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Assessing Ocean and Atmosphere Analyses

by Michael Patterson, Interim Director

Over several decades, atmosphere and ocean model-based analyses have matured and proliferated, with climate modeling centers around the world generating routine real-time analyses as well as periodic retrospective reanalyses of the atmosphere and ocean state. These products support a range of scientific investigations, from initializing climate and Earth system model simulations, predictions, and projections to identifying and tracking the evolution of modes of variability, elucidating trends and extremes in the atmosphere and ocean, and providing a basis for decision support analyses, among a variety of other applications.

Progress in development and assessment of ocean and atmosphere analyses products was reviewed at two workshops held in conjunction last November. The “Evaluation of Reanalyses – Developing an Integrated Earth System Analysis (IESA) Capability Workshop,” surveyed data assimilation-based analyses efforts across the spectrum of Earth system component and coupled models, explored the quality and limitations of assimilation approaches and analyses products, and identified pathways for future improvements. The “3rd

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Driving Ecosystem and Biogeochemical Models with Optimal State Estimates of the Ocean Circulation

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The ocean plays a key role in the cycling of carbon through the earth system. There is a continuous flux of carbon dioxide with the atmosphere driven by the physical circulation of the ocean and by the uptake of carbon by photosynthesizing organisms (phytoplankton) in the surface ocean. Phytoplankton are responsible for about half the primary production of the earth biosphere and form the base of the marine food web. A portion of the carbon they fix in the surface waters is transported ("exported") to the deep ocean. Currently the ocean is a sink of carbon, taking up about one third of anthropogenic carbon dioxide. How does physical variability, and will future changes, affect the ocean's ability to take up carbon? How will a warmer ocean affect the marine primary producers?

Marine biogeochemical models have been developed to understand the controls and variations in the distribution of chemical elements (e.g. carbon, nitrogen, iron) in the ocean. Ecosystem models attempt to understand the structure and function of the marine food web; community structure impacts biogeochemical cycles including export of carbon to the deep ocean. The Ocean Carbon Model Intercomparison Project (OCMIP) highlighted the large sensitivity of results, such as export of carbon, to the physical circulation of the models (Doney et al., 2004; Najjar et al., 2007). Unrealistic physical environments will render the biogeochemical results inadequate to answer some fundamental questions. Biogeochemical and ecosystem models have been increasing in sophistication over the last few decades (Six and Maier-Reimer, 1996; Moore et al, 2002; Le Quéré et al, 2005; Follows et al, 2007), but the need for good physical circulation to drive them remains a crucial mandate.

Ocean state estimation is a least-squares fit of a numerical general circulation model to a variety of observations, including global satellite and scattered in situ ocean data, providing the best possible estimates of the ocean circulation. The methods used to reduce the misfit between model and data vary, ranging from sequential/filter methods such as optimal interpolation or Kalman filters, to variational/smoother methods such as the adjoint or Lagrange multiplier method or the Green's function method (Wunsch, 1996; Talagrand, 1997). The ocean state estimate products typically include time-varying flow fields, temperature, salinity, and mixing. Many data assimilation groups have made these products freely available (see the OceanObs’09 Community White Paper by Lee et al. (2010) for a detailed list). These improved fields of the physical state of the ocean are valuable for ocean biogeochemistry models.

The Estimating the Circulation and Climate of the Oceans (ECCO) consortium (Wunsch et al, 2010) has developed several products that have been used for biogeochemical and ecosystem

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Atmospheric Circulation Reconstructions over the Earth (ACRE) Workshop" examined the use of historical instrumental records and reanalyses, and reviewed efforts to facilitate improved accessibility and utility of the datasets. An overview of topics covered and recommendations is provided herein.

Also featured in this issue of Variations are two papers highlighting research presented at the IESA Workshop. Dr. Stephanie Dutkiewicz (MIT) summarizes physical and biogeochemistry ocean modeling of the ocean state and suggests specific ocean assimilation metrics to constrain both physical ocean circulation and biogeochemistry modeling.

