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Randal D. Koster, Editor

The Effects of Chlorophyll Assimilation on Carbon Fluxes in a Global Biogeochemical Model

Cécile S. Rousseaux and Watson W. Gregg

National Aeronautics and
Space Administration

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Abstract

In this paper, we investigated whether the assimilation of remotely-sensed chlorophyll data can improve the estimates of air-sea carbon dioxide fluxes (FCO_2). Using a global, established biogeochemical model (NASA Ocean Biogeochemical Model, NOBM) for the period 2003-2010, we found that the global FCO_2 values produced in the free-run and after assimilation were within -0.6 mol C m^{-2} y^{-1} of the observations. The effect of satellite chlorophyll assimilation was assessed in 12 major oceanographic regions. The region with the highest bias was the North Atlantic. Here the model underestimated the fluxes by 1.4 mol C m^{-2} y^{-1} whereas all the other regions were within 1 mol C m^{-2} y^{-1} of the data. The FCO_2 values were not strongly impacted by the assimilation, and the uncertainty in FCO_2 was not decreased, despite the decrease in the uncertainty in chlorophyll concentration. Chlorophyll concentrations were within ~25% of the database in 7 out of the 12 regions, and the assimilation improved the chlorophyll concentration in the regions with the highest bias by 10-20%. These results suggest that the assimilation of chlorophyll data does not considerably improve FCO_2 estimates and that other components of the carbon cycle play a role that could further improve our FCO_2 estimates.

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Introduction

Every year, approximately 90 gigatons of carbon are exchanged between the atmosphere and the ocean (Falkowski et al., 2000). Ocean sinks account for ~half of the anthropogenic CO_2 emissions (Sabine et al., 2004). On longer time scales, deep-ocean export of carbon together with land-atmosphere exchanges plays an important role and is expected to be the dominant sink of anthropogenic carbon. In the subtropical ocean (~40°N and S), water loses heat to the atmosphere and consequently takes up CO_2 from the atmosphere (Takahashi et al., 2009). Inversely to the effect of temperature on pCO_2, the phytoplankton community takes up CO_2 and thrives in nutrient-rich (e.g. recently upwelled) water, thereby counteracting and in some cases overwhelming the effects of recently cold, CO_2-rich, upwelled water. The air-sea CO_2 fluxes in high latitude oceans are governed primarily by deep convection in winter and biological uptake during spring and summer. At lower latitudes the warm water increases pCO_2 in the ocean and leads to a loss of CO_2 to the atmosphere. Process-based understanding of ocean carbon cycle is needed to predict future variations in the efficacy of the oceanic carbon sink.

Takahashi et al. (2002) amassed ~1 million surface pCO_2 observations and used these to derive air-sea CO_2 fluxes for a nominal year, namely, 1995 (Takahashi et al., 2002). Uncertainties about these fluxes are directly linked to the spatial and temporal coverage of the measurements as well as the relationship between wind speeds on air-sea CO_2 gas transfer velocity. Others have used biogeochemical models of different level of complexity, whether local or global, to estimate the source and sinks of CO_2. Gregg et al. (2013) used MERRA reanalysis data to force an ocean biogeochemical model (NASA Ocean Biogeochemical Model, or NOBM) and compared the fluxes obtained with those from public archives. The model produced global mean differences of 0.02% (~0.3 µM) for Dissolved Organic Carbon (DIC), -0.3% (-1.2 µatm) for pCO_2 and -2.3% (-0.03 mol C m^{-2} y^{-1}) for FCO_2 compared to in situ estimates. Basin-scale distributions of all three variables were significantly correlated with observations. They found that the regions with the largest differences between the carbon dioxide fluxes from the model and the observations were in the South Atlantic, South Pacific, North Indian, Equatorial Atlantic and North Pacific.

Despite some considerable basin-scale and local departures, they found that all basins were represented as sources to the atmosphere or sinks in agreement with in situ estimates.

Data assimilation techniques can be used to constrain the model to track observation time series and to optimize certain variables. The assimilation of satellite chlorophyll is known to reduce spatial and temporal biases of satellite data. The assimilation of satellite chlorophyll produces estimates within 0.1% bias and 33.4% uncertainty as compared to in situ data (Gregg, 2008) thereby decreasing the bias of satellite data (-1.3%) while keeping the same level of uncertainty (32.7%, Gregg, 2008). Using twin experiments, Tjiputra et al. (2007) assimilated SeaWiFS chlorophyll in an adjoint model and found that the model-data misfit was reduced and that the posteriori run produced realistic carbon flux prediction. Similarly, using 1-D twin experiments for two contrasting locations in the North Atlantic, Hemmings et al. (2008) found that the assimilation of ocean color improved surface pCO_2. Here we investigate whether the assimilation of satellite-derived chlorophyll *a* data can improve carbon dioxide fluxes estimates using a global biogeochemical model that assimilates satellite-derived chlorophyll. We assess the effects of chlorophyll data assimilation on carbon dioxide fluxes globally and in 12 major oceanographic regions (Figure 1) for the period from 2003 until 2010.

