NASA Carbon Monitoring System

Toward a 4D-Var approach for estimating air-sea CO_2 fluxes

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Project summary

A carbon monitoring system requires **accurate estimates of CO_2 exchanges between ocean and atmosphere** due to the magnitude of this component in the global carbon budget and the constraint it places on inferences of land-atmosphere fluxes.

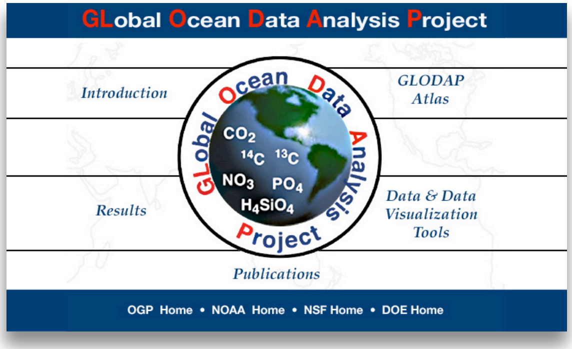
Observations of oceanic carbon content are becoming increasingly available, prompting the need to develop machinery to **synthesize these data with a dynamical model**.

Our goal was to enable production of a global model-observations synthesis of air-sea CO_2 fluxes. This required:

1. compilation of a quality-controlled global dataset of ocean biogeochemical observations;
2. development of the adjoint of a biogeochemical ocean model for data assimilation, and
3. validation of the methodology by producing a biogeochemical state estimate in the California coastal ocean.

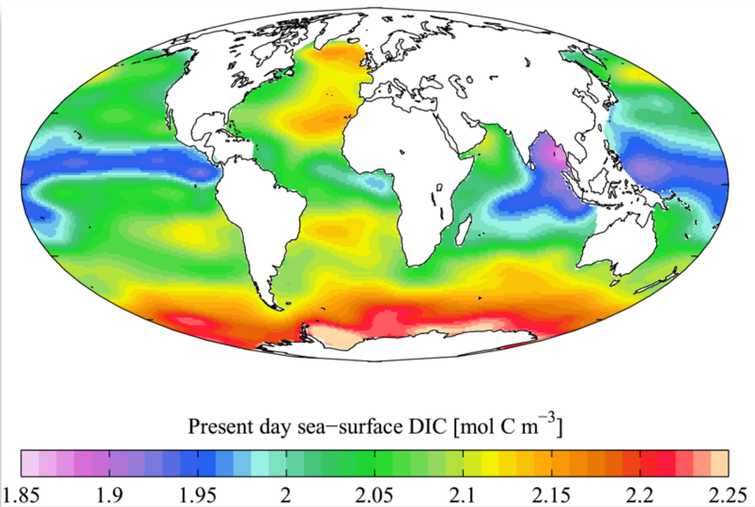
1) Ocean Carbon Dataset

GLobal Ocean Data Analysis Project version 2 (GLODAPv2) is a comprehensive data product of *in situ* ocean carbon and biogeochemistry observations (dissolved inorganic carbon (DIC), alkalinity, pH, oxygen, nutrient concentrations).



http://cdiac.ornl.gov/oceans/glodap/
(screenshot from GLODAPv1, above)

http://cdiac.ornl.gov/ftp/oceans/glodapv2/
(data from GLODAPv2)



Annual mean surface DIC from GLODAPv1 (wikipedia.org)

The original GLODAP product (Key et al. 2004) is widely used by the scientific community; examples include the global ocean inventory for anthropogenic carbon (Sabine et al. 2004) and the validation of several biogeochemical ocean models (e.g. Bopp et al. 2013).

The new product extends the original to the period 1973-2013 and includes approximately 775 cruises (~6 times as many as in v1). It is noteworthy that GLODAPv2 includes many cruises in the Arctic Ocean - a region of great interest for ocean biogeochemical research.

