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Gap winds and their effects on regional oceanography Part I: Cross Sound, Alaska

Carol Ladd [a,*], Wei Cheng [b]

[a] Pacific Marine Environmental Laboratory, NOAA, 7600 Sand Point Way, Seattle 98115-6349, WA, USA
[b] Joint Institute for the Study of the Atmosphere and Ocean, University of Washington, 3737 Brooklyn Ave NE, Box 355672, Seattle, WA 98105-5672, USA

A R T I C L E I N F O

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A B S T R A C T

Gap-wind events flowing from Cross Sound in the eastern Gulf of Alaska (GOA) were examined using QuikSCAT wind data. The average duration of an event is 3.6 days with the longest event recorded in the QuikSCAT dataset being 12 days. Daily offshore directed winds with speeds $> 10\ \mathrm{m\,s^{-1}}$ are more common during the winter months (October–March), averaging 20.0 days per year, and less common during the summer (April – September), averaging 2.8 days per year. Interannual variability in the frequency of gap-wind events is correlated with El Niño. During gap-wind events, the spatial scales of high off-shore directed winds ($> 10\ \mathrm{m\,s^{-1}}$) reach almost 200 km off-shore and 225 km along the shelf break, suggesting that the winds directly influence both the shelf (20–65 km wide) and the off-shore waters. A model experiment suggests that a gap-wind event can result in eddy formation and changes in circulation and water properties. Increased entrainment of water from below the mixed layer due to the gap-wind event implies that mixed-layer nitrate concentrations could increase on the order of 5–10 μmole/l, potentially enhancing primary production in the region. An accompanying paper discusses part II of our study (Ladd et al., 2016) focusing on gap-wind events in the western GOA around Kodiak Island.

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1. Introduction

Winter storms in the North Pacific typically form east of Japan and cross the Pacific toward the Gulf of Alaska (GOA) (Rodionov et al., 2007; Rodionov et al., 2005; Wilson and Overland, 1986). The rugged, mountainous coastline of the GOA can interact with these synoptic-scale disturbances, resulting in strong coastal pressure gradients and gale force winds. In addition, the contrast between relatively warm offshore water and cold continental air over Alaska during winter results in strong hydrostatic pressure gradients along the coast (Macklin et al., 1988). The resulting coastal wind field can manifest as barrier jets, gap winds, downslope winds, and interactions between them (i.e. Loescher et al., 2006; Winstead et al., 2006; Young and Winstead, 2004).

Gap winds, defined here as offshore-directed flow channeled through mountain gaps, have been examined in a number of observational and modeling studies, beginning with Reed's (1931) study of strong winds blowing out of the Strait of Juan de Fuca (~54°N, 130°W). Since that time, gap winds have been examined in many regions around the world. In the GOA, Synthetic Aperture Radar (SAR) data have shown strong gap winds in Prince William Sound (Liu et al., 2008), flowing out of Iliamna Lake northeast of Kodiak Island (Ladd et al., 2016; Liu et al., 2006), and flowing out of Cross Sound in southeastern Alaska (Loescher et al., 2006; Winstead et al., 2006). Loescher et al. (2006) examined the climatology of coastal barrier jets in the GOA from SAR images. They divided the wind jets into two categories: classic barrier jets fed by onshore flow and jets fed by gap flow from the continental interior. They found that most of these wind jets occurred during the cool season, with gap-wind jets commonly found at the outflows of Cross Sound, Yakutat Bay, and Icy Bay in the eastern GOA (Fig. 1).

While gap winds and the conditions leading to them have been relatively well-described, their influence on the coastal ocean has been examined in only a few regions. Perhaps the most complete description of gap winds and their influence has been in the northeastern tropical Pacific. The gap winds associated with three mountain gaps in Central America have been shown to influence regional ocean circulation (Kessler, 2006), eddy formation (e.g. McCreary et al., 1989; Trasviña et al., 1995), and chlorophyll-*a* distributions (McClain et al., 2002). Liang et al. (2009) used

* Corresponding author. Tel.: +1 206 526 6024; fax: +1 206 526 6485.
E-mail addresses: carol.ladd@noaa.gov (C. Ladd), wei.cheng@noaa.gov (W. Cheng).

