

Intro to Biogeochemical Modeling Ocean & Coupled

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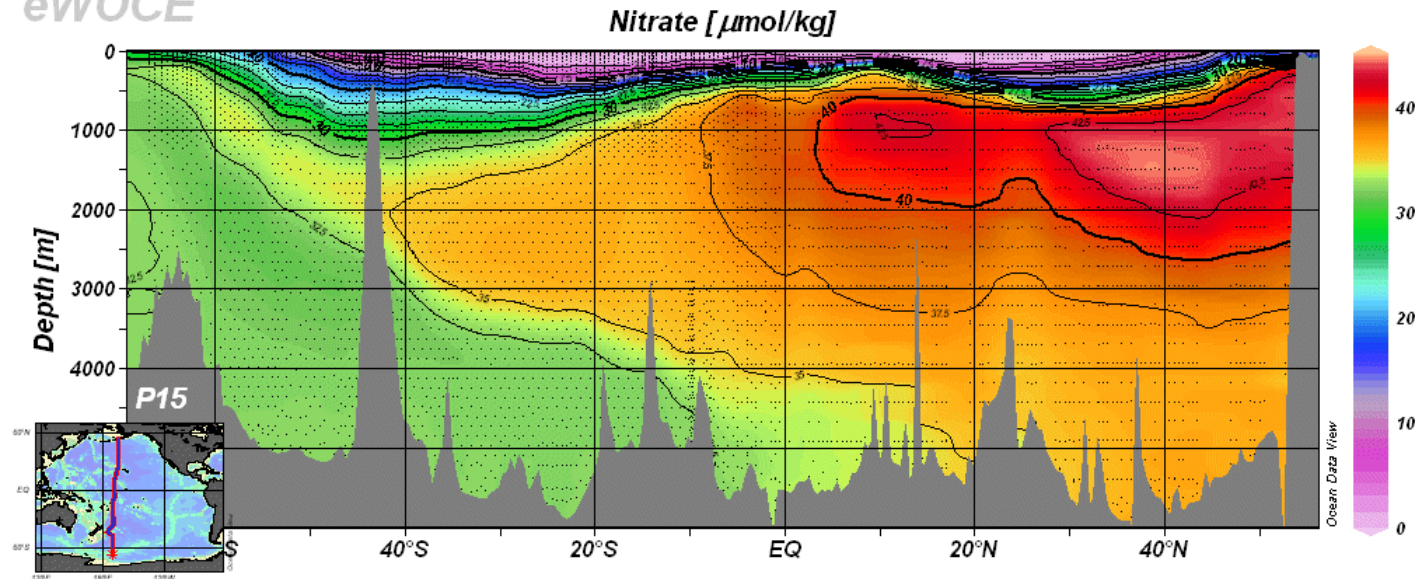


Lecture Outline

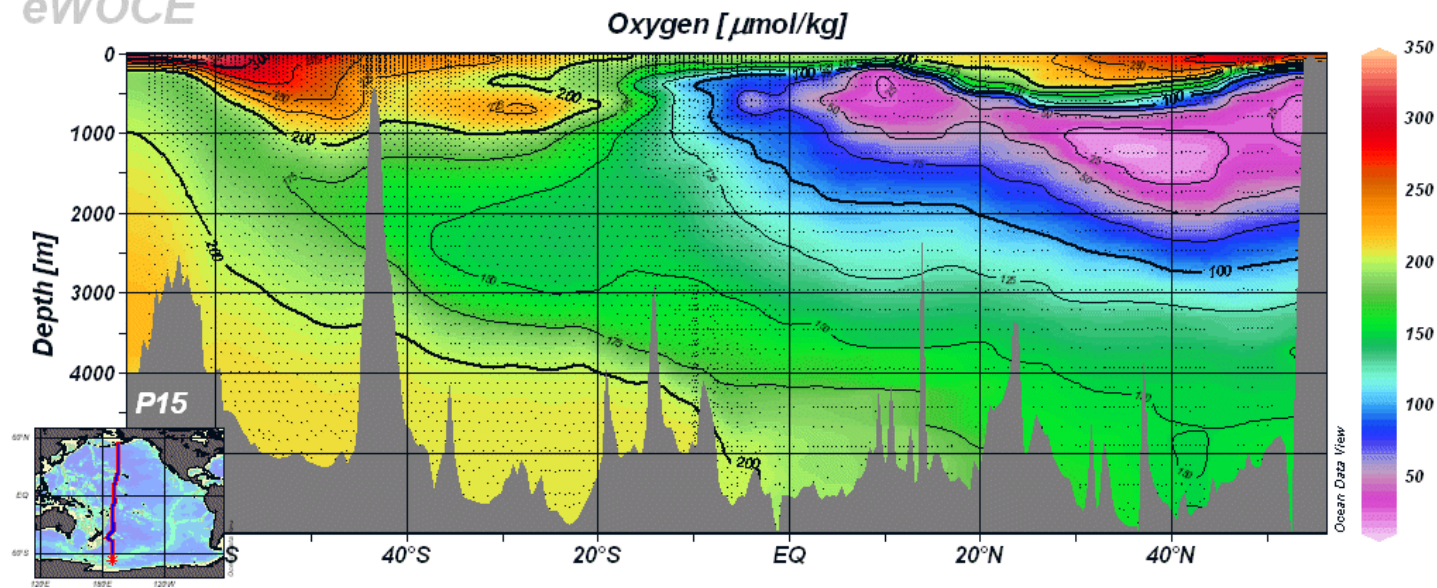
- 1) Large Scale Ocean Biogeochemical Features
- 2) Techniques for Modeling Biological Productivity
- 3) Skill Assessment
- 4) Global Carbon Cycle
- 5) Summary

