

# Intro to Biogeochemical Modeling Ocean & Coupled

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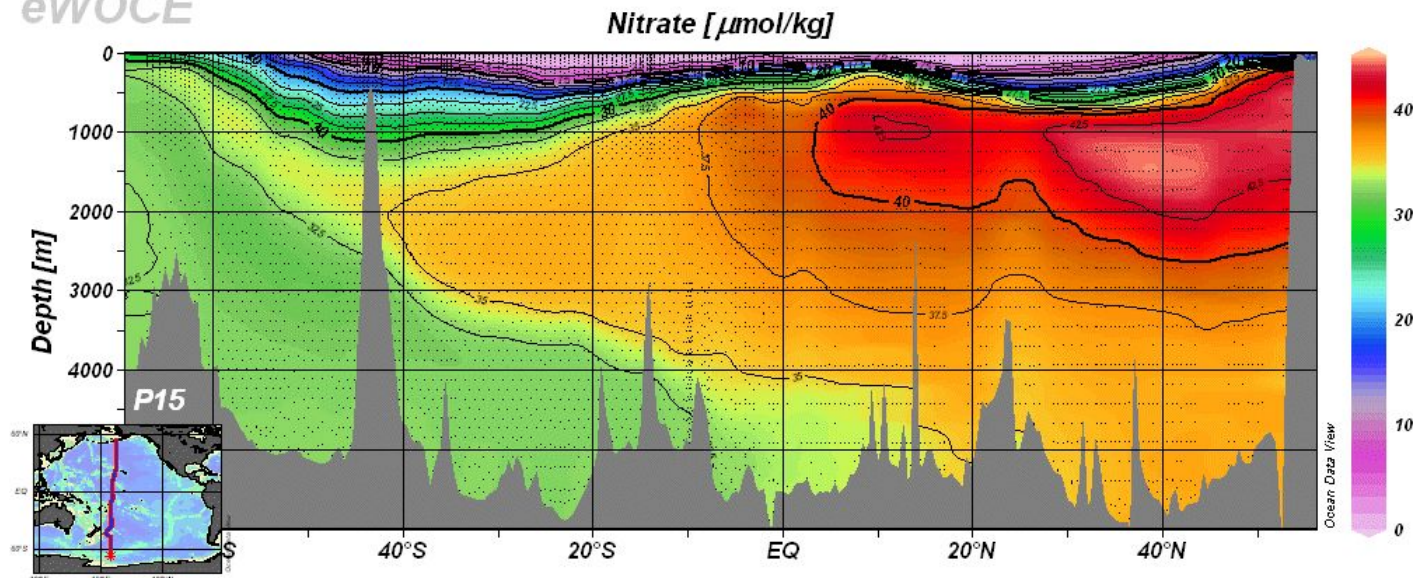


