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# Simulated eddy induced vertical velocities in a Gulf of Alaska model

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ABSTRACT

Mesoscale eddies can distribute nutrients, heat and fresh water into the Gulf of Alaska (GOA) from the coastal margins. While many studies have investigated the physical characteristics of GOA eddies, their effects on passive-dispersive particles have not been previously simulated to investigate eddy induced upwelling. A climatologically forced Parallel Ocean Program simulation of the north Pacific Ocean with an online particle tracking scheme was used to simulate passive-dispersive particles in the Gulf of Alaska. In-eddy vertical Lagrangian velocities of the particles were calculated both inside and outside the eddies and showed upwelling rates are generally greater inside the eddies where the vertical velocities of the particles ranged from 0.2 to 0.7 m/day.



## 1. Introduction

Anti-cyclonic Gulf of Alaska (GOA) mesoscale eddies have been observed to form in late winter off southeast Alaska and northern British Columbia (BC), and generally move from east to west into the gulf impacting the circulation and heat and salt budgets over the region.

The circulation in the GOA (Fig. 1a) is dominated by the subpolar Alaskan Gyre which connects the eastward flowing North Pacific Current to the northward flowing Alaska Current along the BC continental margin and then to the southwestward flowing Alaskan Stream running parallel to the Alaskan Peninsula. These currents vary seasonally but average about 10–20 cm/s with the Alaskan Stream being somewhat faster (50–100 cm/s) and narrower than the Alaska and North Pacific currents (e.g. Favorite et al., 1976; Musgrave et al., 1992). The GOA is influenced by the Aleutian Low Pressure system which, through Ekman transport, induces an upwelling rate of less than 0.1 m/day in the middle of the gyre (Gargett, 1991); however, for much of the year the GOA is under the influence of the North Pacific High Pressure system which induces a downwelling state. The Aleutian Low intensifies during the winter months from September through to about May and is then displaced by the North Pacific High.

Fifteen years of satellite altimetry data have been used to identify three primary eddy formation regions in the gulf: the Haida region off the southern tip of Queen Charlotte Islands, the Sitka region, and the Northern GOA (Henson and Thomas, 2008) (Fig. 1a). A fourth formation region is along the Aleutians (Ueno et al., 2009) where mesoscale eddies have been observed translating along the shelf break (Crawford and Whitney, 1999; Crawford et al., 2000, 2007). These observations are consistent with analyses of eddy energy source regions computed from satellite altimetry (Ladd, 2007) and the model simulations used in this study have also produced similar eddy energy maps for the GOA (Shore et al., 2008).

GOA mesoscale eddies that form along the BC coast are generally anti-cyclonic, form annually and have been observed to persist for up to 3 years (e.g. Crawford, 2002; Crawford et al., 2007; Henson and Thomas, 2008). Thomson and Gower (1998) provided a unique snapshot (Fig. 1b) of eddy generation over the entire GOA from AVHRR data showing a line of eddies detaching along the eastern slope of the gulf in late winter. This snapshot of temperature anomaly is computed relative to a linear north–south temperature gradient of 0.4 °C per 100 km (see their paper for a full discussion).

These anti-cyclonic mesoscale features have been observed to be approximately 100–300 km across, larger than the approximate 20 km internal Rossby radius in the region (Chelton et al., 1998), and can extend down into the watercolumn over 1000 m (e.g. Crawford, 2002, 2005). Estimates of their lateral translation have been given to be on the order of 1 cm/s, on the same order as Rossby wave speeds at those latitudes (White, 1985; Yelland and Crawford, 2005; Crawford et al., 2007).

The GOA is a region of particular interest because of its characteristically rich ecosystem and consequently highly productive commercial fisheries. Since the GOA is in a predominantly downwelling state throughout most of the year, it is thought that

