Introduction to Biogeochemical Modeling

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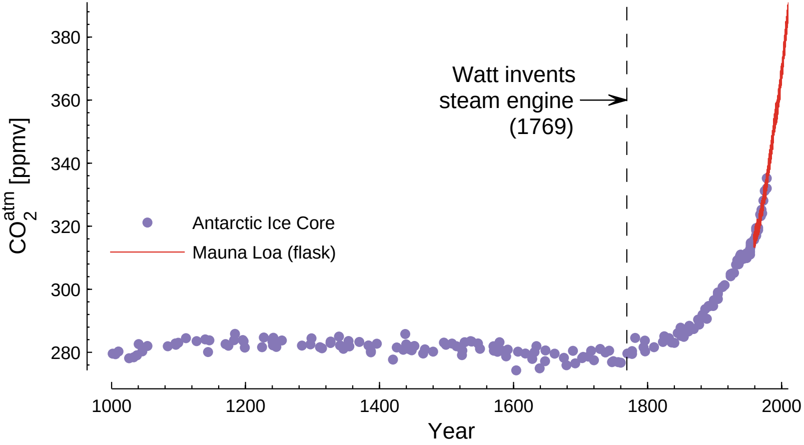
CESM Tutorial 2011

Outline

1. Motivation
2. Large-scale ocean biogeochemical distributions
3. Modeling approach
4. Model skill assessment
5. Coupled model carbon cycle
6. Summary

Global carbon cycle

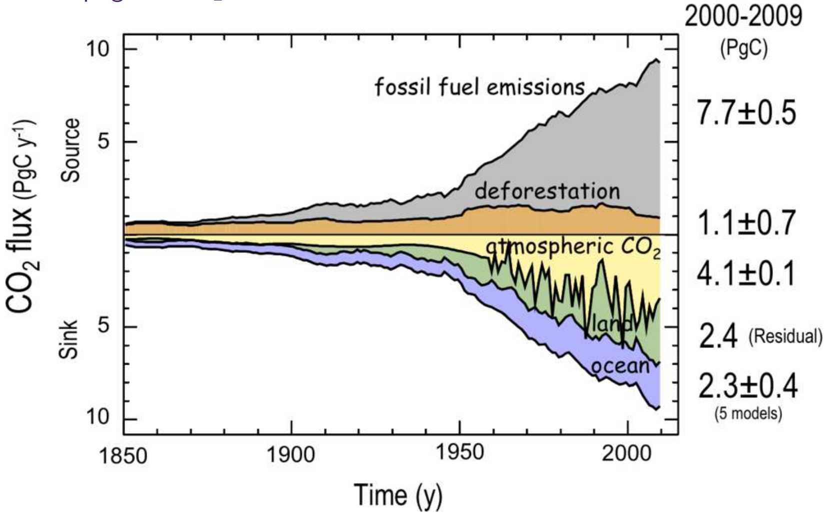
Atmospheric CO_2



NOAA Earth System Research Laboratory

Global carbon cycle

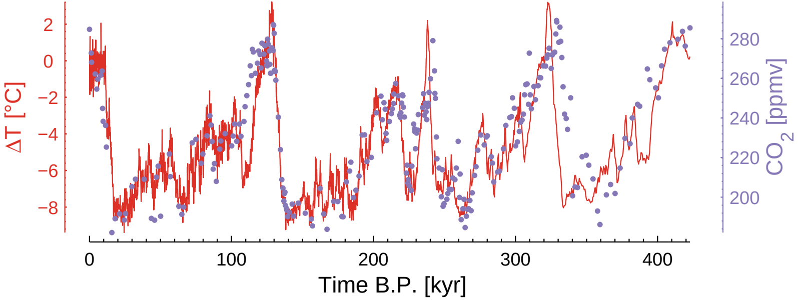
Anthropogenic CO_2: emissions and sinks



www.globalcarbonproject.org, Canadell et al. PNAS 2007; LeQuere et al. Nature Geosciences 2009