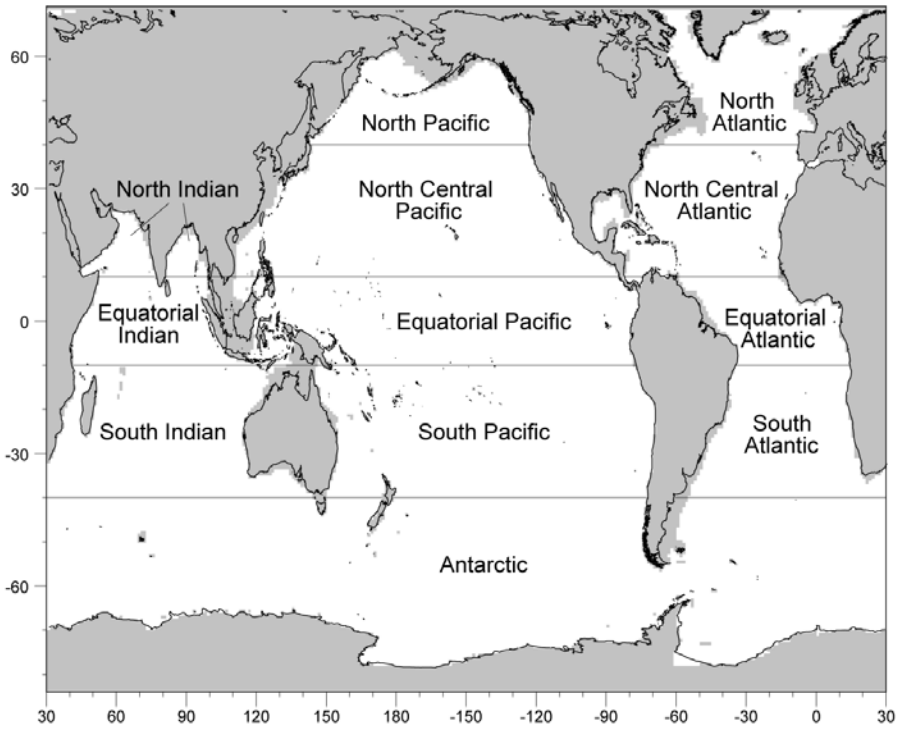

Figure 1: Delineation of the 12 major oceanographic basins.

2. Methods

Global ocean carbon dynamics were simulated using the NASA Ocean Biogeochemical Model (NOBM) for the period 2003-2010. NOBM is a three-dimensional representation of circulation/biogeochemical/radiative processes in a domain that spans from -84° to 72° at a 1.25° resolution in water deeper than 200 m. NOBM is coupled with the Poseidon ocean general circulation model, which is driven by wind stress, sea surface temperature, and shortwave radiation (Gregg and Casey, 2007). The model includes 3 detrital pools (silica, N/C and iron detritus), 4 phytoplankton groups (diatoms, coccolithophores, chlorophytes and cyanobacteria) and 4 nutrients (ammonium, nitrate, iron and silicate). The phytoplankton groups differ in their maximum growth rates, sinking rates, nutrient requirements, and optical properties.

Carbon cycling involves dissolved organic carbon (DOC) and dissolved inorganic carbon (DIC). DOC has sources from phytoplankton, herbivores, and carbon detritus, and a sink to DIC. DIC has sources from phytoplankton, herbivores, carbon detritus, and DOC, and it can be exchanged with the atmosphere, which serves as either a source or a sink. The ecosystem sink

for DIC is phytoplankton, through photosynthesis. A complete description of the model can be found in Gregg et al. (2013). The main output of interest in this effort is the flux of CO_2 (FCO_2 , notation following Arrigo et al., 2010; Doney et al., 2009), representing the exchange of carbon between the atmosphere and ocean. Positive is defined upward, indicating a source to the atmosphere. The fluxes from the model are compared to a data set obtained from the Lamont-Doherty Earth Observatory (LDEO)

(http://cdiac.ornl.gov/oceans/LDEO_Underway_Database/index.html; Takahashi et al., 2009). These in situ LDEO data use pCO_2 and estimate fluxes from wind speed reanalysis data and climatological nutrients from the National Oceanographic Data Center (Takahashi et al., 2009).