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

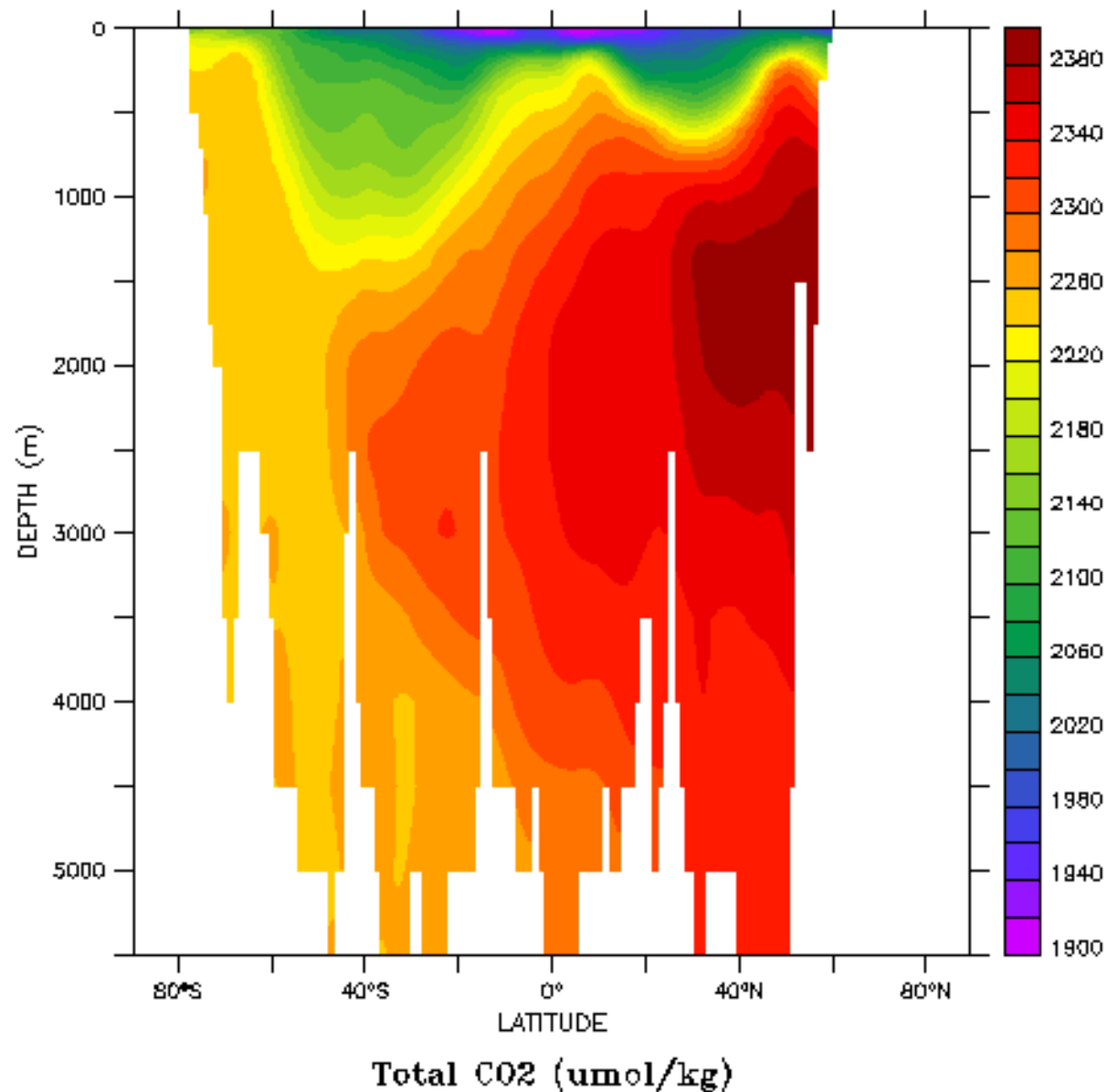
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eWOCE

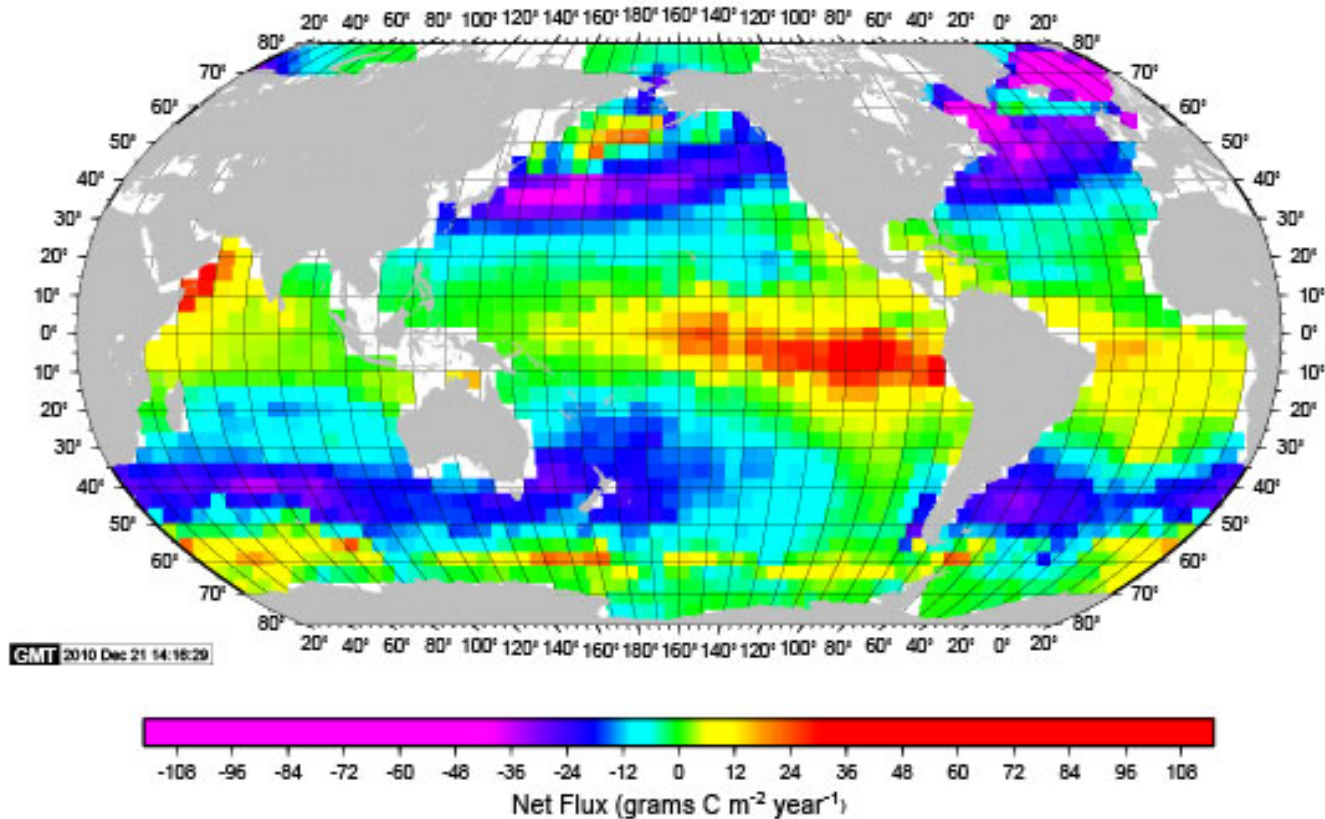


DIC ($\sim\text{CO}_2$) Along Same Pacific Transect



Takahashi Air-Sea CO₂ Gas Flux

Mean Annual Air-Sea Flux for 2000 [Rev Dec 10] (NCEP II Wind, 3,040K, $\Gamma=.26$)



Primary Processes Governing Distribution of Nutrients, O₂, Carbon, etc.

