Variability in Satellite Algorithms for Regional Assessments of pCO$_2$

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INTRODUCTION

Carbon dioxide (CO_2) is the major currency during biological production or destruction of organic matter (OM) and is the dominant greenhouse gas. Atmospheric CO_2 is fixed into biomass in the land and is subsequently transported via rivers into the ocean where it may be metabolized back to inorganic carbon and either released back to the atmosphere or exported into the deep ocean. Thus CO_2 flux between the atmosphere and the ocean is a critical variable in global carbon cycle models. An argument can be made that increasing terrestrial inputs associated with land use change, increasing discharge of sewage and other anthropogenic materials, and changes in the terrestrial hydrological cycle would tend to shift the coastal oceans in particular toward being a source of CO_2. Margin ecosystems receive massive inputs of terrestrial organic and mineral matter and exhibit intense geochemical and biological processing of carbon and other elements. In addition, they exchange large amounts of matter and energy with the open ocean. The complex and variable nature of coastal margins poses significant challenges to efforts to characterize the carbon signals in these regions.

Fig. 1. The Mississippi-Atchafalaya River basin drains approximately 41% of the conterminous U.S. (3.21x10^6 km^2; the third largest among the world major rivers) and carries approximately 65% of all the suspended solids and dissolved solutes that enter the ocean from the U.S., and effectively injects these materials onto the continental shelf as a point source in the northern Gulf of Mexico, causing significant influence on the environmental conditions (such as the wide spread hypoxia under the plume) and carbon cycle.

A series of recent syntheses highlight the lack of information about the northern Gulf of Mexico (e.g., Borges et al. 2005; Cai et al., 2006; Chavez and Takahashi, 2006) highlight the need for additional data regarding carbon fluxes in the Gulf of Mexico.

Satellite-based regional approaches (e.g., Lefevre et al., 2002; Ono et al., 2003; Olsen et al., 2004; Lohrenz and Cai, 2006) can be used to extend the spatial and temporal coverage for broad scale assessments of pCO$_2$ distributions and air-sea fluxes of CO_2.

Initial studies in June 2003 (Lohrenz and Cai, 2006) revealed regions of low pCO$_2$ near the river plume, which indicated net uptake in those regions (Fig. 2). Overall, for the region encompassed by the entire image, there was a net surface in-water flux estimated at 2.0 – 4.2 mmol C m^2 d^{-1}. A key question will be the degree to which satellite imagery can be used to provide regional assessments of carbon system properties over regional spatial scales and seasonal time scales. This will depend on the extent to which algorithms can be generalized beyond a single set of in situ observations.

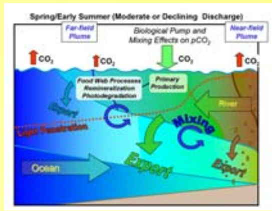


Fig. 2. Conceptual representation of major plume processes and hypothetical relationships to air-sea fluxes of CO_2.

We examined this question by comparing principal component loadings and regression coefficients for four different periods. We have employed a combined strategy of ship-based and satellite observations to provide spatial and temporal coverage for broad scale assessments of pCO2 distributions and air-sea fluxes of CO2. The primary objective of our research is to apply these approaches to the characterization of pCO2 and air-sea fluxes of CO2 in the river influenced margin of the northern Gulf of Mexico.

METHODS

We have developed and implemented an algorithm for assessment of areal distributions of pCO$_2$ from MODIS imagery in the northern Gulf of Mexico based on empirical relationships of in situ measurements of surface pCO$_2$ to environmental variables (*Fig. 5*). Principal component analysis was applied to the T, S and chlorophyll data and regressed the derived orthogonal components against pCO$_2$ to produce an empirical algorithm for the estimation of pCO$_2$. MODIS-Aqua L1B data were processed using SeaDAS and sea-surface temperature (SST), chlorophyll (OC4 algorithm) and dissolved/detrital absorption (Garver-Siegel-Maritorena version 1, acdm_gsm01) products were retrieved. To provide an estimate of salinity, we used previously determined relationships between CDOM absorption (a_{CDOM}) and salinity for the Mississippi delta region (salinity = $-10.4a_{CDOM}^2 - 9.90a_{CDOM} + 34.9$, $r^2 = 0.911$).

