Intro to Biogeochemical Modeling Ocean & Coupled

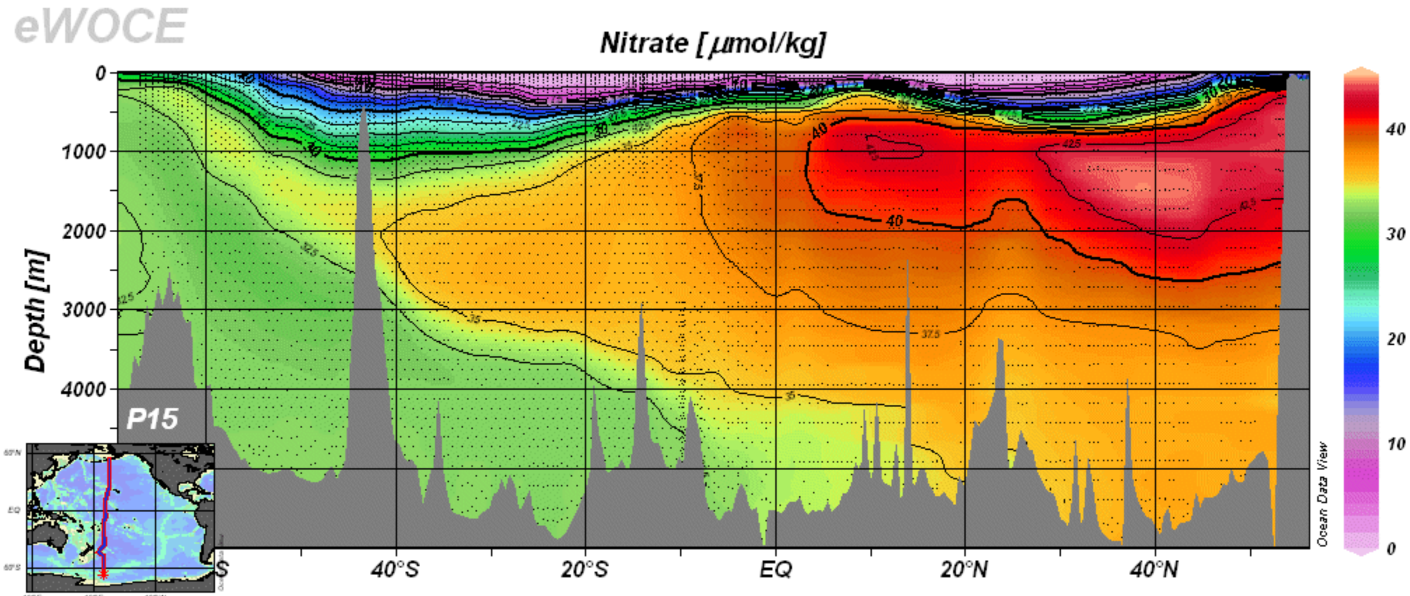
Keith Lindsay, NCAR/CGD

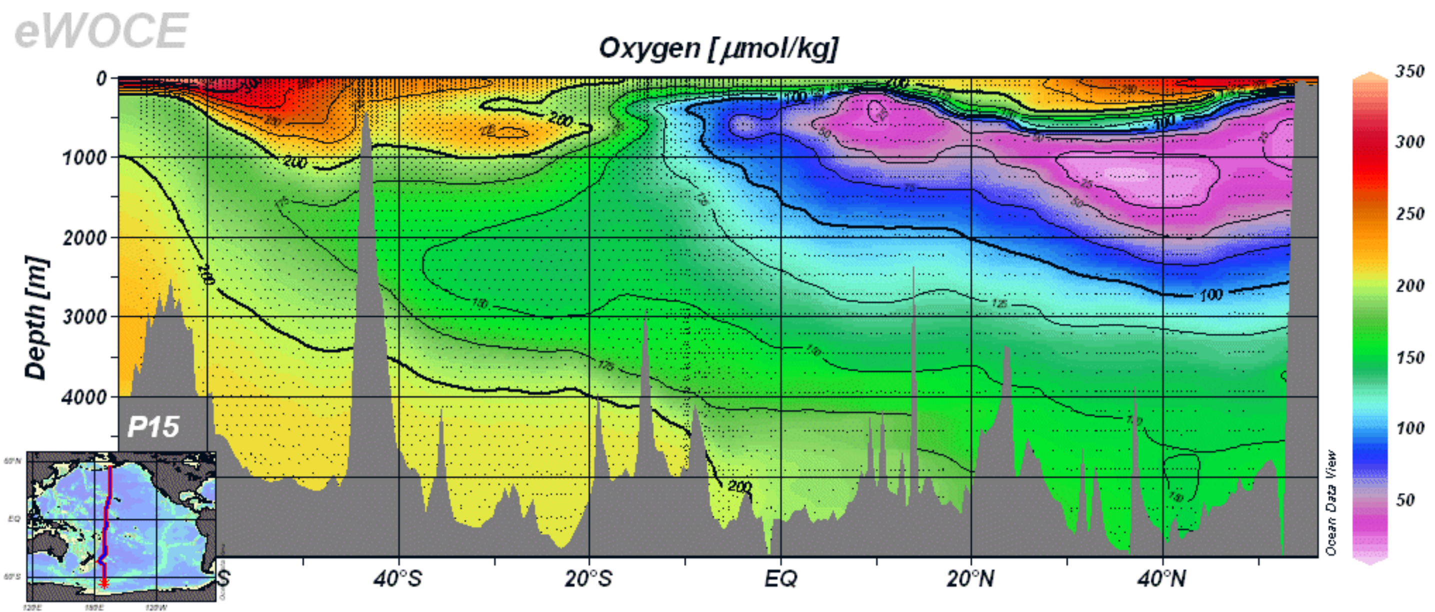
NCAR is sponsored by the National Science Foundation

Lecture Outline

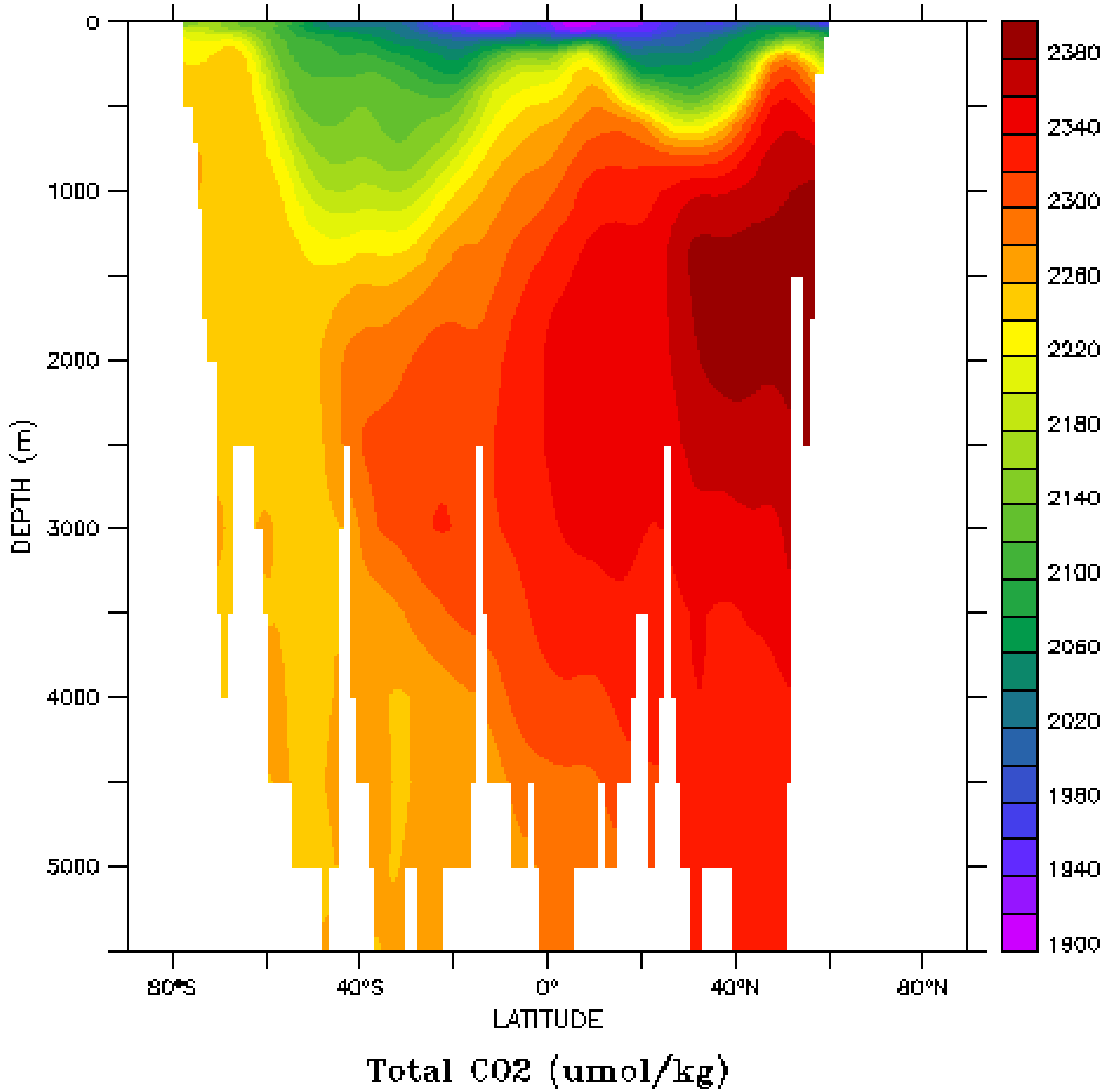
1) Large Scale Ocean Biogeochemical Features
2) Techniques for Modeling Biological Productivity
3) Skill Assessment
4) Global Carbon Cycle
5) Summary

