Intro to Ocean Biogeochemical Modeling

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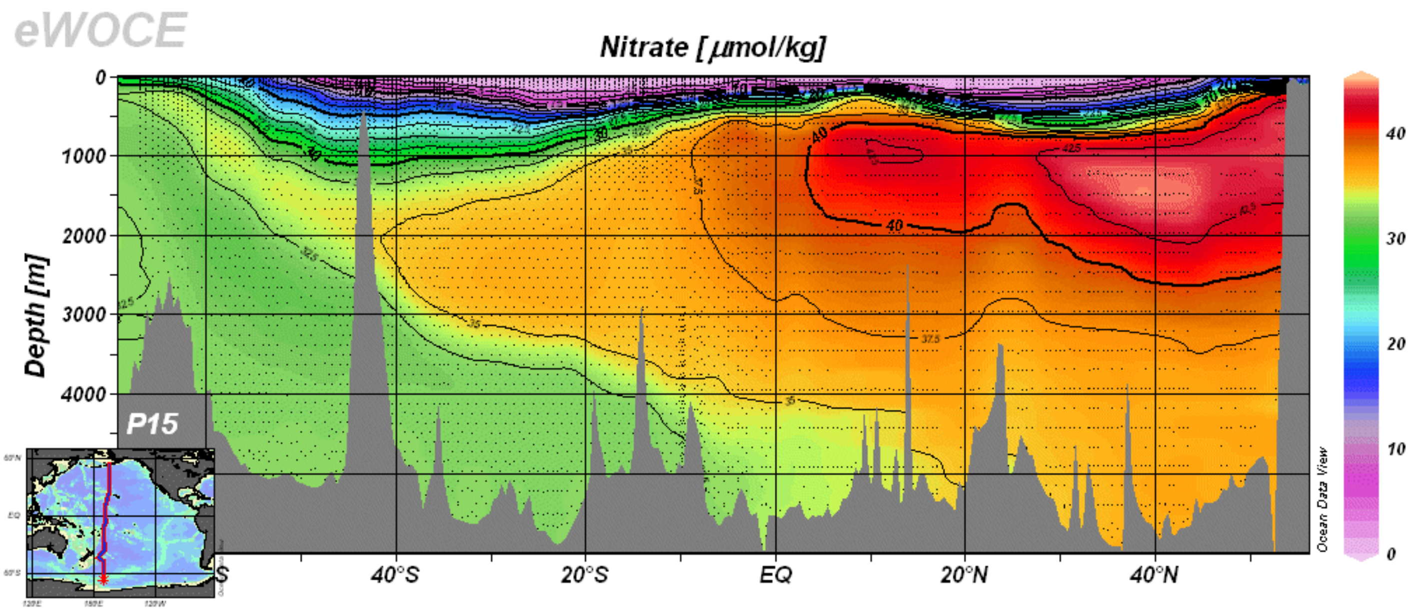
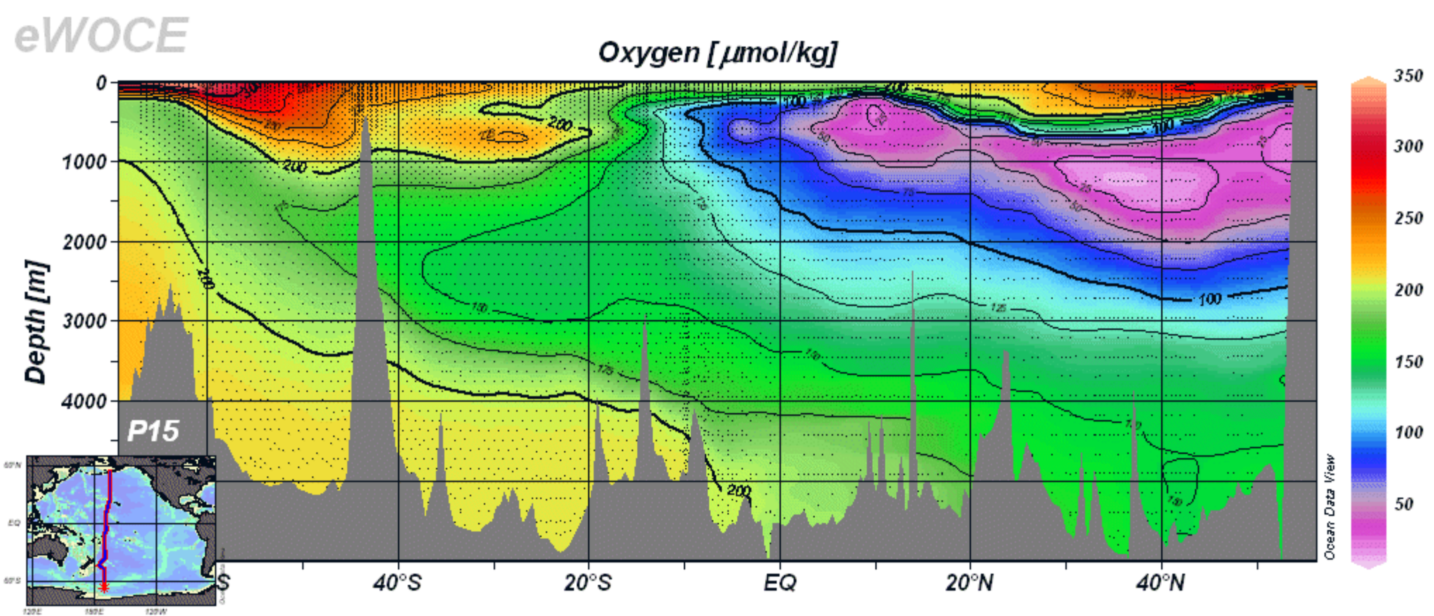
Lecture Outline