Global carbon cycle

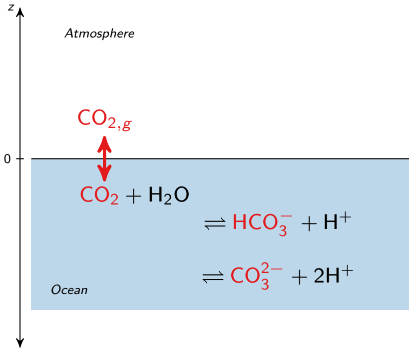
Glacial-interglacial cycles



Petit et al. 1999

Today's primary focus: ocean biogeochemistry

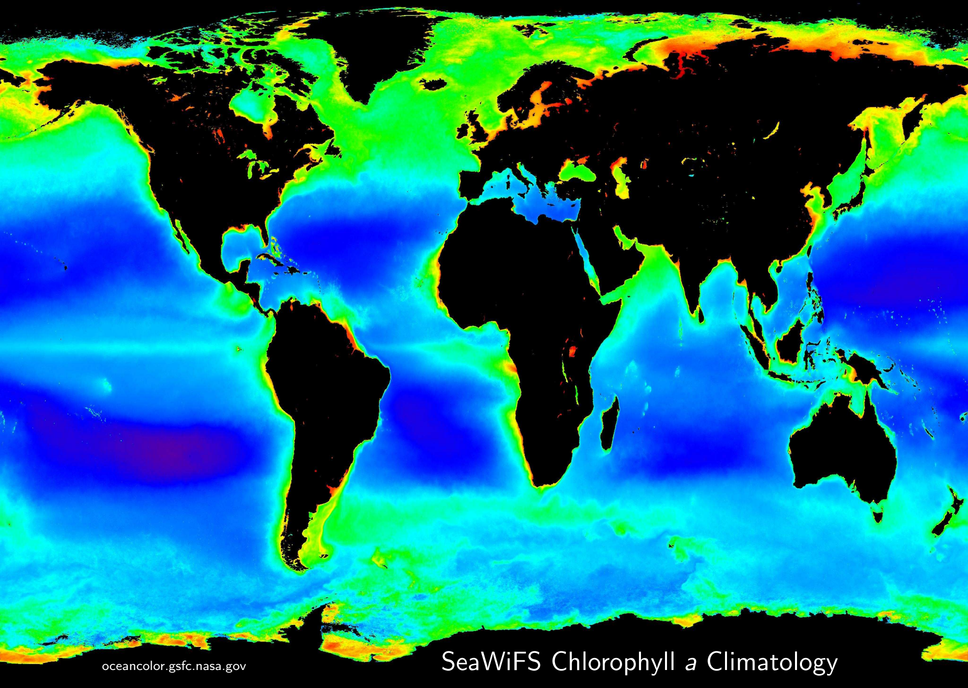
Carbon in seawater



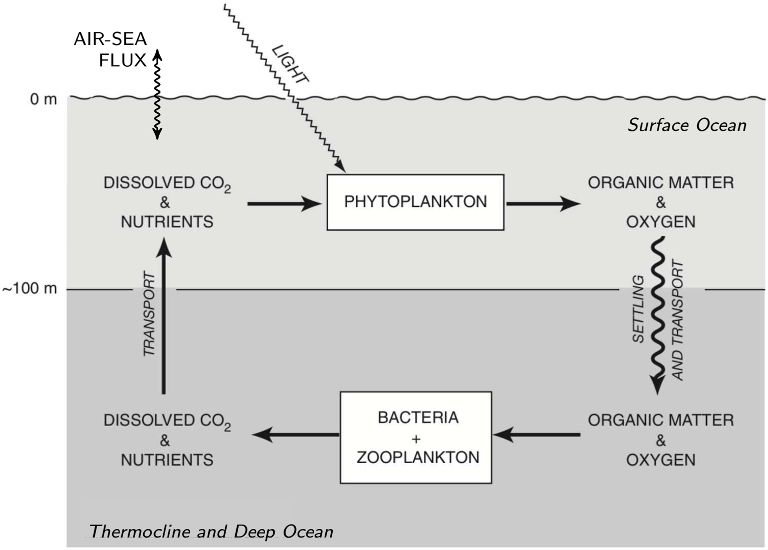
$$DIC = \text{Dissolved inorganic carbon}$$
$$= [CO_2] + [HCO_3^-] + [CO_3^{2-}]$$