NO_3 (a nutrient), O_2 (dissolved gas) Along Pacific Transect

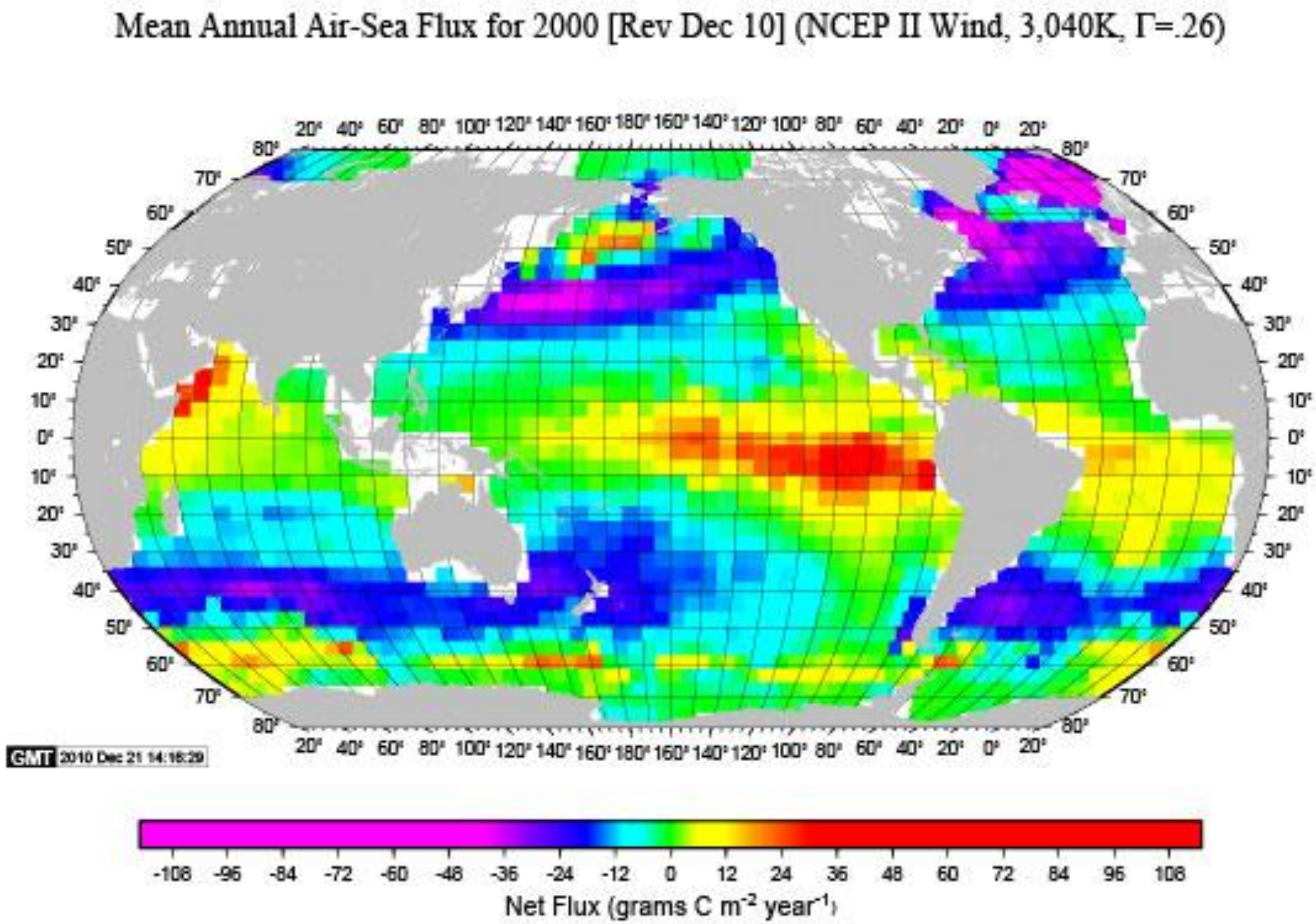




DIC ($\sim CO_2$) Along Same Pacific Transect



Takahashi Air-Sea CO_2 Gas Flux



Primary Processes Governing Distribution of Nutrients, O_2, Carbon, etc.

- Biological Productivity in Euphotic Zone
  - Consumes Nutrients & Inorganic Carbon
  - Produces Organic Matter & O_2
- Export of Organic Matter out of Euphotic Zone
  - Sinking Particles (e.g. detritus, $CaCO_3$ shells, …)
  - Circulation of Suspended Matter
- Remineralization of Organic Matter
  - ‘reverse’ of productivity, consumes O_2
- General Circulation
  - Advective Transport
  - Lateral & Vertical Mixing
- Temperature Dependent Air-Sea Gas Exchange

Other Processes, Smaller Global Impact, Regionally Significant

- Atmospheric Nutrient Deposition
  - Fe, N, P, …
- Sedimentary Burial
- Riverine Inputs

- Nitrogen Fixation
  - Conversion of dissolved N_2 gas into NH_4
- Denitrification
  - Consumption of NO_3 during remineralization

What is an NPZD model?

N Nutrient
 nitrate, ammonium,
 phosphate, silicate, iron, etc.