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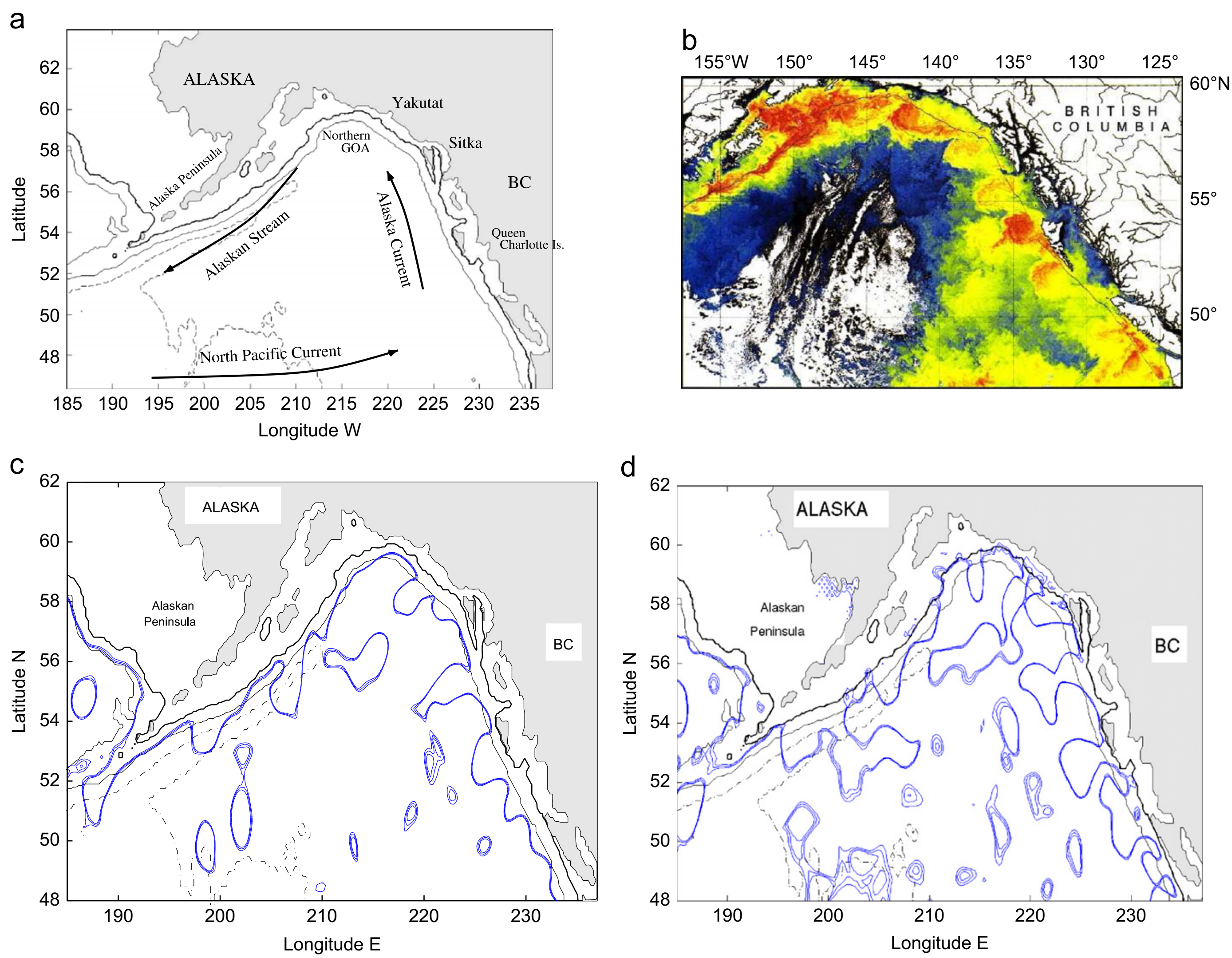


**Fig. 1.** (a) The Gulf of Alaska and major currents forming the Alaska Gyre; (b) satellite-derived, sea-surface temperature anomaly from dark blue (−3 °C) to red (+3 °C) from Thomson and Gower (1998); sea height anomaly (SHA) contours at 3, 4 and 5 cm are shown in blue overlying depth contours at 200 m, 2000 m and 4800 m (solid black lines) for a snapshot when: (c) the 4 cm SHA contour running parallel to the British Columbia coastline has distinctive meanders that have yet to close; (d) the 4 cm SHA contour has almost pinched off a number of mesoscale eddies. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

the eddies are an important mechanism for the distribution of nutrient- and chlorophyll-rich shelf water throughout the gulf, and for the upwelling of cooler, fresher, nutrient-rich water to the surface. Previous studies (Mackas and Galbraith, 2002; Mackas et al., 2005; Crawford et al., 2007) have explored the nature of planktonic communities within these eddies and the correlation of plankton to SHA contours. Crawford et al. (2007) used the 4 cm contour of sea height anomaly (SHA) to identify eddy locations and found that north of 55° in the gulf, more than half of all surface chlorophyll was found within those contours even though they enclosed an area of only 10% of the gulf waters. These studies show that the eddies can and do support planktonic communities in the GOA.

The upward rise of isopycnals as an eddy decays provides a mechanism for in-eddy upwelling (Whitney and Robert, 2002; Johnson et al., 2005; Mackas et al., 2005) and estimates for the upwelling rate have been stated as 0.1 m/day and 0.27 m/day (Johnson et al., 2005). As the anti-cyclonic eddy forms, the isopycnal surfaces are displaced downward so that as the eddy decays and loses kinetic energy these surfaces relax upward to the background state.

Fig. 2 shows a schematic of a decaying anti-cyclonic mesoscale eddy. While the eddy was forming, the internal isopycnals were displaced downward and the sea surface was elevated. During the decay process, divergent surface currents occur while the anomalously elevated surface falls and the isopycnals rise. Surface waters are replaced with nutrient-rich upwelled waters that can also contain non-swimming biota. These eddies continue to spin clockwise through this entire process.

In this paper, simulated passive particles are tracked within a 3-year simulation of the north Pacific Ocean produced using the spectrally nudged Parallel Ocean Program (POP). The spectral nudging data assimilation scheme incorporated into POP allows the model to maintain mean stratification levels over indefinite time periods (thus providing realistic available potential energy which is needed to generate eddies) and as a result, this model can be used to provide novel numerical estimates of eddy-induced upwelling in the GOA.

The intent of this study is to provide vertical velocity estimates from decaying anti-cyclonic (clockwise rotating) eddies in the GOA. Estimates of vertical Lagrangian velocities of the particles from both inside and outside anti-cyclonic eddies are presented