Journal of Geoscience and Environment Protection, 2021, 9, 133-148
https://www.scirp.org/journal/gep
ISSN Online: 2327-4344
ISSN Print: 2327-4336

The Variability of Partial Pressure of Carbon Dioxide (pCO_2) in a River-Influenced Coastal Upwelling System: A Case of the Northeast Pacific Coast

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How to cite this paper: Addey, C. I., Jiang, Z.-P., Chen, J. F., Afelumo, A. J., Adesina, B. R., & Osanyintuyi, A. J. (2021). The Variability of Partial Pressure of Carbon Dioxide (pCO_2) in a River-Influenced Coastal Upwelling System: A Case of the Northeast Pacific Coast. *Journal of Geoscience and Environment Protection, 9,* 133-148.
https://doi.org/10.4236/gep.2021.97009

Received: April 28, 2021
Accepted: July 25, 2021
Published: July 28, 2021

Abstract

The Northeast Pacific coastal ocean, as a typical river-influenced coastal upwelling system, is characterized by significant variability of sea surface partial pressure of carbon dioxide (pCO_2, <200 to >1000 μatm). This study reviewed the pCO_2 variability and its underlying controlling mechanism in this highly dynamic region by bringing together previous scientific findings and historical data. The large pCO_2 variability reflects the complex interactions between physical processes (riverine input and coastal upwelling) and the biological responses to the nutrient transportation associated with these physical processes, while temperature and air-sea gas exchange play a minor role in affecting pCO_2. Both the river water and upwelled subsurface water are characterized by higher concentrations of pCO_2 and nutrients when compared to the coastal surface water. The presence of high chlorophyll-a and low pCO_2 in river plumes and areas adjacent to upwelling locations showed the intense biological CO_2 uptake. The influences of riverine input and coastal upwelling thus mainly depend on the competing effect of high background pCO_2 of river water and upwelled subsurface water vs. the biological dropdown of pCO_2 resulting from the riverine- and upwelling-associated nutrient supplies. The strength of upwelling-favorable wind plays an important role in the pCO_2 variability by affecting the intensity of coastal upwelling, with stronger wind speed causing more intense upwelling. The long-term pCO_2 increasing rate in the Northeast Pacific coast is observed to be lower than that in the North Pacific open ocean.

Keywords

pCO$_2$ Variability, Coastal Upwelling, River-Influenced Coastal Systems, Northeast Pacific Coast, Climate Change

1. Introduction

Since the industrial revolution, the carbon dioxide (CO$_2$) in the atmosphere has increased from 280 ppm to the present level of 415 ppm (January 2021) due to anthropogenic activities (Keeling et al., 2004; Takahashi et al., 2009; IPCC, 2013; Takahashi et al., 2014). The rapid increase in atmospheric CO$_2$ concentration significantly affects the earth's climate as CO$_2$ is one of the most significant greenhouse gases (IPCC, 2013). The ocean exchanges CO$_2$ with the atmosphere at the air-sea interface, absorbing about 25% of the anthropogenic carbon emissions annually and lowering the atmospheric CO$_2$ concentration (Takahashi et al., 2002; Sabine et al., 2013). When CO$_2$ is taken up and transported into the ocean interior, it is isolated from the atmosphere on time scales of hundreds and thousands of years. It is projected that about 90% of anthropogenic CO$_2$ would end up in the ocean on a thousand-year time scale (Sabine et al., 2004), which mitigates the CO$_2$-induced global climate change. On the other hand, the oceanic uptake of anthropogenic CO$_2$ is acidifying the ocean and changing the carbonate chemistry of the seawater. This leads to ocean acidification as "the other CO$_2$ problem" (Doney et al., 2009a), which could have several negative consequences for ocean life, especially for calcifying organisms like corals and coccolithophores (Feely et al., 2004; Doney et al., 2009a; Takahashi et al., 2014; George, 2017; Fassbender et al., 2018; Jiang et al., 2019; Gattuso & Hansson, 2011). As atmospheric pCO$_2$ is relatively steady, the air-sea CO$_2$ exchange is mainly determined by the seawater pCO$_2$ variability. The surface ocean pCO$_2$ variability is strongly influenced by changes in temperature (Takahashi et al., 2006; Bates, 2007; Takahashi et al., 2009; Rödenbeck et al., 2013; Sutton et al., 2017), physical processes (Friederich et al., 2002; Hales et al., 2005; Fiechter et al., 2014) and biological activities (Thomas et al., 2005; Zhai et al., 2005; Yoshikawa Inoue et al., 2017). Understanding the distribution and variability of sea surface pCO$_2$ is thus critical for accurately quantifying the carbon budget (Bates et al., 1998; Sabine et al., 2004; Dai et al., 2009; Evans et al., 2013; Jiang et al., 2013; Fiechter et al., 2014).

Despite the small surface area (~7% of the sea surface), coastal oceans are one of the most dynamic and biologically productive ecosystems playing an important role in global carbon biogeochemical cycles (Gattuso et al., 1998; Cai, 2003; Chen & Borges, 2009; Evans et al., 2011; Hales et al., 2012; Chen et al., 2013; Evans et al., 2013). The coastal oceans serve as a connection between the terrestrial and open ocean ecosystems, buffering the effects from land sources before they impact oceanic systems (Thomas et al., 2005; Chen & Borges, 2009). The strong physical-biogeochemical interactions result in large spatial and temporal variations of sea surface $p\mathrm{CO}_2$ in coastal oceans, making it challenging to quantify carbon fluxes in coastal environments. Estimates based on available data showed that the coastal ocean could either act as a sink (DeGrandpre et al., 2002; Hales et al., 2005; Borges et al., 2006; Chen and Borges, 2009; Hales et al., 2012; Jiang et al., 2013; Turi et al., 2014; Evans et al., 2019; Jiménez-López et al., 2019) or source (Friederich et al., 2002; Borges et al., 2005; Wang et al., 2005; Xue et al., 2012; Robbins et al., 2018; Li et al., 2020) for atmospheric CO_2 depending on the dominant controlling mechanism of sea surface $p\mathrm{CO}_2$ in a specific system.

The Northeast Pacific coast, as a river-influenced coastal upwelling system, is a fascinating region for studying the coastal $p\mathrm{CO}_2$ variability. It was characterized by highly complex physical processes, including coastal currents, river input, and wind-driven upwelling. Furthermore, riverine- and upwelling-associated nutrient supplies promote high biological productivity. The interactions between physical and biological processes result in significant variations of sea surface $p\mathrm{CO}_2$ on different temporal and spatial scales (Friederich et al., 2002; Gan & Allen, 2005; Chavez & Messié, 2009; Hales et al., 2012; Evans et al., 2013; Fassbender et al., 2018). On that note, this study brings together existing knowledge and data to provide a comprehensive review of the $p\mathrm{CO}_2$ variability in this study region using the following outlines.

- ✓ The major physical and biological processes in the Northeast Pacific coast.
- ✓ Spatiotemporal $p\mathrm{CO}_2$ dynamics in the Northeast Pacific coast and the driving factors.
- ✓ Possible future changes affecting $p\mathrm{CO}_2$ variability in the study region.