P Phytoplankton
 photosynthesizers

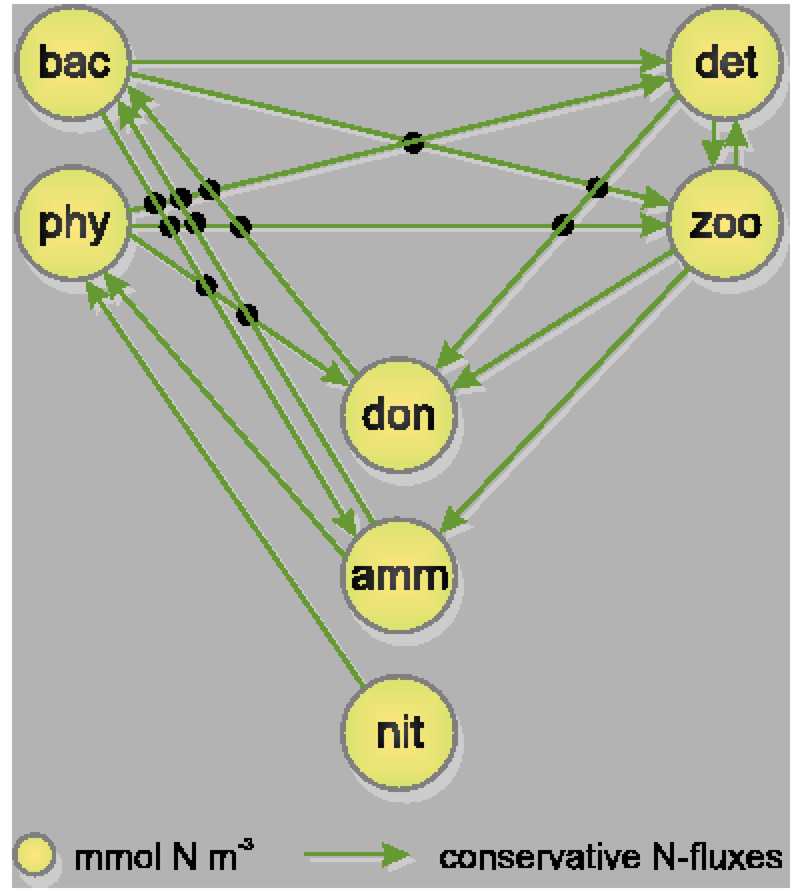
Z Zooplankton
 grazers

D Detritus

Canonical Example

Fasham, Ducklow, McKelvie, J Mar. Res., Vol. 48, pp. 591-639, 1990.

Many more variations are used…



Fasham model diagram from www.gotm.net

Simple NPZ Model

$$\frac{dP}{dt} = \mu_0\left(\frac{N}{k_N + N}\right)\left(1 - e^{\alpha E/\mu 0}\right)P - g\left(\frac{P}{k_P + P}\right)Z - m_P P$$

Nutrient limitation — Light limitation — Grazing — Mortality

$$\frac{dZ}{dt} = ag\left(\frac{P}{k_P + P}\right)Z - m_Z Z$$

$$\frac{dN}{dt} = -\mu_0\left(\frac{N}{k_N + N}\right)\left(1 - e^{\alpha E/\mu 0}\right)P + (1-a)g\left(\frac{P}{k_P + P}\right)Z + m_P P + m_Z Z$$

- Three coupled ordinary differential equations
- Mass conservation

How do you estimate parameters and functional forms?

- Laboratory & field incubations
  - P-I curves
  - Nutrient uptake curves
- Tune/Optimize against field data
- Previous Models

Plankton Functional Types (PFTs)

- Categorize plankton species by how they function and use representative types/groups
- Example definition from Le Quéré et al., Global Change Biology, Vol. 11, pp. 2016-2040, 2005.
  - Explicit biogeochemical role
  - Biomass and productivity controlled by distinct physiological, environmental, or nutrient requirements
  - Behavior has distinct effect on other PFTs
  - Quantitative importance in some region of the ocean

What is the best model?

(b) Simple models do just as well as more complex models when tuned for specific sites.

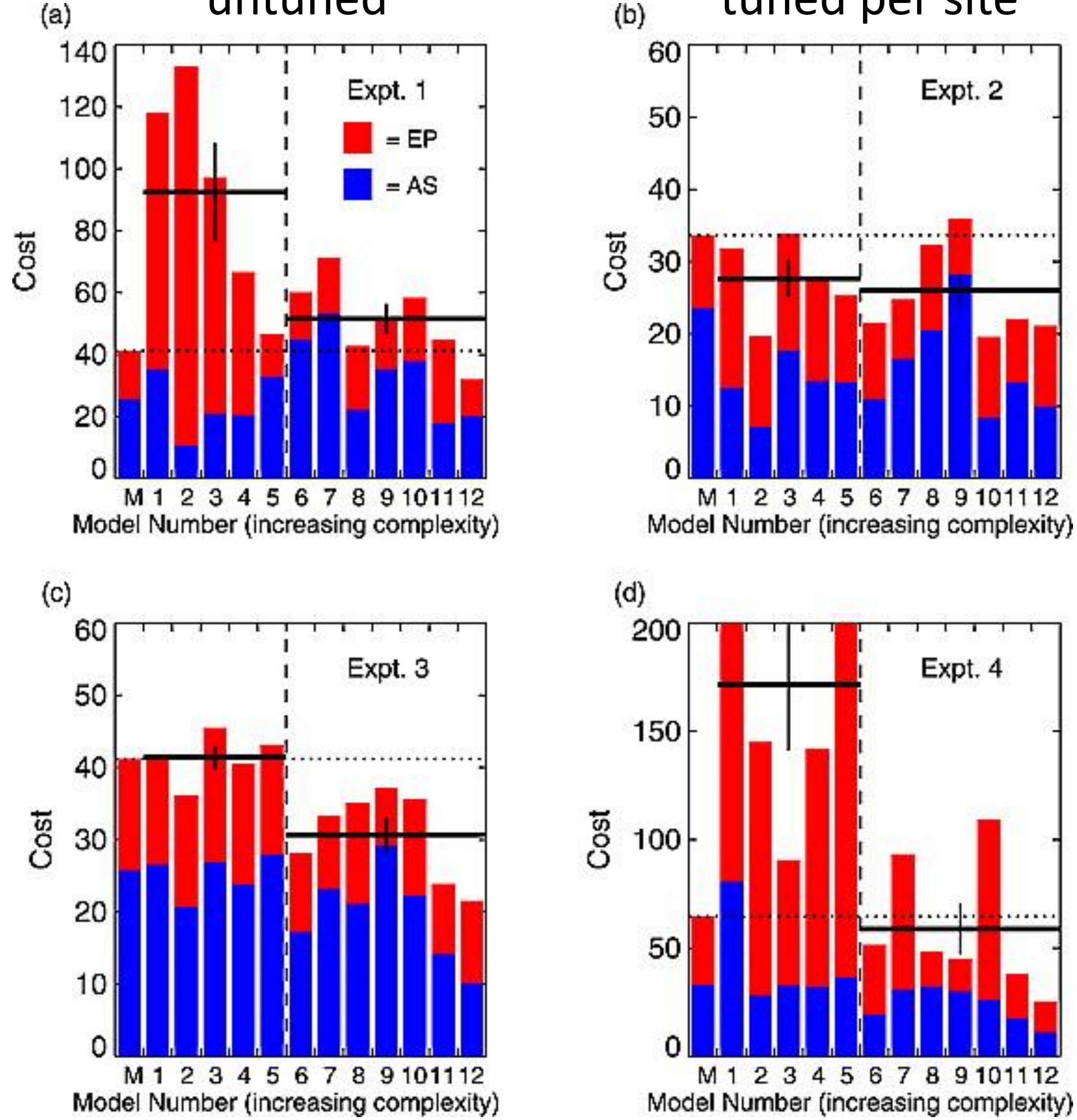
(c) More complex models do better at multiple sites with single parameter sets.

