



Air-sea CO₂ flux estimates from two data-constrained ocean models for the NASA Carbon Monitoring Study Flux Pilot Project

Holger Brix^{1,2}

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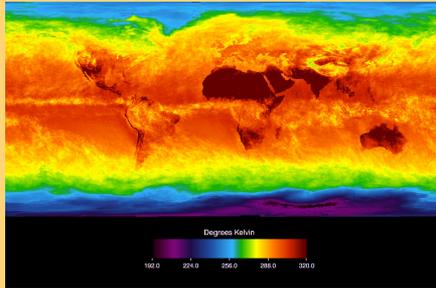
³ NASA Goddard Space Flight Center, Greenbelt, MD

⁴ Massachusetts Institute of Technology, Cambridge, MA

AGU Fall Meeting, San Francisco, December 8, 2011

NASA Carbon Flux System

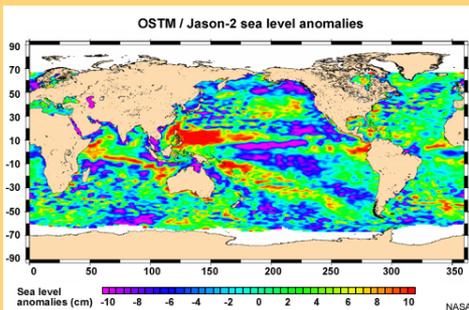
NASA satellites



T, q, p,.. (AIRS)



EVI, FPAR,.. (MODIS)



chlorophyll, altimetry,
... (MODIS, JASON)

NASA models/ assimilation

Atmos
GEOS-5

winds
(u,v)

Terrestrial
CASA/
CASA-
GFED

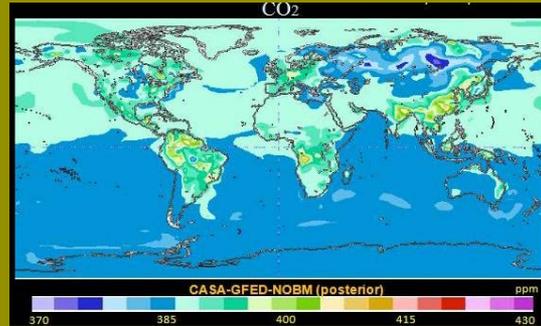
NEE

Ocean
NOBM/
ECCO2-
Darwin

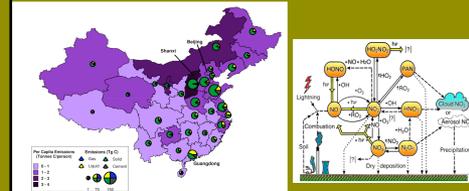
Air/sea CO2
exchange

NASA inverse modeling

Inverse
GEOS-Chem

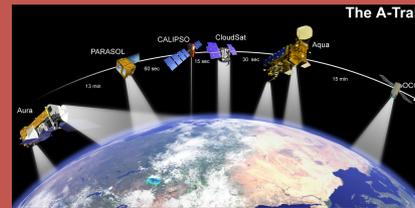


Anthropogenic



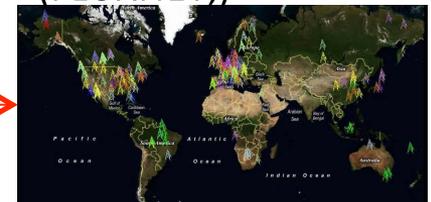
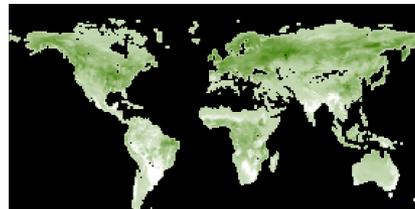
FF, land-use,
chemical production

$$\min_{\mathbf{x}_0} C(\mathbf{x}) = \left\{ \sum_i (\mathbf{y}_i - \mathbf{F}_i(\mathbf{x}))^\top (\mathbf{S}_i^i)^{-1} (\mathbf{y}_i - \mathbf{F}_i(\mathbf{x})) + (\mathbf{x}_0 - \mathbf{x}_a)^\top \mathbf{S}_a^{-1} (\mathbf{x}_0 - \mathbf{x}_a) \right\}$$



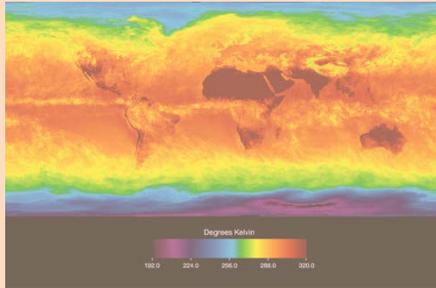
Satellite CO2 sensors
(GOSAT, TES, AIRS)

Optimal flux (gC/m²/day) Independent tests
(FLUXNET,)