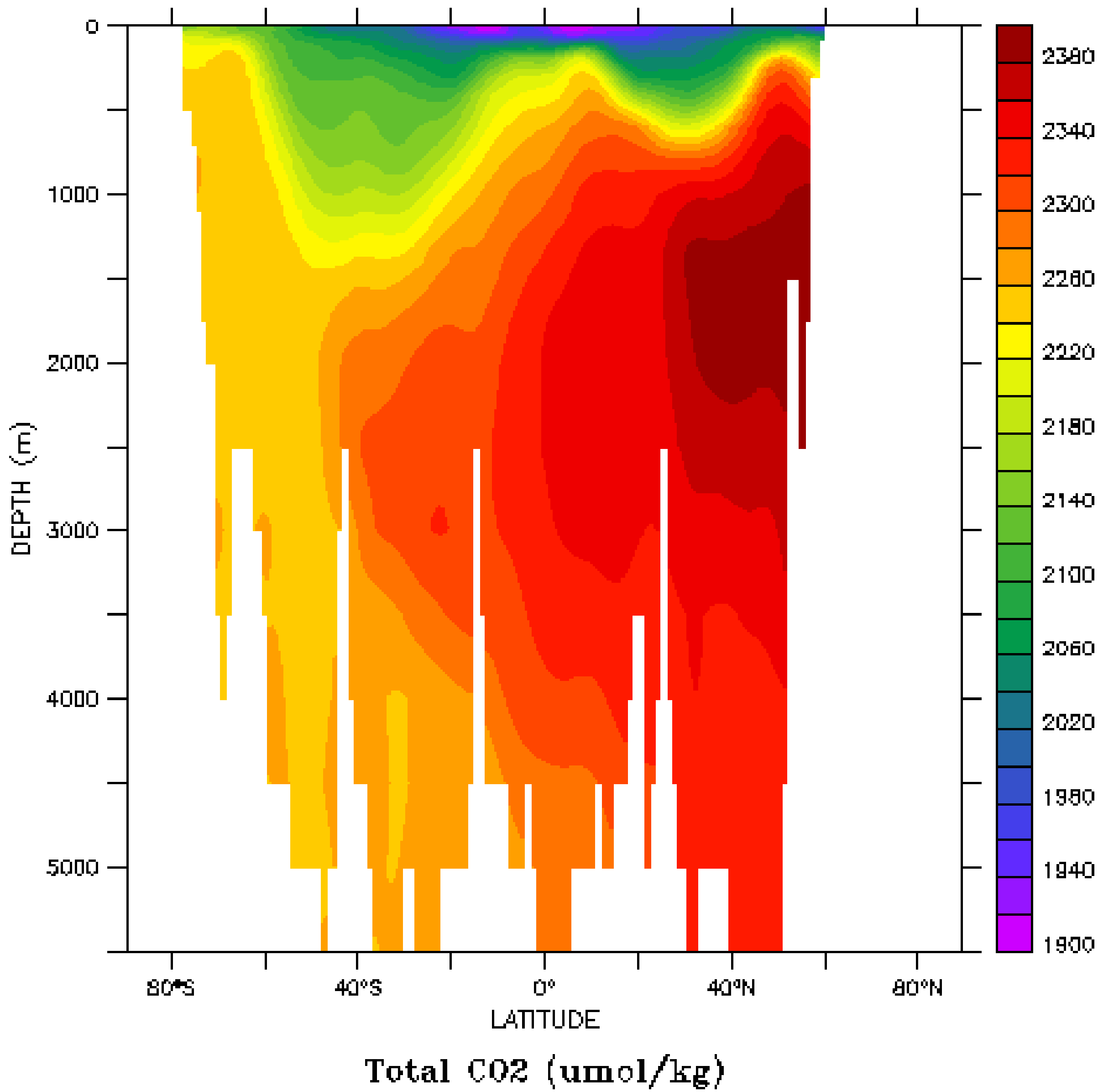
1) Large Scale Ocean Biogeochemical Features
2) Techniques for Modeling Biological Productivity
3) Skill Assessment
4) Summary