RESULTS

Studies were conducted in August 2004, October 2005, and April 2006 spanning a range of seasonal and river discharge conditions (Fig. 3). Estimates of pCO$_2$ from PCA-derived empirical algorithms showed strong correlations between measured and predicted pCO$_2$ (Fig. 4). R-squared values were 0.927 in August 2004, 0.974 in October 2005, and 0.897 in April 2006. The empirical algorithms were used to produce the pCO$_2$ images (Fig. 5).

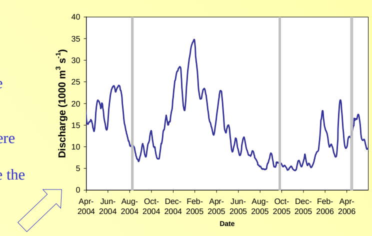


Fig. 3. Mississippi River stage determined at Baton Rouge, LA (data courtesy of USGS). Gray lines indicate cruise periods. River stage is typically high in spring and early summer and declines into the fall.

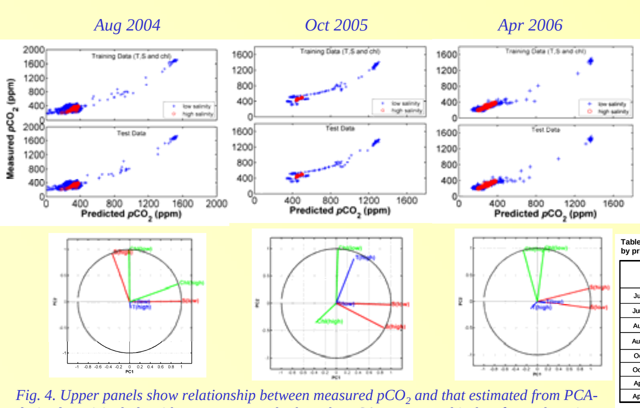


Table 1. Percentage variation accounted for by principal component variables.

	PC1 % Variation Explained	PC2 % Variation Explained
Jun 2003 (low)	84.8	14.4
Jun 2003 (high)	89.3	9.21
Aug 2004 (low)	77.2	21.7
Aug 2004 (high)	74.2	24.8
Oct 2005 (low)	94.0	5.87
Oct 2005 (high)	91.9	7.19
Apr 2006 (low)	77.7	12.0
Apr 2006 (high)	91.8	8.11

Fig. 4. Upper panels show relationship between measured pCO$_2$ and that estimated from PCA-derived empirical algorithms. Lower panels show the PCA component bi-plots for each cruise period. Percentage variation accounted for by each component is given in Table 1.

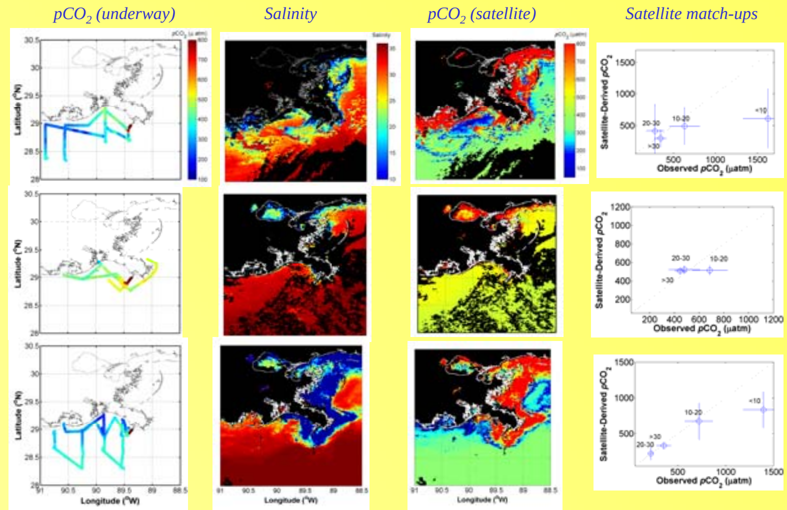


Fig. 5. Scatter plots of pCO$_2$ from underway shipboard surveys illustrate temporal and spatial variation in pCO$_2$. The strong influence of freshwater inputs is evident in the comparison between satellite-derived salinity and pCO$_2$ maps. Match-ups between satellite and in situ pCO$_2$ are shown in the right column binned by salinity range. Satellite-derived pCO2 generally underestimated values at low salinities but performed better at mid- to high salinities.