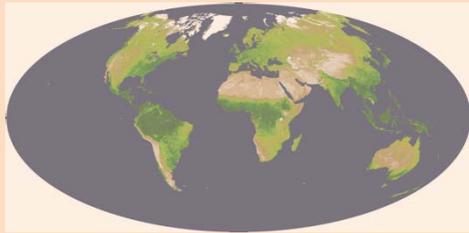


NASA Carbon Flux System

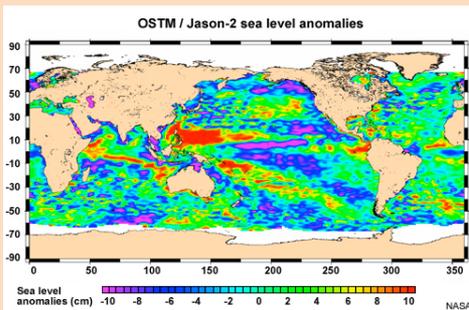
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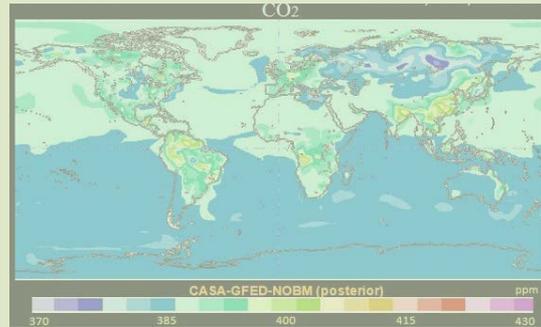
NEE

Ocean
NOBM/
ECCO2-
Darwin

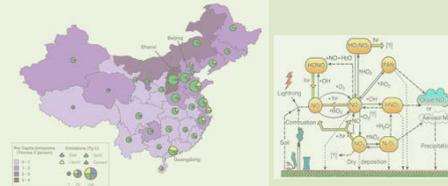
Air/sea CO2
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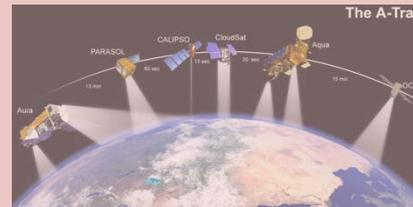


Anthropogenic



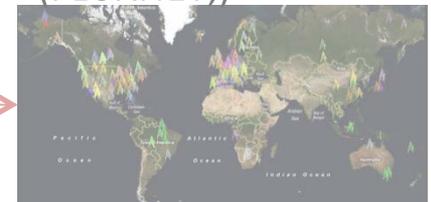
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Satellite CO2 sensors
(GOSAT, TES, AIRS)

Optimal flux (gC/m²/day) Independent tests
(FLUXNET,)



NOBM and ECCO2-Darwin

NASA Ocean Biogeochemical Model (NOBM):

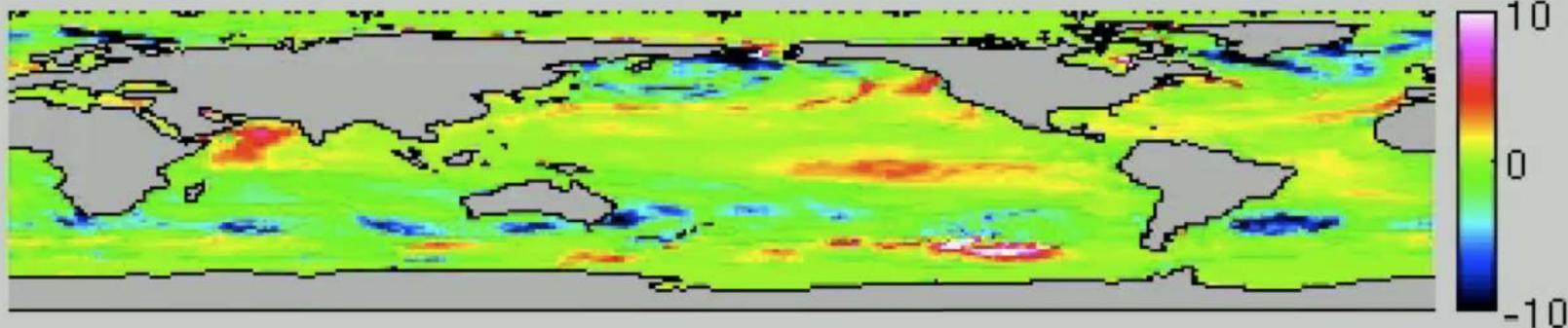
- A biogeochemical processes model, coupled to the
- Poseidon ocean model
- Driven at the surface by the Modern Era Retrospective-analysis for Research and Applications (MERRA)
- Ocean color data is assimilated using MODIS-Aqua chlorophyll.

Estimating the Circulation and Climate of the Ocean, Phase II (ECCO2):

- ECCO2 data syntheses are obtained by least squares fit of a global full-depth-ocean and sea-ice configuration of the Massachusetts Institute of Technology general circulation model (MITgcm), coupled to the
- MIT ecosystem model (Darwin), and
- a marine carbon chemistry model
- The ECCO2 ocean solution assimilates a variety of satellite and in-situ data, including Jason altimetry, AMSRE-E sea surface temperature, and Argo temperature and salinity profiles.