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

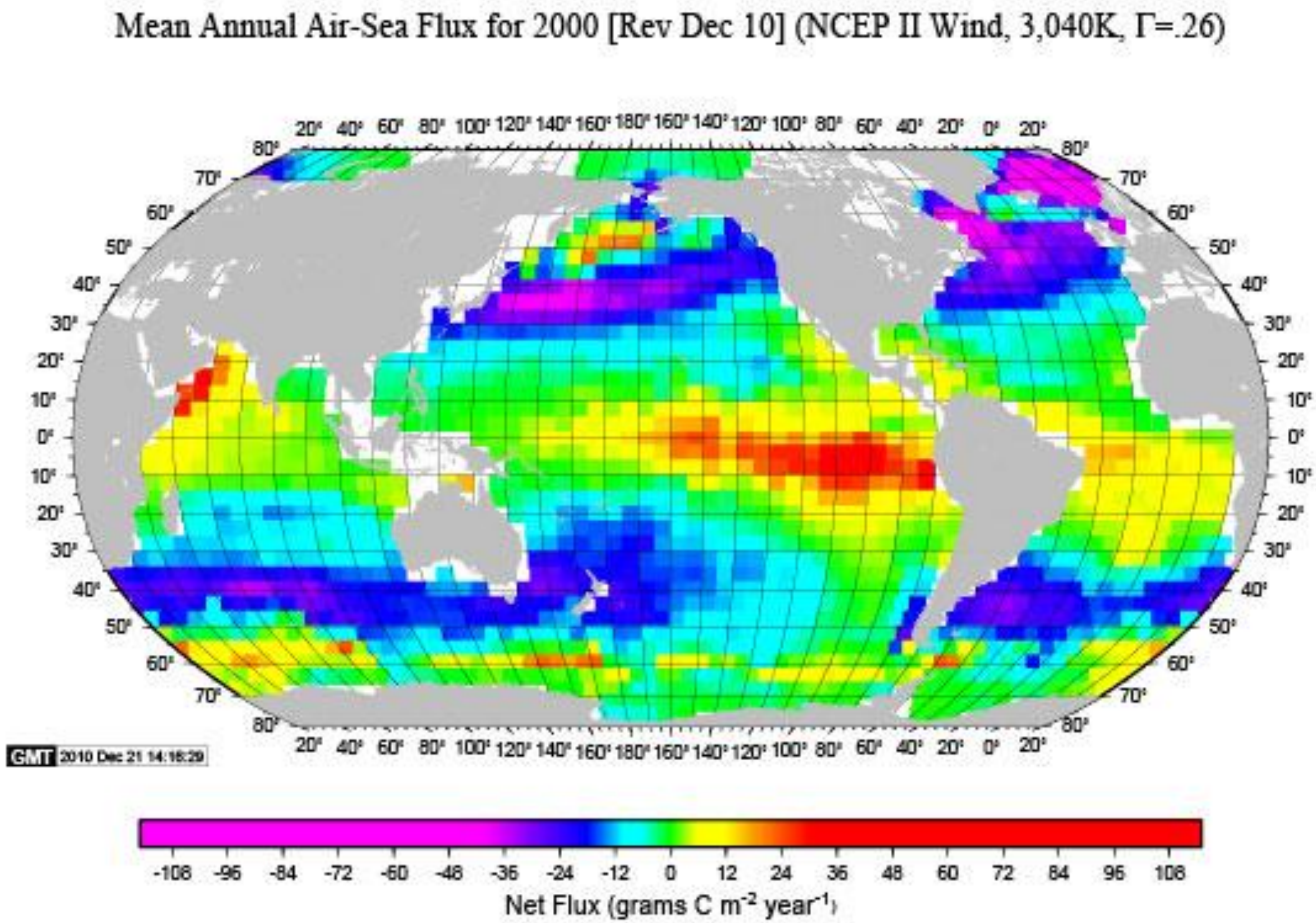




DIC (~CO_2) Along Same Pacific Transect



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

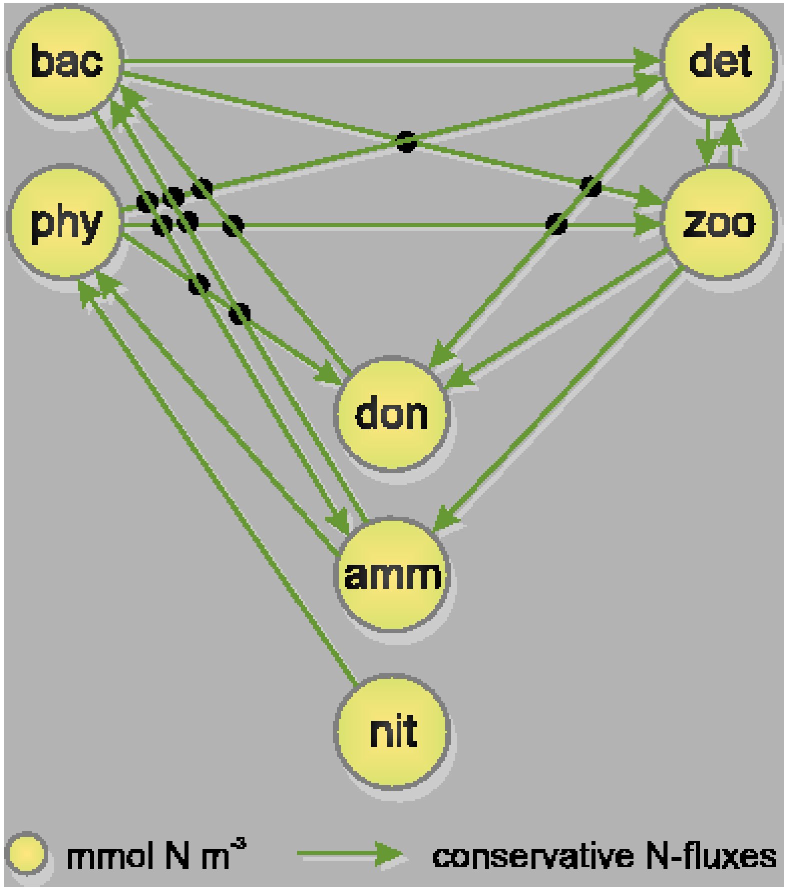
Z Zooplankton
    grazers

D Detritus

<u>Canonical Example</u>

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?

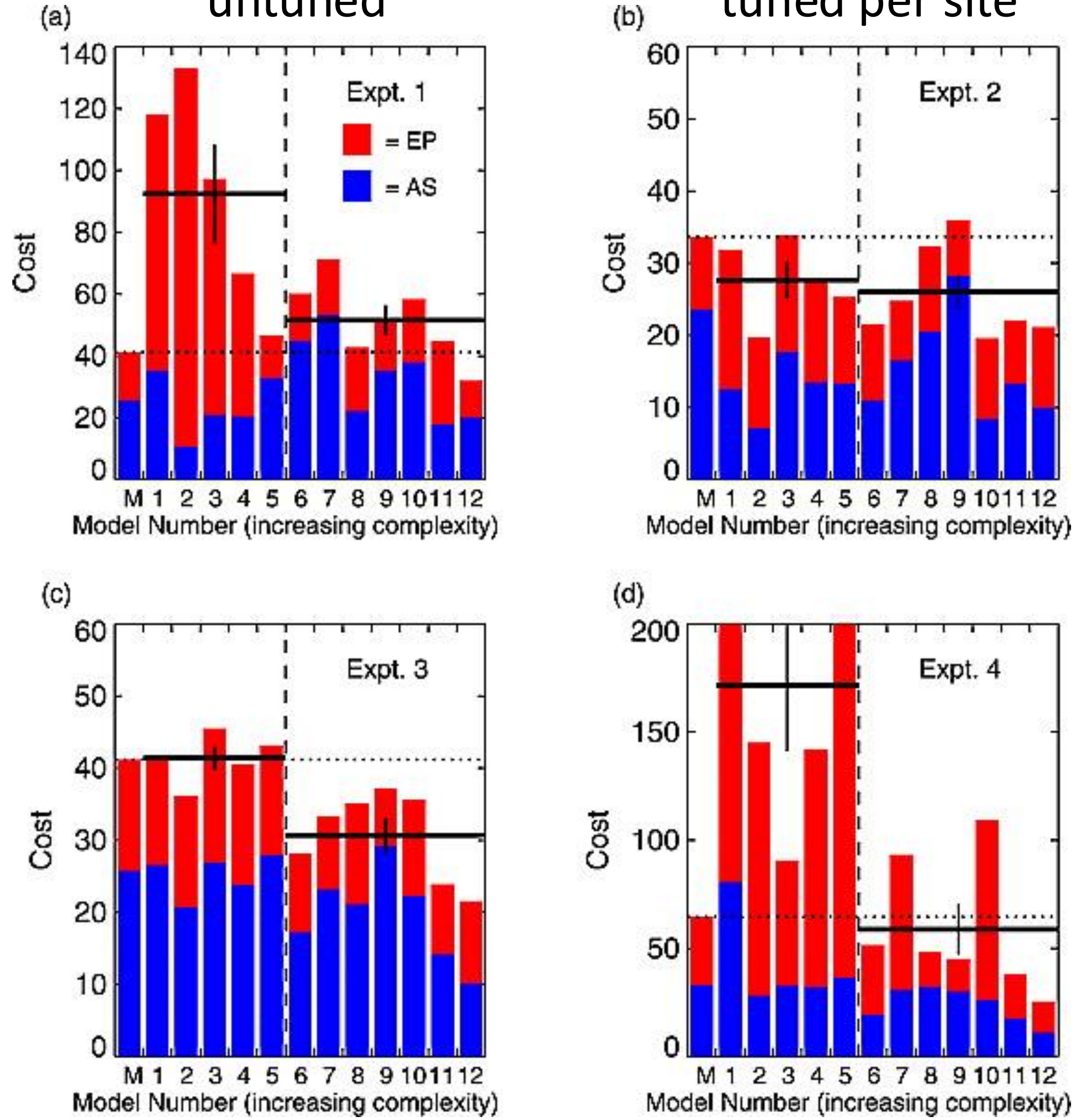
(b) Simple models do just as well as more complex models when tuned for specific sites.

(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.