# Lecture Outline

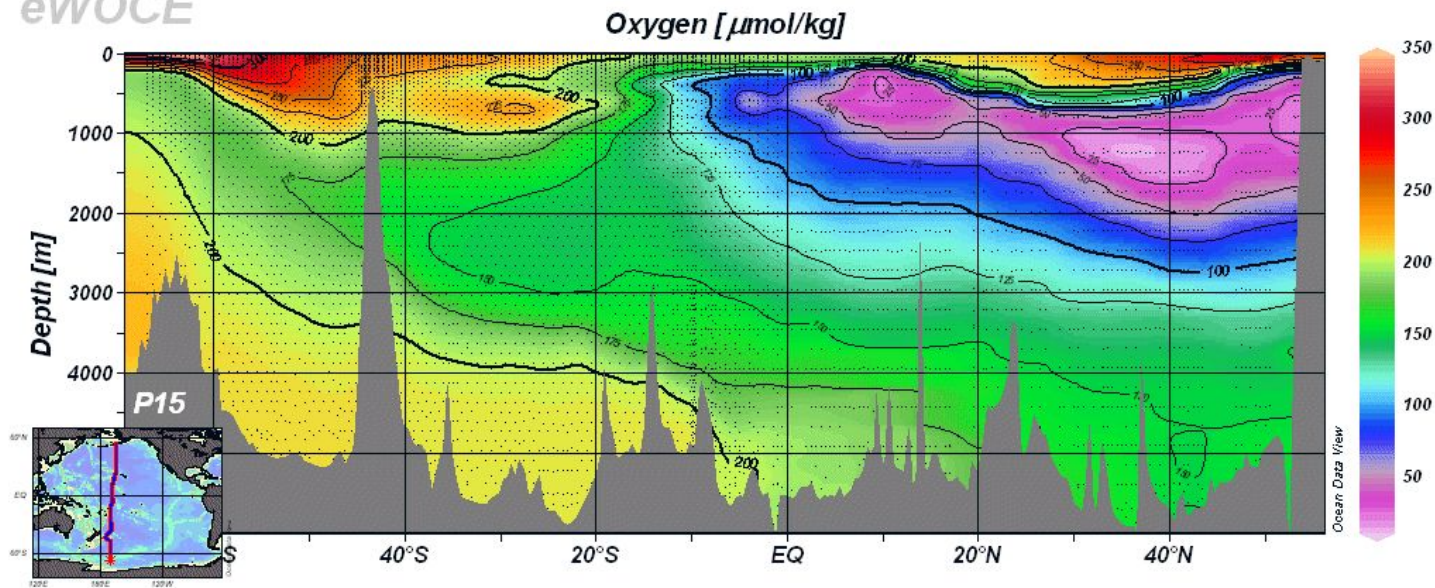
- 1) Large Scale Ocean Biogeochemical Features
- 2) Techniques for Modeling Biological Productivity
- 3) Skill Assessment
- 4) Global Carbon Cycle
- 5) Summary