The model is initialized with DIC from GLODAP (GLobal Ocean Data Analysis Project) and is spun up with climatological forcing data from MERRA and atmospheric pCO_2 data from NOAA ESRL for the year 2000 (368.6 µatm). The model is spun up for 200 years to remove residual trends from the model and produce a steady state (Gregg et al., 2013). It is then run from 2003 to 2010 using time-varying forcing data from MERRA and atmospheric pCO_2 for each year from NOAA ESRL. A concurrent run utilizes MODIS Aqua chlorophyll data in assimilation mode (Gregg, 2008). Multi-variate nutrient adjustments corresponding to the chlorophyll assimilation (Rousseaux and Gregg, 2012) are also included in this latter run. The fluxes derived from a free-running simulation (hereafter referred to as free-run) model are compared to those from the run with MODIS Aqua chlorophyll data assimilation and to the estimates from Takahashi et al. (2009). The chlorophyll concentrations from both the free-run and after assimilation are compared to the Level 3 MODIS Aqua chlorophyll data.

3. Results

3.1 Chlorophyll Comparisons with Data

The correlation coefficients between satellite-derived chlorophyll and chlorophyll from the model increased considerably after assimilation. The correlation coefficients for the free-run ranged over the years from 0.54 to 0.69, whereas those for the assimilation run ranged from 0.84 to 0.96 (Figure 2). The correlation between satellite chlorophyll concentration and chlorophyll concentration from the model (from either run) was significant for all years between 2003 and 2010.

Chlorophyll concentrations were within ~25% of the satellite chlorophyll in seven of the 12 regions (Figure 3). The regions with the highest biases (>30%, both in free-run and after assimilation) were the North Indian, North Pacific and North Atlantic. In those regions, where the bias was high, the assimilation marginally improved the chlorophyll concentration (by 10-20%, Figure 4). Note that these regions also correspond to where the highest chlorophyll concentration was encountered (~0.55 µg chl L^{-1}).

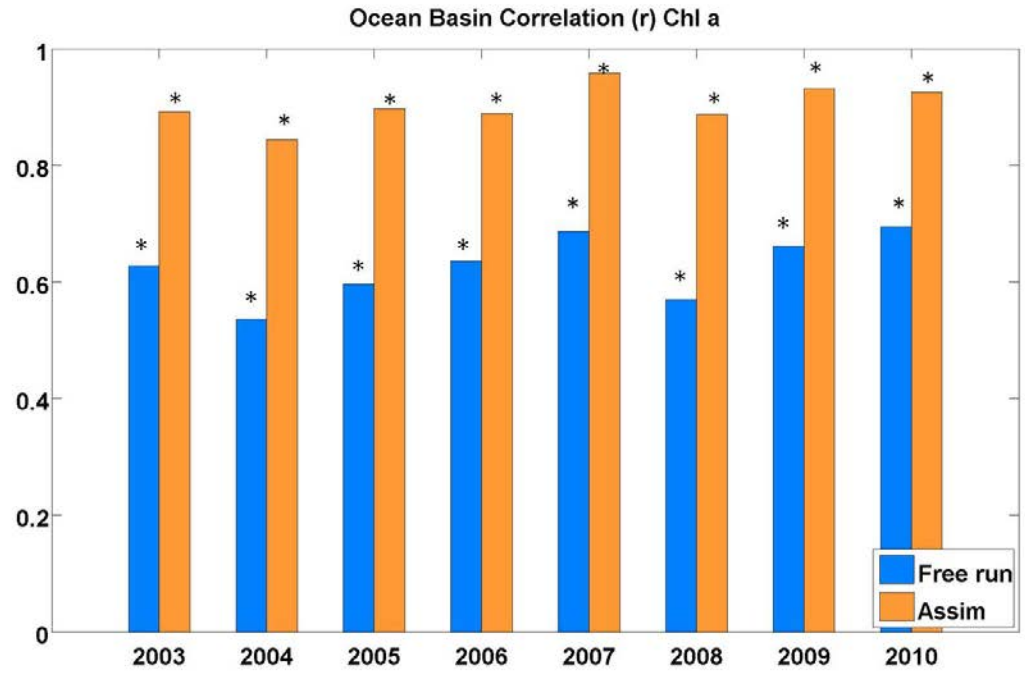

Figure 2: Ocean Basin Correlation between the satellite-based estimates of chlorophyll and both the free-run and the assimilation values over the different ocean basins. (*) indicates statistical significance ($p < 0.05$), NS = not significant.