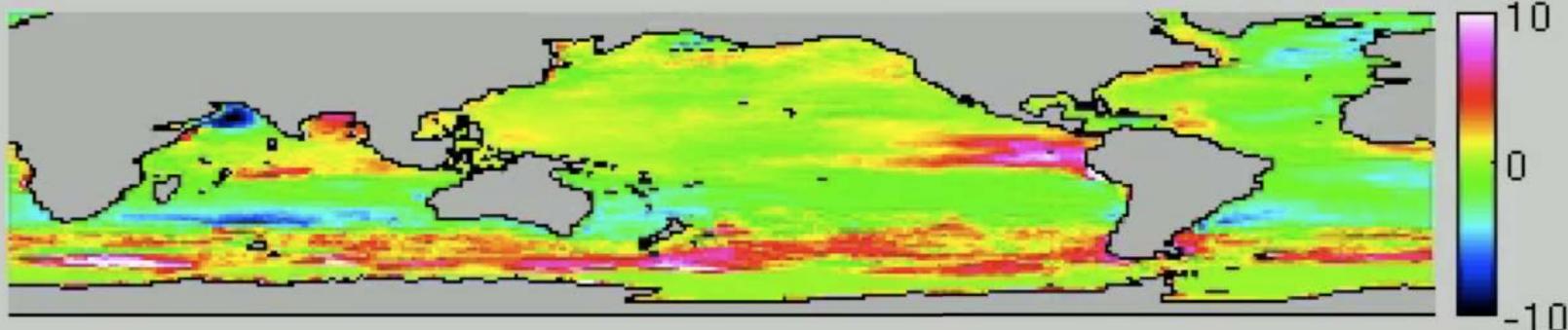
CO2 fluxes ECCO2 - Darwin [molC/m²/yr] 2009-07-01

ECCO2-
Darwin
(CCSM)



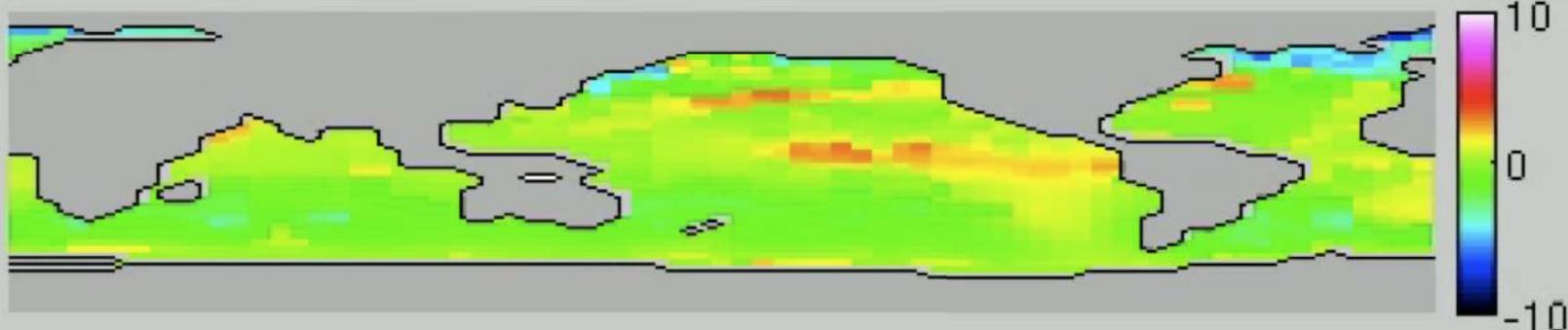
CO2 fluxes NOBM [molC/m²/yr] 2009-07-01

NOBM



CO2 fluxes Takahashi climatology [molC/m²/yr]

Takahashi



Data Assimilation Approach

Least squares method based on computation of model Green's functions.

Previously used for, e.g., ocean circulation estimates (Stammer and Wunsch, 1996; Menemenlis et al., 1997; 2005), atmospheric tracer inversions (Enting and Mansbridge, 1989; Tans et al., 1990; Bousquet et al., 2000), ocean carbon inversions (Gloor et al., 2003; Mikaloff Fletcher et al., 2006; 2007), and joint ocean-atmosphere carbon dioxide inversions (Jacobson et al., 2007a; 2007b).

GCM:
$$\mathbf{s}(t+1) = M[\mathbf{s}(t), \mathbf{x}]$$

$\mathbf{s}(t)$ is the ocean model state vector at time t
 M represents the numerical model
 \mathbf{x} is a set of control parameters,
here the weight of different initial conditions

Data:
$$\mathbf{y} = H[\mathbf{s}] + \mathbf{n} = G[\mathbf{x}] + \mathbf{n}$$

\mathbf{y} is the available observations
 H is the measurement model
 G is a function of M and H
 \mathbf{n} is additive noise

Cost function:
$$J = (G[\mathbf{x}] - \mathbf{y})^T (G[\mathbf{x}] - \mathbf{y})$$

J is an unweighted cost function,
i.e., it is assumed that $\langle \mathbf{n}\mathbf{n}^T \rangle = \mathbf{I}$

Linearization:
$$\mathbf{y} - G[\mathbf{x}_b] \approx \mathbf{G}(\mathbf{x} - \mathbf{x}_b) + \mathbf{n}$$