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

Assessment of skill and portability in regional marine biogeochemical models: Role of multiple planktonic groups, Friedrichs et al., *JGR-Oceans*, 2007.

untuned

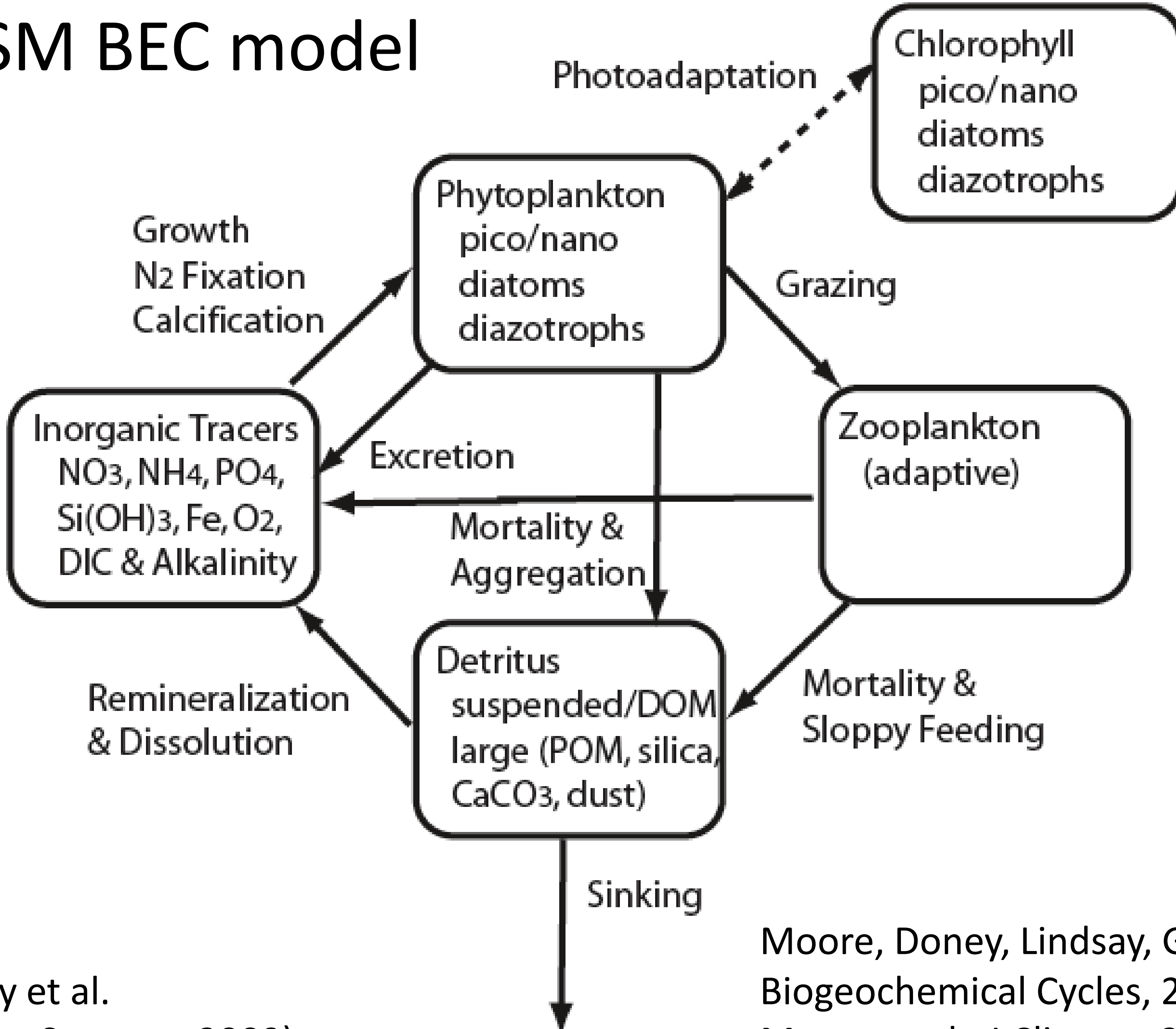
tuned per site



tuned at both sites simultaneously

run at one site with tuning from other

CCSM BEC model



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

Moore, Doney, Lindsay, Global Biogeochemical Cycles, 2004.
Moore et al., J Climate, 2013.

Primary Features of CESM BEC Model

- Nutrients: N, P, Si, Fe
- 4 Plankton Functional Groups
  - 3 Autotrophs, 1 Grazer
  - Implicit coccolithophores
  - 32 tracers in CESM 2.0
    - 27 in CESM 1.2 and 24 in CESM 1.0/1.1
- Fixed C:N ratios in plankton
- Variable P:C, Fe:C, Si:C, Chl:C ratios
  - P:C was fixed in CESM 1.2 and previous versions
- Fe model has prognostic Fe-binding ligand
  - as of CESM 2.0

Known Gaps in Ocean BGC in CESM

- Calcification & open ocean $CaCO_3$ dissolution rates are independent of CO_3 saturation state
- Riverine inputs of BGC tracers are prescribed
- C, N, P, Si, $CaCO_3$ buried in sediments are lost from the system
- No treatment of BGC in sea-ice