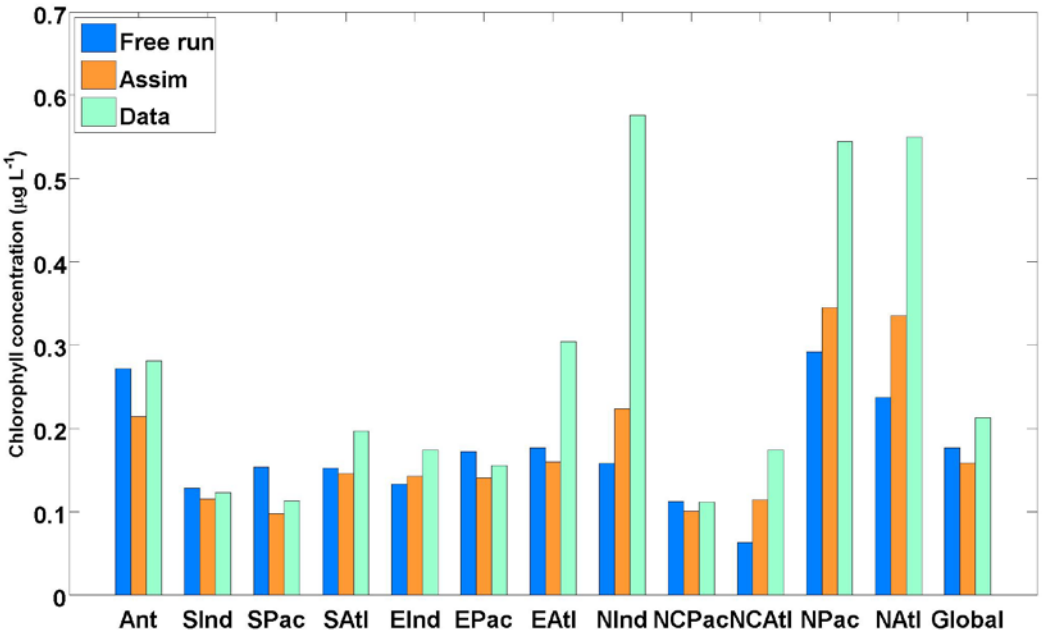

Figure 3: Chlorophyll concentrations for the free-run, the assimilation run, and the satellite database, globally and in the twelve major oceanographic regions.