2. Environmental Settings of the Northeast Pacific Coast

2.1. Circulation Features

The Northeast Pacific coast is located to the west of the North American continent, which is greatly influenced by the California current system (**Figure 1**). The key circulation features of the California current system are the equatorward traveling California Current, the poleward traveling California Undercurrent, and the seasonal poleward Davidson Current (Lynn & Simpson, 1987). The California Current is an all-year-round shallow, wide (60 to 900 km), and relatively slow current, which carries the nutrient-rich, cold, high-latitude North Pacific water from the coast of British Columbia southward to the southern Baja California coast (Lynn & Simpson, 1987; Zaytsev et al., 2003; Turi et al., 2014). The California Undercurrent comes along as a subsurface flow between 100 and 300 m over the continental slope and transports saline, warm, equatorial waters northward (Chelton, 1984; Lynn & Simpson, 1987). The Davidson Current (also named as the Inshore Countercurrent) is a seasonal flow during fall and winter (Lynn & Simpson, 1987). It flows over both the slope and shelf, transporting upper ocean shallow waters, which largely come from the California Current waters

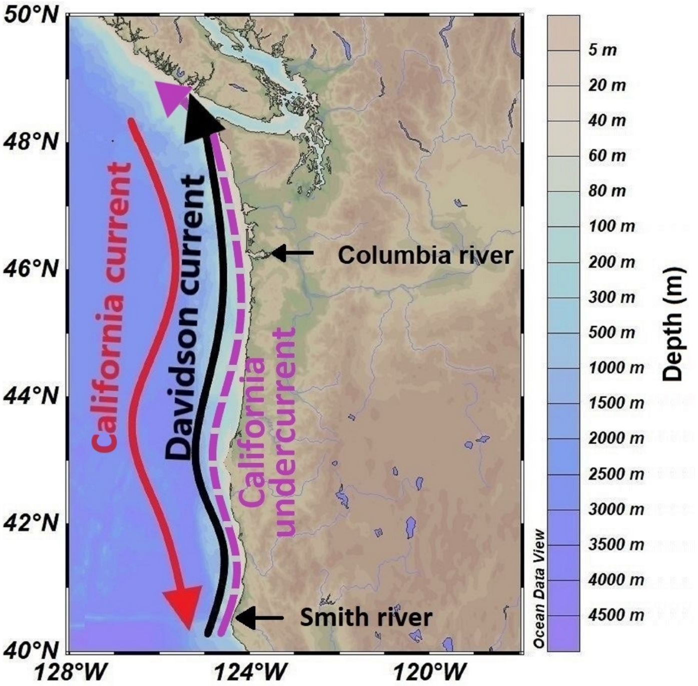

Figure 1. Bathymetry map showing the dominant physical processes in the Northeast Pacific coast. Figure generated by Ocean Data View (Schlitzer, 2017).

with some alterations by coastal processes. Hayward and Venrick (1982) discovered significant variations in phytoplankton biomass and productivity in the California Current. They stated that fluorescence or sea surface chlorophyll values could be used as measures of the biological status of oceanic habitats but should be used with caution due to changes in spatial or temporal relationships (Hayward & Venrick, 1982).

2.2. Riverine Inputs

Rivers are a significant component of the global carbon cycle because they can influence carbon dynamics not just in wetlands but also in coastal areas where river flows are emptied (Ran et al., 2015). Rivers are the main pathways transporting terrestrial organic matter, particles, and human-derived materials to the coastal oceans (Sharples et al., 2017). River water exports not only carbon but also nitrogen, phosphorus, and silica, which are the potentially limiting nutrients for phytoplankton growth. As a result, riverine nutrients promote the phytoplankton biomass and biological productivity of the coastal ocean, especially in the river plume where both nutrients and light are favorable for phytoplankton growth (Hickey & Banas, 2003; Jiang et al., 2019). The Columbia River is the largest river in terms of discharge running into the Pacific from America (**Figure 1**), with an annual average flow of around 7500 $m^3 \cdot s^{-1}$ near the mouth (Kammerer, 1990). The discharge of Columbia River is characterized by a seasonal maximum at the start of summer corresponding to the peak snowmelt (i.e., May to June, 10,000 $m^3 \cdot s^{-1}$) and a minimum during winter (i.e., December to March, 300 $m^3 \cdot s^{-1}$) (Evans et al., 2013). Another minor freshwater input to the Northeast Pacific coast is from the Smith River (**Figure 1**), with an annual average discharge rate of 106 $m^3 \cdot s^{-1}$ (U.S. Geological-Survey, 2014).

2.3. Wind Pattern and Coastal Upwelling

The wind circulation is an important forcing for the movement of surface water in the California current system. The season reversal wind pattern is also closely related to the vertical mixing in this region. During spring and summer, when the wind travels southwards alongshore toward the equator, surface water is moved offshore, resulting in coastal upwelling (King et al., 2011). On the contrary, downwelling favorable winds (northwards along the coast) are observed in autumn and winter (Hickey & Banas, 2003). The California current is one of the five main coastal currents linked to high upwelling regions (Friederich et al., 2002; King et al., 2011). According to Evans et al. (2011), this upwelling event usually starts in April and lasts until October, the same period when the wind is traveling southwards. The upwelling brings cool, saline, CO_2-rich, and nutrient-rich water to the surface layer. The upwelling-derived nutrients promote the growth of sea plants, from microscopic phytoplankton to massive kelp forests. These plants (primary producers) constitute the core of the food web that comprises highly productive fisheries, large populations of sea mammals (dolphins, whales), and sea birds. This biologically active ecosystem can stretch up to 500 kilometers from the coast. Huyer et al. (2005) used the differences in alongshore currents, prevailing wind speed to differentiate two coastal upwelling domains in the Northeast Pacific coast: north and south of the Cape Blanco at 42.9˚N. Both upwelling regions were characterized by southwards traveling wind in summer (Friederich et al., 2002; Huyer et al., 2005; King et al., 2011), with stronger wind speeds and higher coastal upwelling indexes observed in the southern region around 42˚N (**Figure 2**) (Huyer et al., 2005). The coastal upwelling index has proven effective in tracking the strength of wind forcing and upwelling in the California Current System (Bograd et al., 2009). Several studies have used this index to identify the impact of ocean variability on the reproductive performance of many fish and aquatic species in coastal upwelling regions (Jacox et al., 2018). Coastal upwelling in the California Current system is usually reduced during the occurrence of El Nino, leading to a massive drop in primary productivity. This interruption in the marine food web affects the nearby coastal communities where fishers and government depend mainly on revenues from the fishery industry (Friederich et al., 2002).

3. Spatio-Temporal Variation of pCO_2 and Its Controlling Mechanisms in the Northeast Pacific Coastal Waters

3.1. Influences of Riverine Input on pCO_2 Variability

Due to anthropogenic influences and the degradation of terrestrial organic matter (Chen & Borges, 2009; Chen et al., 2013), most rivers have a pCO_2 concentration higher than that in the atmosphere with a large CO_2 emission potential

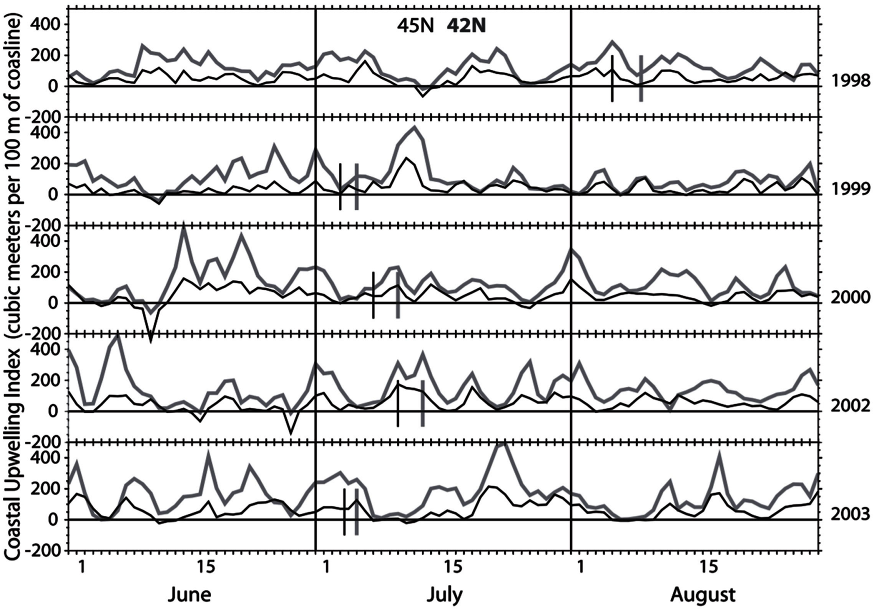

Figure 2. Coastal upwelling index at 42˚N, 125˚W (bold gray) and 45˚N, 125˚W (black) in summer of 1998, 1999, 2000, 2002, and 2003. Figure from Huyer et al. (2005).