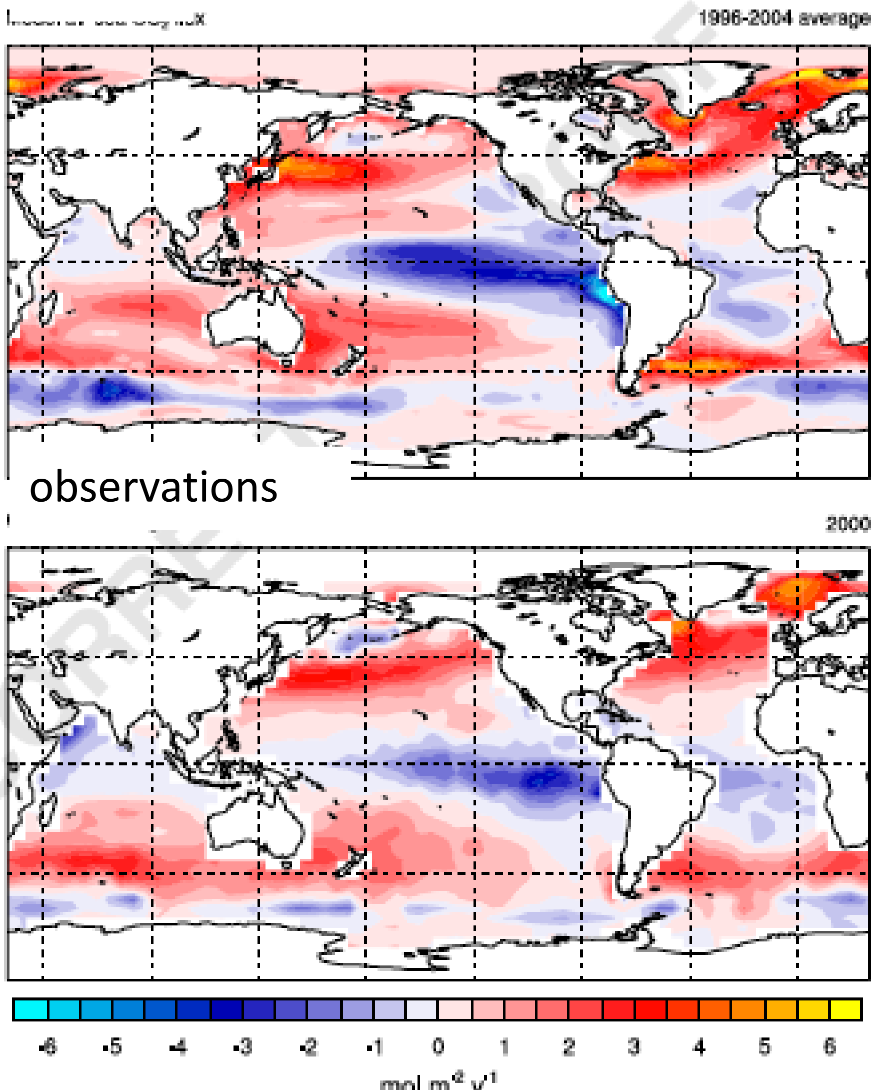
- Focus in on lower trophic levels

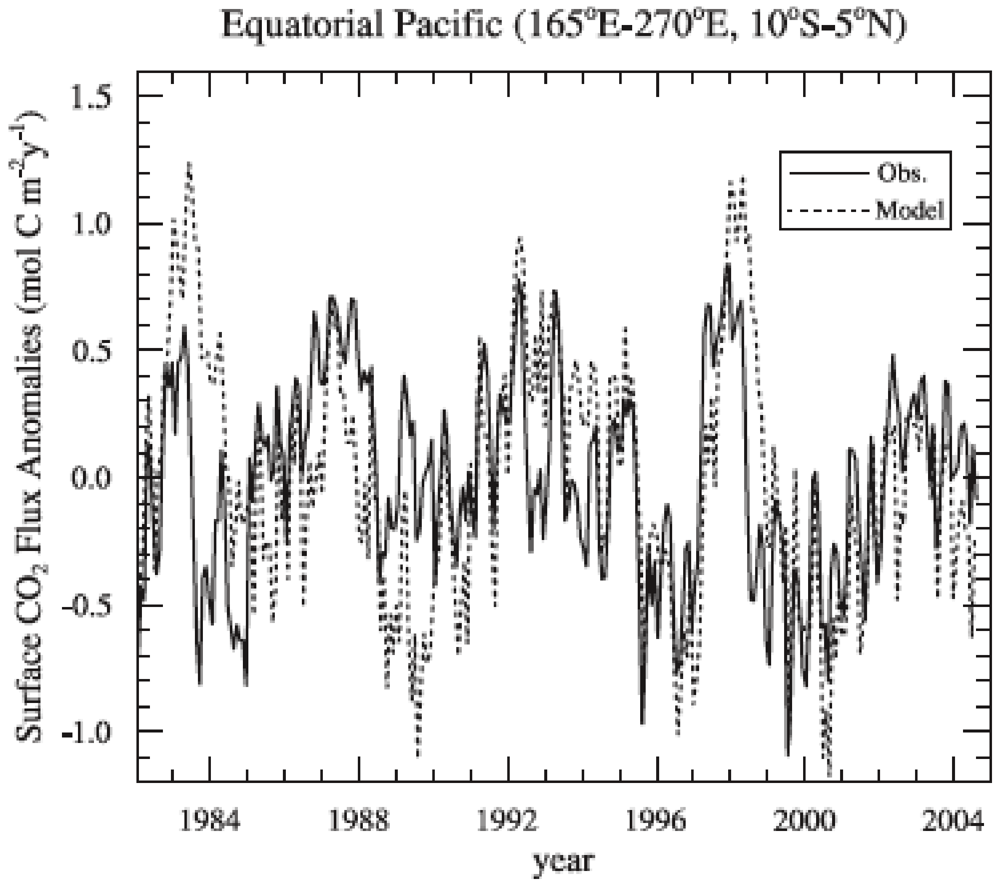
Model Validation: Examples of Data Sets

- Macronutrients (PO_4, NO_3, SiO_3) and O_2 from World Ocean Atlas
- DIC, ALK from GLODAP Analysis
- pCO_2 and CO_2 Flux assembled by Takahashi
- Surface Chl measured by satellite
- Productivity estimated from satellite
- JGOFS study sites
- HOTS & BATS timeseries

Air-sea CO_2 Flux

model





Doney et al. (Deep-Sea Res. II, 2009)

Known Challenges

- Optimize BGC model parameters
  - Functional group approach increases uncertainty of parameters (i.e. multiple species, with different characteristics, are clumped together)
  - Don’t want to overtune too much to compensate for biases in physical model
- Given BGC model parameters and physical circulation, generate balanced BGC state
  - Need to deal w/ diurnal to millenial timescales
  - Using Newton-Krylov for this is a work in progress

Large Scale Global Carbon Cycle

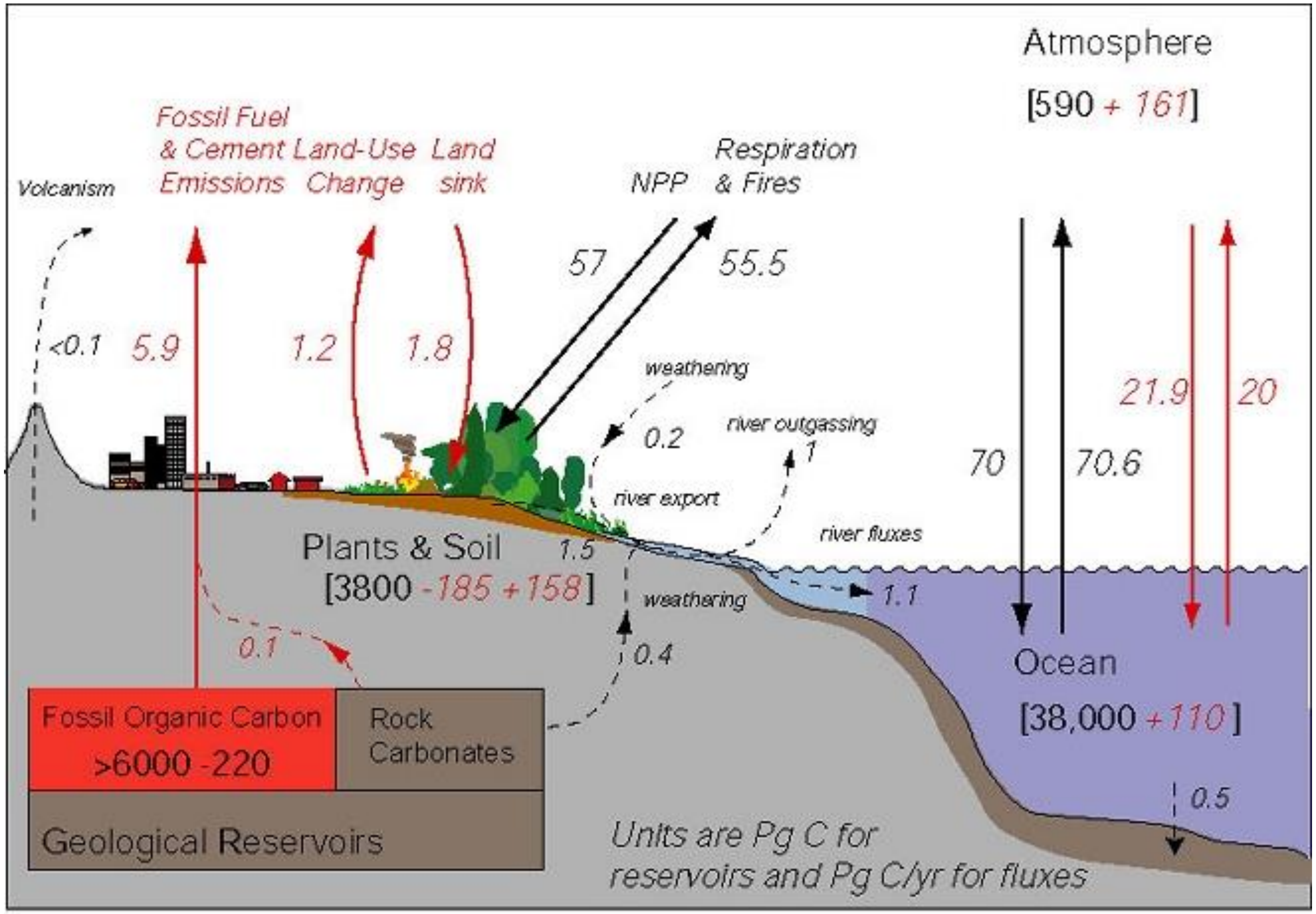
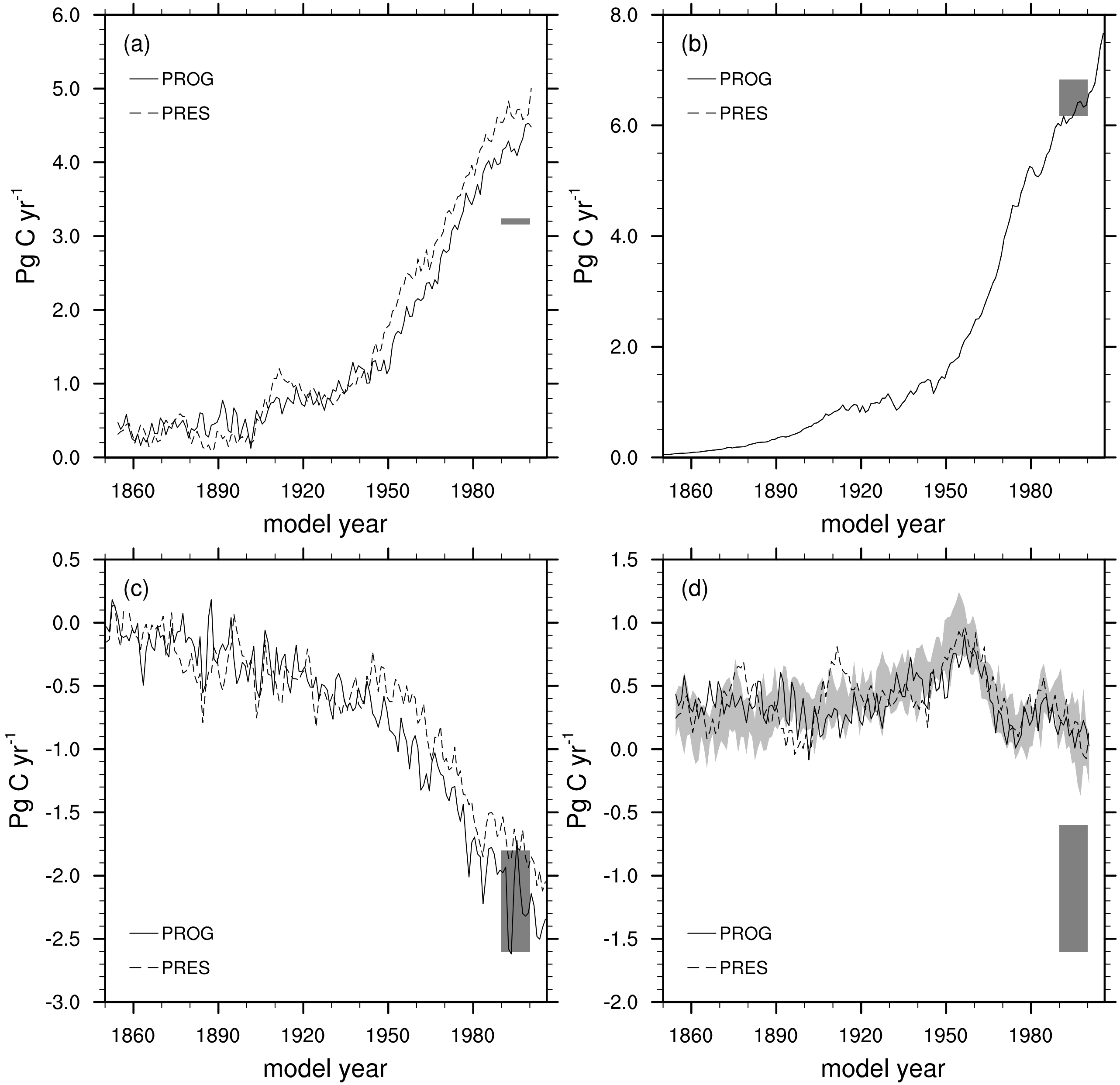