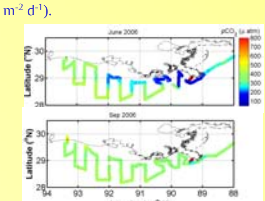
Table 2. Annual sea to air flux of CO_2 in the Mississippi River outflow region (mmol C m^{-2} d^{-1})

Date	Sea to air flux of CO_2
Jun 2003	-3.7 - -4.2
Aug 2004	14 - 18
Oct 2005	84 - 127
Apr 2006	84 - 200

Satellite-derived regional assessments of pCO$_2$ were used in conjunction with estimates of wind fields to produce regional-scale estimates of air-sea fluxes. Various sets of the gas transfer velocity, k, vs. wind speed relationships (Wanninkhof and McGillis, 1999; Nightingale et al., 2000; McGillis et al., 2001) were used to provide a range of values bracket the gas flux.

In contrast to the net uptake of CO_2 in June, air-sea flux estimates revealed a net release during all other cruises. October 2005 followed two major storm events (Katrina and Rita) accompanied by coastal flooding. Fluxes were also high during April 2006, due to a combination of high pCO$_2$ in the nearshore waters and high winds. Winds during both the October and April surveys were high (~12-15 m s^{-1}). These estimates are driven to a large extent by high values in the estuaries and inner shelf regions as seen in Fig. 5 and these regions represent a tremendous source of uncertainty in coastal carbon budgets.

Measured rates of sea-to-air flux for the river outflow region were comparable to those reported for other coastal studies including Friederich et al. (2002) for a coastal upwelling region in S. California(-22 to 140 mmol C m^{-2} d^{-1}), Hales et al. (2005) for a coastal upwelling off Oregon (-20 mmol C m^{-2} d^{-1}), Chavez and Takahashi (2006) for the Gulf of Mexico and Carribean (2.2$\pm$5.5 mmol C m^{-2} d^{-1}) and Cai et al. (2006) for low latitude western boundary current shelves (2.7$\pm$1.1 mmol C m^{-2} d^{-1}).



More recent surveys of the northern Gulf have extended over a larger area and similarly reveal evidence of a strong biological pump in June 2006 resulting in lower levels of surface pCO$_2$. The biological pump appeared to be less active in September 2006, which could likely be attributed to relatively low river discharge and correspondingly low rates of autotrophic carbon fixation.

Fig. 6. Surface water pCO2 (ppmv) mapping during June and September 2006.

CONCLUSIONS

Our findings suggest the late spring and early summer is a period of lower surface pCO$_2$ corresponding to a strong biological pump and autotrophic fixation of inorganic carbon. Other key environmental drivers appear to be seasonal variations in temperature and freshwater discharge. Algorithms relating surface pCO$_2$ to environmental variables, for example, as can be retrieved from satellite imagery, will necessarily have to account for such changes in system properties. This effort will benefit from more extensive in situ data, including ship-based surveys and moored time-series.

More information is needed over a larger region in the Gulf of Mexico and other coastal regions to better constrain CO_2 fluxes at the continental margins. Such information should help to refine models estimating North American carbon fluxes and improve their performance for predicting change and management strategies. *More extensive spatial and temporal resolution of patterns is needed.* Future studies funded through NASA and NSF are in the initial stages and

ACKNOWLEDGEMENTS

MODIS image data were provided by the NASA-GSFC DAAC. Funding was provided by NASA (NNG04GA02G and NNS04AB84).

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