# NO<sub>3</sub> (a nutrient), O<sub>2</sub> (dissolved gas) Along Pacific Transect

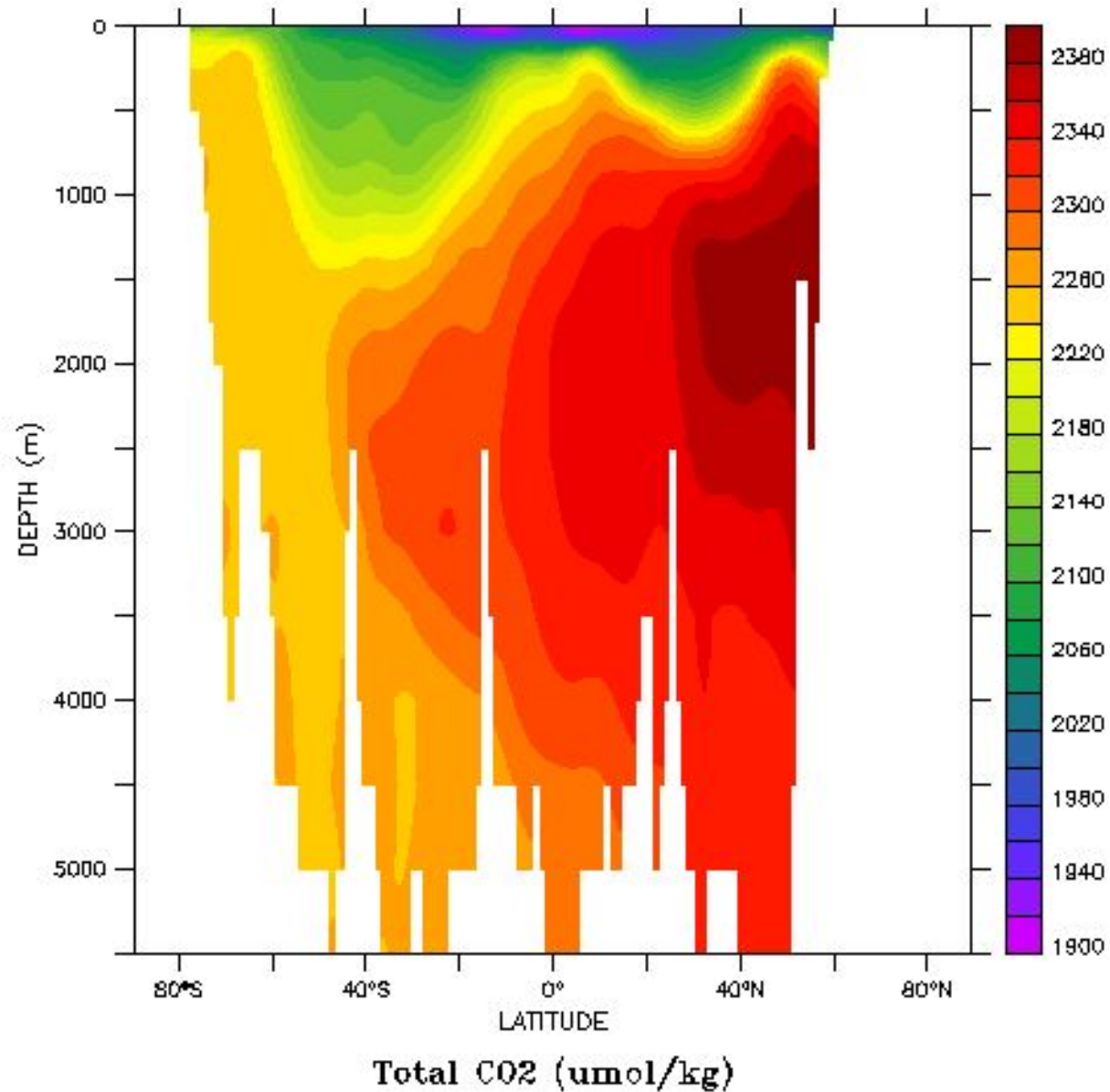
eWOCE



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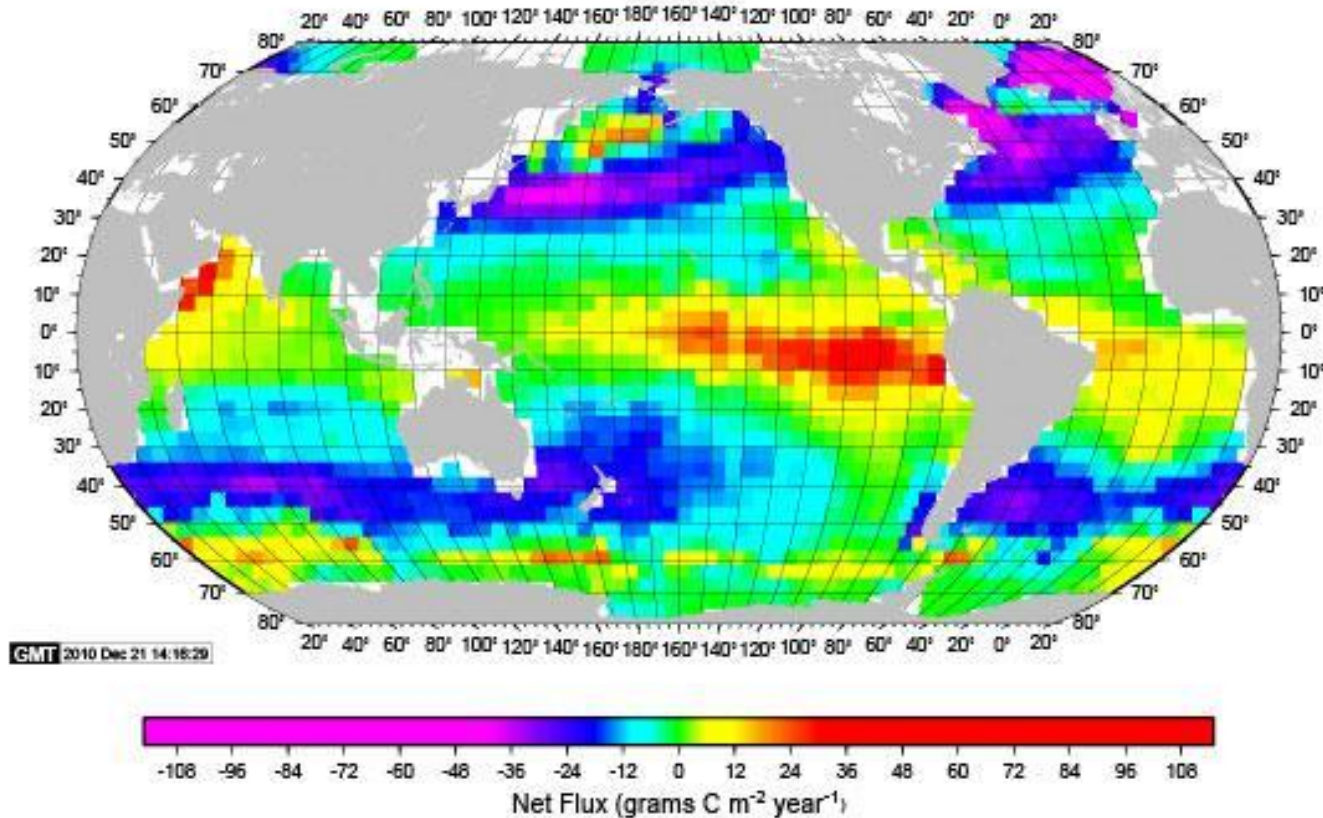


