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Research papers

Remote estimation of surface pCO_2 on the West Florida Shelf

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A R T I C L E I N F O

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A B S T R A C T

Surface pCO_2 data from the West Florida Shelf (WFS) have been collected during 25 cruise surveys between 2003 and 2012. The data were scaled up using remote sensing measurements of surface water properties in order to provide a more nearly synoptic map of pCO_2 spatial distributions and describe their temporal variations. This investigation involved extensive tests of various model forms through parsimony and Principal Component Analysis, which led to the development of a multi-variable empirical surface pCO_2 model based on concurrent MODIS (Moderate Resolution Imaging Spectroradiometer) estimates of surface chlorophyll *a* concentrations (CHL, mg m^{-3}), diffuse light attenuation at 490 nm (Kd_Lee, m^{-1}), and sea surface temperature (SST, °C). Validation using an independent dataset showed a pCO_2 Root Mean Square Error (RMSE) of < 12 µatm and a 0.88 coefficient of determination (R^2) for measured and model-predicted pCO_2 ranging from 300 to 550 µatm. The model was more sensitive to SST than to CHL and Kd_Lee, with a 1 °C change in SST leading to a ~16 µatm change in the predicted pCO_2. Application of the model to the entire WFS MODIS time series between 2002 and 2014 showed clear seasonality, with maxima (~450 µatm) in summer and minima (~350 µatm) in winter. The seasonality was positively correlated to SST (high in summer and low in winter) and negatively correlated to CHL and Kd_Lee (high in winter and low in summer). Inter-annual variations of pCO_2 were consistent with inter-annual variations of SST, CHL, and Kd_Lee. These results suggest that surface water pCO_2 of the WFS can be estimated, with known uncertainties, from remote sensing. However, while the general approach of empirical regression may work for waters from other areas of the Gulf of Mexico, model coefficients need to be empirically determined in a similar fashion.

1. Introduction

Atmospheric CO_2 has increased by 40% since the industrialization era (Sabine et al., 2004; Solomon et al., 2007). Correspondingly, oceanic uptake of CO_2 has resulted in ocean acidification and decreased surface water pH (by ~0.1 units) (Sun et al., 2012; Pachauri and Meyer, 2014), leading to ecological degradation and a decrease of marine biodiversity (Widdicombe and Spicer, 2008; Orr et al., 2005; Feely et al., 2012). Due to large spatial and temporal variations in surface water CO_2 partial pressure (pCO_2), the magnitude and even the sign of air/sea CO_2 fluxes can be highly variable (Takahashi et al., 2002, 2009, 2014; Sarma, 2003; Borges et al., 2005; Hofmann et al., 2011; Sarma et al., 2012; Chen et al., 2013; Wanninkhof et al., 2013). Accurate knowledge of surface pCO_2 distributions is therefore essential to quantify the ocean's role in carbon cycling.

A large number of studies have used field measurements to estimate air-sea CO_2 fluxes for both the open ocean and coastal sites (e.g., Takahashi et al., 2002, 2009, 2014; Tseng et al., 2011; Jiang et al., 2008; Geilfus et al., 2012; Vandemark et al., 2011; Zhai et al., 2005). However, direct field observations are often limited in spatial and temporal coverage. While numerical models have also been used to estimate surface pCO_2 (e.g., Xue et al., 2014; Arruda et al., 2015), model results are strongly influenced by assumed initial conditions and can also be highly model-specific. In contrast, satellite remote sensing can provide frequent synoptic assessments of surface ocean properties, and in view of recent advances in surface pCO_2 algorithm development (e.g., Ono et al., 2004; Sarma et al., 2006; Jamet et al., 2007; Telszewski et al., 2009; Hales et al., 2012; Nakaoka et al., 2013; Signorini et al., 2013; Bai et al., 2015), there is potential for the use of satellite remote sensing to augment direct field assessments of air/sea CO_2 fluxes. Nevertheless, except for two studies that focused on nearshore waters off the Mississippi River delta (Lohrenz and Cai, 2006; Lohrenz et al., 2010), such remote sensing approaches have rarely been applied to major ocean basins such as the Gulf of Mexico (GOM), a semi-enclosed sea of environmental and economic importance.

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Nomenclature

CDIAC	Carbon Dioxide Information Analysis Center
CHL	Chlorophyll-a Concentration
GOM	Gulf of Mexico
Kd_Lee	Diffuse light attenuation coefficient at 490 nm
LC	Loop Current
MB	Mean Bias
MLR	Multi-variate Linear Regression
MNR	Multi-variate Nonlinear Regression
MODIS	Moderate Resolution Imaging Spectroradiometer
MR	Mean Ratio
PCA	Principle Component Analysis
PCR	Principle Component Regression
RMSE	Root Mean Square Error
SSS	Sea Surface Salinity
SST	Sea Surface Temperature
USGS	U.S. Geological Survey
WFS	West Florida Shelf

With a surface area of 1.6 million km^2, the GOM encompasses the West Florida Shelf (WFS), Louisiana Shelf, Texas Shelf, Mexican Shelf, and the open Gulf (Robbins et al., 2009; Coble et al., 2010). As one of the most productive areas for fisheries in the world, it is essential habitat for numerous fish and wildlife species, and is likely to be strongly impacted by ocean acidification (Cai, et al., 2011; Wanninkhof et al., 2015). Thus, it is important to quantify the role of the GOM in modulating CO_2 flux (Takahashi et al., 2009). Based on field measurements, Takahashi et al. (2009) estimated the GOM as a CO_2 source with a net flux of about 0.21 mol C/m^2/year. However, with additional field observations, Robbins et al. (2014) reported that the GOM is a CO_2 sink with a net flux near −0.19 mol C/m^2/year. Using a 3-dimensional numerical model, Xue et al. (2014) estimated the GOM as a sink with a flux of −0.84 mol C/m^2/year. Clearly, such discrepancies necessitate additional studies to better quantify CO_2 flux, and synoptic mapping of surface pCO_2 should play an important role. In particular, with continuous surface pCO_2 collections in the GOM in recent years (see below for data sources), the application of satellite remote sensing can strongly contribute to a better understanding of surface pCO_2 distributions and CO_2 flux.