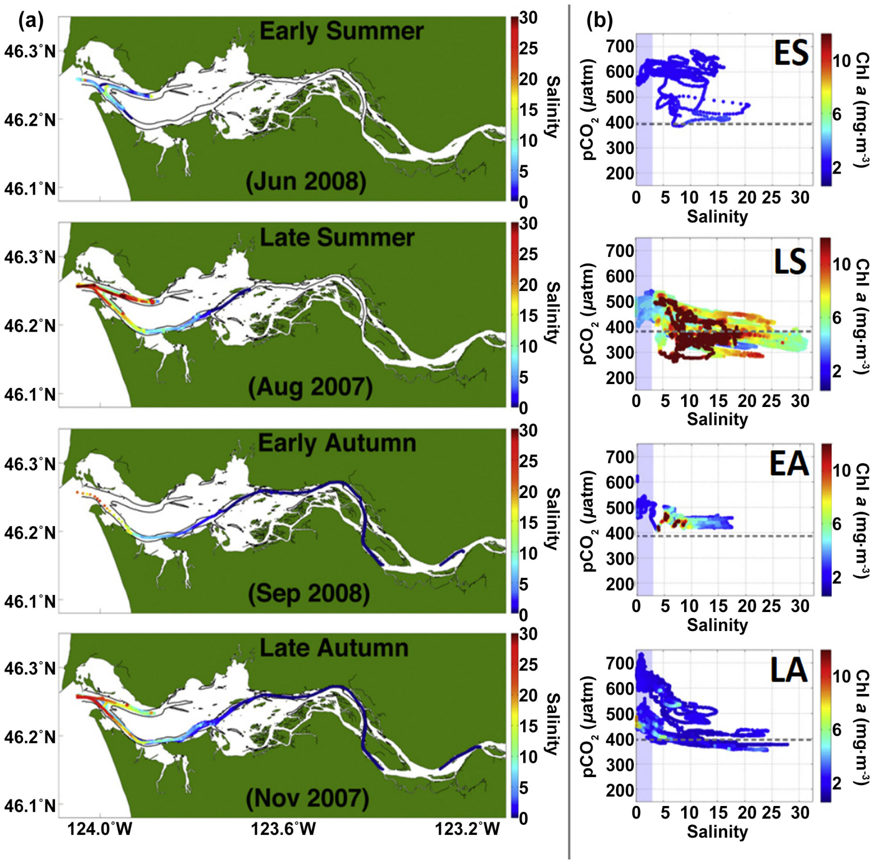

Figure 3. (a) The left column shows surface water salinity along the Columbia River estuary that empties into the Northeast Pacific Ocean. (b) The right column shows $p\mathrm{CO}_2$ (y-axis) versus salinity (x-axis) with chlorophyll-a concentration on the z-axis. The gray dash line indicates the atmospheric $p\mathrm{CO}_2$. Figure from Evans et al. (2013).

(Evans et al., 2013; Ran et al., 2015; Kokic et al., 2018). Although the Columbia River carried a large amount of nutrients into the coastal ocean, the biological response was limited in the nearshore high-turbidity area with low salinity (<5 psu, **Figure 3**) due to low light availability (Borges et al., 2006; Guo et al., 2009). Cruise surveys showed that the seasonal variability of $p\mathrm{CO}_2$ in the Columbia estuary was about 280 to 700 µatm, and it acted as a CO_2 source for the atmosphere in most seasons except for late summer (**Figure 3**). The low $p\mathrm{CO}_2$ occurring in summer was related to the fact that warm temperature favors photosynthesis of phytoplankton, as well as the high discharge providing more nutrients due to the peak of snowmelt freshet (Evans et al., 2013). Because of the alleviation of light limitation in conjunction with the persistence of riverine nutrients during the mixing between freshwater and seawater, high chlorophyll-a concentrations and biological production rates are generally observed in the mid-salinity river plumes where nutrients and light are favorable for phytoplankton growth (**Figure 3**). This biological uptake significantly draws down $p\mathrm{CO}_2$, leading to strong undersaturation (<200 µatm). Therefore, the influences of riverine input on $p\mathrm{CO}_2$ variability in the Northeast Pacific coast depend on the competing effect between the heterotrophic condition of the freshwater and the autotrophic CO_2 uptake in the river plume.

3.2. Influence of Coastal Upwelling on $p\mathrm{CO}_2$ Variability

In the Northeast Pacific coast around April to October, equatorward winds drive Ekman transport, causing upwelling of subsurface water (Evans et al., 2011). As illustrated in **Figure 4(a)**, the subsurface waters are rich in dissolved inorganic carbon (DIC) and have very high $p\mathrm{CO}_2$ reaching or exceeding 1000 µatm (Chavez et al., 2007; Feely et al., 2008). $p\mathrm{CO}_2$ values of about 700 µatm have been found in nearshore upwelling outcrops off the California-Oregon-Washington coast (Hales et al., 2005). Moreover, Feely et al. (2008) reported the upwelling of corrosive "acidified" waters (pH < 7.7) onto the region's shelf deteriorating the acidification status in the Northeast Pacific coast (**Figure 4(b)**). Upwelling not only brings high $p\mathrm{CO}_2$ signals but also transports nutrients from depth to the surface to promote phytoplankton growth. Due to the delayed biological response to the upwelling-induced nutrient supply, elevated Chl-a concentrations were generally observed in areas adjacent to the upwelling center. When the upwelled water moves off and along the shore, as observed by van Geen et al. (2000), $p\mathrm{CO}_2$ can be quickly drawn down to undersaturation levels (<300 µatm) below the atmospheric equilibrium. Therefore, the influences of coastal upwelling on $p\mathrm{CO}_2$ variability in the Northeast Pacific coast mainly depend on the balance between the upwelling-induced DIC transportation (increase $p\mathrm{CO}_2$) and the subsequent biological CO_2 uptake stimulated by the upwelling-associated nutrient supply.