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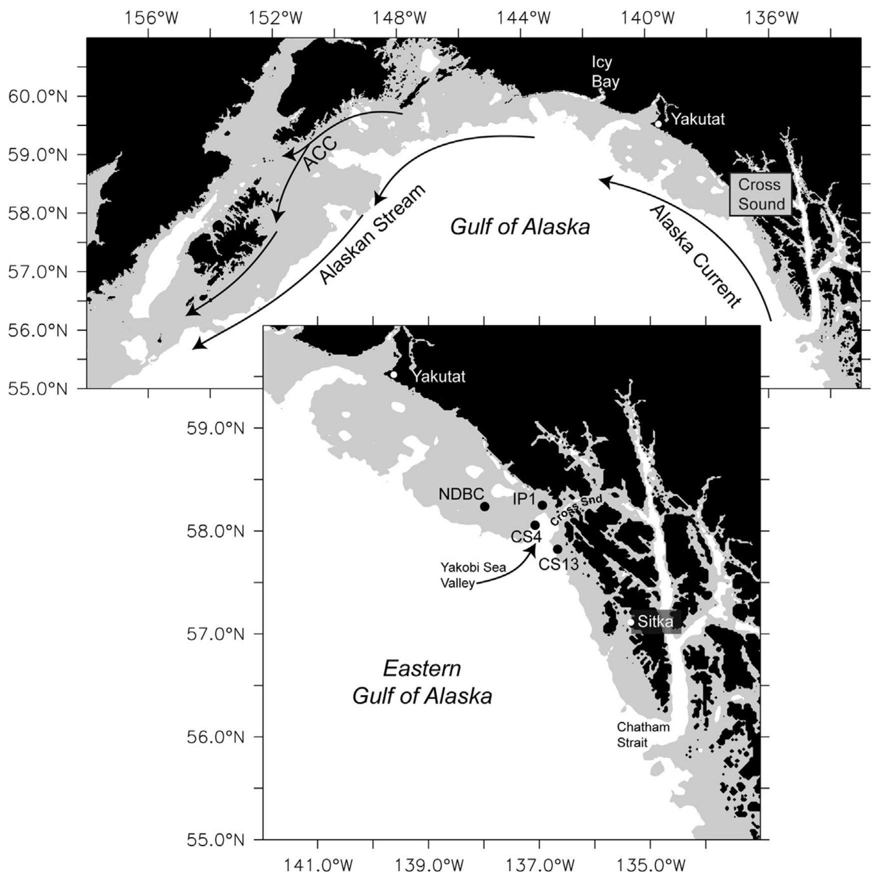

Fig. 1. Schematic of Gulf of Alaska circulation. Locations of moorings (IP1, CS4, and CS13) and NDBC buoy used for QuikSCAT comparison are noted.

satellite data to quantify the magnitude, duration and timing of anomalous ocean conditions associated with gap-wind events in this region.

Due to programs like GLOBEC Northeast Pacific (Batchelder and Bond, 2009) and NOAA's EcoFOCI (www.ecofoci.noaa.gov), the biology and physical oceanography of the western GOA (west of ~145°W) has been relatively well-studied (Fig. 1). However, the eastern GOA is not as well sampled. Circulation in the GOA includes the cyclonic subarctic gyre in the basin and the Alaska Coastal Current on the continental shelf (Fig. 1). The eastern boundary current of the subarctic gyre is the broad and variable Alaska Current. Eddies are regularly formed in the Alaska Current, with important consequences for fluxes of physical and chemical properties and biota (e.g. Atwood et al., 2010; Janout et al., 2009; Ladd et al., 2009; Ladd et al., 2007; Okkonen et al., 2003). At the head of the gulf, the gyre turns southwestward to form the Alaskan Stream, a western boundary current, tightly confined to the shelf-break. The Alaska Coastal Current, a baroclinic coastal current driven by winds and freshwater, has been well described in the northern and western GOA (e.g. Kowalik et al., 1994; Royer, 1981; Schumacher and Reed, 1986; Stabeno et al., 2004; Stabeno et al., 2016-a). It has been described as part of a system of fresh water driven coastal flow extending from the Columbia River in Washington State, along the coast of British Columbia and Alaska, all the way into the Bering Sea (Kowalik et al., 1994). However, the properties and continuity of this coastal current in the *eastern* GOA have not been well studied (Weingartner et al., 2009). South of Cross Sound, the shelf is narrow (~20 km wide). The shelf is interrupted by Yakobi Sea Valley (>200 m deep) at the exit of Cross Sound. North of the sea valley, the shelf is much wider (>65 km). Recent data collected in the eastern GOA finally allow a description of the coastal flow in this under-studied region, suggesting that the Alaska Coastal Current is not continuous across the Yakobi Sea Valley (Stabeno et al., 2016-b). This eastern GOA region is important for transportation, tourism, and fishing, and high winds can be treacherous to these industries. Thus it is important to understand the frequency and magnitude of gap-wind events in this under-studied region, and their impact on the regional oceanography.

Part I of our study focusses on gap winds flowing out of Cross Sound in the eastern GOA (Fig. 1). The focus of Part II of this study (Ladd et al., 2016) is on gap-wind events in the western GOA around Kodiak Island. In both studies, our strategy is to use a combination of observations (satellite data and in situ measurements) and numerical experiments to both document characteristics of gap winds in these regions and to illustrate their influences on the regional oceanography. We treat eastern and western GOA separately because the geographic layout (narrow shelf in the east versus wide shelf in the west), mean ocean circulation (eastern versus western boundary current systems), ecosystem response, and data availability are distinct between these two regions. In Part II (Ladd et al., 2016), we provide a summary comparing across the regions.

2. Methods

2.1. Satellite data

QuikSCAT wind data (downloaded from the NOAA CoastWatch Program http://las.pfeg.noaa.gov/oceanWatch/) were used to quantify the seasonal and interannual frequency of wind events. The SeaWinds instrument, on NASA's QuikSCAT satellite, is a dual-beam microwave scatterometer designed to measure wind magnitude and

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