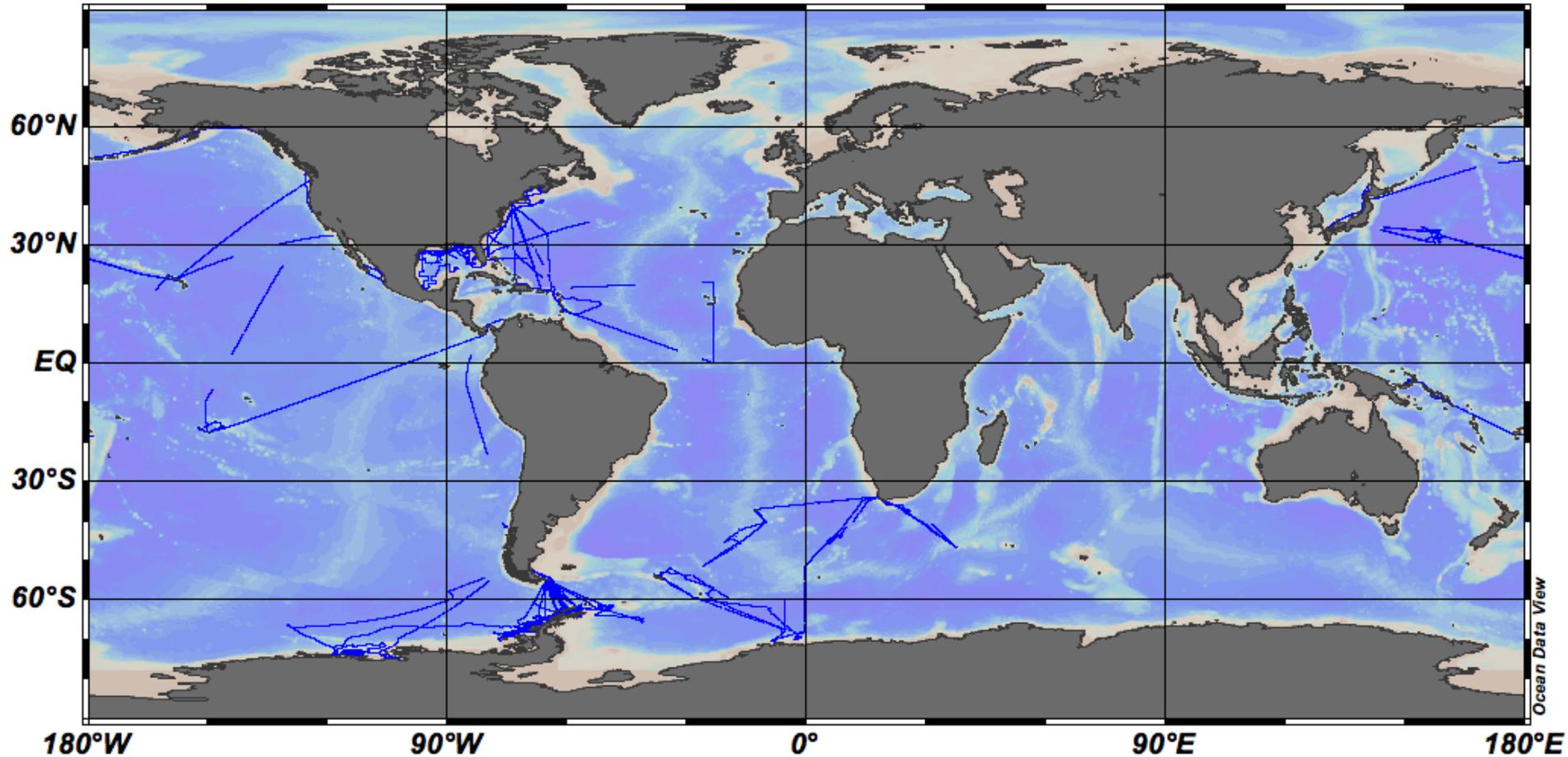
\mathbf{G} is a kernel matrix whose columns are
computed using a GCM sensitivity experiment
for each parameter in vector \mathbf{x} .
Subscript "b" represents baseline GCM
integration used to linearize problem.

Solution:
$$\tilde{\mathbf{x}} = \mathbf{x}_b + (\mathbf{G}^T \mathbf{G})^{-1} \mathbf{G}^T (\mathbf{y} - G[\mathbf{x}_b])$$

Control parameters that minimize cost function J

A first proof-of-concept assimilation of LDEO pCO₂ data for 2009-2010

LDEO_Database_V2010



ECCO2-Darwin sensitivity experiments

(or model Green's functions)

The four ECCO2-Darwin integrations differ in their initial conditions (IC) for dissolved inorganic carbon (DIC), alkalinity (Alk), and oxygen:

CCSM: From previous integration with CCSM biogeochemical model

KS: DIC blended from Key et al. and Sabine et al. data sets, Alk from GLODAP, O₂ from World Ocean Atlas 2009