- Ocean C inventory = 38,000 Pg
  - $\approx 60 \times$ Atmosphere
  - $\approx 16 \times$ Terrestrial biosphere
- Ocean reservoir controls CO_2^{atm} on timescale $> 10^2$ years

$1 \text{ Pg} = 10^{15}\text{g}$

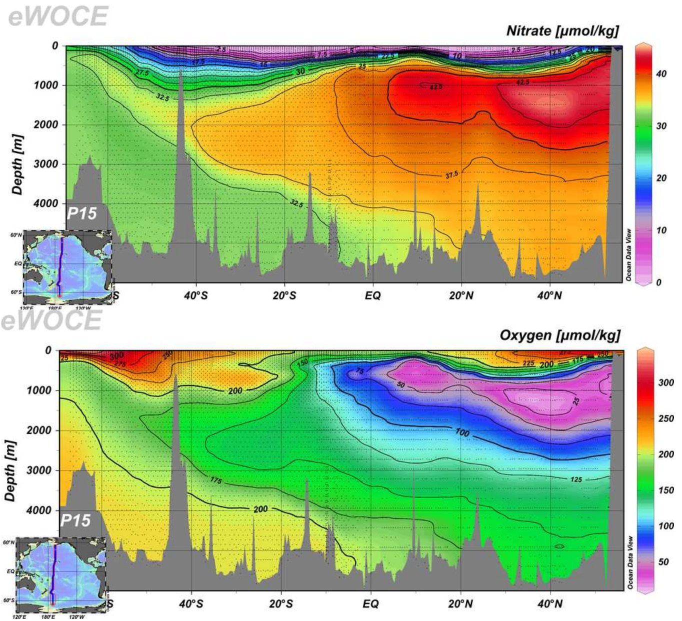

oceancolor.gsfc.nasa.gov
SeaWiFS Chlorophyll *a* Climatology

What controls the ocean carbon sink?

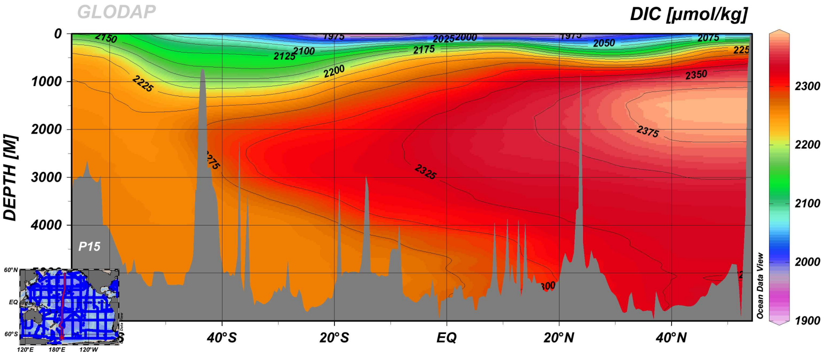


Sarmiento & Gruber 2006

Pacific meridional section: nutrient (NO_3) and dissolved gas (O_2)