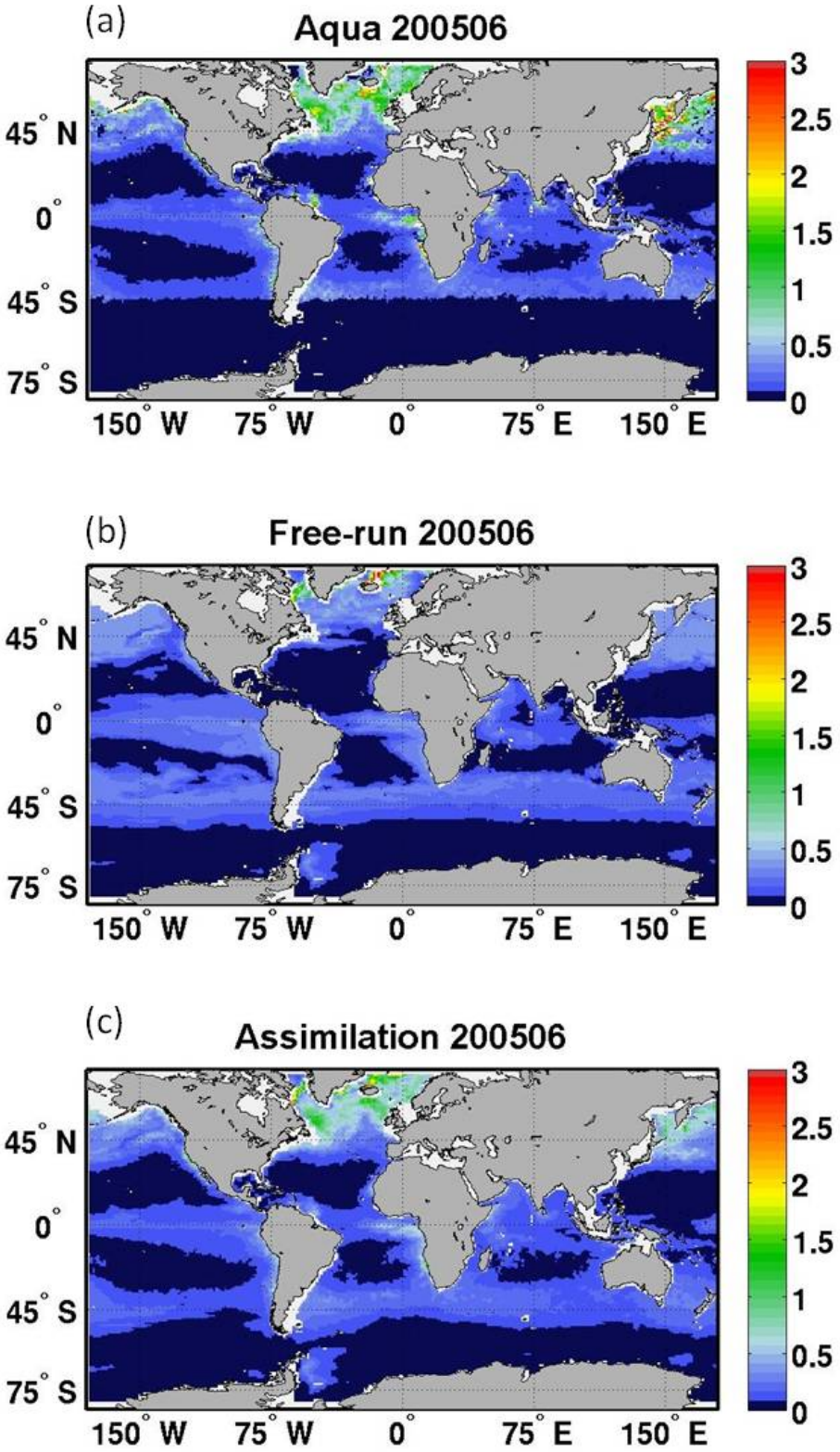

Figure 4: Map of Chlorophyll concentration (µg chl L^{-1}) in June 2005 for (a) MODIS Aqua, (b) Free-run and (c) after assimilation of the MODIS Aqua satellite data.

3.2 FCO_2 Comparisons with Data

Globally and regionally, we found that the fluxes were not greatly impacted by the assimilation of satellite chlorophyll (Figure 5 and Figure 6). In nine out of the twelve regions, the difference between the fluxes from the free-run and those after assimilation was less than 0.1 mol C m^{-2} y^{-1}. The three regions where these differences were greater than 0.1 mol C m^{-2} y^{-1} were the North Central Atlantic, South Pacific and South Indian. In the southern basins the assimilation run produced the more biased flux estimates, though the increase in bias was small (Figure 5 and Figure 6).

Globally the fluxes produced by the free-run and after assimilation were -0.25 mol C m^{-2} y^{-1}, which represents an underestimate of FCO_2 by ~0.6 mol C m^{-2} y^{-1} (Figure 5). The region with the greatest difference between the data and modeled FCO_2, for both runs, was the North Atlantic, where the model underestimated the fluxes by 1.4 mol C m^{-2} y^{-1}. All the other regions were within ~1 mol C m^{-2} $y^{-1}$of the data. In the North Atlantic, the assimilation improved the FCO_2 by a marginal 0.04 mol C m^{-2} y^{-1}. In general the fluxes produced by the model were weaker than the in situ estimates (Figure 5). This was especially true in the regions north and south of 10°.

The regions that served as the highest sinks and sources of FCO_2 were the same before and after assimilation. For both runs, the region with the highest FCO_2 sink was the North Atlantic (~-0.7 mol C m^{-2} y^{-1}) followed by the South Atlantic (~-0.6 mol C m^{-2} y^{-1}). Of the twelve major regions, only two (Equatorial Indian and Equatorial Pacific) were a source of CO_2 (FCO_2 of 0.05 and 0.26 mol C m^{-2} y^{-1}). The Equatorial Pacific also became a source of CO_2 after assimilation (0.24 mol C m^{-2} y^{-1}), but the FCO_2 in the Equatorial Indian became slightly negative after the assimilation (-0.003 mol C m^{-2} y^{-1}). The Equatorial Atlantic and North Indian were the only two regions for which the fluxes from the database were positive but the FCO_2 produced by the model in both the free-run and assimilation were negative.

The assimilation of chlorophyll did not decrease the uncertainty in FCO_2 (Figure 7). There was a significant correlation between modeled FCO_2 and the fluxes from the database for six out of the eight years analyzed, namely, 2003-2008. Correlation coefficients for these six years were a minimum of 0.72 for the free-run and a minimum of 0.76 for the assimilation run. The correlation between the data and the model at regional levels was highly dependent on the number of observations available. In 2009 and 2010, when the number of months of available

data dropped to 7 and 4, the correlation was no longer significant. Out of the six years for which significant correlations were found, the correlation coefficients for the assimilation run were only slightly improved over those in the free-run for three years.