untuned

tuned per site



tuned at both sites simultaneously

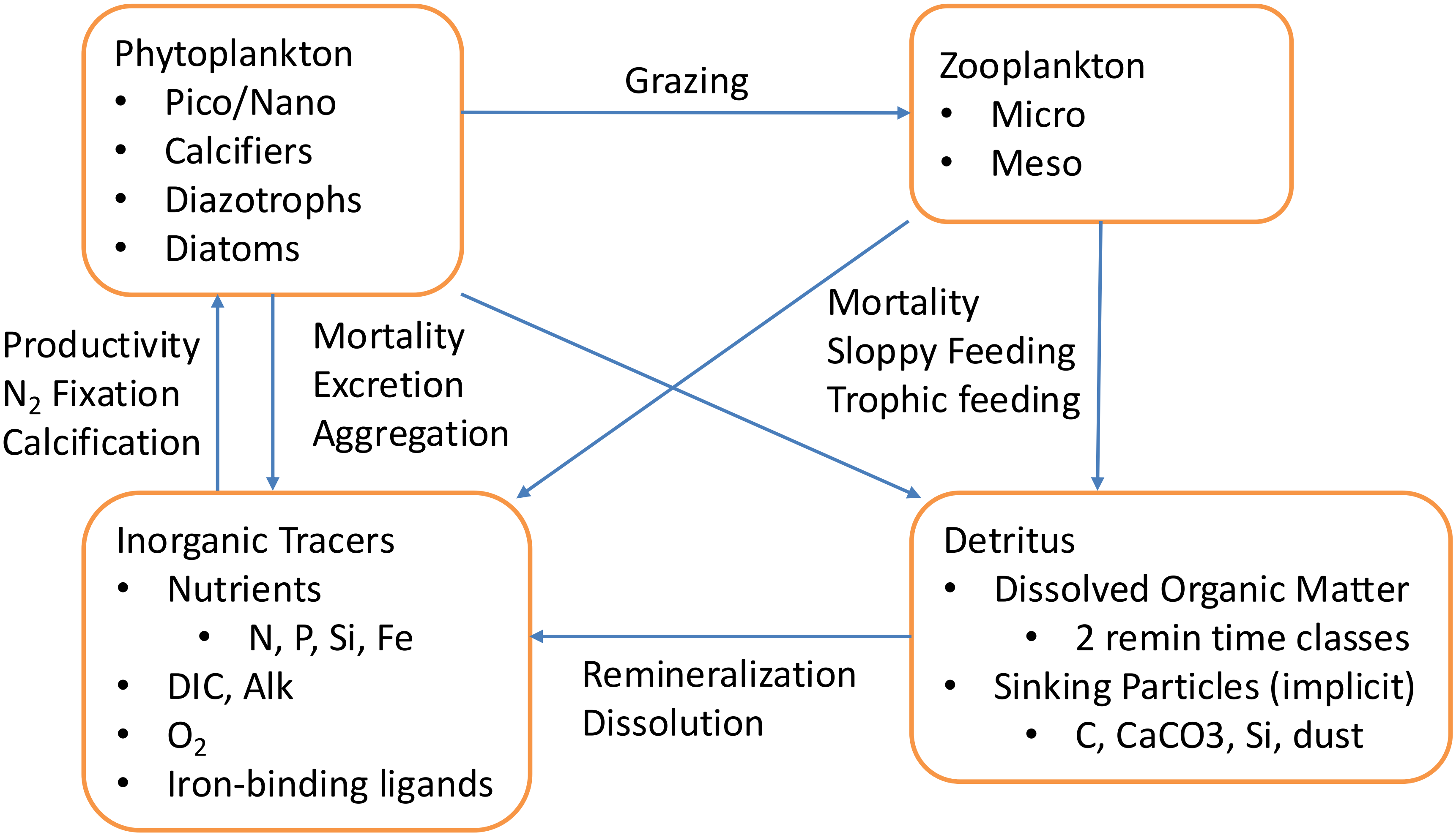
run at one site with tuning from other

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

Primary Features of CESM 3.0 MARBL Model

- Nutrients: N, P, Si, Fe
- 6 Plankton Functional Groups
  - 4 Autotrophs, 2 Grazers
    - 3 Autotrophs, 1 Grazer in CESM 2.0 and previous versions
  - Explicit calcifiers new in CESM 3.0
  - 41 tracers in CESM 3.0
    - 32 in CESM 2.0, 27 in CESM 1.2, 24 in CESM 1.0/1.1
- Variable N:C, P:C, Fe:C, Si:C, Chl:C autotroph ratios
  - N:C was fixed in CESM 2.0 and previous versions
  - P:C was fixed in CESM 1.2 and previous versions
- Iron model has prognostic iron-binding ligand
  - as of CESM 2.0

CESM 3.0 MARBL model



Krumhardt et al., Prog. Oceanogr., 2024
Long et al., JAMES, 2021.
Moore et al., J Climate, 2013.

Moore, Doney, Lindsay, Glob. Biogeochem. Cycles, 2004.

Some Gaps in Ocean BGC in CESM

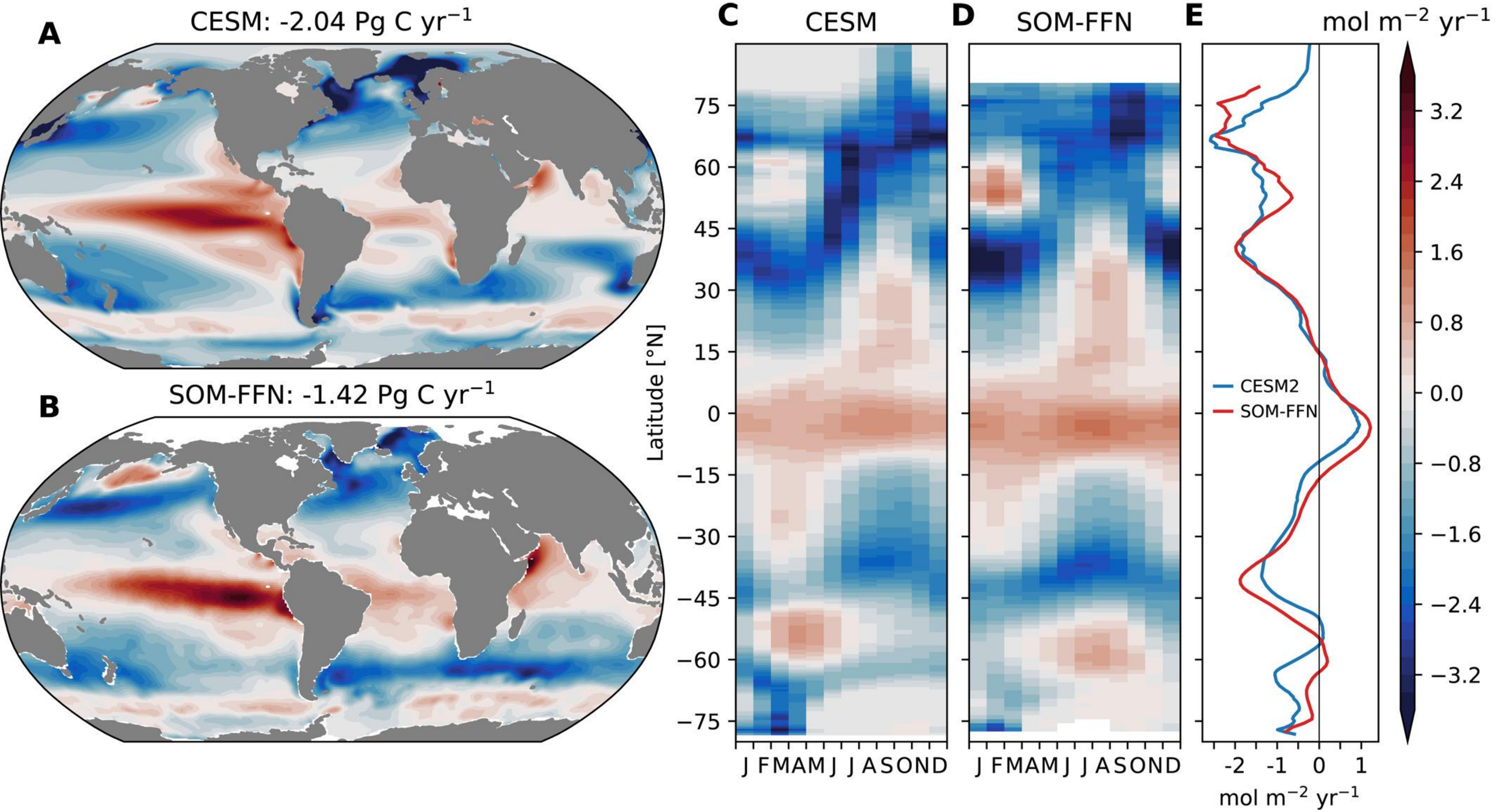
- Riverine inputs of BGC tracers are prescribed
- C, N, P, Si, $CaCO_3$ buried in sediments are lost from the system
- No treatment of BGC in sea-ice

- Focus is on lower trophic levels
  - Model output can be used as input/forcing for an offline fish model (FEISTY)

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
- Surface Chl measured by satellite
- Productivity estimated from satellite
- pCO_2 and CO_2 Flux, obs filled by neural net
- Fe, databases of obs

Air-sea CO_2 Flux



Long et al., JAMES, 2021.