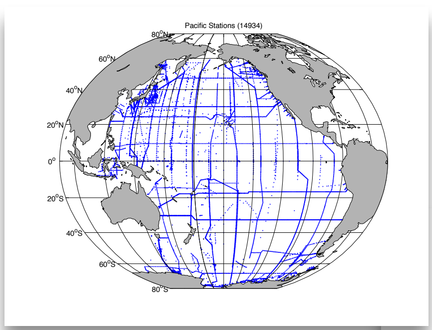
1) Ocean Carbon Dataset

GLODAPv2 consists of 2 major components:

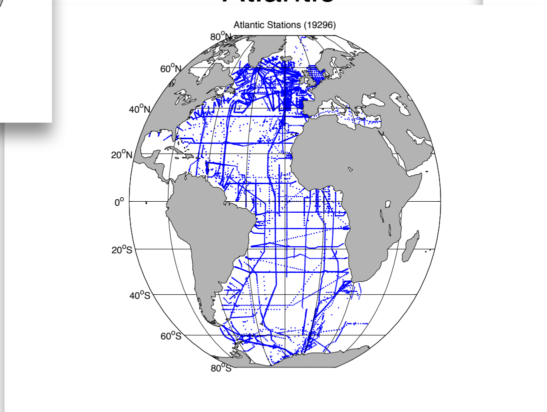
(a) **discrete data collections**, grouped into 4 subsets: Arctic, Atlantic, Indian, Pacific; these are distributed via CDIAC: http://cdiac.ornl.gov/ftp/oceans/GLODAPv2/

(b) **global gridded fields** (1x1 degree) for the most critical biogeochemical parameters (to be released soon).

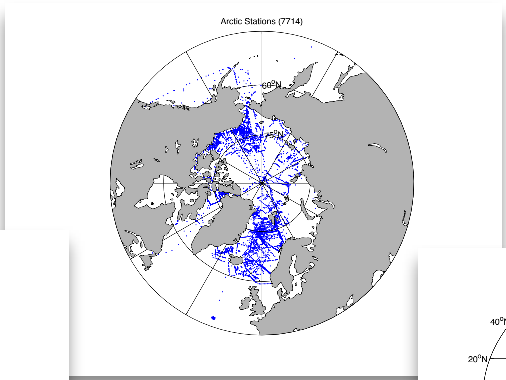
Pacific



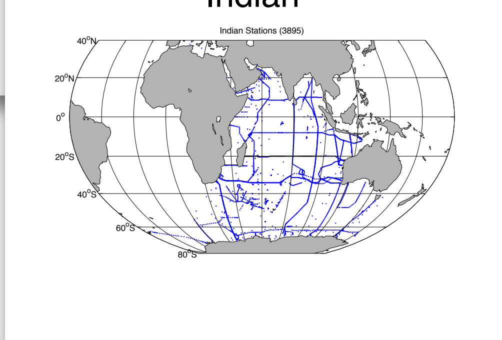
Atlantic



Arctic



Indian



location of discrete data samples (from 775 cruises) used in GLODAPv2

1) Ocean Carbon Dataset

Quality control:

New quality control tools and the larger data inventory enabled us to re-evaluate all the bias corrections derived during the previous efforts. One primary goal of GLODAPv2 is that the discrete data products are sufficiently calibrated to serve as a basis against which future ocean monitoring data can be tested. All parameters are subject to 2 rounds of quality control including basin scale inversion as well as crossover type data comparisons.

Products:

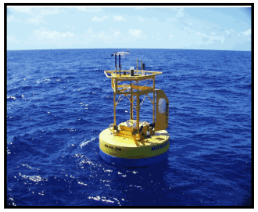
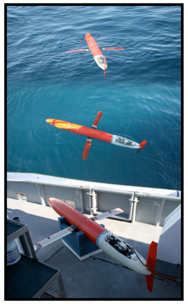
GLODAPv2 was released at the IMBER meeting in Bergen, Norway in June 2014.

Olsen et al (2014), GLODAPv2 – A new and updated global ocean carbon data product. IMBER news. http://www.imber.info/index.php/News/Newsletters/Issue-n-27-September-2014.

Peer-reviewed publications describing the data product development will follow later this year.

Formal documentation for the individual data sets as well as the products is well developed and has been implemented as the data accumulated (mostly via data DOI).

2) Adjoint model for ocean biogeochemistry


We have developed a **coupled physical-biogeochemical model for data assimilation.**

It assimilates *in situ* observations such as the GLODAPv2 product, temperature and salinity profiles, as well as remotely-sensed data such as

- Altimetry
- Microwave sea surface temperature
- Bottom pressure
- Sea ice concentration
- Properties derived from ocean color (in development): chlorophyll-a, particulate backscatter, particulate organic carbon, particle size distribution, carbon export

2) Adjoint model for ocean biogeochemistry

The model and its adjoint are used to estimate of the physical and biogeochemical state of the ocean, including the **ocean carbon content and air-sea fluxes of CO_2.**

