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The Gulf of Alaska coastal ocean as an atmospheric CO_2 sink

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ABSTRACT

A new data set of directly measured surface seawater carbon dioxide partial pressures (pCO_2) was compiled for the Gulf of Alaska (GOA) coastal ocean. Using this information, along with reconstructed atmospheric pCO_2 data, we calculate sea–air CO_2 fluxes over two interconnected domains: the coastal ocean defined by the Surface Ocean CO_2 Atlas (SOCAT) Continental Margin Mask, and the continental margin shoreward of the 1500 m isobath. The continental margin in this region lies within the coastal ocean. Climatological sea–air CO_2 fluxes were calculated by constructing monthly climatologies of sea–air pCO_2 difference (ΔpCO_2), sea surface temperature, salinity, and CO_2 solubility, coupled with the monthly second moment of wind speeds from the Scatterometer Climatology of Ocean Winds (SCOW; http://cioss.coas.oregonstate.edu/scow). Climatological sea–air CO_2 fluxes showed instances of atmospheric CO_2 uptake and outgassing in both domains for nearly all months; however, uptake dominated from April through November, with distinct spring and autumn peaks that coincided with periods of strong winds and undersaturated surface seawater pCO_2 with respect to atmospheric levels. Atmospheric CO_2 uptake during the spring and autumn peaks was stronger on the continental margin compared with the coastal ocean. Annual mean area-weighted fluxes for the coastal ocean and continental margin were −2.5 and −4 mmol CO_2 m^{-2} d^{-1}, respectively. Scaling these annual means by the respective surface areas of each domain resulted in estimates of substantial atmospheric CO_2 uptake between 34 and 14 Tg C yr^{-1}. This region is a large sink for atmospheric CO_2, which impacts the current view of weak net CO_2 emission from coastal waters surrounding North America.

1. Introduction

Large deviations in surface seawater carbon dioxide partial pressures (pCO_2) from atmospheric levels have been observed in coastal ocean settings and used to suggest that these regions play a significant role in global carbon budgets (Thomas et al., 2004; Tsunogai et al., 1999). There is great uncertainty, however, because of the observational constraint associated with resolving the heterogeneous nature of the coastal ocean. In these settings, the dynamic range of surface seawater pCO_2 can trump that seen in the open ocean and be witnessed over kilometers within hours (Chavez et al., 2007; Evans et al., 2011, 2012, 2013; Hales et al., 2005). The diagnosis of annual mean sea–air CO_2 flux in the global coastal ocean suffers because temporal and spatial data coverage is limited relative to the observed variability (Hales et al., 2008); regional and global flux estimates are generally the result of extrapolating limited measurements beyond their confines. As has been described by Hales et al. (2008), the issue of data scarcity relative to the observed variability is exemplified by an analysis of sea–air CO_2 fluxes for the coastal ocean surrounding North America (Chavez et al., 2007). Chavez et al. (2007) have produced a best estimate of annual mean sea–air CO_2 flux for the North American coastal ocean using measurements from the Lamont-Doherty Earth Observatory (LDEO) global CO_2 database (now maintained by the Carbon Dioxide Information Analysis Center; CDIAC). This effort determined that the North American coastal ocean, defined as waters surrounding the continent within 300 km from shore, is a small source of CO_2 to the atmosphere of 2 Tg C yr^{-1} (1 Tg$=10^{12}$ g). This result was mostly due to the balance of large net fluxes out of the ocean from the Gulf of Mexico and Caribbean Sea and large net fluxes into the ocean in the Bering and Chukchi Seas. However, Hales et al. (2008) clarify that these large flux regions are areas where the number of direct pCO_2 measurements are the most limited (see their Fig. 1.4). In short, our understanding of annual mean sea–air CO_2 exchange in the coastal ocean surrounding North America is corrupted by the problem of data scarcity in regions that are presumed to have large net fluxes. The Gulf of Alaska (GOA) coastal ocean is one such region where large net fluxes are believed to exist, but data had previously been too sparse to quantify the annual mean sea–air CO_2 exchange.