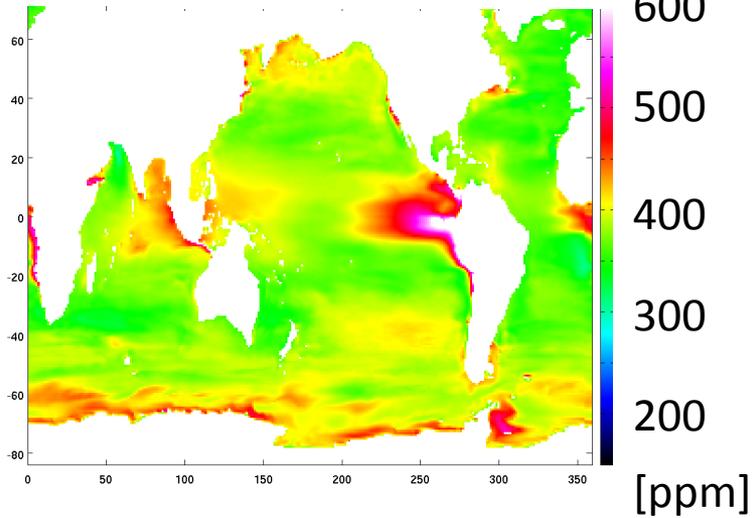
BLEND: Blend of modified **CCSM** and **KS** initial conditions

NOBM IC: DIC and DOC from NOBM, Alk and O₂ from **BLEND**

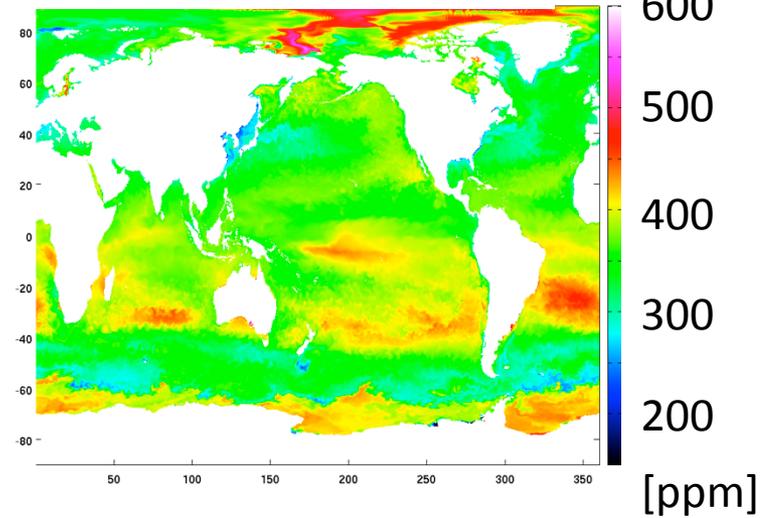
Each column of the kernel matrix **G** is computed as the difference between perturbed and baseline integration (CCSM) sampled at the location and time of the observations (blue lines in previous slide)

Simulated surface pCO₂ (monthly mean July 2009)

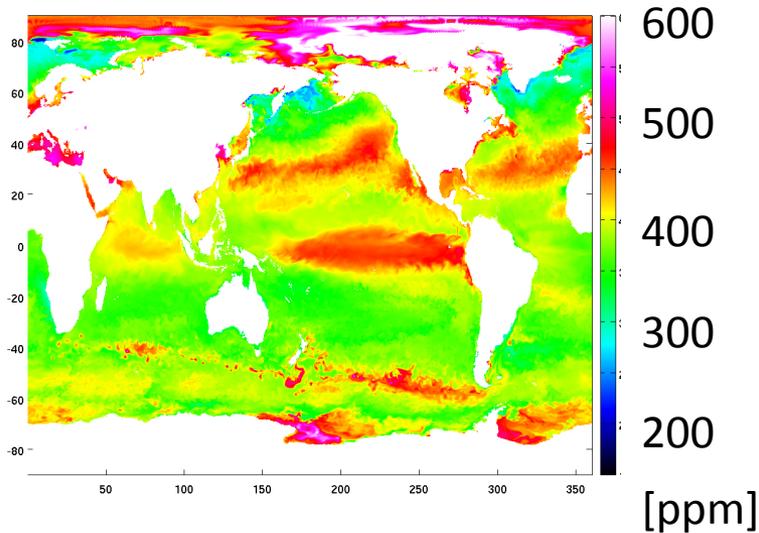
NOBM



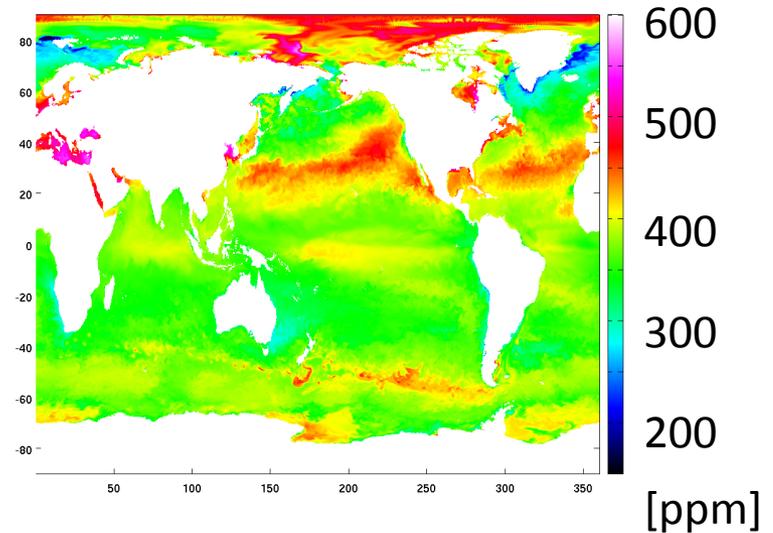
ECCO2-Darwin (CCSM)