- Biological Productivity in Euphotic Zone
 - Consumes Nutrients & Inorganic Carbon
 - Produces Organic Matter & O₂
- Export of Organic Matter out of Euphotic Zone
 - Sinking Particles (e.g. detritus, CaCO₃ shells, ...)
 - Circulation of Suspended Matter
- Remineralization of Organic Matter
 - ‘reverse’ of productivity, consumes O₂
- 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

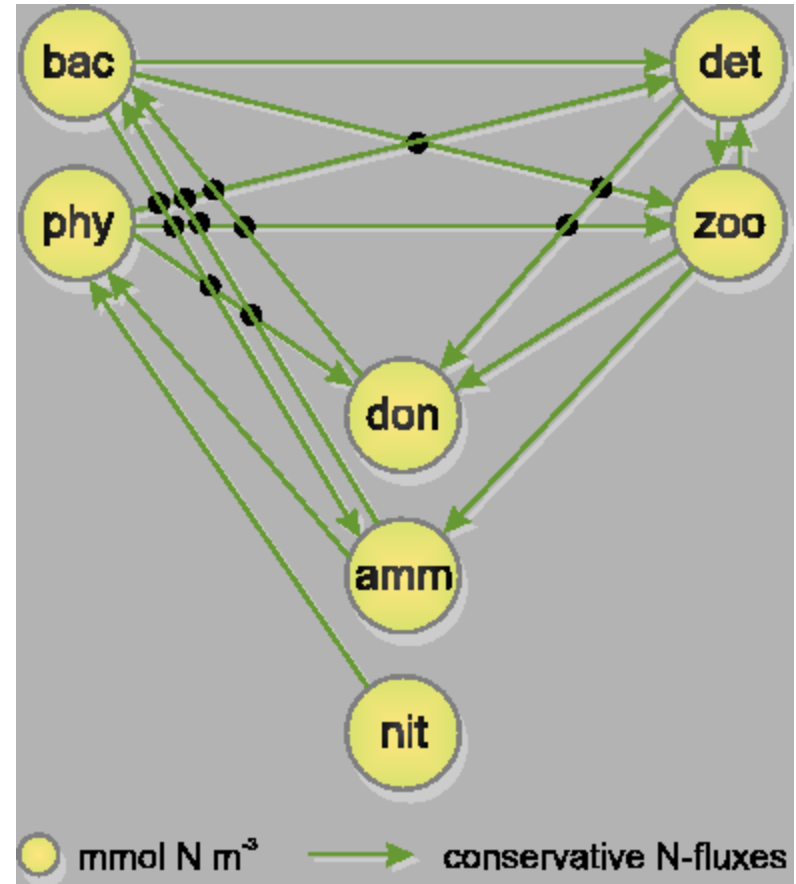
What is an NPZD model?

- 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

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

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

- 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

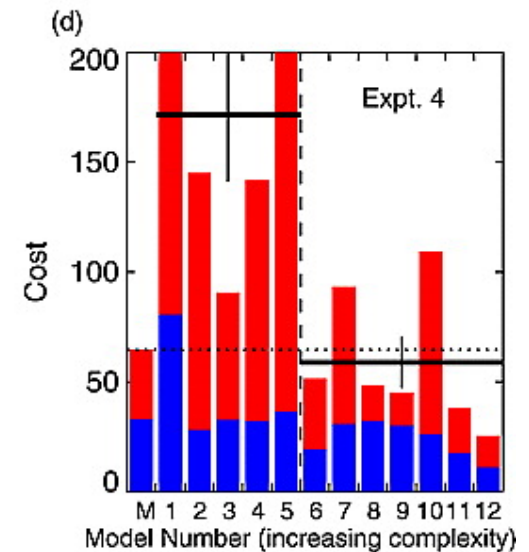
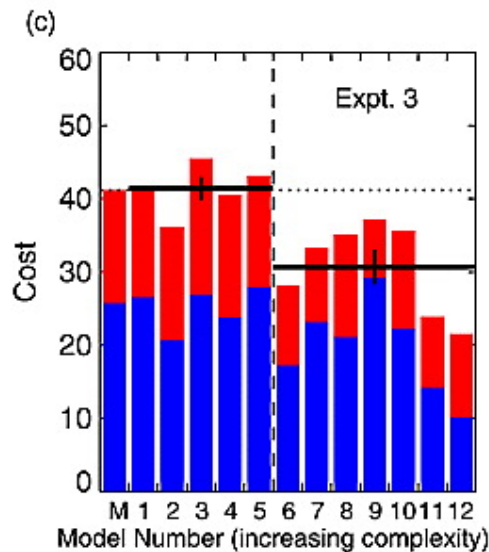
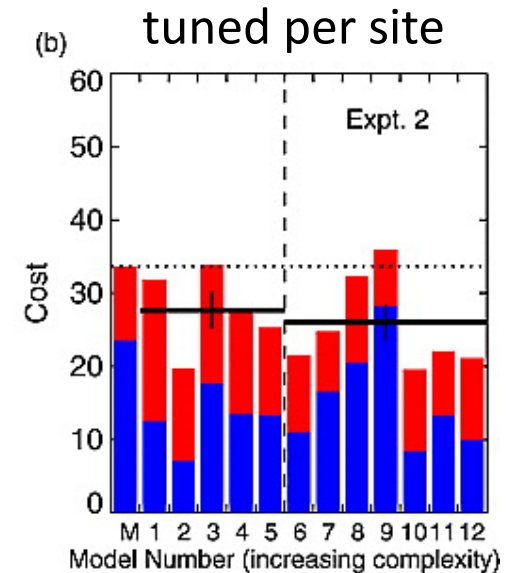
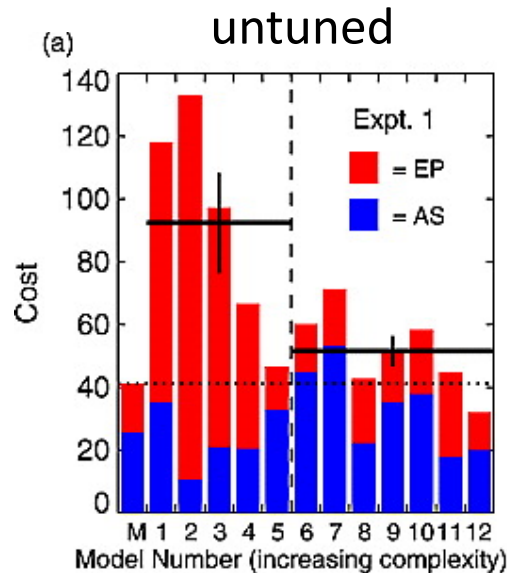
What is the best model?

(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.