Pacific meridional section: carbon distribution

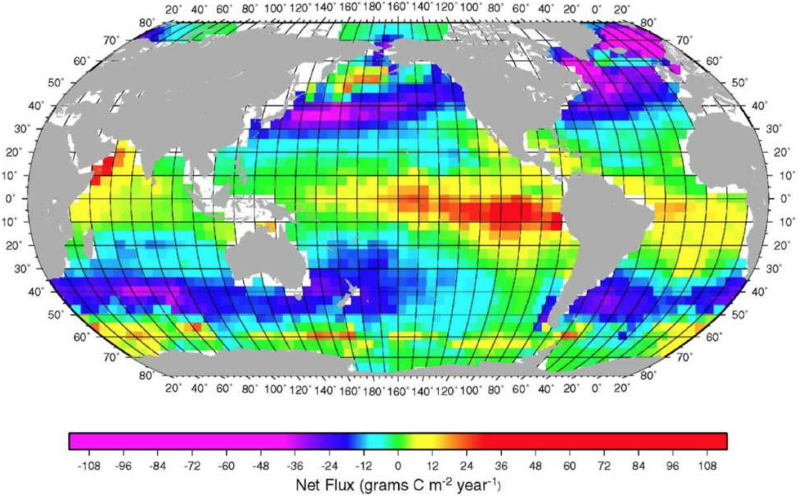


DIC = Dissolved inorganic carbon

$$= [H_2CO_3^*] + [HCO_3^-] + [CO_3^{2-}]$$

Air-sea CO_2 gas flux

Mean annual air-sea flux (year 2000; NCEP II wind, ΔpCO_2 climatology)



Ocean uptake ← → Ocean outgassing

Takahashi et al. 2009

Primary processes governing biogeochemical distributions

- Biological productivity in euphotic zone
  - Consumes nutrients & inorganic carbon
  - Produces organic matter and O_2
- Export of organic matter out of euphotic zone
  - Sinking particles (soft tissue & $CaCO_3$)
  - Circulation of ‘dissolved’ organic matter
- Remineralization of organic matter
  - Respiration: [organic matter] $\rightarrow$ [inorganic carbon and nutrients]
- General circulation
  - Advective transport
  - Lateral & vertical mixing
- Temperature-dependent air-sea gas exchange

Modeling primary productivity and export

The NPZD model

Nutrient

nitrate, ammonium,
phosphate, silicate, iron, ...

Phytoplankton

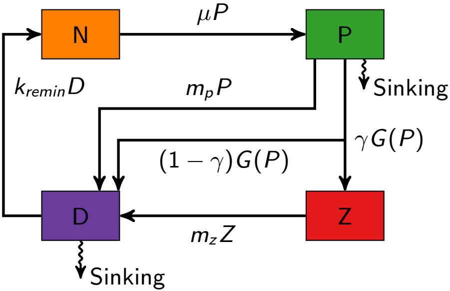
photosynthesizers

Zooplankton

grazers

Detritus

remineralizable material



Canonical example:

M.Fasham, H.Ducklow, and S.McKelvie. A nitrogen-based model of plankton dynamics in the oceanic mixed layer. *Journal of Marine Research*, 48:591–639, 1990.

Simple NPZ model

Phytoplankton

$$\frac{dP}{dt} = \mu_0 \left(\frac{N}{K_N + N}\right) \left(1 - e^{\alpha E/\mu_0}\right) P - g \left(\frac{P}{K_P + P}\right) Z - m_p P$$

Nutrient limitation | Light limitation | Grazing | Mortality

Zooplankton

$$\frac{dZ}{dt} = \gamma g \left(\frac{P}{K_P + P}\right) Z - m_z Z$$

Nutrient

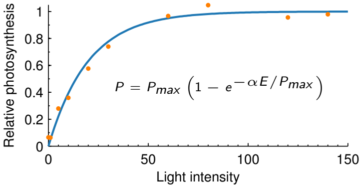
$$\frac{dN}{dt} = -\mu_0 \left(\frac{N}{K_N + N}\right) \left(1 - e^{\alpha E/\mu_0}\right) P + (1-\gamma) g \left(\frac{P}{K_P + P}\right) Z + m_P P + m_z Z$$

- Three coupled ordinary differential equations
- Mass conserving
- 3 state variables (NPZ), 8 parameters $(\mu_0, K_N, \alpha, g, K_P, m_P, m_Z, \gamma)$

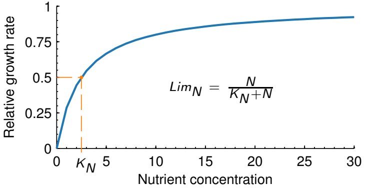
How do you estimate parameters and functional forms?