# DIC ( $\sim\text{CO}_2$ ) Along Same Pacific Transect



# Takahashi Air-Sea CO<sub>2</sub> Gas Flux

Mean Annual Air-Sea Flux for 2000 [Rev Dec 10] (NCEP II Wind, 3,040K,  $\Gamma=2.6$ )



# Primary Processes Governing Distribution of Nutrients, O<sub>2</sub>, Carbon, etc.

- Biological Productivity in Euphotic Zone
  - Consumes Nutrients & Inorganic Carbon
  - Produces Organic Matter & O<sub>2</sub>
- Export of Organic Matter out of Euphotic Zone
  - Sinking Particles (e.g. detritus, CaCO<sub>3</sub> shells, ...)
  - Circulation of Suspended Matter
- Remineralization of Organic Matter
  - ‘reverse’ of productivity, consumes O<sub>2</sub>
- 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

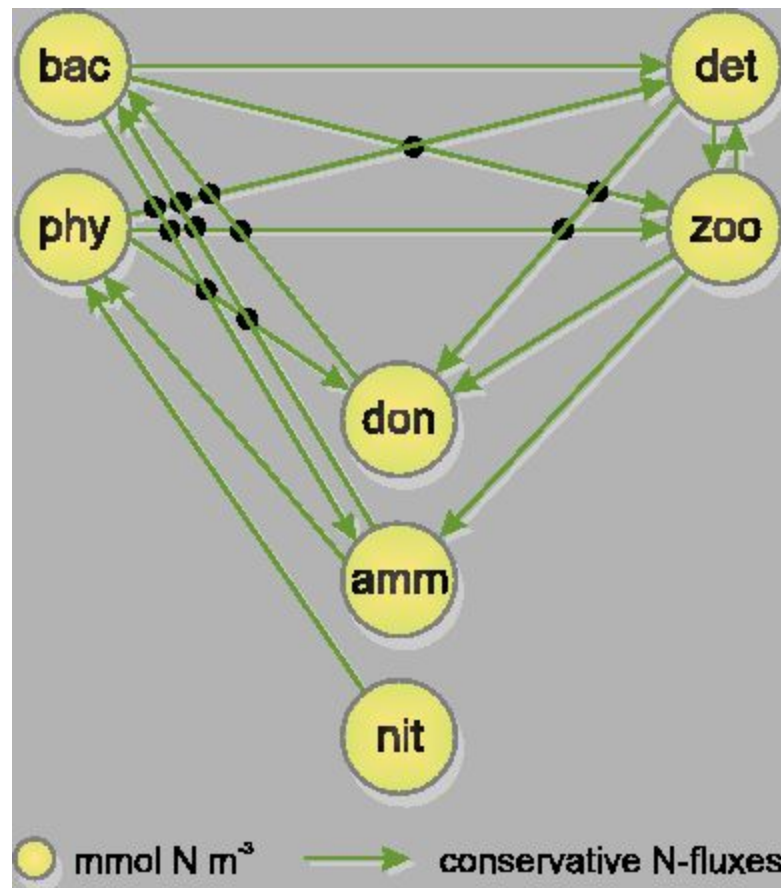
# What is an NPZD model?