Figure courtesy PMEL

20th Century CO_2 Fluxes into Atmosphere in CESM1(BGC)

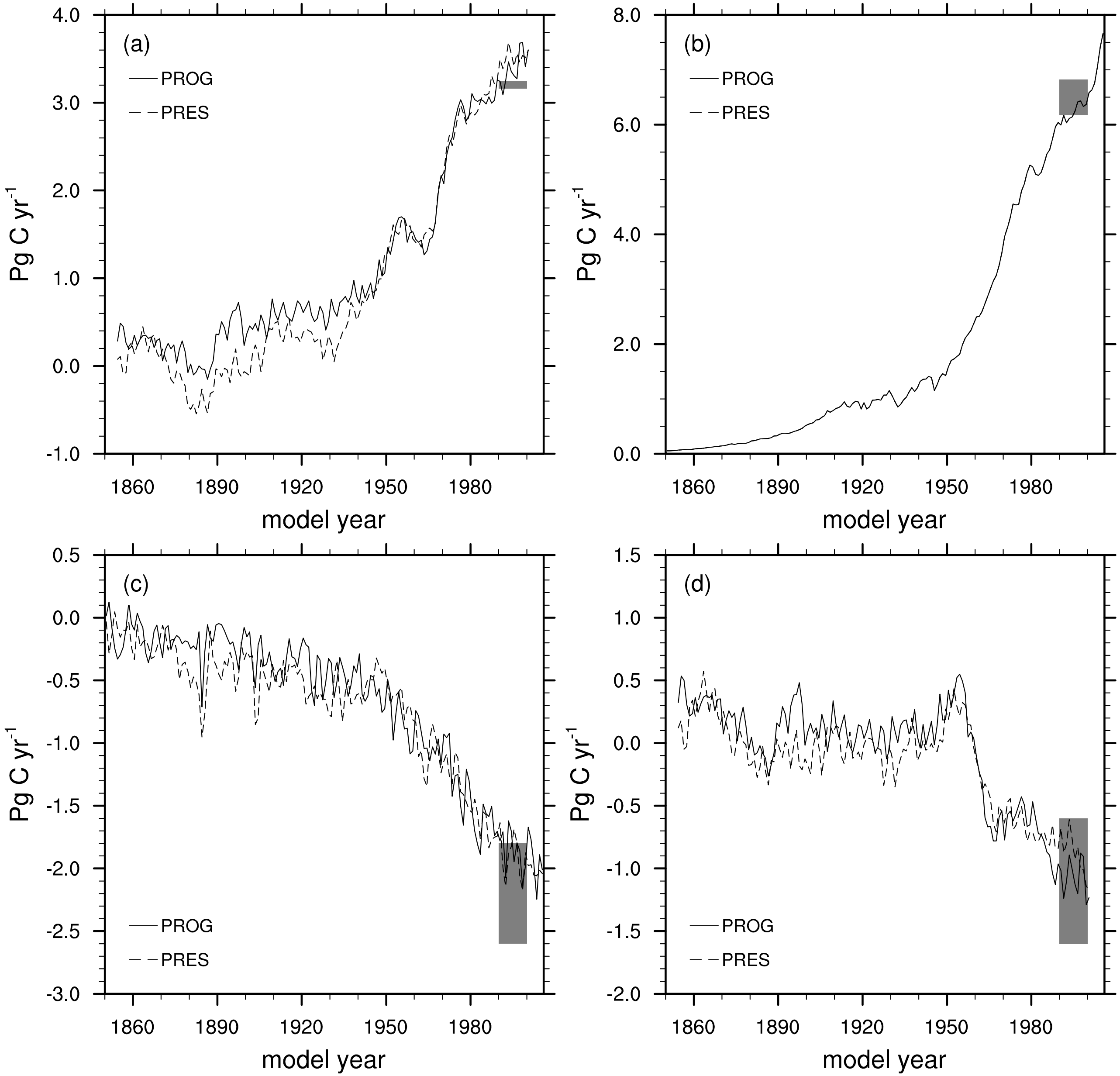
(a) Total
(b) Fossil Fuels
(c) Sea-to-Air
(d) Land-to-Air