- Incubation experiments

P-I curves

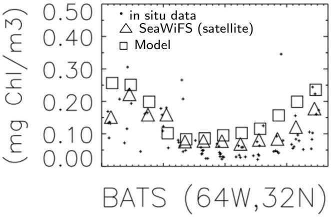


Nutrient uptake curves



- Optimize with respect to data

e.g. Chlorophyll

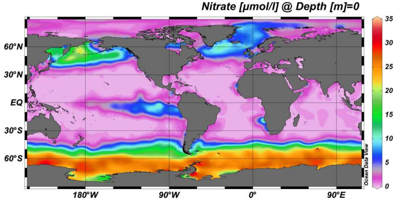


Moore et al. 2002

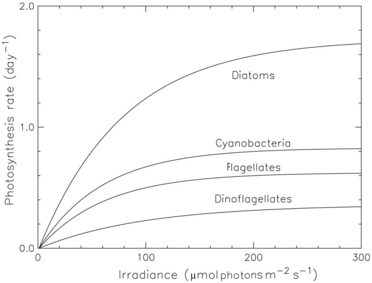
- Previous models

Plankton functional types (PFTs)

Environmental variability

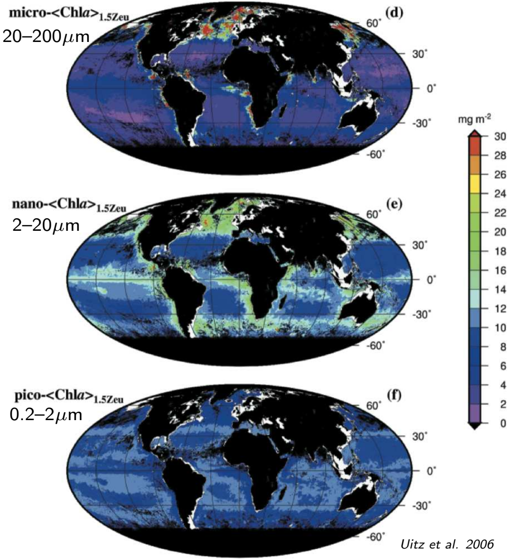


Physiological specialization



Le Quéré et al. 2005

Biogeography



Uitz et al. 2006

Plankton functional types (PFTs)

Definition

- Conceptual grouping of phytoplankton species by ecological or biogeochemical function.

- Examples:
  - Nitrogen fixers (e.g. *Trichodesmium*)
  - Calcifiers (e.g. coccolithophores)
  - Silicifiers (e.g. diatoms)
  - Dimethyl sulfide (DMS) producers (e.g. *Phaeocystis*)

- Robust prediction requires representation of key processes; e.g., export production may change with climate due to ecosystem shifts.

See: Le Quéré et al., Ecosystem dynamics based on plankton functional types for global ocean biogeochemistry models. *Global Change Biology*, 11(11):2016–2040, 2005.

Benefits of complexity

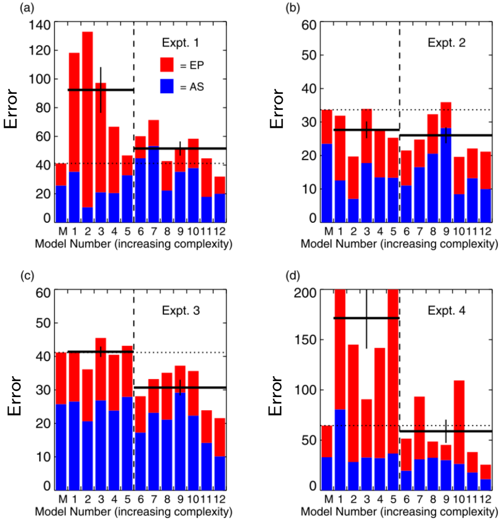
Skill and portability

(a) No optimization;