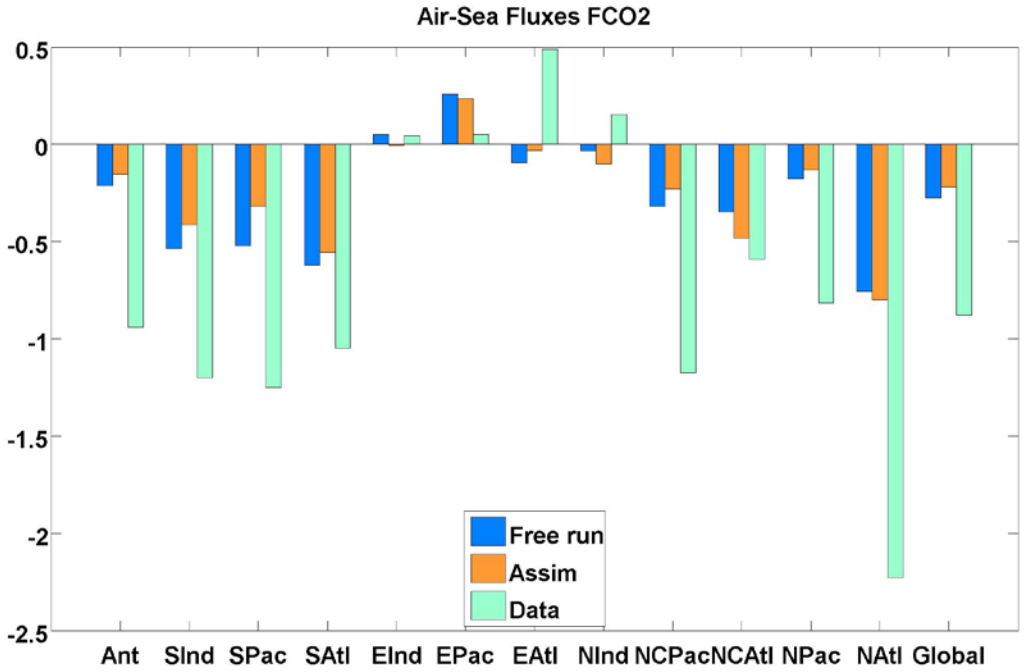

Figure 5: Air-Sea fluxes (mol C m^{-2} y^{-1}) for the free-run, the assimilation run, and the database globally and in the twelve major oceanographic regions.