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 or Anderson Acceleration for this is a work in progress

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.

- Practical Notes for activating the coupled prognostic carbon cycle in CESM 2.1 are in BGC challenge exercises. This feature is still under development in CESM 3.0.

(older) extra slides

Large Scale Global Carbon Cycle

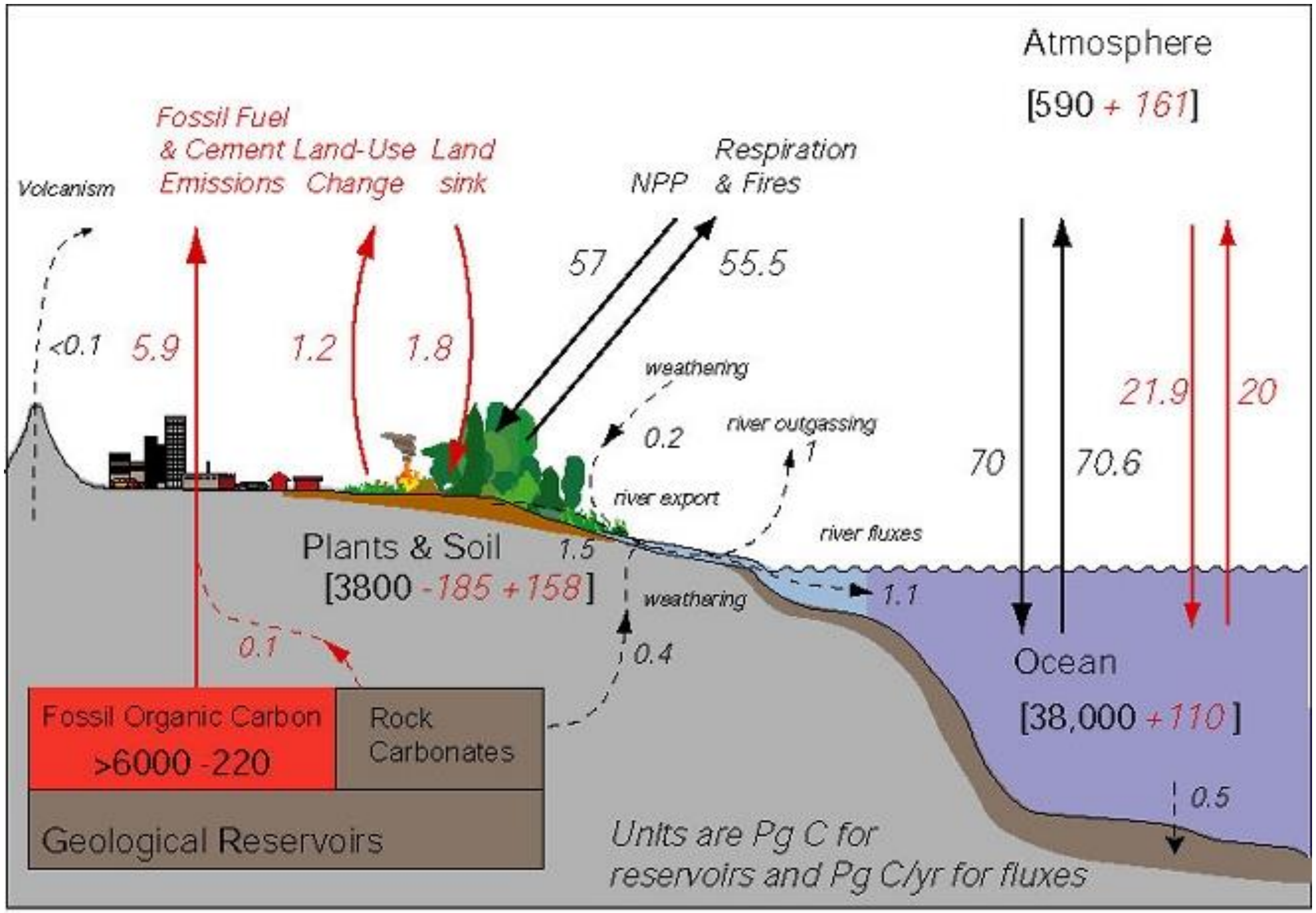
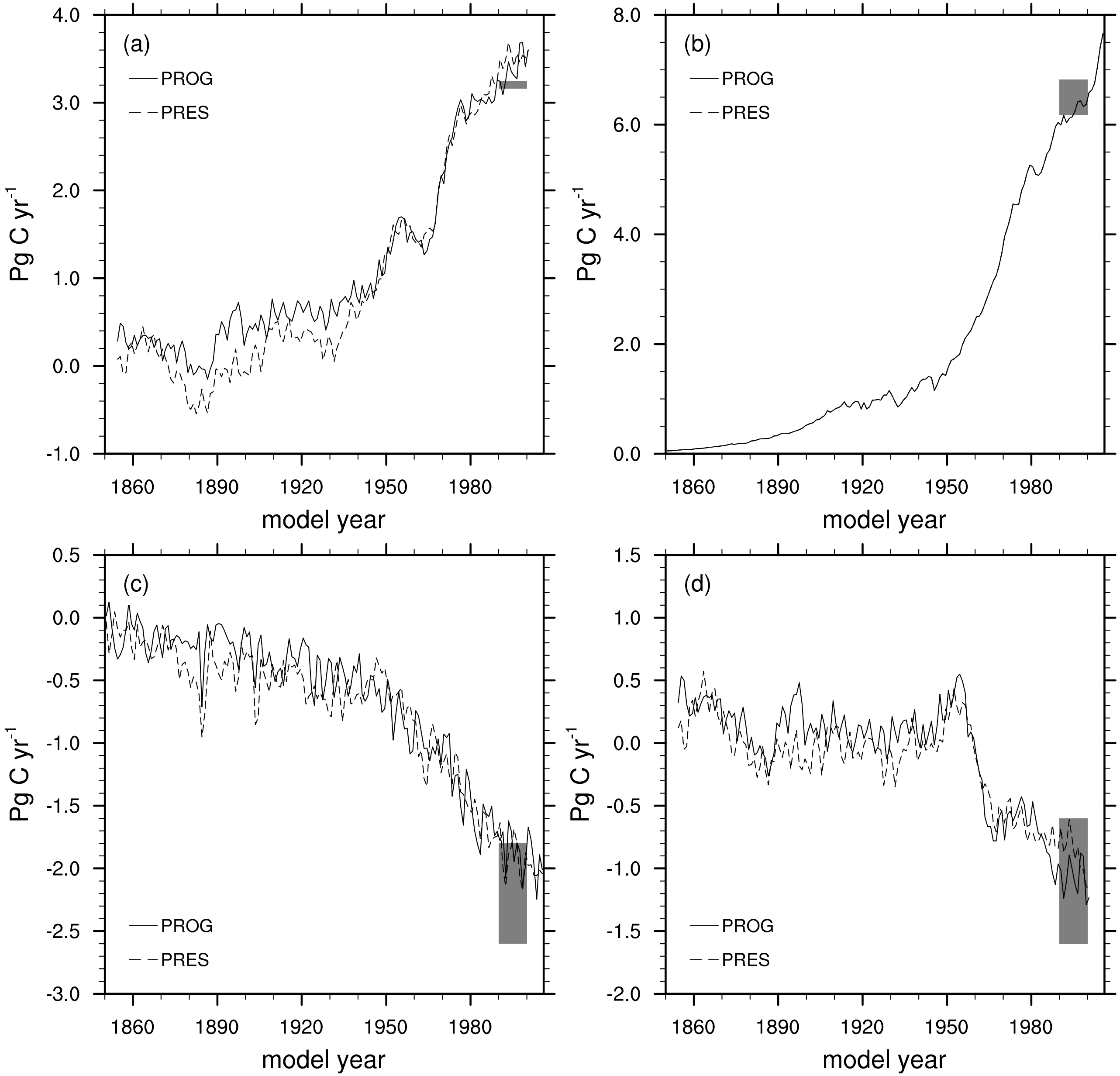