ECCO2-Darwin (NOBM IC)



ECCO2-Darwin (BLEND)



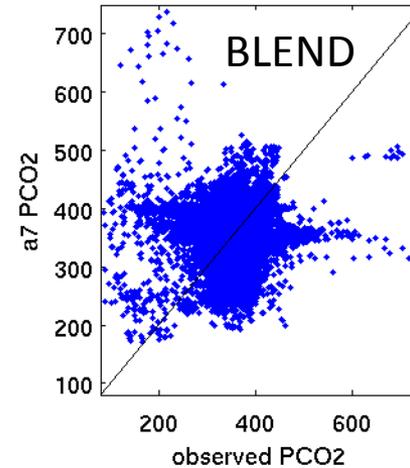
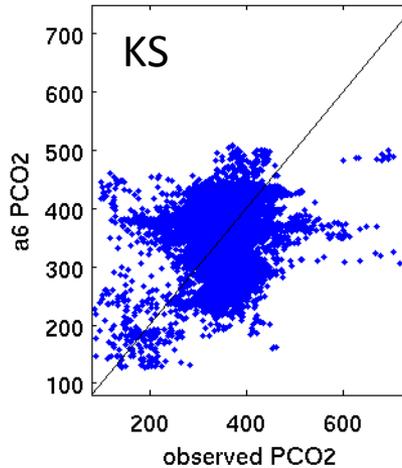
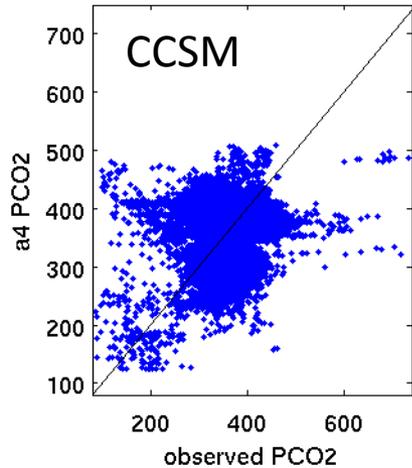
Model (ECCO2) vs. Data: pCO₂

Cost:

$J = 74.6$

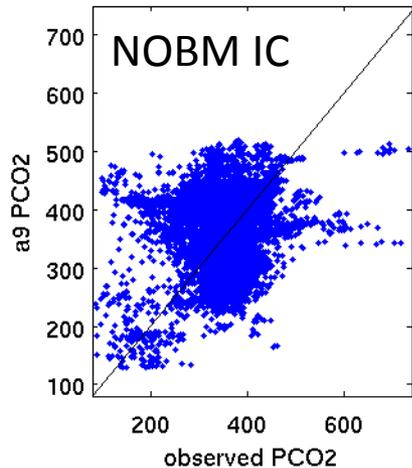
$J = 69.1$

$J = 75.7$



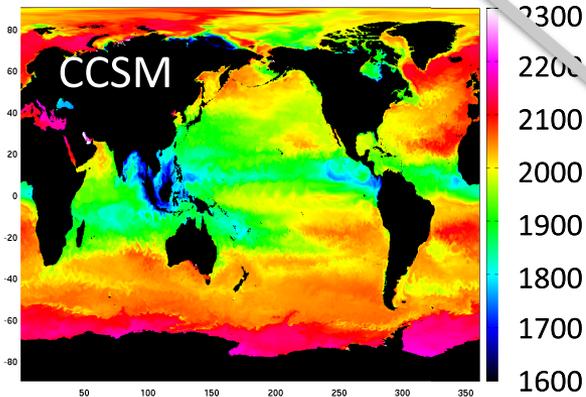
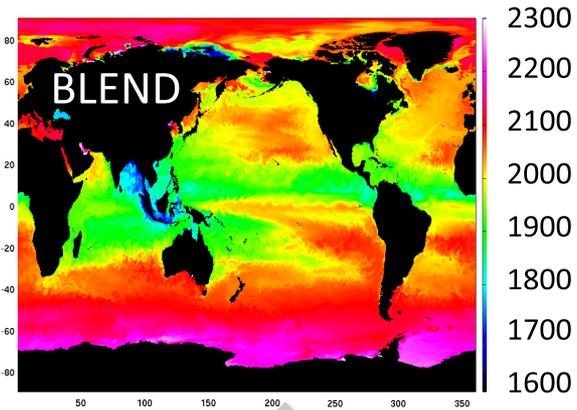
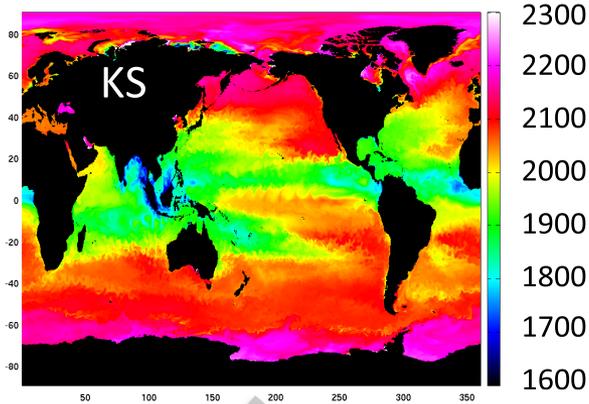
Cost:

$J = 78.2$

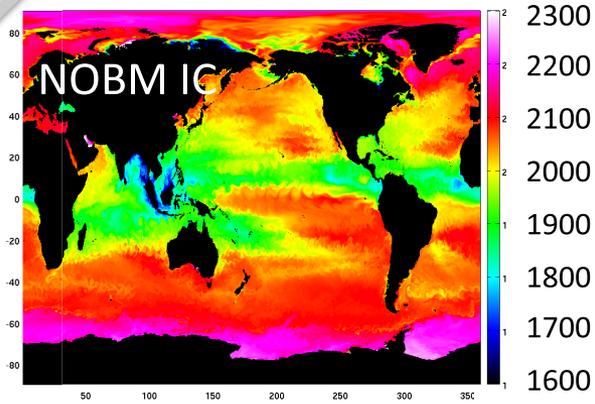


Four different realizations of ECCO2-Darwin compared to LDEO pCO₂ data for 2009 and 2010.

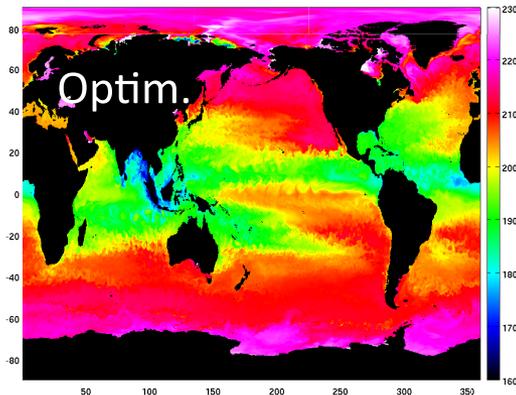
Optimizing biogeochemical initial conditions



$$\begin{aligned} \text{Optimized} &= \\ &-0.35 * \text{CCSM} + \\ &1.19 * \text{KS} + \\ &0.38 * \text{BLEND} + \\ &-0.23 * \text{NOBM IC} \end{aligned}$$



Shown:
Surface DIC
[mmolC/m³]



The model physics of the optimized run are identical to the original runs, i.e., all runs have identical physical fields.

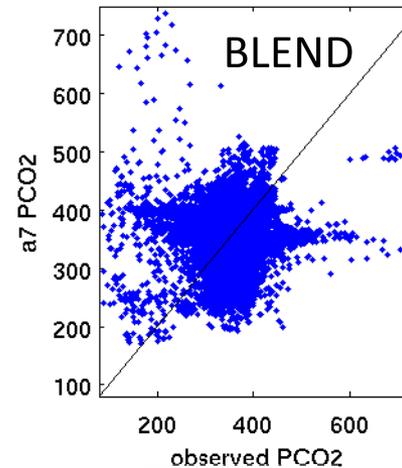
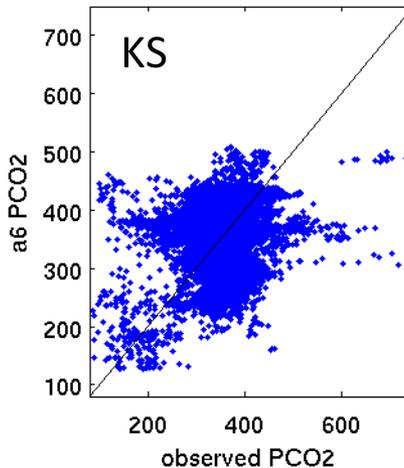
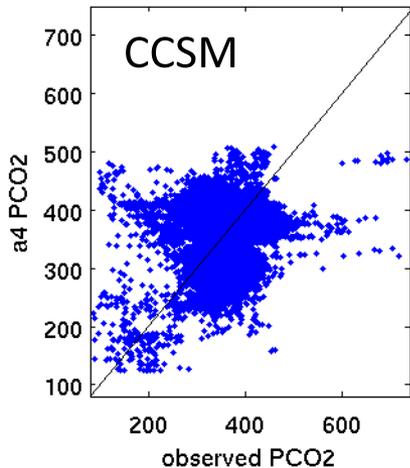
Model (ECCO2) vs. Data: pCO₂

Cost:

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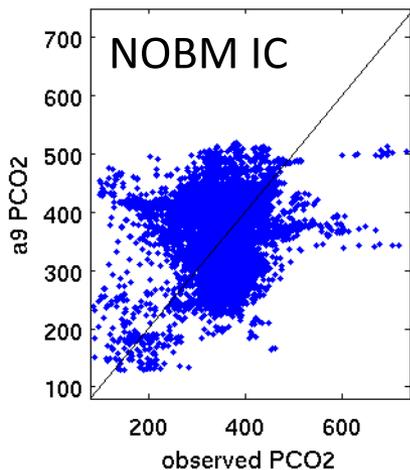
$J = 75.7$