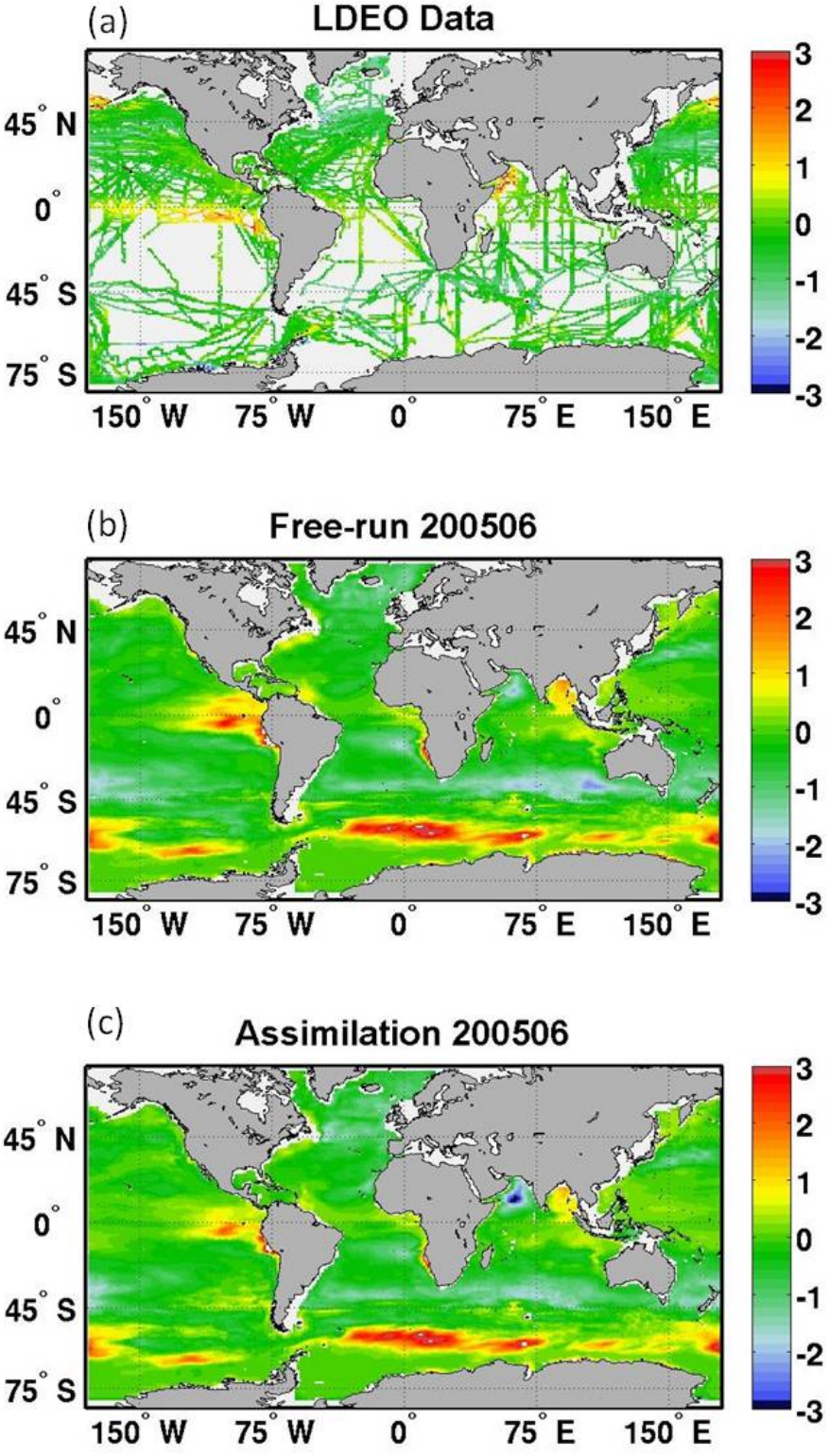

Figure 6: Map of FCO_2 (mol C m^{-2} y^{-1}) from (a) the LDEO database, (b) the free-run and (c) after assimilation of satellite chlorophyll for June 2005.

