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# Sensitivity of simulated global ocean carbon flux estimates to forcing by reanalysis products

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ABSTRACT

Reanalysis products from MERRA, NCEP2, NCEP1, and ECMWF were used to force an established ocean biogeochemical model to estimate air–sea carbon fluxes ($FCO_2$) and partial pressure of carbon dioxide ($pCO_2$) in the global oceans. Global air–sea carbon fluxes and $pCO_2$ were relatively insensitive to the choice of forcing reanalysis. All global $FCO_2$ estimates from the model forced by the four different reanalyses were within 20% of in situ estimates (MERRA and NCEP1 were within 7%), and all models exhibited statistically significant positive correlations with in situ estimates across the 12 major oceanographic basins. Global $pCO_2$ estimates were within 1% of in situ estimates with ECMWF being the outlier at 0.6%. Basin correlations were similar to $FCO_2$. There were, however, substantial departures among basin estimates from the different reanalysis forcings. The high latitudes and tropics had the largest ranges in estimated fluxes among the reanalyses. Regional $pCO_2$ differences among the reanalysis forcings were muted relative to the $FCO_2$ results. No individual reanalysis was uniformly better or worse in the major oceanographic basins. The results provide information on the characterization of uncertainty in ocean carbon models due to choice of reanalysis forcing.


## 1. Introduction

The oceans play a critical role in the global carbon cycle. More than 90% of the active non-geological carbon pool resides in the oceans (Kaufman et al., 1998). Estimates of global primary production suggest that the oceans contribute about half (Field et al., 1998). One quarter (Le Quéré et al., 2010) of the carbon emitted by anthropogenic sources is thought to be sequestered in the oceans, annually. Understanding the role of the ocean in the global carbon cycle is a driving question in modern Earth science. It requires foremost a geographically-distributed, well-maintained observational capability. We are fortunate that such a capability exists or is in development, and that global data sets of ocean carbon inventories (Key et al., 2004), partial pressure of $CO_2$ (Takahashi et al., 2006, 2009) and ocean-atmospheric exchange (Takahashi et al., 2006, 2009) are publicly available.

Global ocean carbon models require external information to drive the ocean circulation dynamics that determine the distributions, abundances, and atmospheric exchange of carbon. Additionally, biological and chemical constituents that play important roles in the ocean carbon cycle are affected by ocean circulation. These forcing fields can be from a coupled atmosphere model or from atmospheric and ocean data. In the latter case, the data typically come from publicly available reanalysis products (e.g., Le Quéré et al., 2010; Gorgues et al., 2010; Doney et al., 2009). It is clear that different ocean models produce different estimates of air–sea fluxes (Khatiwala et al., 2013), but less effort has been given to the influences of different reanalysis products. These differences in reanalysis products and their potential effects on simulated ocean carbon distributions and trends have been cause for concern by ocean modelers (Le Quéré et al., 2010).

Here we intercompare model air–sea flux estimates and partial pressure of carbon dioxide ($pCO_2$) from a model forced by four reanalysis products. These include The Modern-Era Retrospective analysis for Research and Applications (MERRA; Rienecker et al., 2011), two from the National Center for Environmental Prediction (NCEP): NCEP2 (Kanamitsu et al., 2002) and NCEP1 (Kalnay et al., 1996), and one from the European Centre for Medium-range Weather Forecasts (ECMWF; Dee et al., 2011). This study provides an opportunity to evaluate how the differences in reanalysis products propagate through the same ocean biogeochemical model to affect representations of carbon fluxes and $pCO_2$.

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This effort is potentially important not only to ocean carbon modelers, but also for reanalysis developers and analysts, satellite mission conceptual designers, and atmospheric scientists as well. The objective of this study is to provide quantitative information on the spatial distributions of air–sea carbon fluxes and ocean $pCO_2$ globally, regionally, and sub-regionally in a model forced by the four state-of-the-art, widely used reanalysis products listed above. Such information can guide scientists and analysts in their selection, uses, and potential pitfalls of different reanalysis products in the context of ocean carbon models.

## 2. Material and methods

### 2.1. Global three-dimensional circulation model

Global ocean carbon dynamics are simulated by the NASA Ocean Biogeochemical Model (NOBM; Fig. 1). It is a three-dimensional representation of coupled circulation/biogeochemical/radiative processes in the global oceans (Gregg et al., 2003; Gregg and Casey, 2007). It spans the domain from 84°S to 72°N latitude in increments of 1.25° longitude by 2/3° latitude, including only open ocean areas, where bottom depth > 200 m. The circulation model is quasi-isopycnal, with 14 vertical layers, driven by the forcing fields shown in Fig. 1 (Schopf and Loughe, 1995). It relaxes to sea surface temperature obtained from MERRA and surface salinity obtained from the National Oceanographic Data Center (NODC, Conkright et al., 2002). The biogeochemical processes model contains 4 phytoplankton groups, 4 nutrient groups, a single herbivore group, and 3 detrital pools. The phytoplankton groups differ in maximum growth rates, sinking rates, nutrient requirements, and optical properties. The 4 nutrients are nitrate, regenerated ammonium, silica to regulate diatom growth, and iron. Three detrital pools provide storage of organic material, sinking, and eventual remineralization.