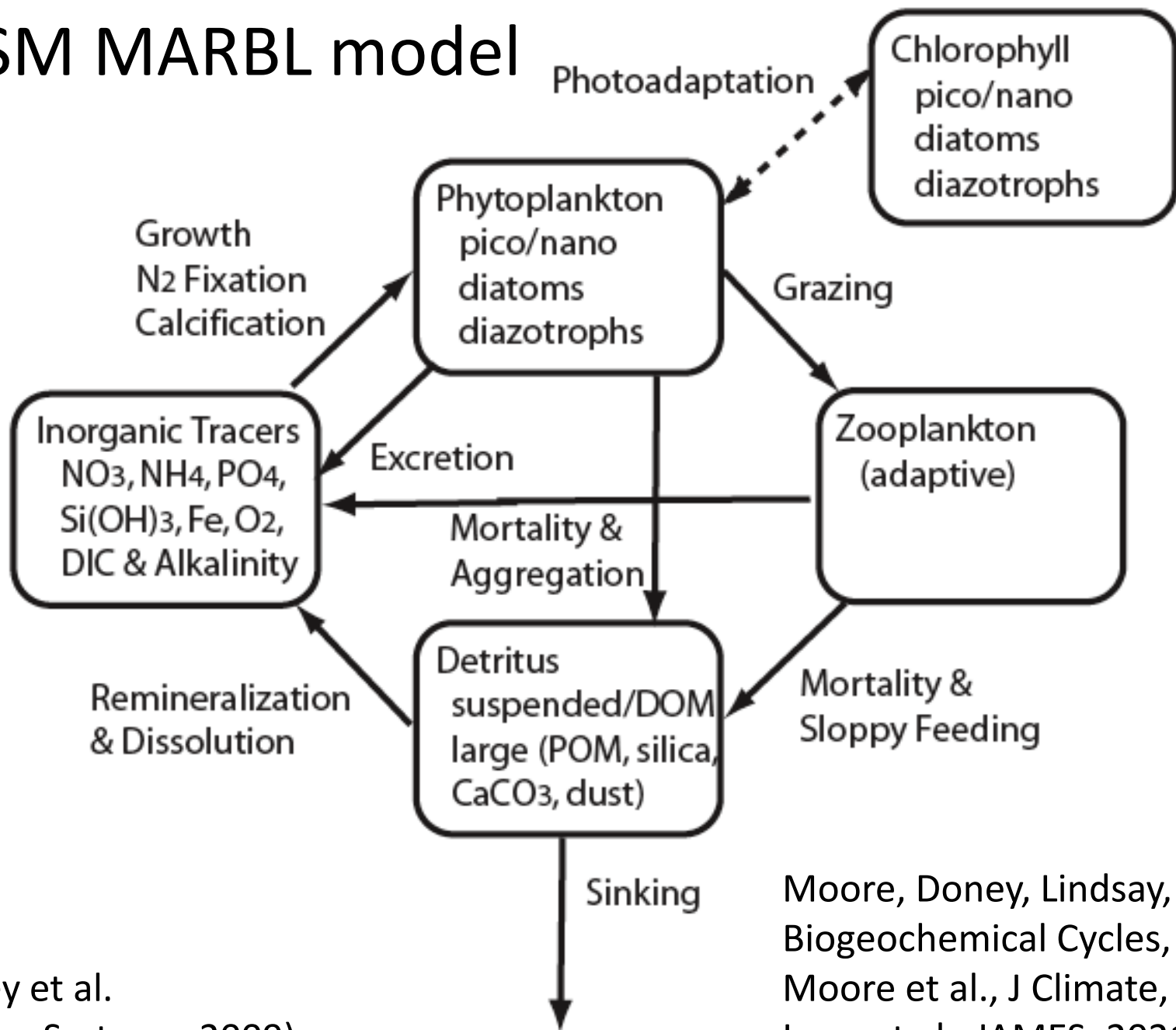
Assessment of skill and portability in regional marine biogeochemical models: Role of multiple planktonic groups, Friedrichs et al., *JGR-Oceans*, 2007.



tuned at both sites simultaneously

run at one site with tuning from other

CESM MARBL model



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

Moore, Doney, Lindsay, Global
Biogeochemical Cycles, 2004.
Moore et al., J Climate, 2013.
Long et al., JAMES, 2021.

Primary Features of CESM MARBL 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

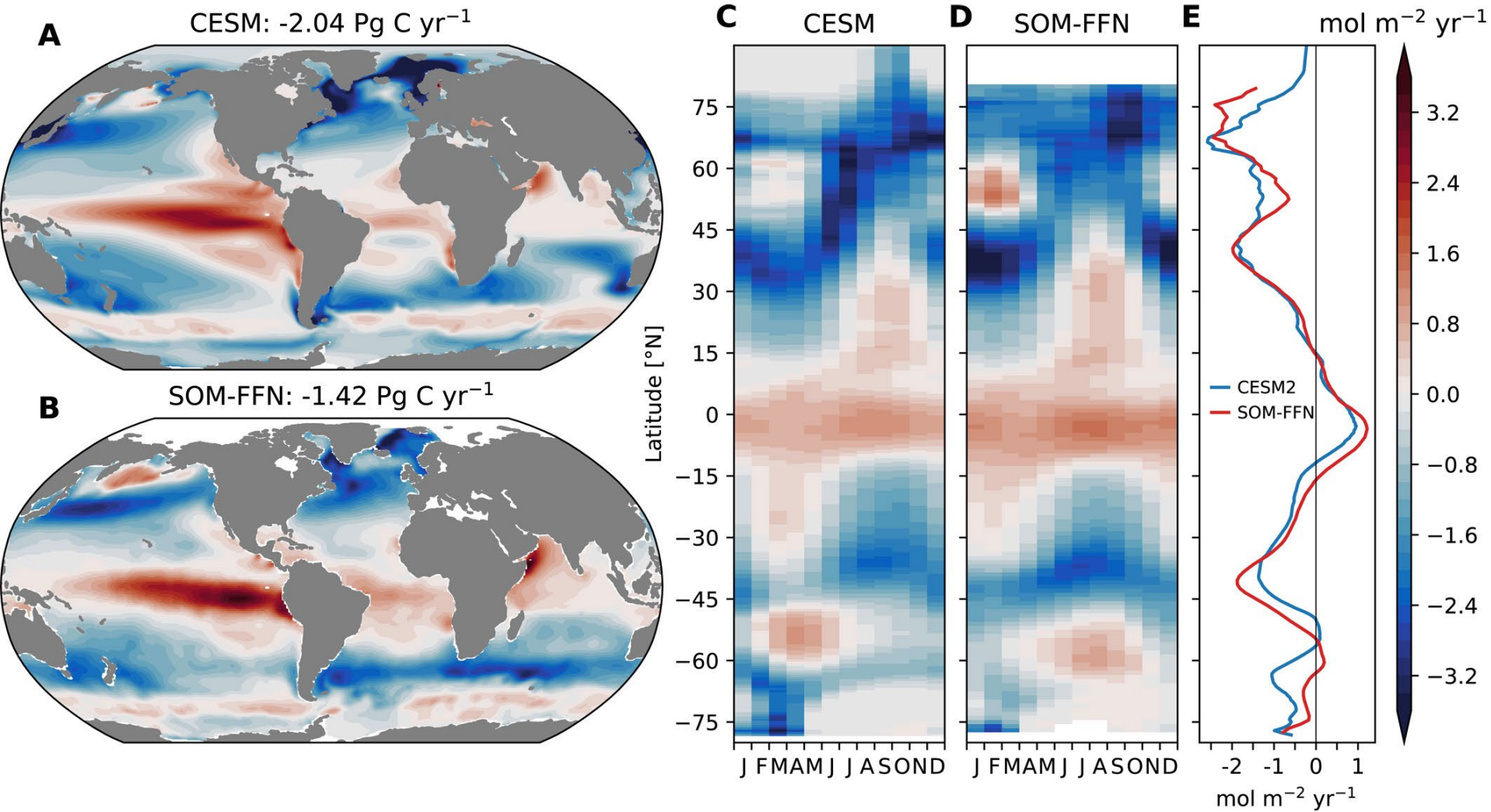
Known Gaps in Ocean BGC in CESM

- 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
- 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 CO₂ Flux