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Coastal sea–air CO_2 fluxes may in part be affected by how one defines the coastal ocean. A process-oriented definition of the coastal ocean would be one that encapsulates all the environments that are impacted by the numerous processes associated with being within the land-open ocean continuum (Liu et al., 2010). However, in practice, process definitions are difficult to employ, and more often definitions are based on hard boundaries such as bathymetric delineations (Evans et al., 2012; Hales et al., 2005) or distance from shore (Chavez et al., 2007). Recently, a 400 km distance from shore definition has been proposed and used by the Surface Ocean CO_2 Atlas (SOCAT) community (Burke Hales, personal communication; Bfeil et al., 2013). This criterion is both easily employable and somewhat process-oriented because it approximates the size of near shore pixels (4° latitude $\times$ 5° longitude) excluded in open ocean syntheses of sea–air CO_2 fluxes (Takahashi et al., 2002; Takahashi et al., 2009), and it is roughly the distance from shore where signals of coastal influence are completely extinguished (Chavez et al., 2007; Hales et al., 2012). This 400 km distance from shore definition of the coastal ocean includes the continental margin in the GOA, which is defined here as shoreward of the 1500 isobath (Fig. 1). The continental margin in this region has a $\sim$300 m deep shelf punctuated with numerous canyons and troughs. The 1500 m depth criterion enables these bathymetric features that intersperse the shelf to be included in the definition of the continental margin. The continental margin is widest ($\sim$200 km) southwest and northeast of Kodiak Island, and narrowest ($<$15 km) along portions of the Alexander Archipelago (Fig. 1). The approximate length of the GOA continental margin is 3000 km; nearly 1.5 times that of the U.S. continental margin from the northern and southern state borders of Washington and California, respectively. The eastern boundary of the GOA coastal ocean is north of the region where the North Pacific Current (West Wind Drift) bifurcates at the approximate latitude of Vancouver Island, British Columbia (Foreman et al., 2011; Freeland, 2006). This cutoff point is Queen Charlotte Sound and the adjacent coastal waters north of Vancouver Island (Fig. 1). Waters flowing northward along the continental slope from the bifurcation region of the North Pacific Current form the Alaska Current, which intensify to become the Alaska Stream at the northern-most point of the central gulf (Stabeno et al., 2004; Weingartner et al., 2002). Over the inner shelf, the most prominent circulation feature is the wind- and buoyancy-driven Alaska Coastal Current (ACC), which likely forms in the vicinity of Vancouver Island and flows poleward around the GOA and through Unimak Pass, the division between the Alaska Peninsula and the Aleutian Islands, onto the Bering Sea shelf (Weingartner et al., 2005; Weingartner et al., 2009). Here, we define the western boundary of the GOA coastal ocean as the longitude of Unimak Pass (Fig. 1). The ACC is fed by massive freshwater discharge to the coastal ocean from steep mountainous terrain and the narrow drainage area surrounding the GOA continental margin. Precipitation rates in this region can surpass 8 m yr^{-1}, with the bulk of freshwater discharge entering the coastal ocean from southeast Alaska (Royer, 2005; Weingartner et al., 2005). The resulting discharge from the Alaska coastal drainage area exceeds 23,000 $m^3\,s^{-1}$ (725 $km^3\,yr^{-1}$), which would rank this coastline 5th amongst the largest river discharges globally (Dai et al., 2009; Dai and Trenberth, 2002).

The GOA coastal ocean is a highly dynamic region forced by strong storm systems from the North Pacific and Bering Sea (Stabeno et al., 2004). The time-averaged sea level pressure field associated with these storms is known as the Aleutian low (Overland et al., 1999). Variability in circulation of the GOA coastal ocean is largely driven by the strength and position of the Aleutian low, and its related wind fields (Stabeno et al., 2004). During non-summer months, these storms drive downwelling-favorable winds along the margin that result in shoreward surface flow over the shelf (Royer, 2005; Weingartner, 2007). In summer (July through September) winds relax, and perhaps at times reverse, allowing ACC water to spread further over the shelf (Royer, 2005; Weingartner, 2007). Despite the downwelling nature of the GOA coastal ocean, the ecosystem supports abundant upper trophic level marine life (Weingartner et al., 2002). However, only moderate rates of primary production have been observed, with levels near 500 mg C $m^{-2}\,d^{-1}$ integrated over the euphotic zone (Strom et al., 2010). These levels are lower than those seen further south in the California Upwelling System (Pennington et al., 2010) and are believed to result largely from macronutrient limitation in the coastal ocean (Strom et al., 2006), although light limitation has also been observed (Strom et al., 2010). Near shore waters in the GOA coastal ocean are replete with micronutrients (iron; Cullen et al., 2009) and experience complete nitrate drawdown in the summer months (Childers et al., 2005). Some offshore waters of the coastal ocean, and the greater GOA basin, on the other hand, never show complete nitrate utilization, yet are iron limited (Ana M. Aguilar-Islas, personal communication; Boyd et al., 2004; Whitney et al., 2005). Sustained moderate summer rates of primary production are likely the result of physical circulation that mixes these two water masses over the shelf (Coyle et al., 2012; Crawford et al., 2007; Ladd et al., 2005; Whitney et al., 2005).

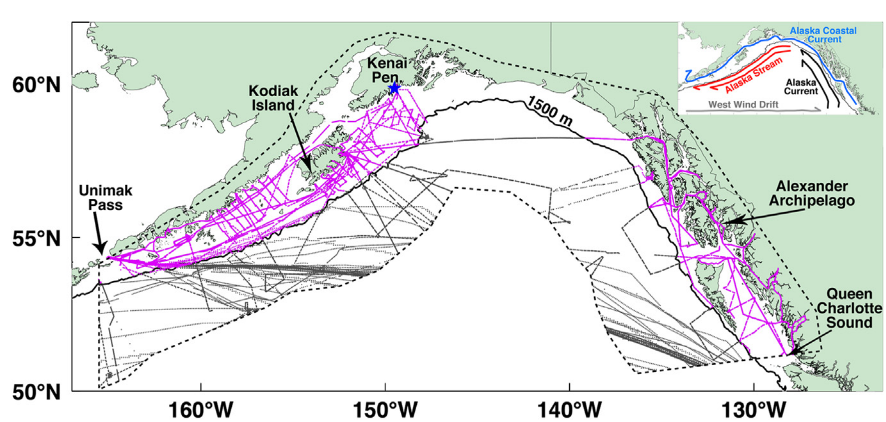

Fig. 1. Spatial distribution of directly measured surface ocean pCO_2 data from Gulf of Alaska (GOA) coastal ocean. The Surface Ocean CO_2 Atlas (SOCAT) Continental Margin Mask is used to define the coastal ocean (dashed polygon; http://ferret.pmel.noaa.gov/SOCAT/). The GOA continental margin is shoreward of the 1500 m isobath (black line), and lies within the coastal ocean. Magenta dots are data collected on the continental margin; and all dots are coastal ocean data. The blue star is the position of the Gulf of Alaska Ocean Acidification (GAKOA; http://pmel.noaa.gov/co2/story/GAKOA) buoy. Dominant surface currents in the GOA are shown in the inset, with arrowheads marking the direction of flow, following Weingartner et al. (2002) and Stabeno et al. (2004). pCO_2 data were collected between 1991 and 2011. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)