Carbon cycling involves dissolved organic carbon (DOC) and dissolved inorganic carbon (DIC; Fig. 2). 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 is allowed to exchange with the atmosphere, which can be either a source or sink. The ecosystem sink for DIC is phytoplankton, through photosynthesis. This represents the biological pump portion of the carbon dynamics. The solubility pump portion is represented by the interactions among temperature, alkalinity (parameterized as a function of salinity), silica, and phosphate (parameterized as a function of nitrate). The alkalinity/salinity parameterization utilizes the spatial variability of salinity in the model adjusted to mean alkalinity

$$TA = \underline{TA}\, S/\underline{S}$$

where TA is total alkalinity and S is salinity. The underscore represents global mean values. $\underline{TA}$ is specified as 2310 μE $kg^{-1}$ (Ocean Model Intercomparison Project (OCMIP; www.ipsl.jussieu.fr/OCMIP) and $\underline{S}$ as 34.8 PSU (global model mean). Since the model contains nitrate but not phosphate, we estimate phosphate by multiplying nitrate by 0.1. This is derived from the global mean ratio of nitrate to phosphate from NODC for their top three standard levels. The calculations for the solubility pump follow the standards set by the Ocean Model Intercomparison Project (reference above). We recognize that this approximation for alkalinity is not optimal, but the surface results compare favorably with data (see Gregg et al., 2013). The difference between the model and GLODAP global surface alkalinity is 2.7 μEq $l^{-1}$ (=0.1%) with basin correlation of 0.95 ($P < 0.05$) (Gregg et al., 2013). We consider this sufficient for the present purpose of intercomparing model results from forcing by different reanalysis products.

We employ a locally-developed lookup table valid over modern ranges of DIC, salinity, temperature, and nutrients for computational efficiency, at little cost to accuracy. Air–sea $CO_2$ exchange as a function of wind uses the Wanninkhof (1992) formulation, as is common in global and regional ocean carbon models (e.g., McKinley et al., 2006). A more complete description of NOBM can be found in Gregg et al. (2013).

NOBM is spun-up for 200 years under climatological forcing from each reanalysis. Initial conditions for DIC are derived from the Global Data Analysis Project (GLODAP; Key et al., 2004). DOC initial conditions are set to 0 μM. Subsequent tests with non-zero DOC initial conditions showed negligible differences. Other initial conditions are described in Gregg and Casey (2007). For MERRA forcing, the first ten years of the run show a net $pCO_2$ difference $\Delta pCO_2$ (year 10-year 1) of −0.982 μatm, at the first hundred years the 10-year $\Delta pCO_2$ (year 100-year 91) is 0.413 μatm, and at 200 years, the 10-year $\Delta pCO_2$ (year 200-year 191) is 0.102 μatm (Fig. 3). This 200-year model spinup may not be sufficient for full adjustment of all variables at all depths, but appears satisfactory for surface $pCO_2$ and nutrients, which is the focus of this effort. The results from the last year (year 200 of each reanalysis spinup) are compared with in situ data and with one another.

### 2.2. Data sets

#### 2.2.1. Forcing data

Forcing data variables are shown in Fig. 1. Monthly climatologies are used in all cases. All are obtained from reanalysis products except soil dust (iron), ozone, clouds, and atmospheric $CO_2$. Iron is

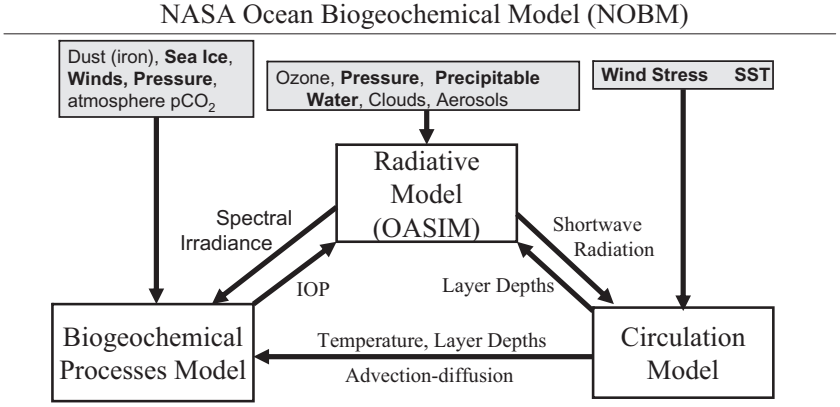


**Fig. 1.** Interactions among the main components of NOBM, nominal outputs, and forcing fields. IOP indicates inherent optical properties. Forcing variables are shown in the gray boxes. Reanalysis forcing variables are in bold. Surface pressure and precipitable water effects on surface irradiance play a small role in the inorganic carbon results and are ignored in this effort.

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