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 millennial timescales
 - Using Newton-Krylov for this is a work in progress

Large Scale Global Carbon Cycle

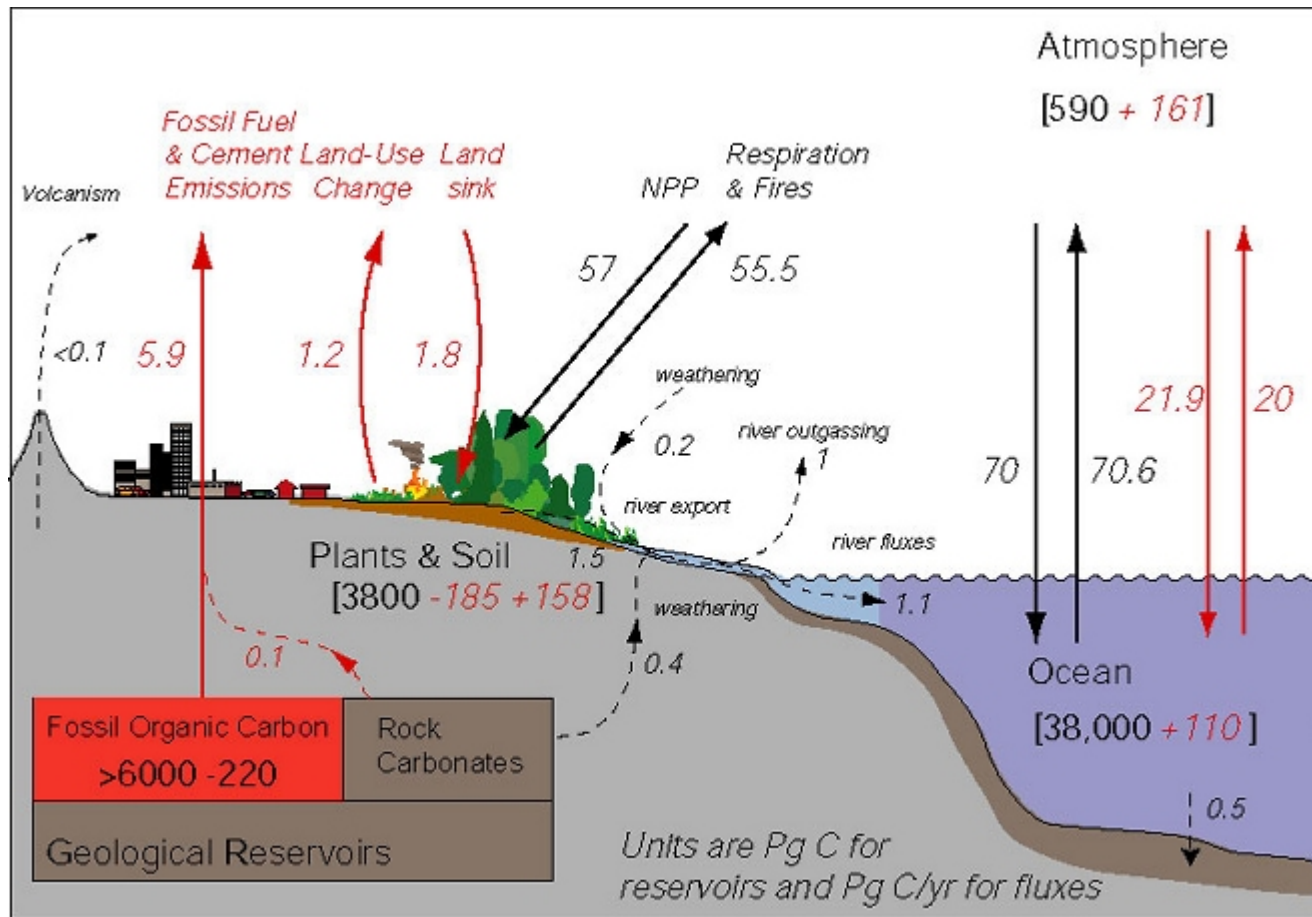
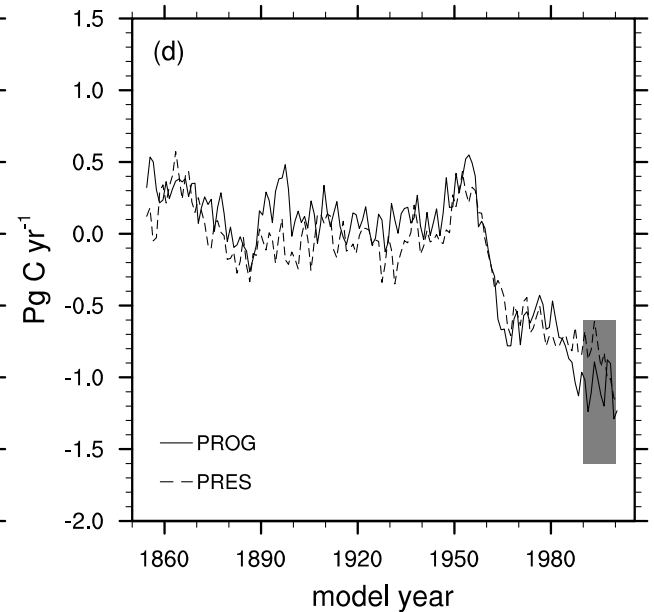
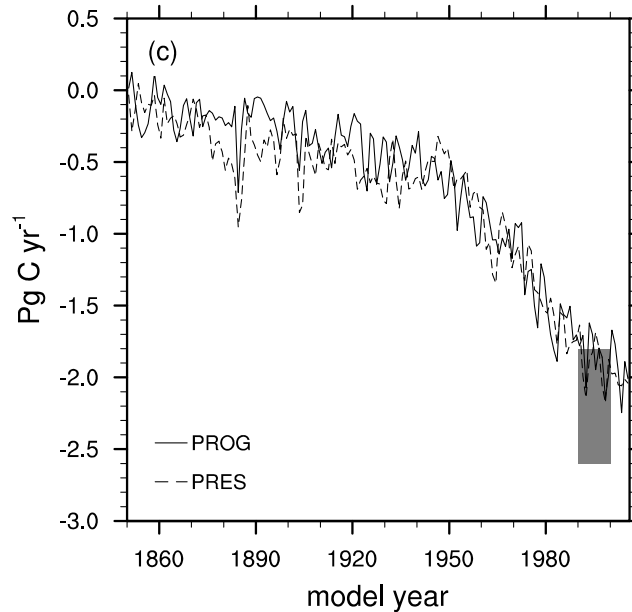
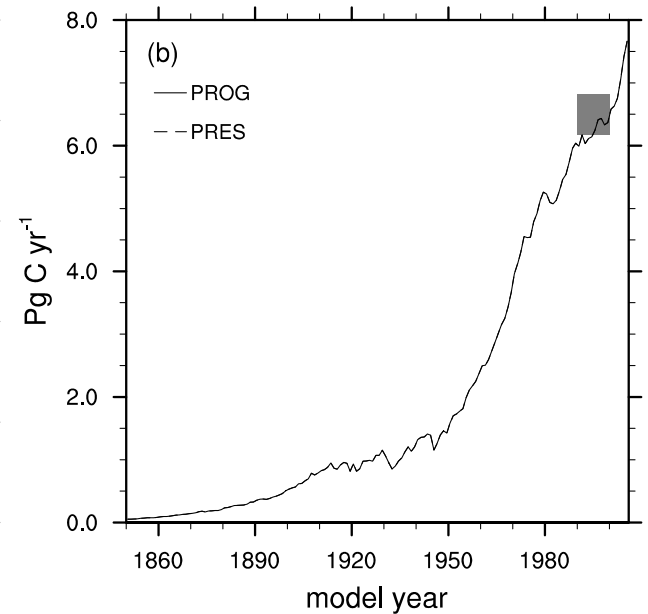
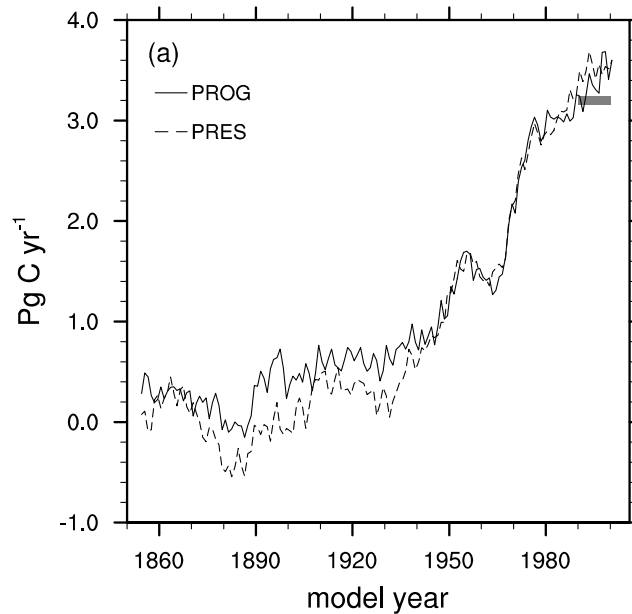