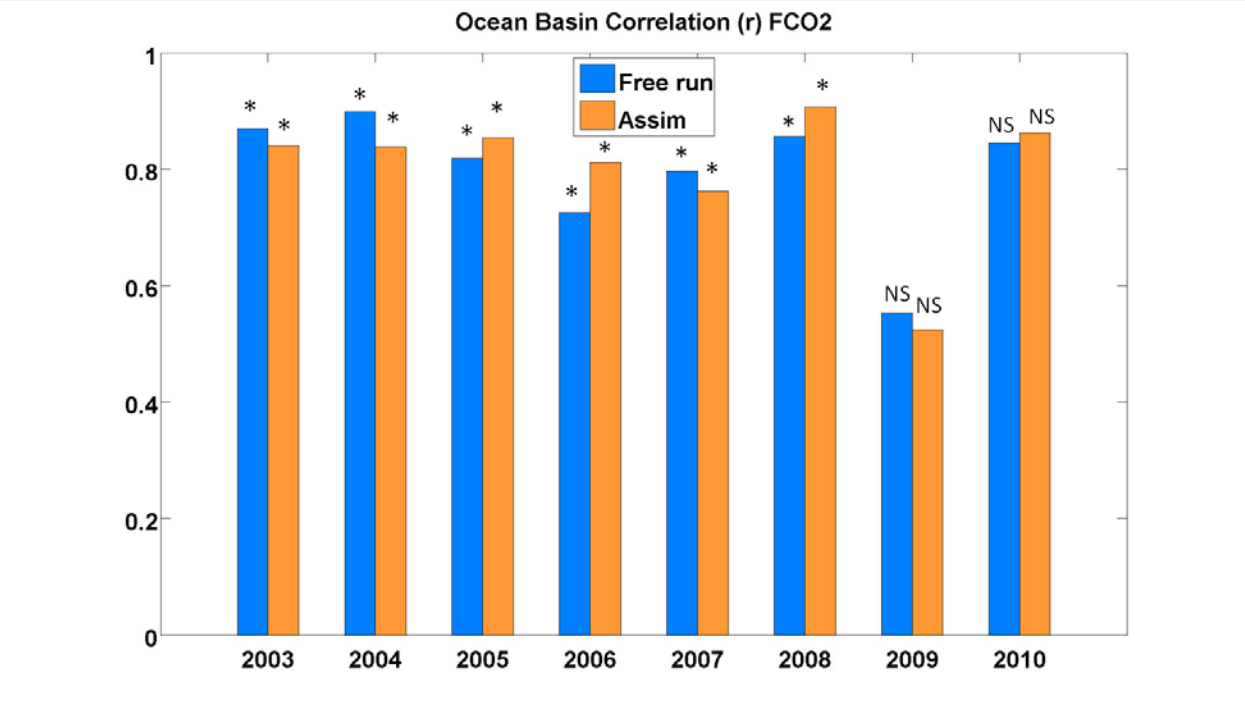

Figure 7: Correlation between the satellite database of FCO_2 and the FCO_2 values produced in the free-run and after assimilation. (*) indicates statistical significance ($p < 0.05$), NS = not significant.

4. Discussion

The assimilation of satellite chlorophyll in NOBM was shown to decrease the uncertainties in chlorophyll concentration but to have little impact on simulated FCO_2. The regions where the highest biases in FCO_2 were found (North Indian, North Pacific and North Atlantic) were not improved by the assimilation. Note that these three regions also show the greatest bias in chlorophyll concentration. Monthly maps of chlorophyll concentration (not shown) in these three regions highlight the fact that the satellite-based estimates there are particularly high during specific times of the year. For example, in the North Pacific and North Atlantic, the satellite chlorophyll is considerably higher than the model during the spring and summer. Clouds are one of the largest sources of sampling error, especially in the North Pacific (Gregg and Casey, 2007). Here, even in the middle of the growing season, there can be <5 days of observations per month. The presence of these clouds can lead to overestimate in chlorophyll concentration that are driven by period of high growth that occur during limiting periods of clear skies suitable for

remote sensing. Gregg and Casey (2007) also reported biases due to clouds in the North Atlantic, although they noted that the overestimates tend to be smaller than in the North Pacific. The third region where bias is considerable is the North Indian. In this region, aerosols are known to contribute to sampling error (Gregg and Casey 2007). Aerosol obscurations increase before and during the Monsoon season, at the same time as does chlorophyll. In this study, we found that the satellite chlorophyll values were considerably higher than those produced by the model in either the free-run and assimilation only during the northeast monsoon (between November and February). Other sources of bias include sun glint, inter-orbit gap, and sensor tilt changes, all of which occur primarily in mid-latitudes (Gregg & Casey 2007).

The correlations between the FCO_2 values estimated from in situ measurements and those produced by the model in either the free-run model/assimilation were significant for the first six years of the study (2003-2008). The high correlation coefficients indicate a reasonably low uncertainty in our model-derived FCO_2. The correlation for FCO_2 was again not significant for 2009 and 2010 due to a lack of data in those years. No clear improvements in either correlation or bias resulted from the assimilation of satellite chlorophyll.

The North Atlantic was the region with the greatest difference between the observations-based data and the modeled FCO_2 (from either run). Although the biased sampling in satellite chlorophyll is likely to have played a role here, the limited effect the assimilation had on FCO_2 in other regions indicates that other processes may be responsible. Chlorophyll is only one of the several components in the ocean carbon system, and therefore modest changes from the assimilation are not unrealistic. Deficiencies in carbon cycling processes in the model are not ameliorated by the improved chlorophyll abundances and distributions associated with the satellite chlorophyll assimilation. In fact, the simulated fluxes can actually get worse through assimilation (e.g., in the southern basins, as shown in Figure 5). This is likely the result of compensating deficiencies in the free-run model, where flaws in the simulated biological components compensate flaws in the carbon components. The chlorophyll compensation corrects the estimates of chlorophyll but not the underlying biological processes, exposing the carbon cycling issues. It is not clear whether this issue is unique to our model formulation or whether it is, in fact, general. It is reassuring that the correlations between data estimates and models are significant when sufficient in situ data are available, but it is also disconcerting that the biases are large.

In conclusion, these results suggest that ocean carbon and biological systems are complex and that work is needed to improve their representations in models, independently and simultaneously. Data assimilation of chlorophyll is not a panacea for model deficiencies. The number of products that can be derived from satellite ocean color is increasing, and the assimilation of products other than chlorophyll may further improve the fluxes estimates. Finally, the regions with the highest biases are complex regions which further reinforce our need to improve, through combined satellite and modeling efforts, our understanding of the complex interactions underlying the global carbon cycle. Further sensitivity analyses are needed to detect the components of the ocean carbon system that, if modeled and quantified more accurately, can lead to improved FCO_2 estimates both regionally and globally.

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Appendix A: Acknowledgements

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