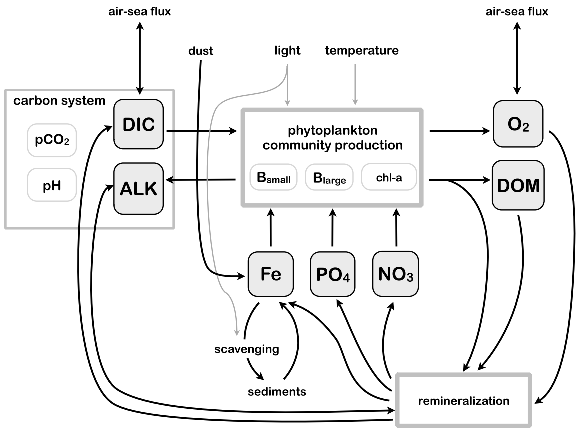
We adopt the machinery developed by the consortium for Estimating the Circulation and Climate of the Oceans (ECCO).

The state estimate is produced using the 4D-Var approach, also called the adjoint method.

- The model is fit by constrained least-squares to observational datasets.
- Inputs of the model to be optimized are adjusted, through an iterative process, in such a way that minimizes the misfit between model and observations available for the time window of the simulation.

2) Adjoint model for ocean biogeochemistry

We implemented the BLING biogeochemical model (Biogeochemistry with Light, Iron, Nutrients and Gases; Galbraith et al. 2010) into the MIT ocean general circulation model (MITgcm).



Products:

The code has been uploaded to the MITgcm repository; it is now publicly available for download (http://mitgcm.org/viewvc/MITgcm/MITgcm_contrib/bling/).

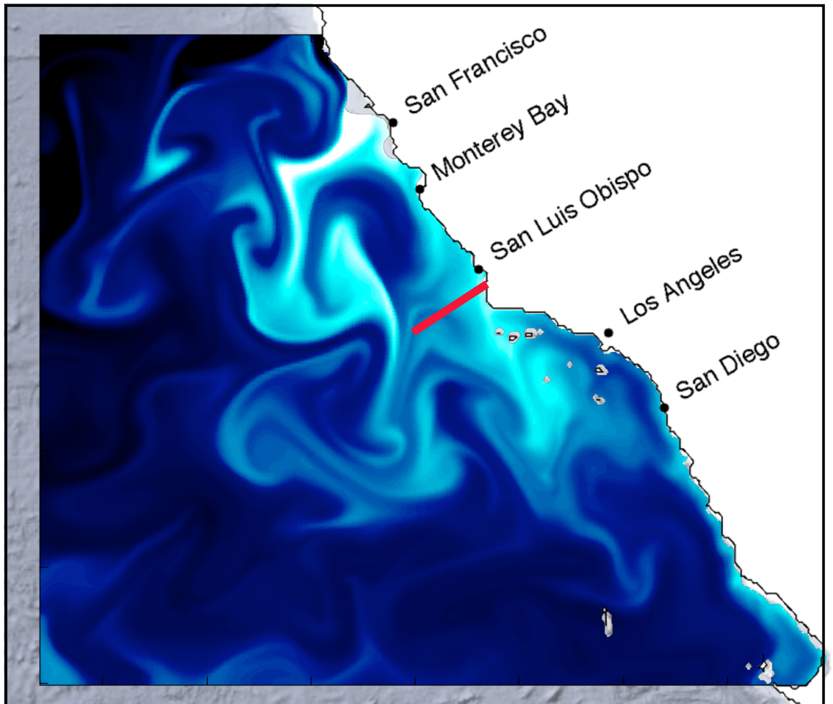
A publication describing the methodology is in final stages of preparation:

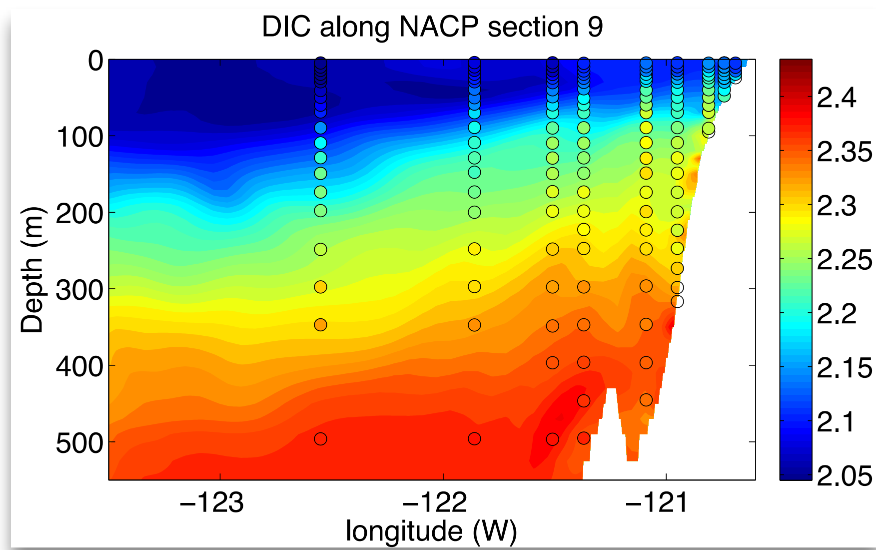
Verdy, A, M. Mazloff, B. Carter and B. Cornuelle, A coupled physical–biogeochemical data assimilating model for estimating the oceanic carbon system, In preparation for Ocean Modeling.