Within the GOM, of particular importance is the WFS between 24–31 °N and 80–85 °W (Fig. 1). The WFS is a broad carbonate-based shelf with a width of 220–275 km and a gentle slope, influenced by the Loop Current (LC) system as well as upwelling, river discharge, blooms of both harmful and non-harmful algae, summer and winter storms, and groundwater influx (Jolliff et al., 2003; Weisberg and He, 2003; Hu et al., 2005; Hu et al., 2006; Walsh et al., 2006; Benway and Coble, 2014). Although the GOM is typically characterized as being oligotrophic, the WFS is one of the most productive continental shelves in the United States, supporting numerous fisheries and diverse organisms (Saul et al., 2013; Chagaris et al., 2015). As one of the broadest continental shelves of United States (He and Weisberg, 2002), the WFS may play a big role in modulating CO_2 flux in the GOM, and knowledge of synoptic surface pCO_2 distributions as well as their temporal changes can help to quantify air-sea CO_2 fluxes, biochemical and ocean acidification processes. However, despite significant efforts to collect surface pCO_2 data through numerous ship surveys, and one study (Xue et al., 2014) to model pCO_2 variability on the Louisiana Shelf and the GOM as a whole, little information is available for the WFS.

The objectives of this study are thus two-fold: (a) development of a remote sensing model to scale up ship-based surface pCO_2 observations in order to take advantage of the more synoptic and frequent remote sensing observations for the WFS, and (b) application of the model to long-term remote sensing data to examine spatial-temporal distributions of surface pCO_2 on the WFS. The present work is directed toward bridging knowledge gaps by providing, for the first time, monthly pCO_2 distribution maps at medium resolution (1-km) and their temporal variations on the WFS.

2. Data and methods

2.1. A brief review of pCO_2 remote sensing

While the details of different methods to estimate surface pCO_2

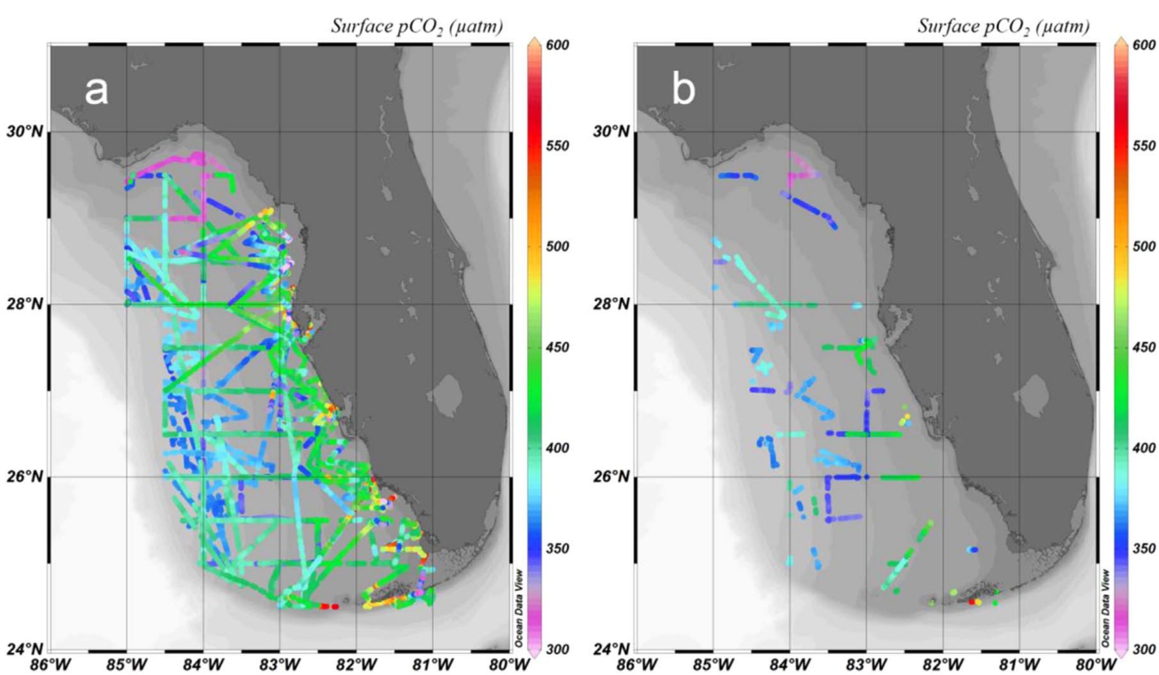

Fig. 1. (a) Spatial distributions of the field-measured pCO_2 along the ship transects (Table 2). (b) The same field data where near-concurrent (± 6 h) high-quality MODIS data exist.

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