Xue et al. evaluate upper ocean heat content from eight model analyses based on ocean data assimilation systems and two objective analyses based on in situ observations. The authors present time series and trend analyses demonstrating the reliability of ocean analysis in estimating heat content variability and their use in monitoring climate signals.

Recommendations from the reanalyses workshops will be considered at the U.S. CLIVAR Summit this July in Woods Hole, MA. The first day of the Summit will co-convene with the Ocean Carbon and Biogeochemistry Summer Workshop to explore collaboration on intersecting research interests including modeling issues raised in Dr. Dutkiewicz' article and a full range of integrated observation and data needs, coupled process understanding, and prediction and impacts research.

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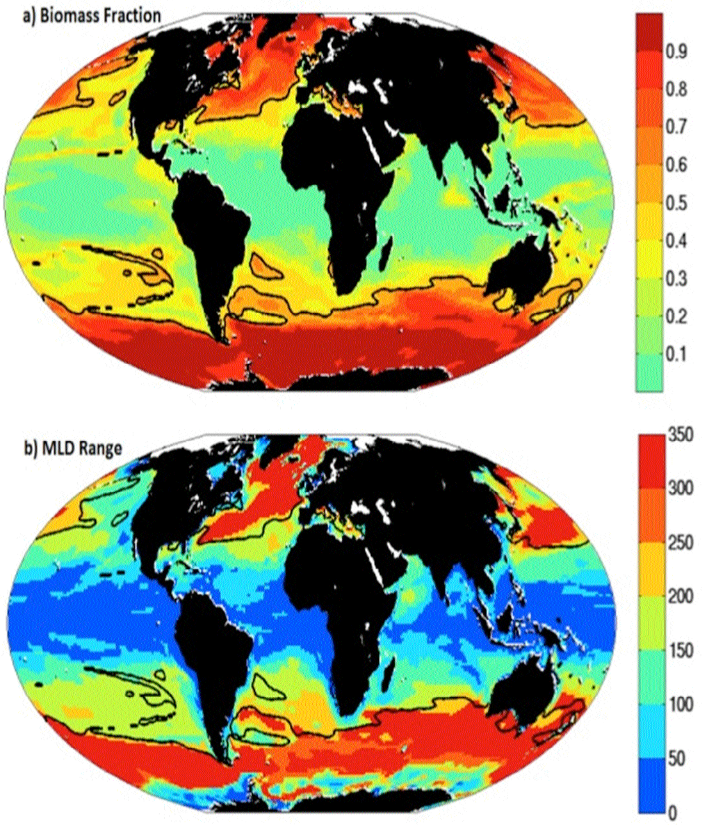

Figure 1. Output from the ECCO-GODAE state estimate (Heimbach and Wunsch, 2007) drive an ecosystem model with self-assembling community structure. (a) Fraction of total phytoplankton biomass made up of large, opportunistic species. (b) Relative regional stability shown by annual range of mixed layer depth (m). Contour indicates where half the biomass are opportunists. Opportunistic species, with quick growth rates, dominate where the water column is less stable. Slower growing phytoplankton whose small size makes them better at nutrient acquisition dominate in the more stable environments. (Figure modified from Dutkiewicz et al., 2009)

applications. ECCO -GODAE state estimates using the adjoint method, at 1^{o} resolution (Heimbach and Wunsch, 2007), have provided a strong physical background for the development of the ocean ecosystem and biogeochemistry model of Follows et al., (2007). The estimates of the physical ocean state transport the biogeochemical tracers (such as nutrients, organic matter) and many phytoplankton types. The biogeochemical and biological tracers interact through the formation, transformation and remineralization of organic matter.