(b) Simple and complex models are similar when tuned for specific site;

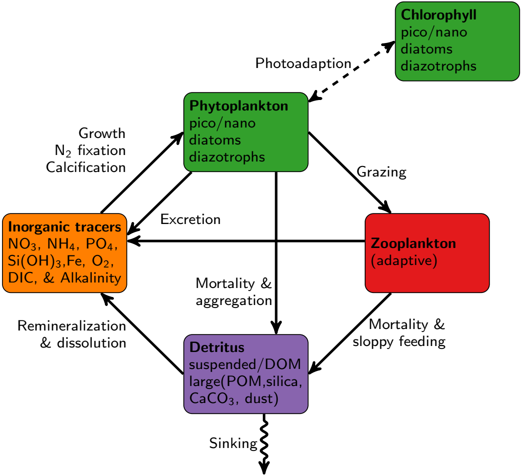
(c) More complex models do better at multiple sites with one parameter set;

(d) More complex models perform better at different sites when tuned for one site.



Friedrichs et al. *J. Geophys. Res*, 2007

CESM Biogeochemical Element Model (BEC)



Doney et al., J. Mar. Systems, 2009

- 4 Plankton functional types
  - 3 autotrophs, 1 grazer
  - implicit calcifiers
  - explicit N fixers
- Nutrients: N, P, Si, Fe
- Fixed C:N:P stochiometry
- Variable Fe:C, Si:C, & Chl:C
- Nonlinear carbon chemistry
- Atm. deposition: Fe & N
- Dynamic Fe cycle

References:

Moore et al., *Deep Ses Res.*, 2002.

Moore, Doney, & Lindsay, *GBC*, 2004.

Moore & Braucher, *Biogeosciences*, 2008.

CESM Biogeochemical Element Model (BEC)

Known gaps:

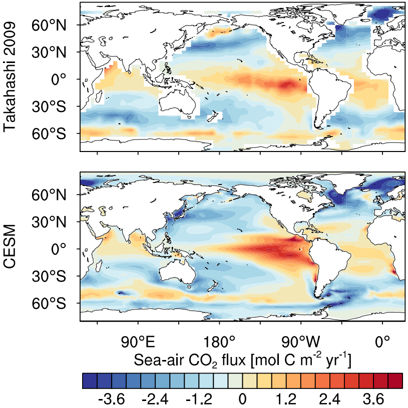
- $CaCO_3$ calcification & dissolution rates not dependent on CO_3^{2-} saturation state;
- No riverine input of BGC tracers;
- No sediment model;
- No treatment of BGC in sea ice;
- Focus on lower trophic levels.

Model Validation: example data sets

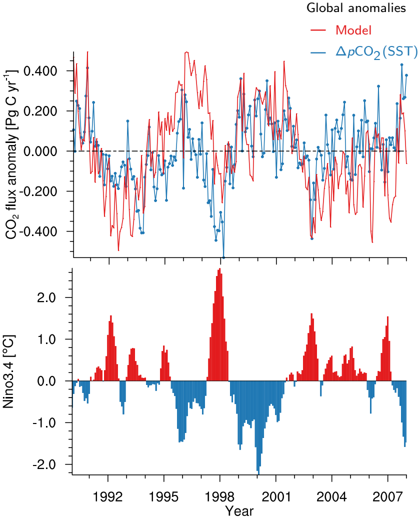
- Macronutrients (NO_3, PO_4, SiO_3) and O_2 (World Ocean Atlas)
- DIC, Alk, and CFCs (GLODAP: GLobal Ocean Data Analysis Project)
- $p$$CO_2$ and CO_2 flux (e.g., Takahashi et al. 2009, Park et al. 2010)
- Surface chlorophyll (SeaWiFS, MODIS)
- Net primary productivity (satellite algorithms)
- Process cruises (e.g., JGOFS study sites)
- Ocean time series stations (e.g., HOTS, BATS, Station Papa, etc.)