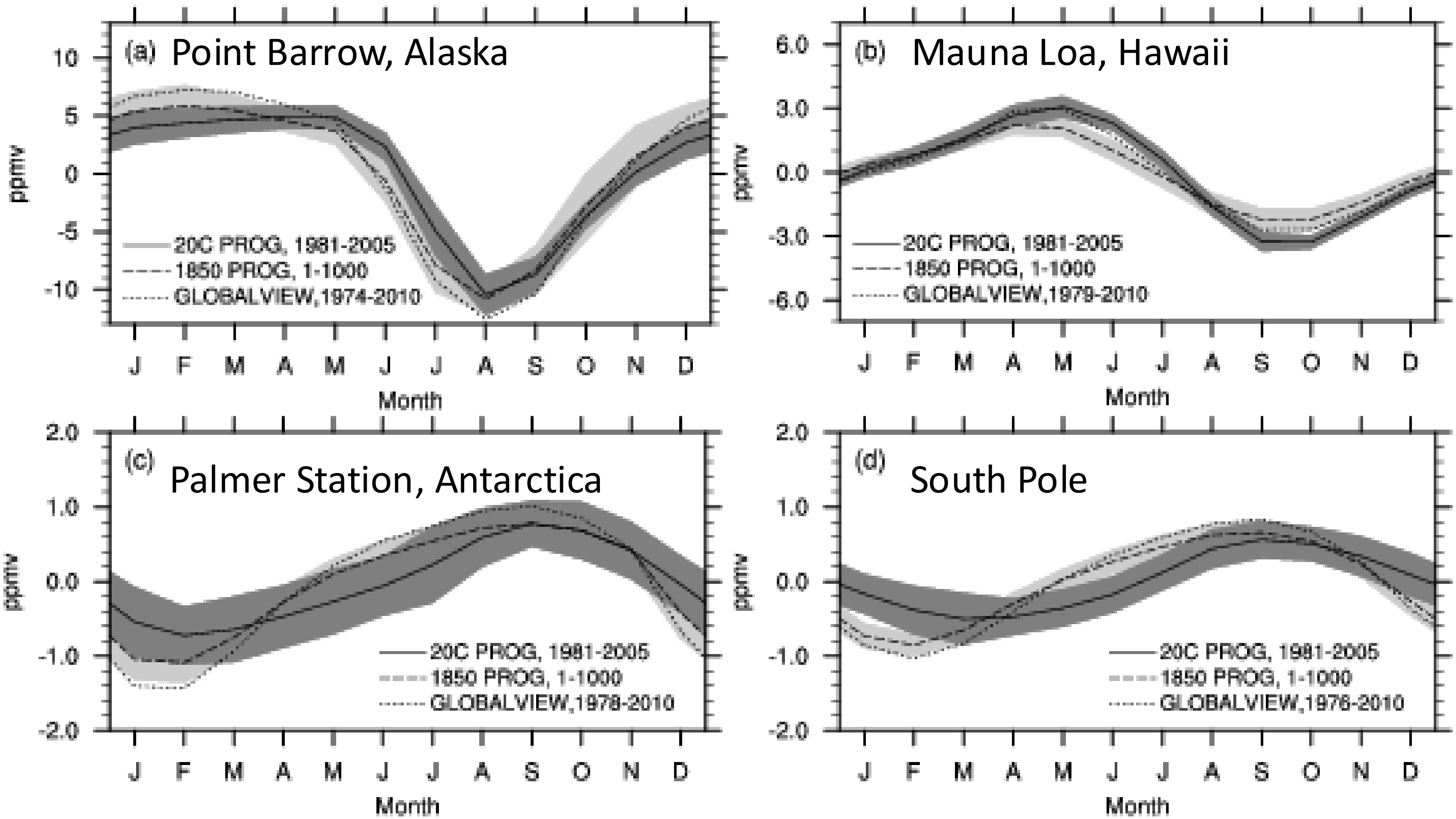
Figure courtesy PMEL

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, CESM1.2+(BGC)



Subset of Literature on Carbon Cycle in Earth System Models

- C4MIP
  - Friedlingstein et al., J Clim, 2006
  - CMIP6 papers
- 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

(older) 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, CMIP6) is ever growing.

- Practical Notes for activating the prognostic carbon cycle in CESM 2.1 are in BGC challenge exercises.