3.3. Surface Water $p\mathrm{CO}_2$ Variability and Its Controlling Mechanisms

Previous studies have proved that one of the most significant controls governing the sea surface $p\mathrm{CO}_2$ variability in the open ocean is sea surface temperature (SST), and $p\mathrm{CO}_2$ generally showed a positive correlation with SST (Hales et al., 2005; Hales et al., 2012; Xue et al., 2012; Sutton et al., 2017; Yoshikawa Inoue et al., 2017; Ogundare et al., 2021). However, the $p\mathrm{CO}_2$ and SST distributions in the Northeast Pacific coast (**Figure 5(a)**) indicated that factors other than SST played the dominant role in modulating $p\mathrm{CO}_2$ while the temperature effect was minor. To further investigate the non-thermal controlling factors on $p\mathrm{CO}_2$ variability, we applied temperature normalization on the surface $p\mathrm{CO}_2$ following Takahashi et al. (2006).

$$\mathrm{n}p\mathrm{CO}_2 = p\mathrm{CO}_{2,\mathrm{SSTobs}} \times \exp\left(0.0423 \times \left(\mathrm{SST}_{\mathrm{mean}} - \mathrm{SST}_{\mathrm{obs}}\right)\right) \tag{1}$$

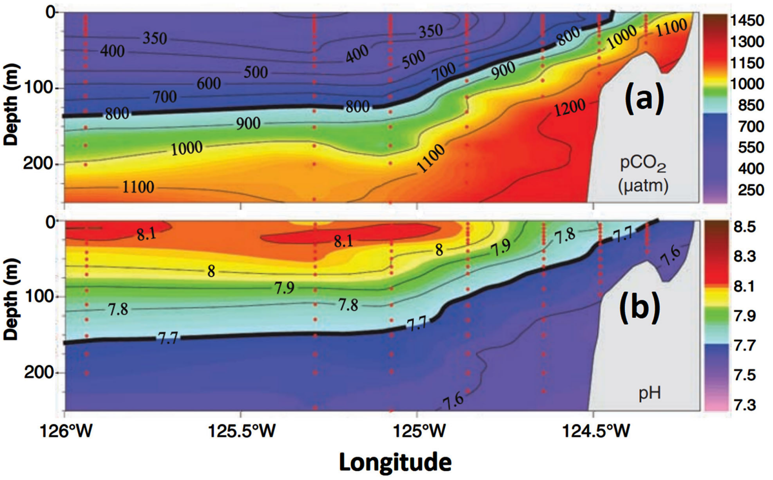

Figure 4. Vertical sections of (a) $p\mathrm{CO}_2$ and (b) pH around the Northeast Pacific coast (41 - 42˚N). The 26.2 potential density surface (thick black line) delineates the location where the high $p\mathrm{CO}_2$ (acidic water) is upwelled from depths around 150 to 200 m onto the shelf. Figure from Feely et al. (2008).

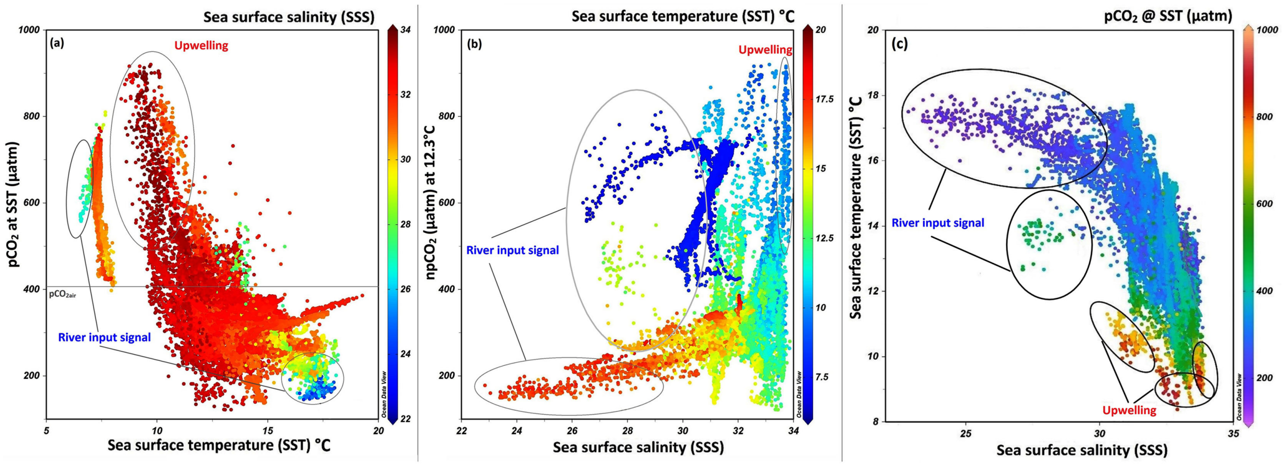

Figure 5. (a) The distributions of $p\mathrm{CO}_2$ (y-axis) versus sea surface temperature (SST on the x-axis), with salinity as the z-axis. The atmospheric $p\mathrm{CO}_2$ reference line in January 2021 (415 ppm) is highlighted (see https://www.esrl.noaa.gov/gmd/ccgg/trends/global.html). (b) Temperature-normalized $p\mathrm{CO}_2$ (n$p\mathrm{CO}_2$ on the y-axis) versus salinity (x-axis), with SST as the z-axis. (c) temperature vs. salinity distribution highlighting the different water sources and the processes influencing $p\mathrm{CO}_2$ variability in the Northeast Pacific coast. Figure generated by Ocean Data View (Schlitzer, 2017).

where SST is sea surface temperature, $pCO_{2,SSTobs}$ denotes the pCO_2 observed at in situ SST (SST_{obs}), and SST_{mean} refers to the mean SST. The temperature-normalized $npCO_2$ represents the pCO_2 changes caused by non-thermal processes such as air-sea CO_2 exchange, physical mixing, and biological activity (**Figure 5(b)**).

The variations of pCO_2 and $npCO_2$ were clearly related to different water masses with characteristic temperature and salinity (**Figure 5**). The riverine signals characterized by lower salinity (SSS < 30, **Figure 5**) and high chlorophyll concentration (**Figure 6**) were mainly observed in the area adjacent to the river mouth of the Columbia River (Huyer et al., 2005). Fassbender et al. (2018) also reported a similar observation in the low salinity Columbia River Plume 30 - 90 km from shore, which is advected ashore by the Ekman transportation and towards the south by the coastal jet in summer. The observed pCO_2 values at the salinity range of 22 - 30 were mostly below the atmospheric level (**Figure 5**), which suggests the dominance of biological CO_2 uptake in the river plume over the high background pCO_2 of freshwater as discussed in Section 3.1. However, high pCO_2 values (up to 780 μatm) were sometimes observed, which may be a result of a delayed biological response to riverine-borne nutrients because of the high discharge rate or sustained high-turbidity conditions. The newly upwelled subsurface waters, observed at the upwelling centers (**Figure 6**), were characterized by low SST (<10˚C), high salinity (>32 psu), high pCO_2 (>500 μatm), and high $npCO_2$ (>500 μatm) (**Figure 5**). On the contrary, high Chl-a concentration in areas adjacent to upwelling showed the phytoplankton growth response to the upwelling-associated nutrient supply, which significantly draw down pCO_2 leading to strong undersaturation (**Figure 6**). Overall, the Northeast Pacific coast is a river-influenced coastal upwelling system characterized by large variations in sea surface temperature (SST, 8˚C - 18˚C), sea surface salinity (SSS, 22 - 34), and pCO_2 (120 to 912 μatm). Previous findings reported the Northeast Pacific coastal region acted as a sink for atmospheric CO_2 (Hales et al., 2005; Chen & Borges, 2009; Hales et al., 2012; Turi et al., 2014; Evans et al., 2019).