Circulation and mixing controls the rate of vertical and horizontal supply of nutrients to the surface ocean. Mixing within the water column determines the amount of light to which phytoplankton are exposed. The many different phytoplankton types have growth characteristic that are randomly assigned from ranges suggested by laboratory studies, with some simple imposed trait tradeoffs. The chemical and physical environments in the ocean model set which types and combinations of phytoplankton survive in any region (e.g. Follows et al., 2007; Dutkiewicz et al., 2009; Monteiro et al., 2011). For instance, trade-offs in growth strategies lead to large fast growing opportunists dominating the communities in regions of high seasonal disturbances, while strategies for efficient uptake of scarce resources are more useful in stable environments (Fig. 1, Dutkiewicz et al., 2009). The physical environment has a strong control not only on the emergent communities, but also has a role in setting the patterns of biodiversity of phytoplankton. A poleward decline in biodiversity can be explained by the relative stability of the environment (Barton et al. 2010); overlain are regional "hotspots" of high diversity (Fig. 2). These patterns are captured in a simulation where the ecosystem model is driven by the ECCO2 global eddy-permitting general circulation model, which uses a Green's function method to partially adjusted the model to observations (Menemenlis et al., 2008). Enhanced biodiversity is seen in western boundary current regions where different water masses, with disparate communities of phytoplankton, are mixed together.

Biological processes lead to a constant downward flux of elements, such as carbon, to the deep ocean. Physical processes bring these elements back up from the deep and redistribute them horizontally, particularly in mode waters (see e.g. Sarmineto et al., 2004). Carbon dioxide enters the ocean from the atmosphere in some regions and is expelled in others, driven largely by temperature differences in those surface waters. Biogeochemical models can explore the processes that are most relevant for these redistributions of carbon. Regional eddy-permitting (1/6°) adjoint-based state estimates of the Southern Ocean (SOSE, Mazloff et al., 2010) have helped elucidate the crucial role of Ekman transport (Ito et al., 2010), especially in relation to anthropogenic carbon. In the Southern Ocean most of the anthropogenic carbon uptake occurs near the Antarctic polar front. However, the column inventory of this carbon is largest further equatorward (Fig. 3) . Though locally the anthropogenic carbon is advected away from the uptake sites by mesoscale eddies, it is the wind driven Ekman transport that leads to the cross frontal redistribution. Time scales are important in these processes, and adequate capture of the Ekman processes are essential in obtaining such results.

Biogeochemical models require accurate and dynamically consistent ocean circulation fields. This is often in contrast to other applications, especially in forecasting, where “re-analysis” produces optimal initial conditions of temperature and salinity at discrete intervals, but which do not require budget closure between any two “analysis” steps. Such imbalances can cause inaccurate circulation, especially vertical velocities, causing spurious adjustments to biogeochemical fields. However, the use of estimates based on variational/smoother methods (e.g. Fukumori, 2002) can minimize these inconsistencies (McKinley, 2002). Some physical metric may be relatively more important to biogeochemical models than other applications using physical state estimation products. Mixed layers play a key role in determining the light environment of phytoplankton growth, and the rate of water mass formation plays a key role in redistributing carbon and nutrients. A stronger emphasis on these metrics in the assimilations could improve physical general circulation models in a manner useful for biogeochemical applications.