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

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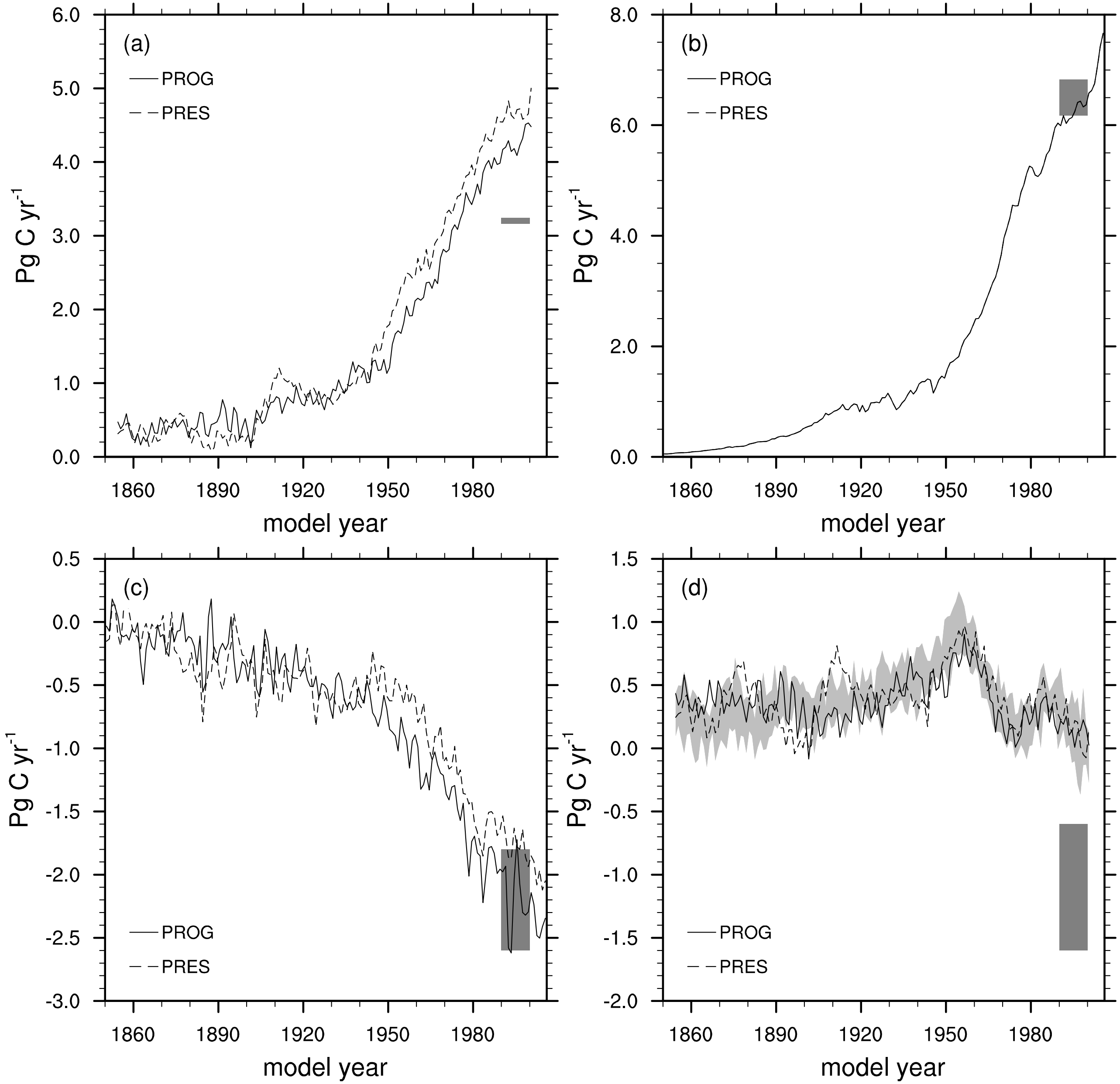
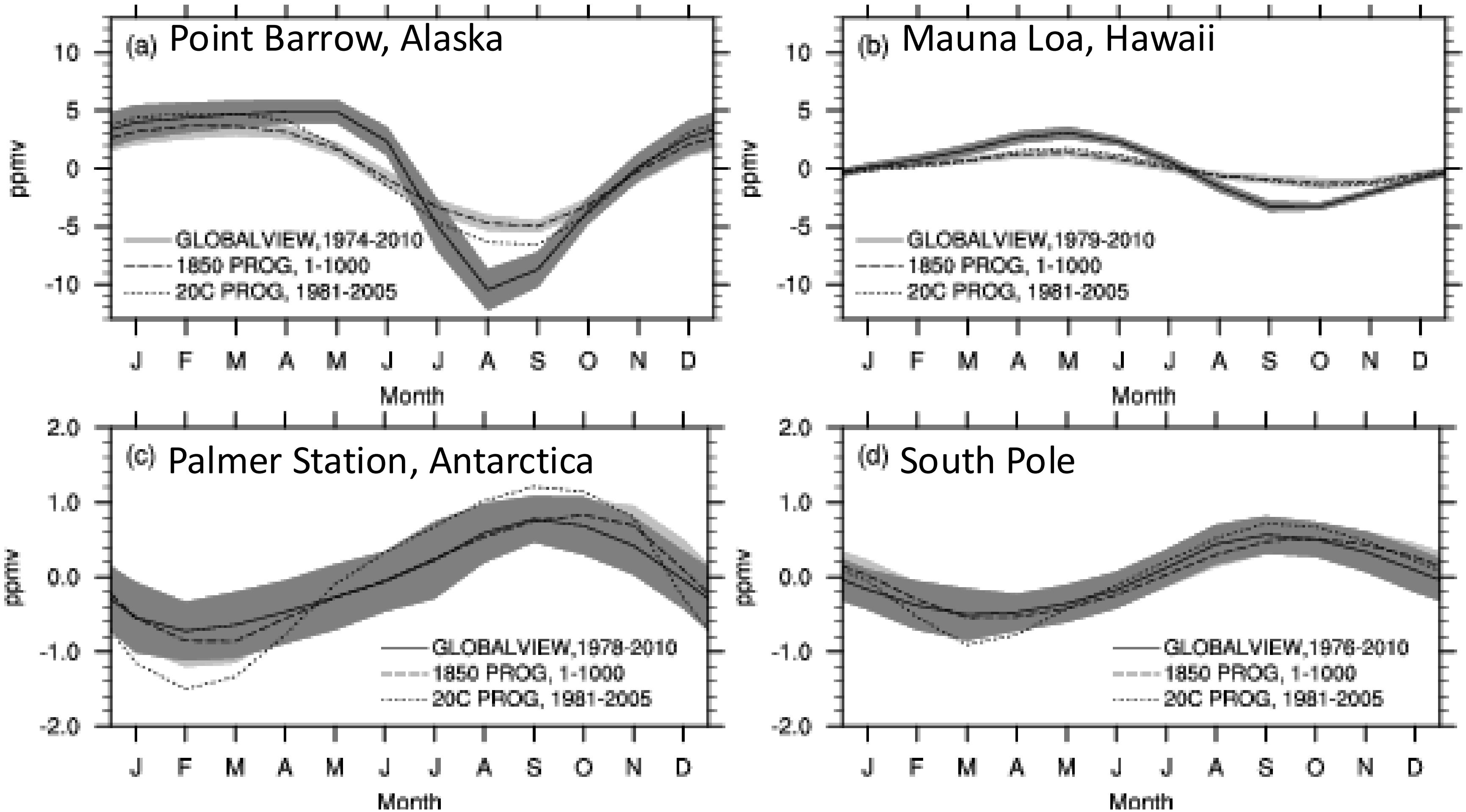