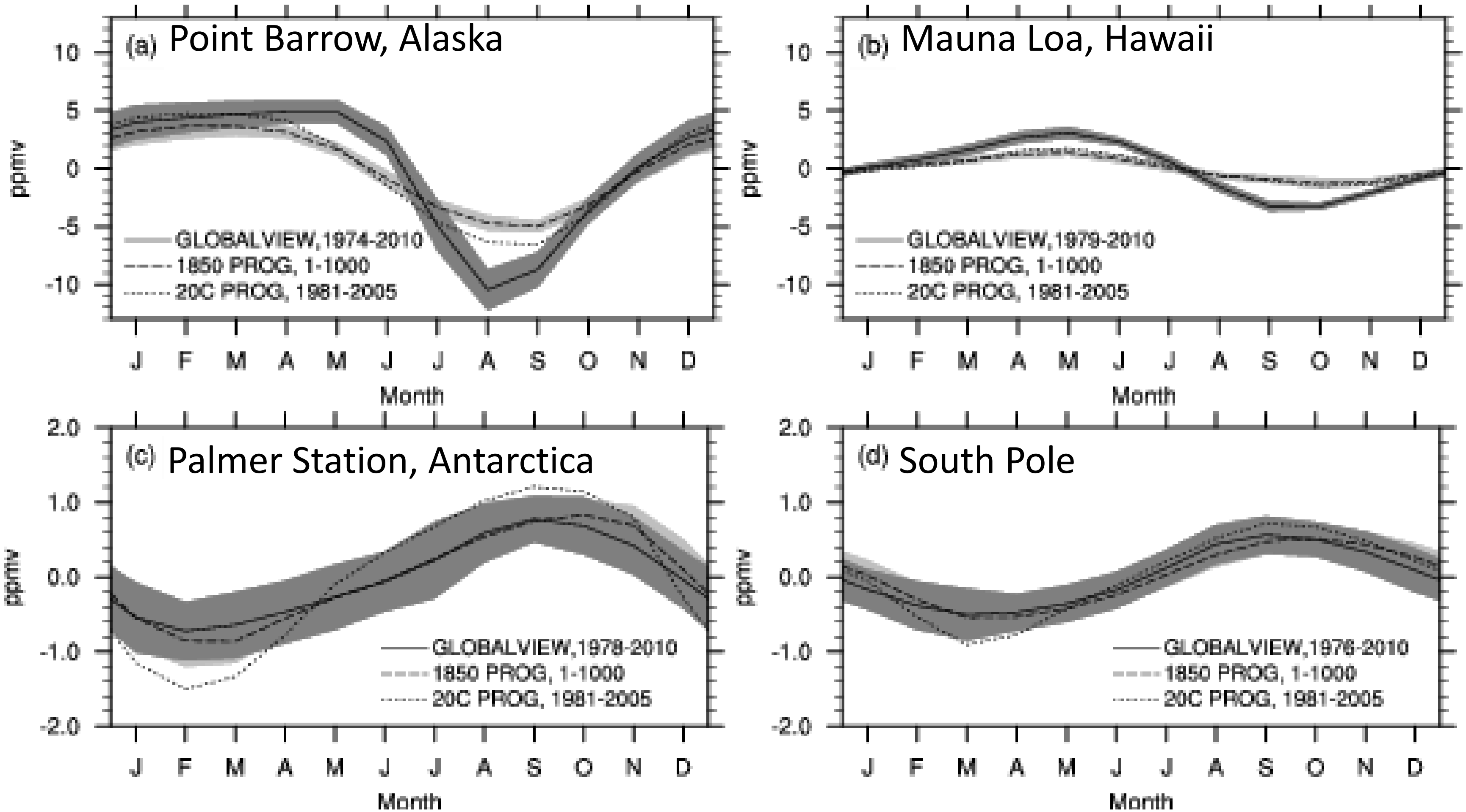
Lindsay et al., 2014, J Clim

20^{th} Century CO_2 Fluxes into Atmosphere in CESM1.2+(BGC)

(a) Total
(b) Fossil Fuels
(c) Sea-to-Air
(d) Land-to-Air

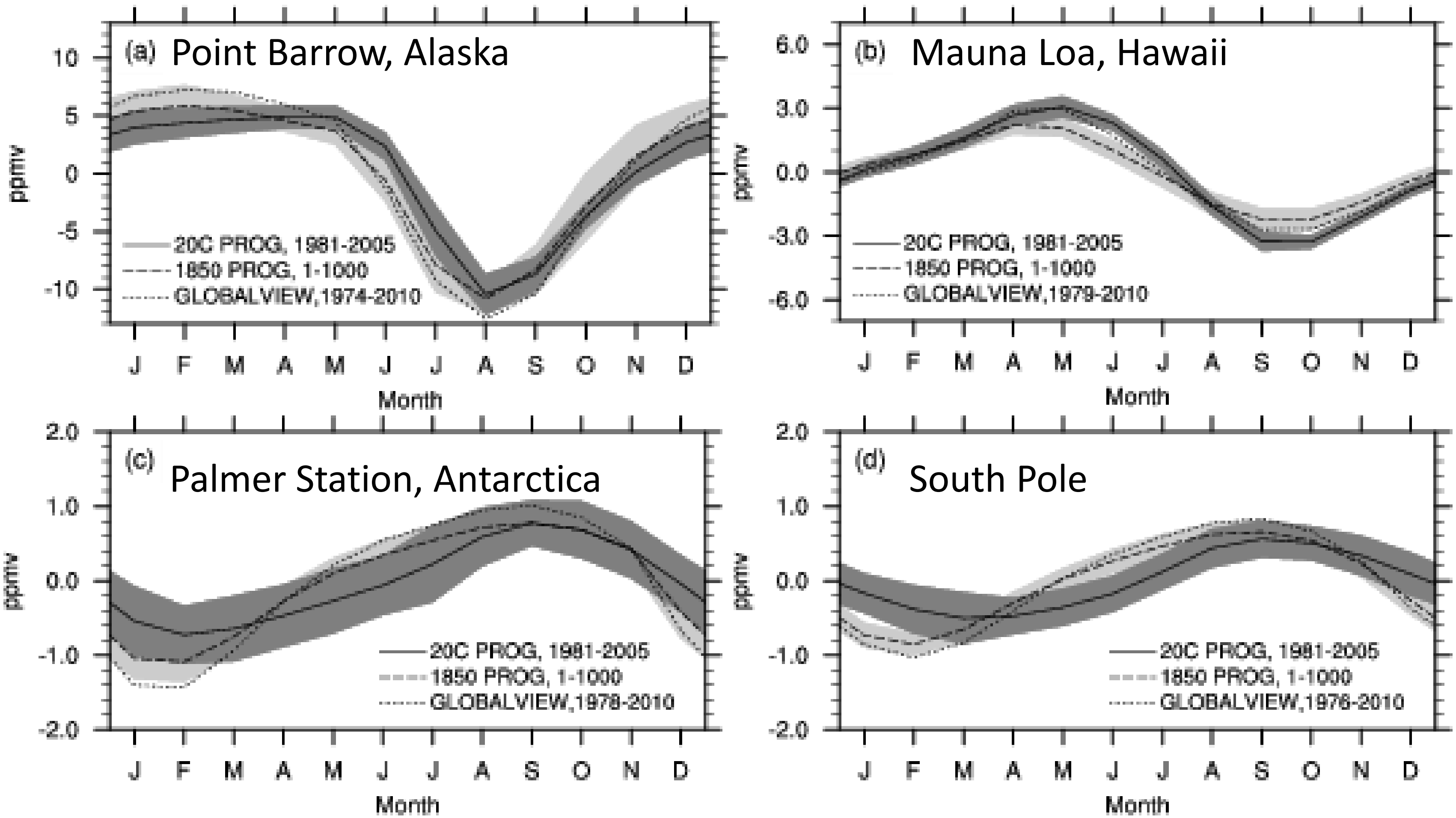


Seasonal Cycle of CO_2, CESM1(BGC)