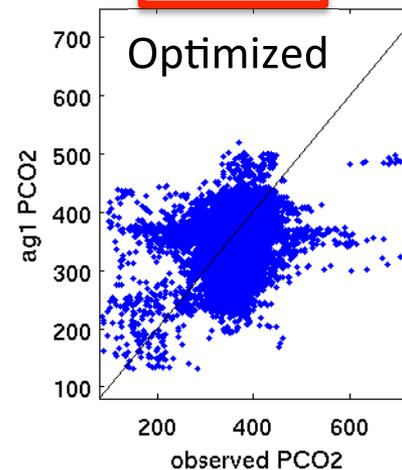
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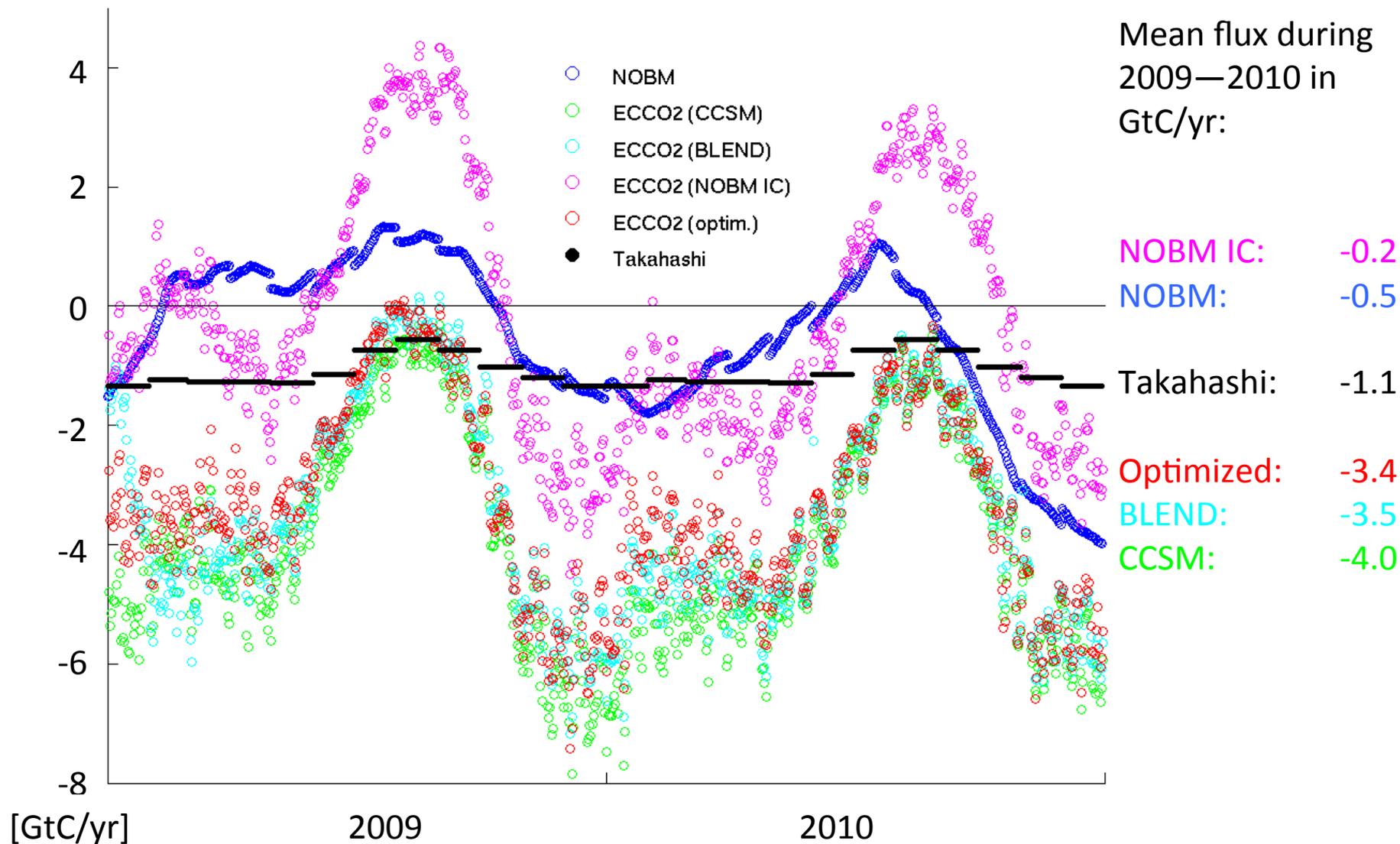
$J = 62.7$



$$\begin{aligned} \text{Optimized} &= \\ &-0.35 * \text{CCSM} + \\ &1.19 * \text{KS} + \\ &0.38 * \text{BLEND} + \\ &-0.23 * \text{NOBM IC} \end{aligned}$$



Simulated air-sea CO₂ fluxes (global integral)



Summary and Planned Work

- Long spin-ups of high-resolution ocean biogeochemical models are problematic because of computational cost and model drift.
- This leads to unrealistic air-sea carbon flux estimates.
- A simple, physically-consistent data assimilation approach based on model Green's functions (forward sensitivity experiments) has been used to reduce model-data mismatch.
- Ongoing work:
 - Computation of additional model Green's functions is underway.
 - Use additional in situ and satellite (e.g., color) data constraints.
 - Use adjoint method to increase number of control parameters.