3) Biogeochemical state Estimation in the California Coastal Ocean

The data-assimilating model was tested in a regional set-up of the California Current Ecosystem. A hindcast was produced for the year 2007.

The solution of the numerical model was brought into consistency with available observations by adjusting the **initial conditions** (biogeochemical tracers, temperature, salinity), **lateral boundary conditions**, and **atmospheric forcing** (winds, precipitation, radiative fluxes, dust deposition).

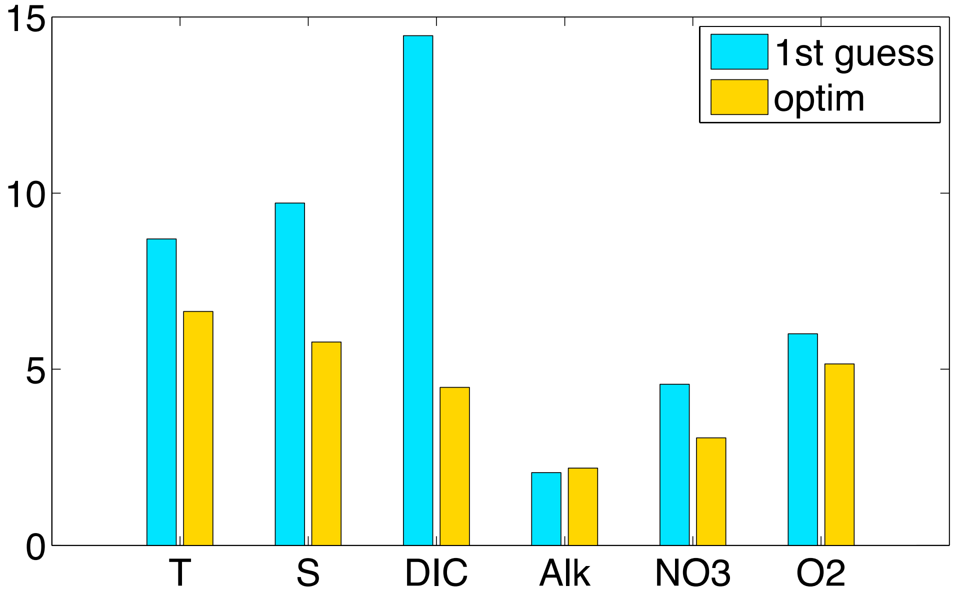


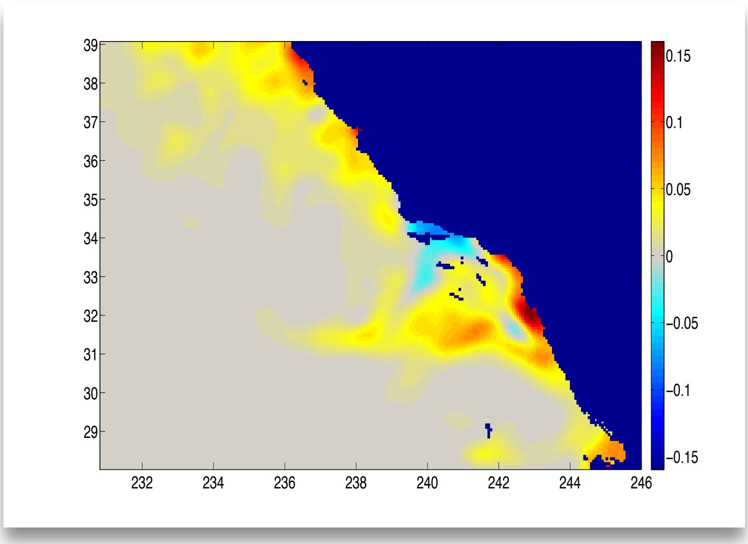


Left: **model domain**, with a snapshot of surface DIC concentration. Right: **simulated DIC (colored contours) and observations (filled circles)** along section shown as red line on left plot, showing good agreement.