3.4. Long-Term Seawater pCO_2 Variability

Several investigators estimated similar pCO_2 increasing rates in the North Pacific open ocean as 1.3 ± 0.2 $\mu atm \cdot yr^{-1}$ by Takahashi et al. (2006), 1.39 ± 0.18 $\mu atm \cdot yr^{-1}$ by Yoshikawa-Inoue et al. (2014), and 1.36 ± 0.16 $\mu atm \cdot yr^{-1}$ by Wong et al. (2010). These rates were generally in pace with the increasing rate of atmospheric pCO_2 of 1.5 $\mu atm \cdot yr^{-1}$ estimated by Takahashi et al. (2009). Despite the existence of previous pCO_2 investigations in the Northeast Pacific coastal region (Friederich et al., 2002; Gan & Allen, 2005; Hales et al., 2012; Evans et al., 2013; Fassbender et al., 2018), the long-term changing rate of pCO_2 in the Northeast Pacific coast is still with significant uncertainties because of undersampling in the highly dynamic system. The closest estimates available are those of Wong et al. (2010) and Takahashi et al. (2006). The former estimated the

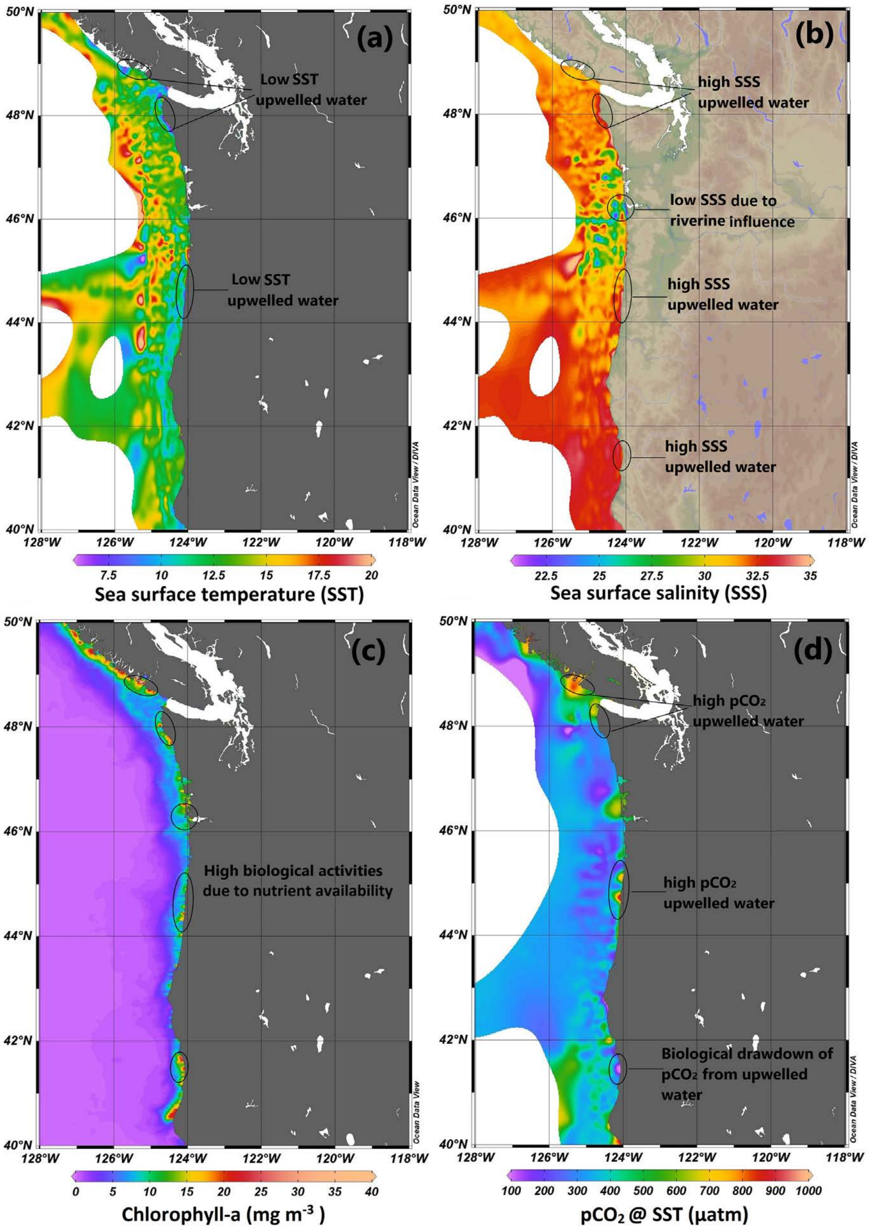

Figure 6. Surface distribution of (a) sea surface temperature, (b) salinity, (c) Chlorophyll-a, and (d) $p\text{CO}_2$. Figure generated by Ocean Data View (Schlitzer, 2017).

$p\text{CO}_2$ increasing rate of change in Line P (48 - 49˚N, 130 - 125˚W) to be 0.57 ± 0.36 $\mu\text{atm}\cdot\text{yr}^{-1}$, and the latter revealed a range from 0.2 ± 0.8 $\mu\text{atm}\cdot\text{yr}^{-1}$ to 1.0 ± 0.5 $\mu\text{atm}\cdot\text{yr}^{-1}$ along the North American west coast. The average long-term $p\text{CO}_2$ increasing rate in the Northeast Pacific coastal ocean seems to be lower than that in the North Pacific open ocean.

4. Future Changes in CO_2 Dynamics of the Region

Possible future changes in biological and physical processes can potentially cause negative and positive feedbacks affecting the carbonate system in the Northeast Pacific coast. An increase in SST due to climate change tends to increase seawater $p\mathrm{CO}_2$ by reducing the solubility of CO_2 in seawater (Doney et al., 2009b; Takahashi et al., 2009). The circulation pattern of the northwesterly winds may enhance more intense vertical upwelling (Bogden & Edwards, 2001; Xiu et al., 2018). Increased upwelling will bring more DIC (to increase sea surface $p\mathrm{CO}_2$) and nutrients (to enhance the biological dropdown of $p\mathrm{CO}_2$) (Jiang et al., 2014). Moreover, the circulation pattern may be affected by the impact of more frequent strong El Niño events, which deepens the thermocline and subsequently suppresses the upwelling of nutrient-rich subsurface waters, which are needed by phytoplankton to draw down CO_2 (Wang et al., 2019). The interplay between intense upwelled CO_2-rich waters and photosynthetic reactions is vital in estimating the shelf's overall sink-source status. Additionally, anthropogenic activities such as marine eutrophication, fisheries overexploitation, and potential geotechnical projects could have drastic future consequences for coastal carbon biogeochemistry (Doney et al., 2009b). For example, the building of dams has been known to massively drop river discharge volumes, trapping suspended solids and nutrient-rich water, which subsequently alters the river-borne carbon dynamics (Ran et al., 2015).

Data Availability

SST, SSS, and $p\mathrm{CO}_2$ data are publicly available at Coastal Ocean Data Analysis Product in North America (CODAP-NA, Version 2021; NCEI Accession 0219960) https://www.ncei.noaa.gov/access/ocean-carbon-data-system/oceans/Coastal/north_america_west.html, Chlorophyll-a data was downloaded from Aqua MODIS, NASA https://polarwatch.noaa.gov/catalog/chl-aqua/download/.