Sea-air CO_2 flux

Annual mean (coupled)



Ocean-ice hindcast (forced)



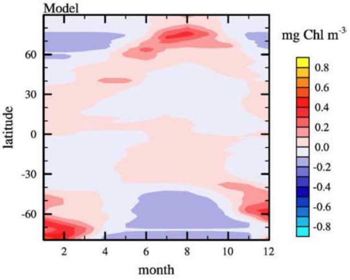
Negative := ocean uptake

Park et al. 2010

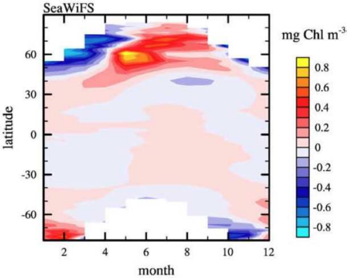
Satellite ocean color comparison

Mean annual cycle

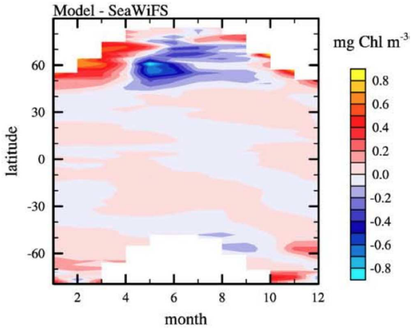
CESM-3



Obs



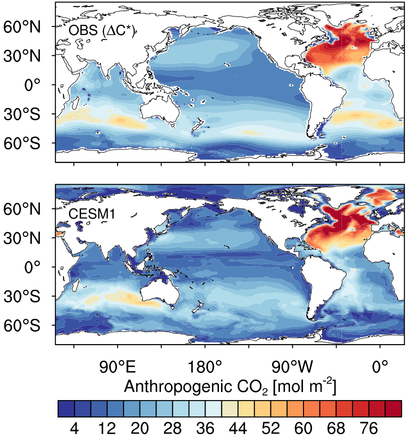
Bias



- Chl*a* too high in subtropical gyres, too low in subpolor gyres.
- NH bloom phasing is about right, but peak Chl*a* and bloom duration are poorly simulated.

Anthropogenic CO_2 uptake

Anthropogenic CO_2 inventory



Total ocean inventory

GLODAP:	118 Pg C	(±16%)
CESM1:	90.3 Pg C	(23% low)

- High C_{ant} inventories in N. Atlantic; possibly related to deep convection patterns—and/or biased observations.
- Southern Ocean uptake too weak: overturning circulation too fast or biological uptake too weak?

Known challenges

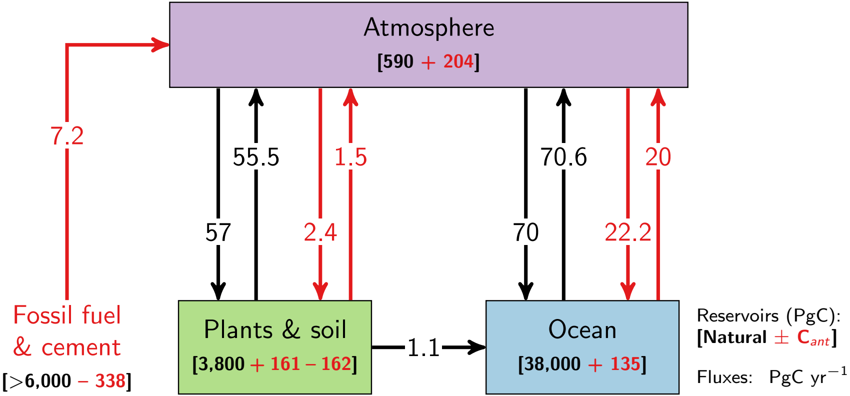
- Optimization of BGC model parameters
  - Functional group approach increases parameter uncertainty (multiple unique physiologies are lumped as one);
  - Physical simulation is biased: don't over-tune BGC.