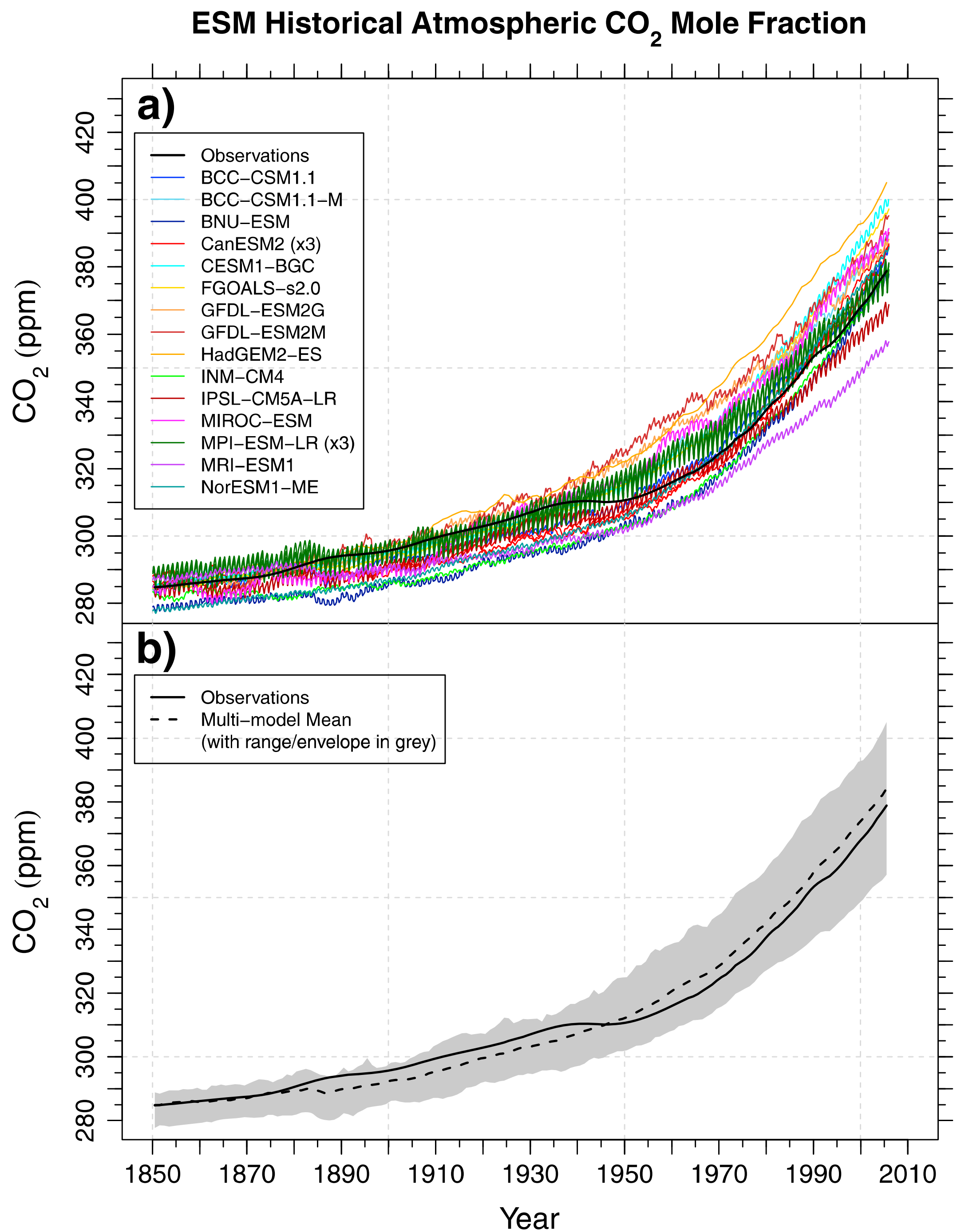


Lindsay et al., 2014, J Clim

Seasonal Cycle of CO_2, CESM1.2+(BGC)

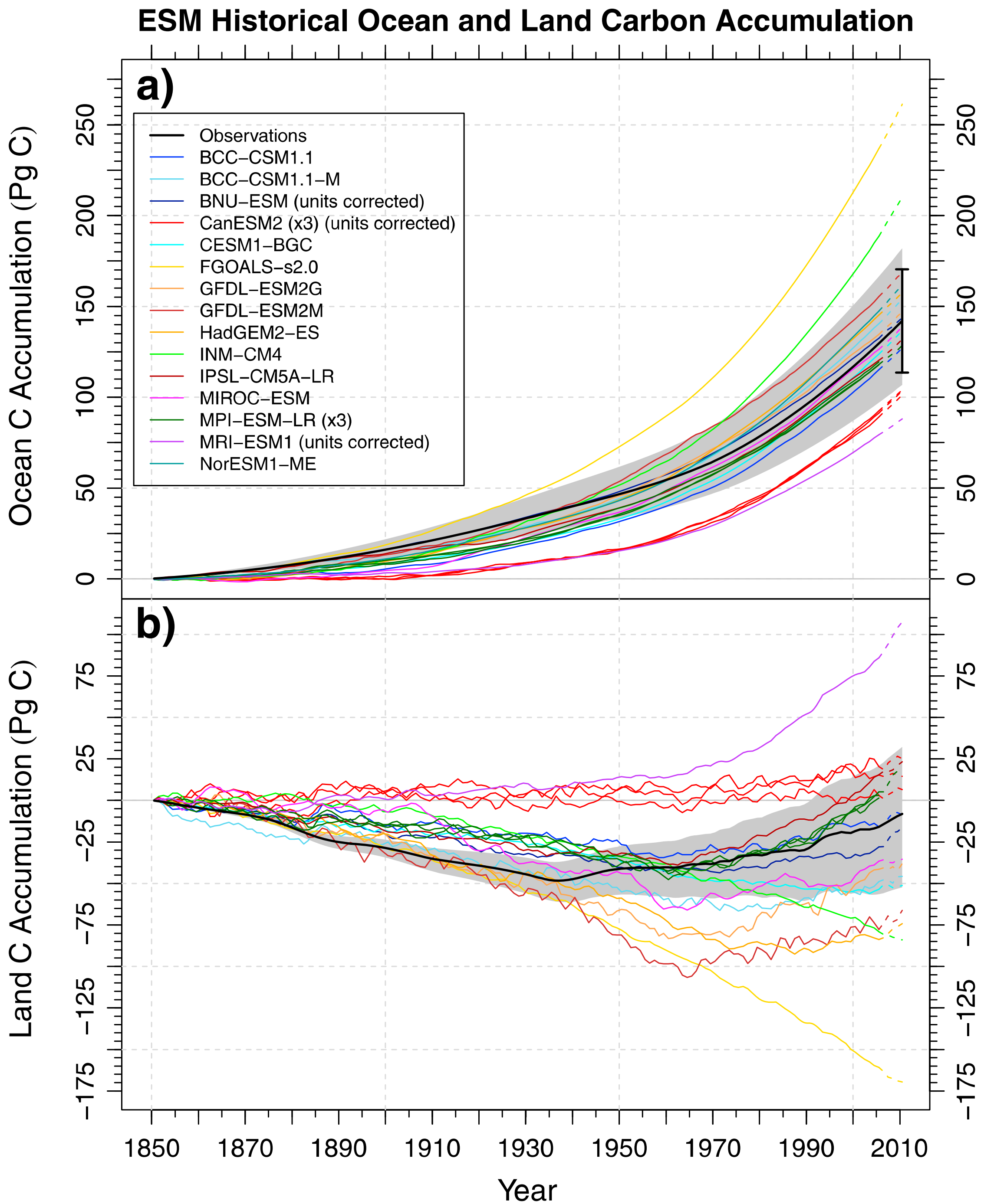


Atmospheric CO_2 in CMIP5 Earth System Models



Hoffmann et al, JGR-BGS, 2013

Ocean and Land Carbon Accumulation in CMIP5 Earth System Models



Hoffmann et al, JGR-BGS, 2013

Subset of Literature on Carbon Cycle in Earth System Models

- C4MIP
  - Friedlingstein et al., J Clim, 2006
- Carbon Cycle Model Evaluation
  - Randerson et al., Global Change Biology, 2009
  - Cadule et al., GBC, 2010
  - Anav et al., J Clim, 2013
  - Hoffmann et al., JGR-BGS, 2013
- Emissions Compatible w/ Prescribed CO_2 Concentrations
  - Jones et al., J Clim, 2013
- Feedbacks in 1% CO_2 ramping CMIP5 experiments
  - Arora et al., J Clim, 2013
  - Schwinger et al., J Clim, 2014
- Emergent constraints
  - Cox et al., Nature, 2013
  - Wang et al., GRL, 2014
  - Wenzel et al., JGR-BGS, 2014

Summary

- Large scale ocean biogeochemical features are determined by handful of processes
- ‘Perfect’ ecosystem model doesn’t exist, many simplifications need to be made. Improving models is ongoing research. Scientific questions and observational constraints guide this process.

- Global carbon cycle is now present in numerous CMIP class models (ESMs). Observations of atmospheric CO_2, on multiple timescales, are valuable constraint on models.
- Land & ocean uptake of anthropogenic CO_2, particularly sensitivity to climate change is ongoing research.
- Literature on the global carbon cycle in ESMs (e.g. CMIP5) is growing rapidly. Analyses with CMIP6 ESMs are in progress.

- Practical Notes for activating the prognostic carbon cycle in CESM2.1 are available and will be presented in Land/BGC breakout.