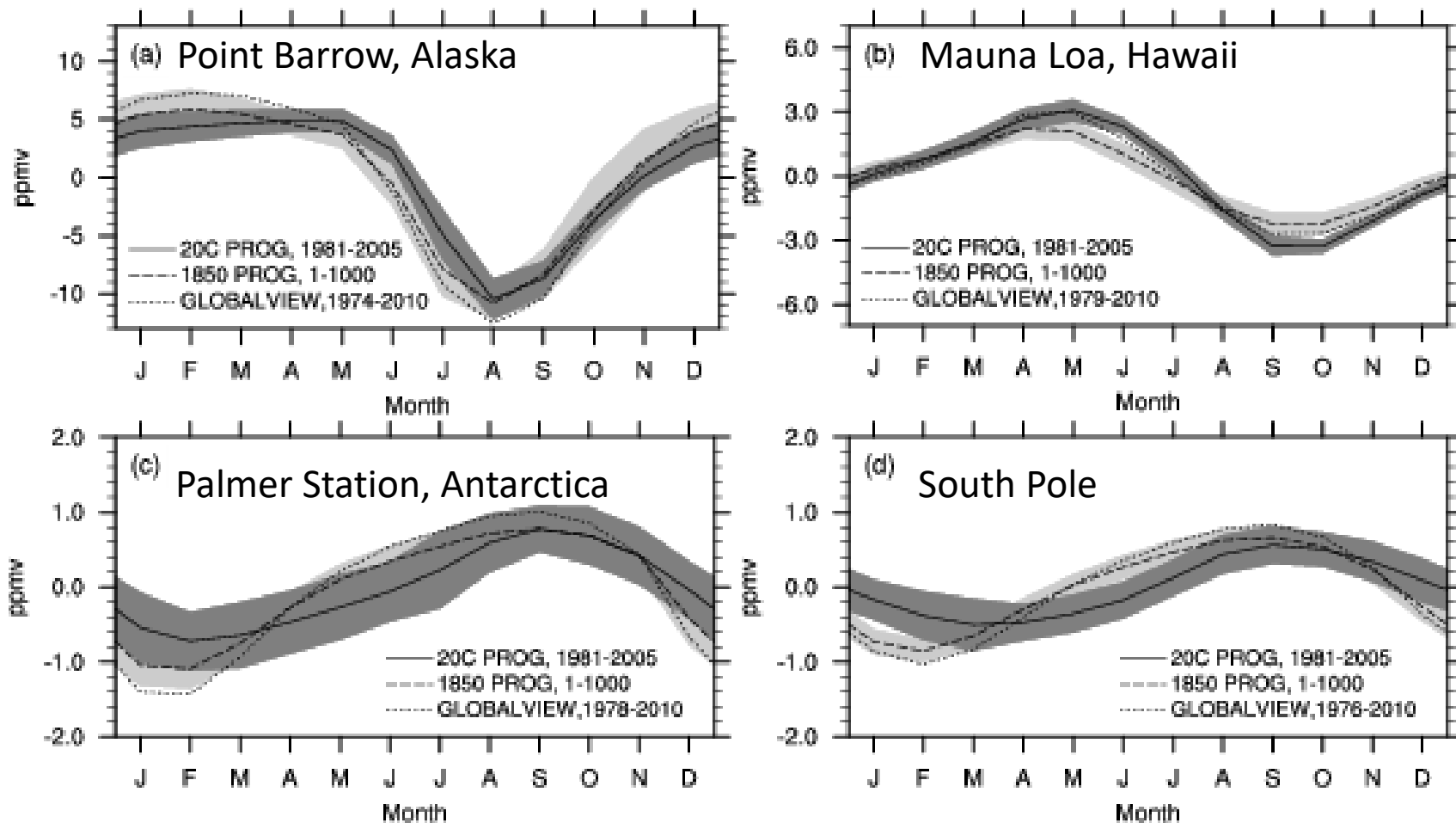
Figure courtesy PMEL

20th Century CO₂ Fluxes into Atmosphere in CESM1.2+(BGC)