Acknowledgements

This research was funded by the National Key Research and Development Program of China (2016YFA0601404), the Bureau of Science and Technology of Zhoushan, Zhejiang (2019C81037), and NSFC-Zhejiang Joint Fund for the Integration of Industrialization and Informatization (No. U1709201). The authors acknowledge NOAA's North America Coastal Ocean Data Analysis program and Aqua MODIS, NASA for the availability of public data. Addey, C. I. acknowledges the support of the China Scholarship Council during his postgraduate study. The authors are grateful to the reviewers for their comments which helped improve the manuscript.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

Bates, N. R. (2007). Interannual Variability of the Oceanic CO_2 Sink in the Subtropical Gyre of the North Atlantic Ocean over the Last 2 Decades. *Journal of Geophysical Re-*

search: Oceans, 112, C09013. https://doi.org/10.1029/2006JC003759

Bates, N. R., Takahashi, T., Chipman, D. W., & Knap, A. H. (1998). Variability of $p\mathrm{CO}_2$ on Diel to Seasonal Timescales in the Sargasso Sea near Bermuda. *Journal of Geophysical Research: Oceans, 103,* 15567-15585. https://doi.org/10.1029/98JC00247

Bogden, P. S., & Edwards, C. A. (2001). Wind Driven Circulation. In J. H. Steele (Ed.), *Encyclopedia of Ocean Sciences* (pp. 3227-3236). Academic Press. https://doi.org/10.1006/rwos.2001.0110

Bograd, S. J., Schroeder, I., Sarkar, N., Qiu, X., Sydeman, W. J., & Schwing, F. B. (2009). Phenology of Coastal Upwelling in the California Current. *Geophysical Research Letters, 36,* L01602. https://doi.org/10.1029/2008GL035933

Borges, A. V., Delille, B., & Frankignoulle, M. (2005). Budgeting Sinks and Sources of CO_2 in the Coastal Ocean: Diversity of Ecosystems Counts. *Geophysical Research Letters, 32,* L14601. https://doi.org/10.1029/2005GL023053

Borges, A. V., Schiettecatte, L. S., Abril, G., Delille, B., & Gazeau, F. (2006). Carbon Dioxide in European Coastal Waters. *Estuarine, Coastal and Shelf Science, 70,* 375-387. https://doi.org/10.1016/j.ecss.2006.05.046

Cai, W.-J. (2003). Riverine Inorganic Carbon Flux and Rate of Biological Uptake in the Mississippi River Plume. *Geophysical Research Letters, 30,* 1032. https://doi.org/10.1029/2002GL016312

Chavez, F. P., & Messié, M. (2009). A Comparison of Eastern Boundary Upwelling Ecosystems. *Progress in Oceanography, 83,* 80-96. https://doi.org/10.1016/j.pocean.2009.07.032

Chavez, F., Takahashi, T., Cai, W.-J., Friedrich, G., Hales, B., Wanninkhof, R. et al. (2007). Chapter 15. Coastal Oceans. In A. W. King et al. (Eds.), *The First State of the Carbon Cycle Report (SOCCR): North American Carbon Budget and Implications for the Global Carbon Cycle* (pp. 157-166). US Climate Change Science Program and the Subcommittee on Global Change Research, National Ocean and Atmospheric Administration, Climate Program Office. https://cdiac.ess-dive.lbl.gov/SOCCR/pdf/sap2-2-final-all.pdf

Chelton, D. B. (1984). Seasonal Variability of Alongshore Geostrophic Velocity off Central California. *Journal of Geophysical Research: Oceans, 89,* 3473-3486. https://doi.org/10.1029/JC089iC03p03473

Chen, C. T. A., Huang, T. H., Chen, Y. C., Bai, Y., He, X., & Kang, Y. (2013). Air-Sea Exchanges of CO_2 in the World's Coastal Seas. *Biogeosciences, 10,* 6509-6544. https://doi.org/10.5194/bg-10-6509-2013

Chen, C.-T. A., & Borges, A. V. (2009). Reconciling Opposing Views on Carbon Cycling in the Coastal Ocean: Continental Shelves as Sinks and Near-Shore Ecosystems as Sources of Atmospheric CO_2. *Deep Sea Research Part II: Topical Studies in Oceanography, 56,* 578-590. https://doi.org/10.1016/j.dsr2.2009.01.001

Dai, M., Lu, Z., Zhai, W., Chen, B., Cao, Z., Zhou, K. et al. (2009). Diurnal Variations of Surface Seawater $p\mathrm{CO}_2$ in Contrasting Coastal Environments. *Limnology and Oceanography, 54,* 735-745. https://doi.org/10.4319/lo.2009.54.3.0735

DeGrandpre, M. D., Olbu, G. J., Beatty, C. M., & Hammar, T. R. (2002). Air-Sea CO_2 Fluxes on the US Middle Atlantic Bight. *Deep Sea Research Part II: Topical Studies in Oceanography, 49,* 4355-4367. https://doi.org/10.1016/S0967-0645(02)00122-4

Doney, S. C., Fabry, V. J., Feely, R. A., & Kleypas, J. A. (2009a). Ocean Acidification: The Other CO_2 Problem. *Annual Review of Marine Science, 1,* 169-192. https://doi.org/10.1146/annurev.marine.010908.163834

Doney, S. C., Tilbrook, B., Roy, S., Metzl, N., Le Quéré, C., Hood, M. et al. (2009b). Surface-Ocean CO_2 Variability and Vulnerability. *Deep Sea Research Part II: Topical Studies in Oceanography, 56,* 504-511. https://doi.org/10.1016/j.dsr2.2008.12.016

Evans, W., Hales, B., & Strutton, P. G. (2011). Seasonal Cycle of Surface Ocean $p\mathrm{CO}_2$ on the Oregon Shelf. *Journal of Geophysical Research: Oceans, 116,* C05012. https://doi.org/10.1029/2010JC006625

Evans, W., Hales, B., & Strutton, P. G. (2013). $p\mathrm{CO}_2$ Distributions and Air-Water CO_2 Fluxes in the Columbia River Estuary. *Estuarine, Coastal and Shelf Science, 117,* 260-272. https://doi.org/10.1016/j.ecss.2012.12.003

Evans, W., Pocock, K., Hare, A., Weekes, C., Hales, B., Jackson, J. et al. (2019). Marine CO_2 Patterns in the Northern Salish Sea. *Frontiers in Marine Science, 5,* 536. https://doi.org/10.3389/fmars.2018.00536

Fassbender, A. J., Alin, S. R., Feely, R. A., Sutton, A. J., Newton, J. A., Krembs, C. et al. (2018). Seasonal Carbonate Chemistry Variability in Marine Surface Waters of the US Pacific Northwest. *Earth System Science Data, 10,* 1367-1401. https://doi.org/10.5194/essd-10-1367-2018

Feely, R. A., Sabine, C. L., Hernandez-Ayon, J. M., Ianson, D., & Hales, B. (2008). Evidence for Upwelling of Corrosive "Acidified" Water onto the Continental Shelf. *Science, 320,* 1490-1492. https://doi.org/10.1126/science.1155676

Feely, R. A., Sabine, C. L., Lee, K., Berelson, W., Kleypas, J., Fabry, V. J. et al. (2004). Impact of Anthropogenic CO_2 on the $CaCO_3$ System in the Oceans. *Science, 305,* 362-366. https://doi.org/10.1126/science.1097329

Fiechter, J., Curchitser, E. N., Edwards, C. A., Chai, F., Goebel, N. L., & Chavez, F. P. (2014). Air-Sea CO_2 Fluxes in the California Current: Impacts of Model Resolution and Coastal Topography. *Global Biogeochemical Cycles, 28,* 371-385. https://doi.org/10.1002/2013GB004683

Friederich, G. E., Walz, P. M., Burczynski, M. G., & Chavez, F. P. (2002). Inorganic Carbon in the Central California Upwelling System during the 1997-1999 El Nino-La Nina Event. *Progress in Oceanography, 54,* 185-203. https://doi.org/10.1016/S0079-6611(02)00049-6

Gan, J., & Allen, J. S. (2005). Modeling Upwelling Circulation off the Oregon Coast. *Journal of Geophysical Research: Oceans, 110,* C10S07. https://doi.org/10.1029/2004JC002692