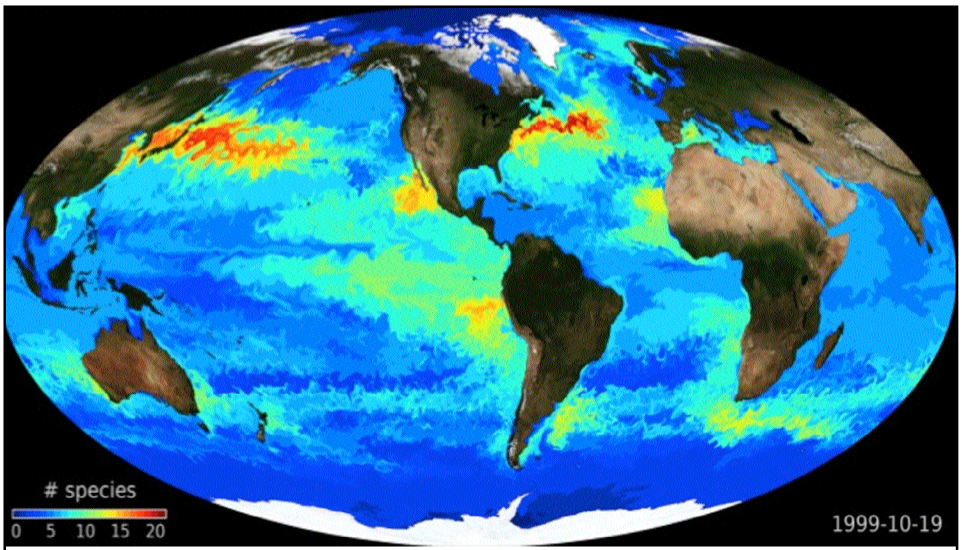

Figure 2. Output from the ECCO2 state estimate (Menemenlis et al., 2008) drive the ecosystem model with many phytoplankton types. Biodiversity of phytoplankton, defined here as number of species with biomass above a threshold value, shows distinct global patterns. A poleward reduction in diversity is linked to the amount of disturbances to the environment (Barton et al., 2010). Hot spots of diversity in western boundary currents and other regions of energetic circulation show the importance of mixing of different water masses. Simulation performed by Oliver Jahn and Chris Hill at MIT. (Figure credit: Oliver Jahn)

Data assimilation remains relatively new in ocean biogeochemistry itself. However, the expanding satellite ocean colour and biogeochemically relevant in situ observations are leading to increased use of these techniques (see Gregg et al., 2009 for a list of studies). Global models assimilating satellite derived chlorophyll suggest the utility of these approaches (e.g. Gregg 2008; Tjiputra et al., 2007). In most of these studies, the physical circulation remains unconstrained. Since biogeochemical model results are sensitive to the model physical circulation, marine biogeochemical metrics could be key in improving the modeling of physical processes (Najjar et al., 2007). Including Chlorofluorocarbon (CFC) and radiocarbon observations to constrain deep and bottom water transport rates and pathways in a global (though time-invariant) model, has important implications for the strength of the overturning circulation (Schlitzer, 2005). As ocean biogeochemical models rise to meet the challenge of quantifying air-sea fluxes of carbon dioxide in a changing world, it is likely that simultaneous assimilation of physical and biogeochemical observations will be of greater value.

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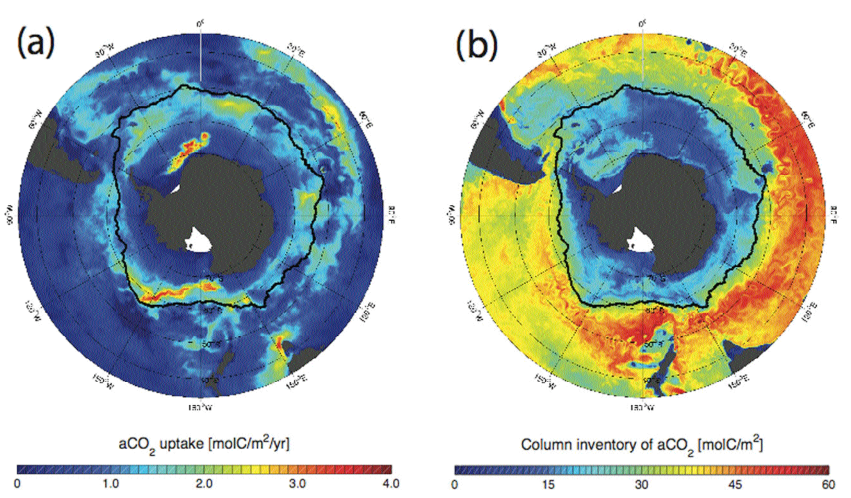

Figure 3. Output from the Southern Ocean State Estimate (SOSE, Mazloff et al., 2010) drive a model of anthropogenic carbon. (a) 2 year average of uptake of anthropogenic carbon dioxide; (b) column inventory of anthropogenic carbon after 2 years of simulation. Black line indicates the location of the Antarctic Polar Front. Ekman transport is crucial in redistributing the anthropogenic carbon equatorward. (Figure from Ito et al., 2010 with permission of the authors).

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