- Drift in BGC fields requires long spin-up
  - multiple timescales: diurnal to millenial

- Representations are semi-mechanistic (at best)
  - we can capture extant distributions,
    $\longrightarrow$ can we predict dynamics under novel forcing?

The Global Carbon Cycle

Natural & anthropogenic CO_2



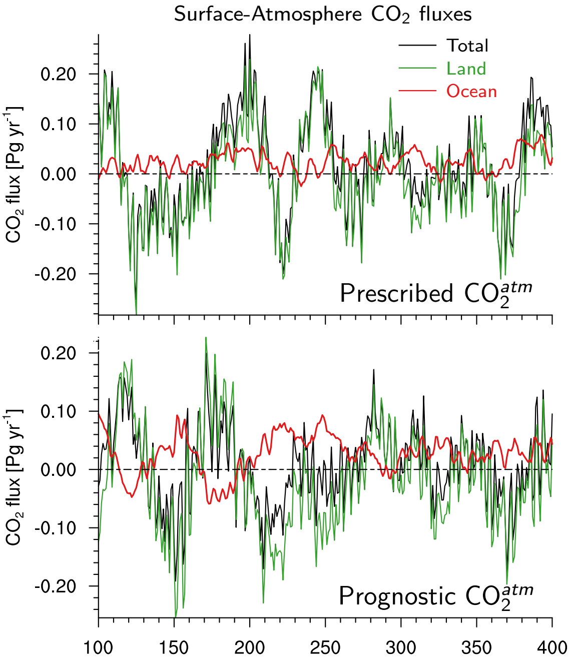
Sabine & Tanhua [2010]

1 Pg = 10^{15} g

Coupled carbon cycle

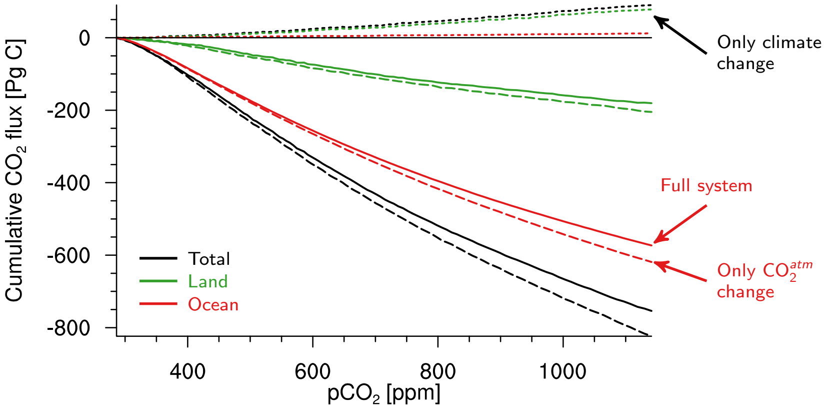
CESM control simulations

- Terrestrial biosphere dominates annual to decadal scale variability in global CO_2 fluxes;
- Climate variability drives flux variance;
- Variance in ocean flux increases with prognostic CO_2^{atm}; land and ocean are coupled by the atmospheric reservoir.



Land and ocean uptake of fossil fuel emissions

Cumulative anthropogenic CO_2 sinks



Summary

- An interplay of physical and biological processes determine biogeochemical distributions in the ocean.
- "Perfect" ecosystem models don't exist; many simplifications must be made. Model improvement is ongoing—scientific questions guide this process.
- Climate drives variability in CO_2 fluxes; atmospheric reservoir couples land and ocean.
- The ocean & terrestrial biosphere are important sinks for anthropogenic CO_2; the sensitivity of these sinks to changing climate is of major concern and an area of active research.