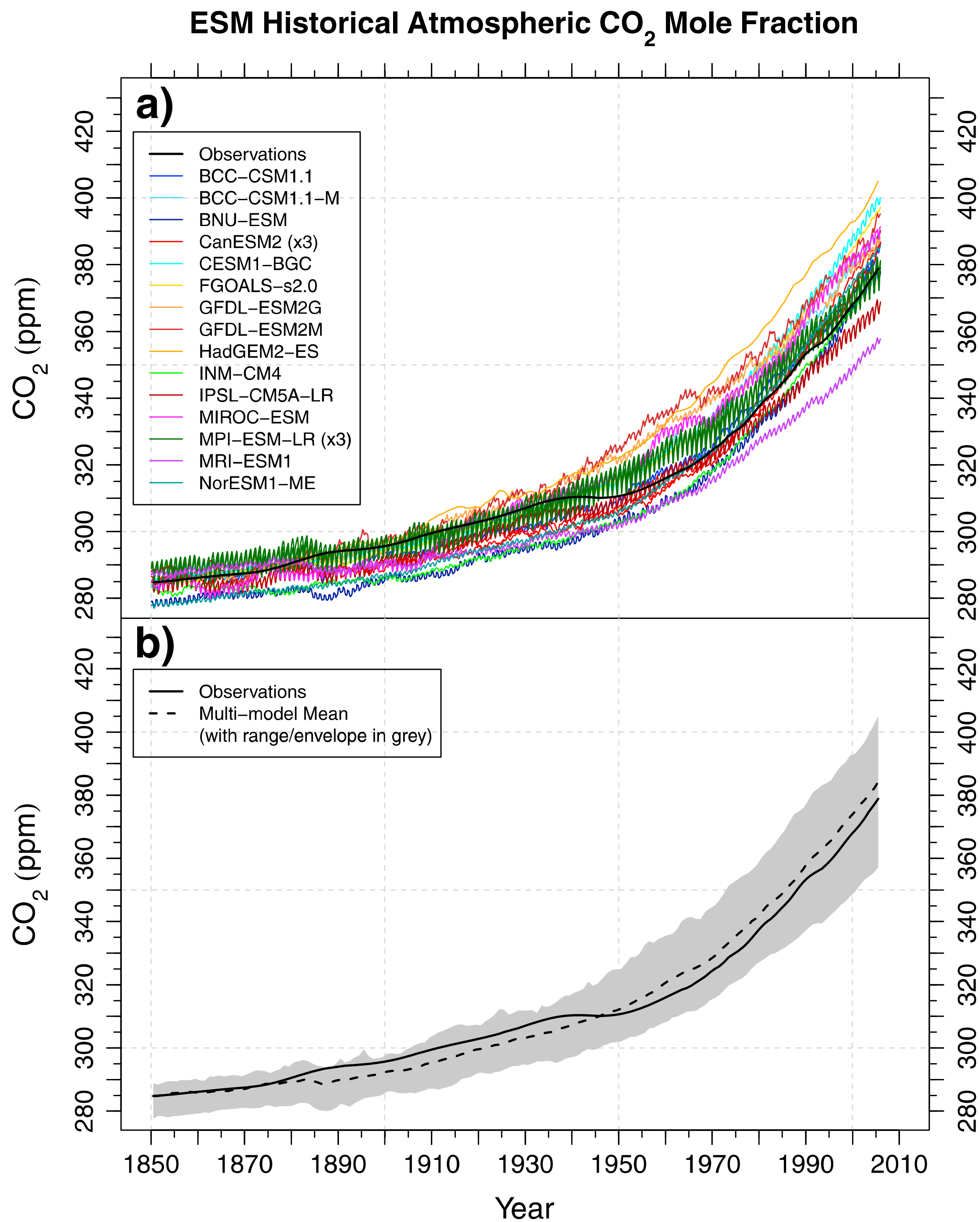
Lindsay et al., 2014, J Clim

Seasonal Cycle of CO_2, CESM1(BGC)



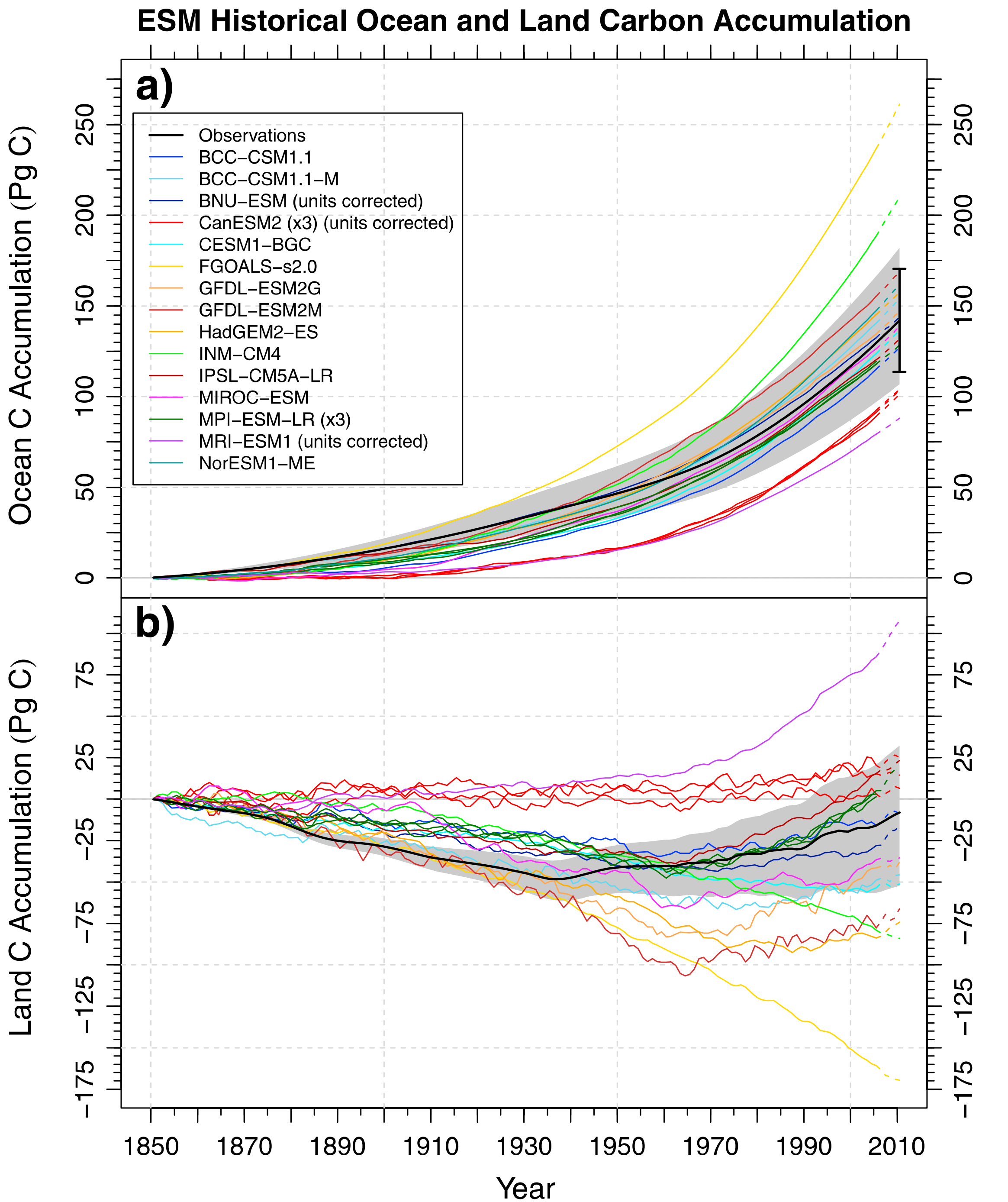
Lindsay et al., 2014, J Clim

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