Gattuso, J.-P., & Hansson, L. (2011). *Ocean Acidification* (pp. 1-20). Oxford University Press. https://doi.org/10.1093/oso/9780199591091.001.0001

Gattuso, J.-P., Frankignoulle, M., & Wollast, R. (1998). Carbon and Carbonate Metabolism in Coastal Aquatic Ecosystems. *Annual Review of Ecology and Systematics, 29,* 405-434. https://doi.org/10.1146/annurev.ecolsys.29.1.405

George, R. Y. (2017). Potential Impact of Carbonate Chemistry Change ($p\mathrm{CO}_2$) on Krill and Krill-Based Food Chain in the Southern Ocean with Emphasis on Embryogenesis of Antarctic Krill. *Biogeosciences Discuss, 2017,* 1-20. https://doi.org/10.5194/bg-2017-207

Guo, X., Dai, M., Zhai, W., Cai, W.-J., & Chen, B. (2009). CO_2 Flux and Seasonal Variability in A Large Subtropical Estuarine System, the Pearl River Estuary, China. *Journal of Geophysical Research: Biogeosciences, 114,* G03013. https://doi.org/10.1029/2008JG000905

Hales, B., Strutton, P. G., Saraceno, M., Letelier, R., Takahashi, T., Feely, R. et al. (2012). Satellite-Based Prediction of $p\mathrm{CO}_2$ in Coastal Waters of the Eastern North Pacific. *Progress in Oceanography, 103,* 1-15. https://doi.org/10.1016/j.pocean.2012.03.001

Hales, B., Takahashi, T., & Bandstra, L. (2005). Atmospheric CO_2 Uptake by a Coastal

Upwelling System. *Global Biogeochemical Cycles, 19,* GB1009. https://doi.org/10.1029/2004GB002295

Hayward, T. L., & Venrick, E. L. (1982). Relation between Surface Chlorophyll, Integrated Chlorophyll and Integrated Primary Production. *Marine Biology, 69,* 247-252. https://doi.org/10.1007/BF00397490

Hickey, B. M., & Banas, N. S. (2003). Oceanography of the U.S. Pacific Northwest Coastal Ocean and Estuaries with Application to Coastal Ecology. *Estuaries, 26,* 1010-1031. https://doi.org/10.1007/BF02803360

Huyer, A., Fleischbein, J. H., Keister, J., Kosro, P. M., Perlin, N., Smith, R. L. et al. (2005). Two Coastal Upwelling Domains in the Northern California Current System. *Journal of Marine Research, 63,* 901-929. https://doi.org/10.1357/002224005774464238

IPCC (2013). *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (1535 p). Cambridge University Press.

Jacox, M. G., Edwards, C. A., Hazen, E. L., & Bograd, S. J. (2018). Coastal Upwelling Revisited: Ekman, Bakun, and Improved Upwelling Indices for the U.S. West Coast. *Journal of Geophysical Research: Oceans, 123,* 7332-7350. https://doi.org/10.1029/2018JC014187

Jiang, Z.-P., Cai, W. J., Lehrter, J., Chen, B., Ouyang, Z., Le, C. et al. (2019). Spring Net Community Production and Its Coupling with the CO_2 Dynamics in the Surface Water of the Northern Gulf of Mexico. *Biogeosciences, 16,* 3507-3525. https://doi.org/10.5194/bg-16-3507-2019

Jiang, Z.-P., Hydes, D. J., Tyrrell, T., Hartman, S. E., Hartman, M. C., Dumousseaud, C. et al. (2013). Key Controls on the Seasonal and Interannual Variations of the Carbonate System and Air-Sea CO_2 Flux in the Northeast Atlantic (Bay of Biscay). *Journal of Geophysical Research: Oceans, 118,* 785-800. https://doi.org/10.1002/jgrc.20087

Jiang, Z.-P., Tyrrell, T., Hydes, D. J., Dai, M., & Hartman, S. E. (2014). Variability of Alkalinity and the Alkalinity-Salinity Relationship in the Tropical and Subtropical Surface Ocean. *Global Biogeochemical Cycles, 28,* 729-742. https://doi.org/10.1002/2013GB004678

Jiménez-López, D., Sierra, A., Ortega, T., Garrido, S., Hernández-Puyuelo, N., Sánchez-Leal, R. et al. (2019). $p\text{CO}_2$ Variability in the Surface Waters of the Eastern Gulf of Cádiz (SW Iberian Peninsula). *Ocean Science, 15,* 1225-1245. https://doi.org/10.5194/os-15-1225-2019

Kammerer, J. C. (1990). *Largest Rivers in the United States: The United States Geological Survey.* USGS. https://pubs.usgs.gov/of/1987/ofr87-242/ https://doi.org/10.3133/ofr87242

Keeling, C. D., Brix, H., & Gruber, N. (2004). Seasonal and Long-Term Dynamics of the Upper Ocean Carbon Cycle at Station ALOHA near Hawaii. *Global Biogeochemical Cycles, 18,* GB4006. https://doi.org/10.1029/2004GB002227

King, J. R., Agostini, V. N., Harvey, C. J., McFarlane, G. A., Foreman, M. G. G., Overland, J. E. et al. (2011). Climate Forcing and the California Current Ecosystem. *ICES Journal of Marine Science, 68,* 1199-1216. https://doi.org/10.1093/icesjms/fsr009

Kokic, J., Sahlée, E., Sobek, S., Vachon, D., & Wallin, M. B. (2018). High Spatial Variability of Gas Transfer Velocity in Streams Revealed by Turbulence Measurements. *Inland Waters, 8,* 461-473. https://doi.org/10.1080/20442041.2018.1500228

Li, Q., Guo, X., Zhai, W., Xu, Y., & Dai, M. (2020). Partial Pressure of CO_2 and Air-Sea CO_2 Fluxes in the South China Sea: Synthesis of an 18-Year Dataset. *Progress in Oceanography, 182,* Article ID: 102272. https://doi.org/10.1016/j.pocean.2020.102272

Lynn, R. J., & Simpson, J. J. (1987). The California Current System: The Seasonal Variability of Its Physical Characteristics. *Journal of Geophysical Research: Oceans, 92,* 12947-12966. https://doi.org/10.1029/JC092iC12p12947

Ogundare, M. O., Fransson, A., Chierici, M., Joubert, W. R., & Roychoudhury, A. N. (2021). Variability of Sea-Air Carbon Dioxide Flux in Autumn across the Weddell Gyre and Offshore Dronning Maud Land in the Southern Ocean. *Frontiers in Marine Science, 7,* Article ID: 614263. https://doi.org/10.3389/fmars.2020.614263

Ran, L., Lu, X. X., Richey, J. E., Sun, H., Han, J., Yu, R. et al. (2015). Long-Term Spatial and Temporal Variation of CO_2 Partial Pressure in the Yellow River, China. *Biogeosciences, 12,* 921-932. https://doi.org/10.5194/bg-12-921-2015

Robbins, L. L., Daly, K. L., Barbero, L., Wanninkhof, R., He, R., Zong, H. et al. (2018). Spatial and Temporal Variability of pCO_2 Carbon Fluxes, and Saturation State on the West Florida Shelf. *Journal of Geophysical Research: Oceans, 123,* 6174-6188. https://doi.org/10.1029/2018JC014195

Rödenbeck, C., Keeling, R. F., Bakker, D. C. E., Metzl, N., Olsen, A., Sabine, C. et al. (2013). Global Surface-Ocean pCO_2 and Sea-Air CO_2 Flux Variability from an Observation-Driven Ocean Mixed-Layer Scheme. *Ocean Science, 9,* 193-216. https://doi.org/10.5194/os-9-193-2013