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



Seasonal Cycle of CO₂, 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 CO₂ Concentrations
 - Jones et al., J Clim, 2013
- Feedbacks in 1% CO₂ 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

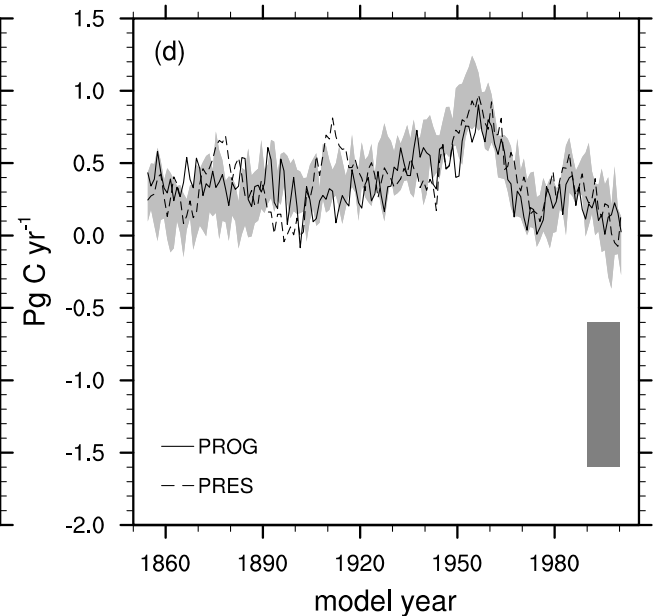
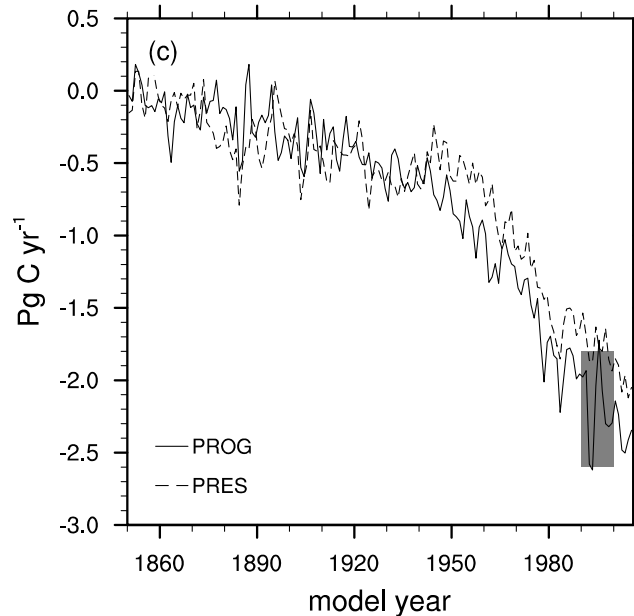
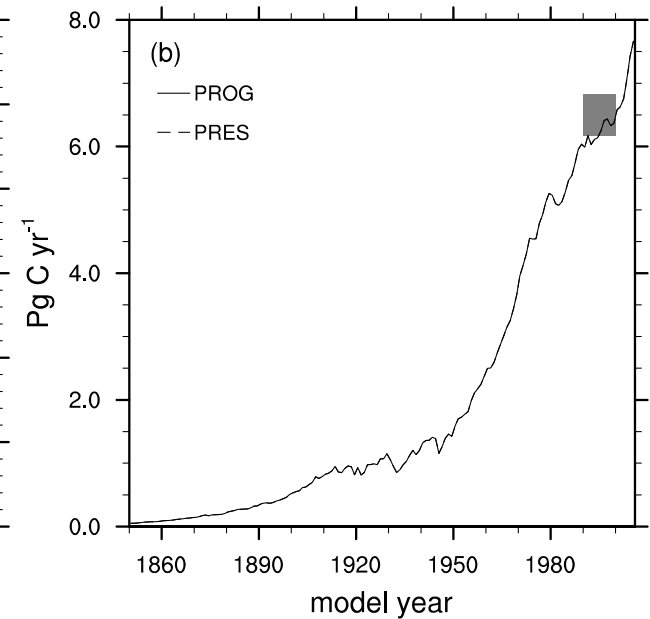
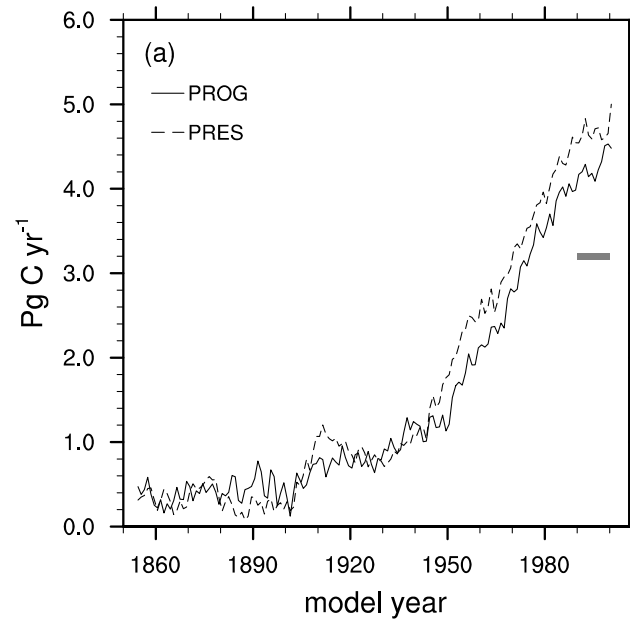
Summary

- 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 CO₂, on multiple timescales, are valuable constraint on models.
- Land & ocean uptake of anthropogenic CO₂, 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 CESM2.1 are in BGC challenge exercises.