3) Biogeochemical state Estimation in the California Coastal Ocean

The assimilation worked remarkably well, as shown by the decreasing “cost”, a sum of the weighted model-observations squared misfits. After 13 iterations the total cost decreased by 26% and the cost from biogeochemical constraints decreased by 38%.



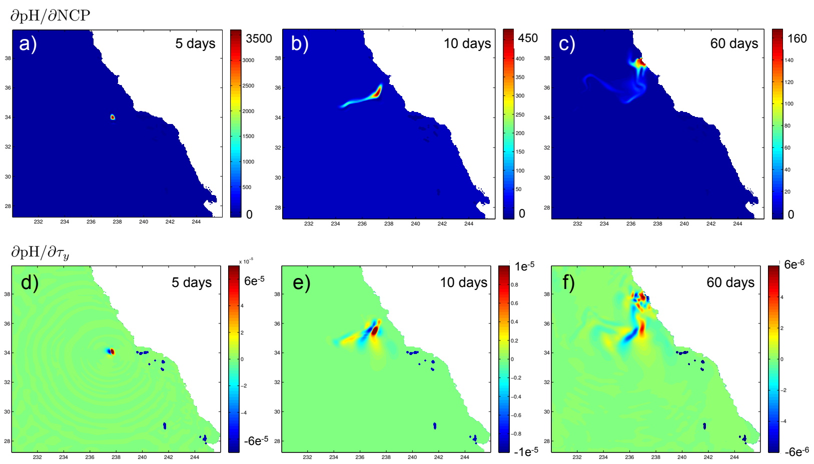


Results from coupled assimilation (Jan - Dec 2007). Left: **Change in cost** for NACP West Coast cruise data. Right: **Change in DIC initial conditions** at 100m from optimization (mol C/m3).

3) Biogeochemical state Estimation in the California Coastal Ocean

The adjoint model is used to examine how oceanic carbon inventories respond to atmospheric and climate forcing. This is particularly interesting near the coast, where winds drive upwelling of carbon-rich water, causing CO_2 outgassing.

As a first step toward understanding the physical factors influencing upwelling, we analyzed the sensitivity of coastal SSH (Verdy et al, 2014). Analysis of the sensitivity of coastal DIC and pH to physical and biogeochemical forcing is in progress.



Sensitivity of surface pH at an offshore mooring location to Net Community Production, NCP (top row) and to meridional winds (bottom row). The 3 snapshots show the sensitivities 5 days, 30 days and 60 days prior to the pH response.

Products*:*

A. Verdy, M. Mazloff, B. Cornuelle, and S.Y. Kim (2014). Wind-driven sea level variability on the California coast: an adjoint sensitivity analysis, Journal of Physical Oceanography, vol. 44 (1), 297-318.

A manuscript in preparation documents the regional DIC budget, i.e. the attribution of DIC variability to various physical and biogeochemical processes.

The physical and biogeochemical state estimate, including air-sea CO_2 fluxes, is available on our server, http://iod.ucsd.edu/~averdy/becco.html

Summary and future directions

- The adjoint of the coupled model has been shown to perform well for a 1-year state estimate in the California Coastal Ocean, bringing the model solution into consistency with the physical and biogeochemical observations.
- The intermediate complexity biogeochemical model, however, does not adequately capture phytoplankton dynamics in the coastal environment, making the solution irreconcilable with chlorophyll observations. We are currently implementing BLINGv2, with improved biological dynamics representation, to allow better use of ocean color satellites in constraining the solution.
- We have begun work on a **coupled state estimate in the Southern Ocean**; new biogeochemical observations from Argo floats will be assimilated, including pH, nitrate, and fluorescence (for estimating chlorophyll). The project is funded by NSF with contributions from NASA (fluorescence sensors on floats). http://soccom.princeton.edu/

SOCCOM

Unlocking the mysteries of the Southern Ocean

- **Comparison of our regional products with the CMS ECCO2-Darwin product** is a priority. The high-resolution coastal domain is complementary to the global model, and together can be used to address problems such as the flux of carbon from land to sea to open ocean, and the contributions of eddy transport, upwelling-driven transport, and biological production on the coastal carbon budget.