Sabine, C. L., Feely, R. A., Gruber, N., Key, R. M., Lee, K., Bullister, J. L. et al. (2004). The Oceanic Sink for Anthropogenic CO_2. *Science, 305,* 367-371. https://doi.org/10.1126/science.1097403

Sabine, C. L., Hankin, S., Koyuk, H., Bakker, D. C. E., Pfeil, B., Olsen, A. et al. (2013). Surface Ocean CO_2 Atlas (SOCAT) Gridded Data Products. *Earth System Science Data, 5,* 145-153. https://doi.org/10.5194/essd-5-145-2013

Schlitzer, R. (2017). *Ocean Data View.* https://odv.awi.de/

Sharples, J., Middelburg, J. J., Fennel, K., & Jickells, T. D. (2017). What Proportion of Riverine Nutrients Reaches the Open Ocean? *Global Biogeochemical Cycles, 31,* 39-58. https://doi.org/10.1002/2016GB005483

Sutton, A. J., Wanninkhof, R., Sabine, C. L., Feely, R. A., Cronin, M. F., & Weller, R. A. (2017). Variability and Trends in Surface Seawater pCO_2 and CO_2 Flux in the Pacific Ocean. *Geophysical Research Letters, 44,* 5627-5636. https://doi.org/10.1002/2017GL073814

Takahashi, T., Sutherland, S. C., Chipman, D. W., Goddard, J. G., Ho, C., Newberger, T. et al. (2014). Climatological Distributions of pH, pCO_2, Total CO_2, Alkalinity, and $CaCO_3$ Saturation in the Global Surface Ocean, and Temporal Changes at Selected Locations. *Marine Chemistry, 164,* 95-125. https://doi.org/10.1016/j.marchem.2014.06.004

Takahashi, T., Sutherland, S. C., Feely, R. A., & Wanninkhof, R. (2006). Decadal Change of the Surface Water pCO_2 in the North Pacific: A Synthesis of 35 Years of Observations. *Journal of Geophysical Research: Oceans, 111,* C07S05. https://doi.org/10.1029/2005JC003074

Takahashi, T., Sutherland, S. C., Sweeney, C., Poisson, A., Metzl, N., Tillbrook, B. et al. (2002). Global Sea-Air CO_2 Flux Based on Climatological Surface Ocean pCO_2, and Seasonal Biological and Temperature Effects. *Deep Sea Research Part II: Topical Studies in Oceanography, 49,* 1601-1622. https://doi.org/10.1016/S0967-0645(02)00003-6

Takahashi, T., Sutherland, S. C., Wanninkhof, R., Sweeney, C., Feely, R. A., Chipman, D. W. et al. (2009). Climatological Mean and Decadal Change in Surface Ocean pCO_2, and Net Sea-Air CO_2 Flux over the Global Oceans. *Deep Sea Research Part II: Topical Studies in Oceanography, 56,* 554-577. https://doi.org/10.1016/j.dsr2.2008.12.009

Thomas, H., Bozec, Y., Elkalay, K., de Baar, H. J. W., Borges, A. V., & Schiettecatte, L. S. (2005). Controls of the Surface Water Partial Pressure of CO_2 in the North Sea. *Biogeosciences, 2,* 323-334. https://doi.org/10.5194/bg-2-323-2005

Turi, G., Lachkar, Z., & Gruber, N. (2014). Spatiotemporal Variability and Drivers of $p$$CO_2$ and Air-Sea CO_2 Fluxes in the California Current System: An Eddy-Resolving Modeling Study. *Biogeosciences, 11,* 671-690. https://doi.org/10.5194/bg-11-671-2014

U.S. Geological-Survey (2014). *Water-Resources Data for the United States, Water Year 2013.* U.S. Geological Survey Water-Data Report WDR-US-2013. http://wdr.water.usgs.gov/wy2013/pdfs/11532500.2013.pdf

van Geen, A., Takesue, R. K., Goddard, J., Takahashi, T., Barth, J. A., & Smith, R. L. (2000). Carbon and Nutrient Dynamics during Coastal Upwelling off Cape Blanco, Oregon. *Deep Sea Research Part II: Topical Studies in Oceanography, 47,* 975-1002. https://doi.org/10.1016/S0967-0645(99)00133-2

Wang, B., Luo, X., Yang, Y.-M., Sun, W., Cane, M. A., Cai, W. et al. (2019). Historical Change of El Niño Properties Sheds Light on Future Changes of Extreme El Niño. *Proceedings of the National Academy of Sciences of the United States of America, 116,* 22512-22517. https://doi.org/10.1073/pnas.1911130116

Wang, Z. A., Cai, W.-J., Wang, Y., & Ji, H. (2005). The Southeastern Continental Shelf of the United States as an Atmospheric CO_2 Source and an Exporter of Inorganic Carbon to the Ocean. *Continental Shelf Research, 25,* 1917-1941. https://doi.org/10.1016/j.csr.2005.04.004

Wong, C. S., Christian, J. R., Emmy Wong, S. K., Page, J., Xie, L., & Johannessen, S. (2010). Carbon Dioxide in Surface Seawater of the Eastern North Pacific Ocean (Line P), 1973-2005. *Deep Sea Research Part I: Oceanographic Research Papers, 57,* 687-695. https://doi.org/10.1016/j.dsr.2010.02.003

Xiu, P., Chai, F., Curchitser, E. N., & Castruccio, F. S. (2018). Future Changes in Coastal Upwelling Ecosystems with Global Warming: The Case of the California Current System. *Scientific Reports, 8,* Article No. 2866. https://doi.org/10.1038/s41598-018-21247-7

Xue, L., Xue, M., Zhang, L., Sun, T., Guo, Z., & Wang, J. (2012). Surface Partial Pressure of CO_2 and Air-Sea Exchange in the Northern Yellow Sea. *Journal of Marine Systems, 105-108,* 194-206. https://doi.org/10.1016/j.jmarsys.2012.08.006

Yoshikawa Inoue, H., Matsueda, H., Ishii, M., Fushimi, K., Hirota, M., Asanuma, I. et al. (2017). Long-Term Trend of the Partial Pressure of Carbon Dioxide ($p$$CO_2$) in Surface Waters of the Western North Pacific, 1984-1993. *Tellus B: Chemical and Physical Meteorology, 47,* 391-413. https://doi.org/10.3402/tellusb.v47i4.16057

Yoshikawa-Inoue, H., Midorikawa, T., & Takamura, T. (2014). Temporal and Spatial Variations in Carbonate System and Air-Sea CO_2 Flux in the Kuroshio and Kuroshio Extension. In M. Uematsu, Y. Yokouchi, Y. W. Watanabe, S. Takeda, & Y. Yamanaka (Eds.), *Western Pacific Air-Sea Interaction Study* (pp. 151-161). TERRAPUB. https://doi.org/10.5047/w-pass.a02.004

Zaytsev, O., Cervantes-Duarte, R., Montante, O., & Gallegos-Garcia, A. (2003). Coastal Upwelling Activity on the Pacific Shelf of the Baja California Peninsula. *Journal of Oceanography, 59,* 489-502. https://doi.org/10.1023/A:1025544700632

Zhai, W., Dai, M., Cai, W.-J., Wang, Y., & Hong, H. (2005). The Partial Pressure of Carbon Dioxide and Air-Sea Fluxes in the Northern South China Sea in Spring, Summer and Autumn. *Marine Chemistry, 96,* 87-97. https://doi.org/10.1016/j.marchem.2004.12.002