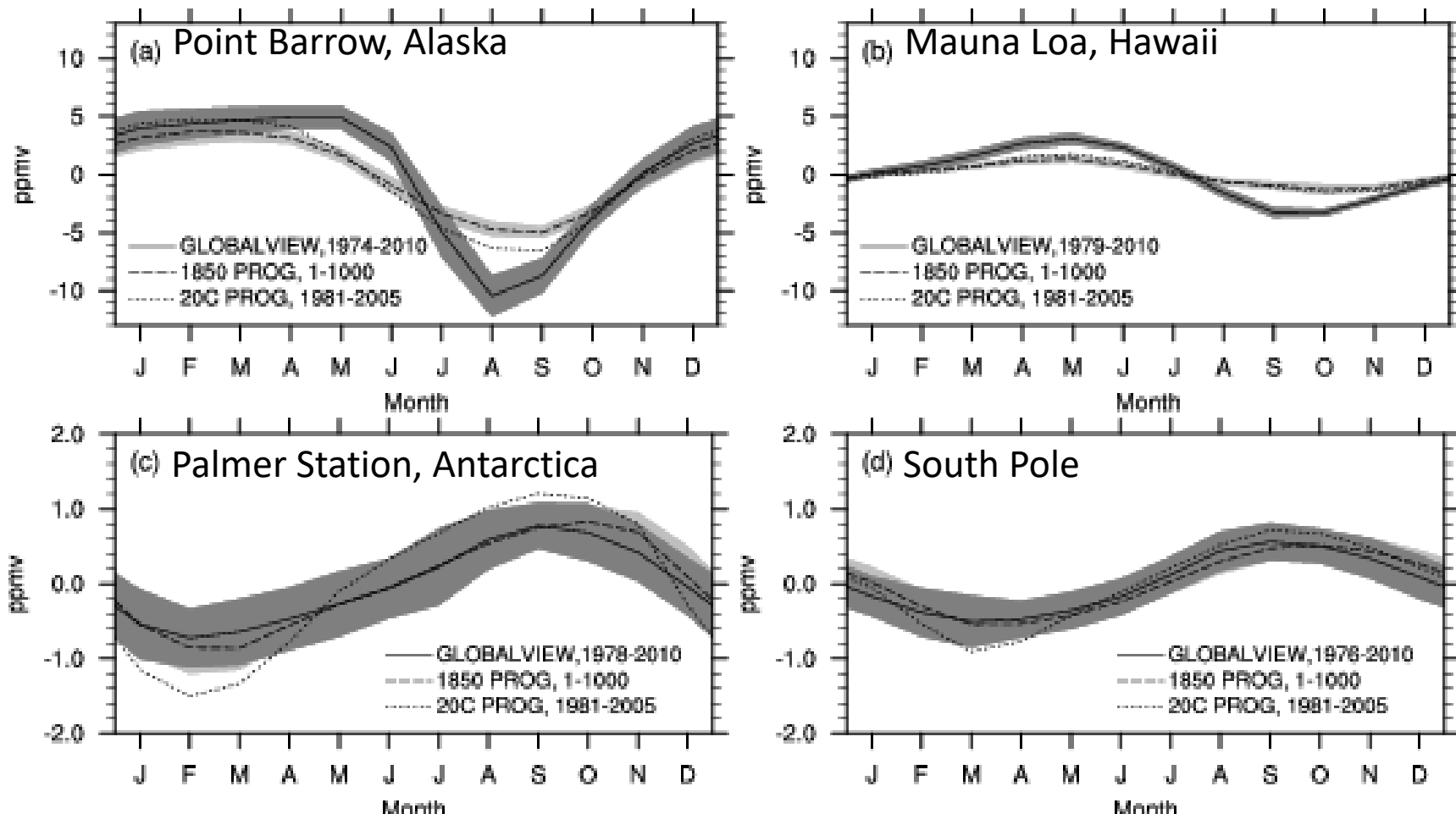
extra slides

20th Century CO₂ Fluxes into Atmosphere in CESM1(BGC)

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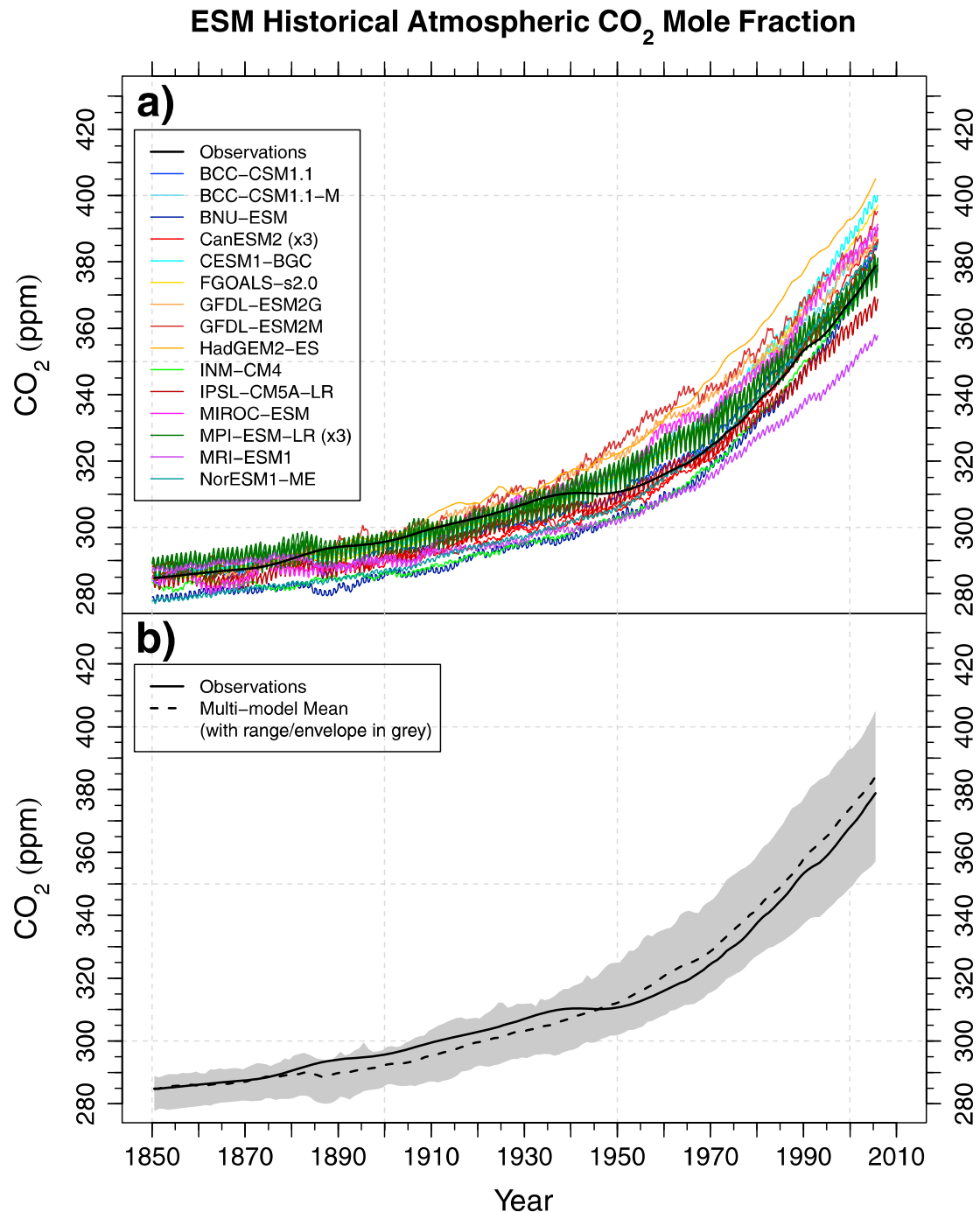


Seasonal Cycle of CO₂, CESM1(BGC)



Atmospheric CO₂ 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

