulf. Between 2001 and 2004, the eddy activity along the western boundary was particularly strong and consistent.

3.2. Chlorophyll

[17] To evaluate the influence of eddies on interannual variability of chlorophyll, we calculated correlations between monthly averaged chlorophyll and monthly averaged EKE, both averaged over the same three regions. In all three regions, chlorophyll is maximum in May (spring bloom) with a secondary maximum in September (fall bloom).

[18] In the NGOA region, significant correlations were found between EKE and chlorophyll in March, September, and October, using 9 years of data (Table 1). Lagged correlations, with February EKE leading March chlorophyll and September EKE leading October chlorophyll, were also significant. Correlations for all other months were insignificant. These correlations suggest that eddies have an influence on chlorophyll early in the spring and in the fall in the NGOA region (as has been noted for individual eddies;

Table 1. Correlations Between Monthly Average EKE and Chlorophyll Averaged Over the NGOA Region for the Years 1998–2006[a]

	Non-Lagged	EKE Leads by 1 Month
Feb	0.49	−0.09
Mar	**0.60**	**0.75**
Apr	−0.27	−0.01
May	−0.04	0.15
Jun	0.50	0.21
Jul	−0.11	0.05
Aug	−0.16	−0.23
Sep	**0.86**	0.26
Oct	**0.84**	**0.65**

[a]Bold implies significant correlations (at 95%).

[*Ladd et al.*, 2005; Crawford et al., submitted manuscript, 2007]). The success of lagged correlations suggests predictability. In the NGOA region, February near-real-time SLA data could predict March chlorophyll, with potential implications for success of higher trophic levels.

[19] In the Sitka region, no months exhibited significant correlations between EKE and chlorophyll. In the Haida region, only June showed a significant correlation (0.75). Thus EKE in the eastern GOA may not be as useful a predictor of chlorophyll.

4. Summary

[20] High EKE near the shelf break of the GOA corresponds to eddy formation and transit regions. In the NGOA eddy transit region, EKE changed from a low energy state prior to 1999 to a high energy state between 1999 and 2004. This may have been due to an intensification of the Alaska Gyre [*Volkov and van Aken*, 2005] that occurred around 1999, changing the translation pathways of eddies formed in the eastern GOA. The change in gyre intensity may have been related to a climate shift that occurred in 1998/1999 [*Peterson and Schwing*, 2003].

[21] In the two eastern GOA regions, interannual variability was dominated by a few particularly high years that may have been related to El Niño. Similar east-west asymmetry, where the eddy field in the western GOA became stronger after the 1976/77 climate shift while that in the eastern GOA remained unchanged was suggested by a circulation model [*Miller et al.*, 2005].

[22] Correlations between monthly EKE and chlorophyll were significant for March, September, and October in the NGOA region and June in the Haida region. No significant correlations were found in the Sitka region (using monthly averages). Because chlorophyll is low in March (high chlorophyll associated with the spring bloom typically occurs in May), the spring correlations may not be reliable. However, the significant correlation may imply that eddies can induce an earlier start to the spring bloom.

[23] Because SeaWiFS data are available only after 1997, it is difficult to determine whether changes in EKE around 1999 caused multi-annual changes in chlorophyll distributions. Significant lagged correlations, with EKE leading chlorophyll by 1 month, suggest that EKE may be a valuable index for predicting chlorophyll concentrations in the spring and fall in the NGOA region. Longer datasets and further research are required but the link between EKE and chlorophyll could be exploited to interpolate ocean color data to fill in data gaps due to clouds.

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