- 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](http://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

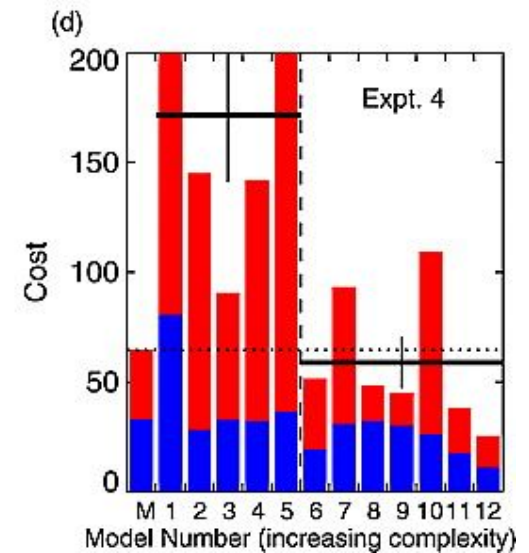
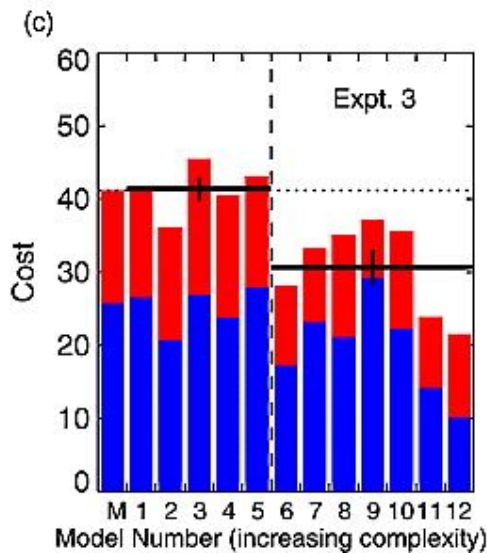
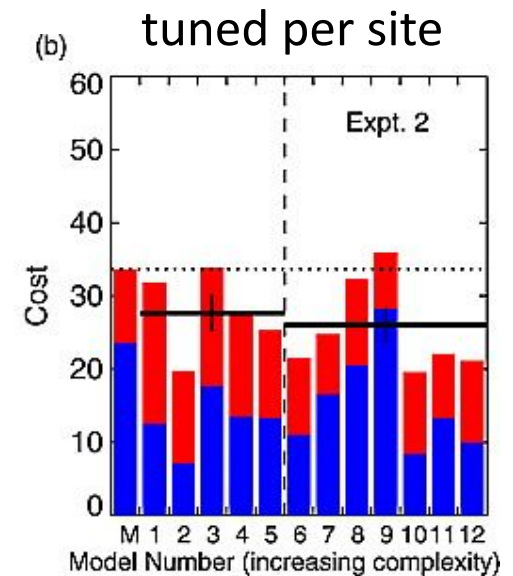
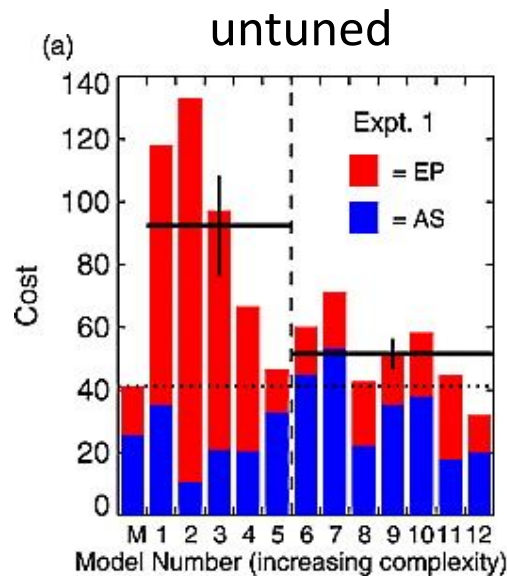
# What is the best model?

(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.

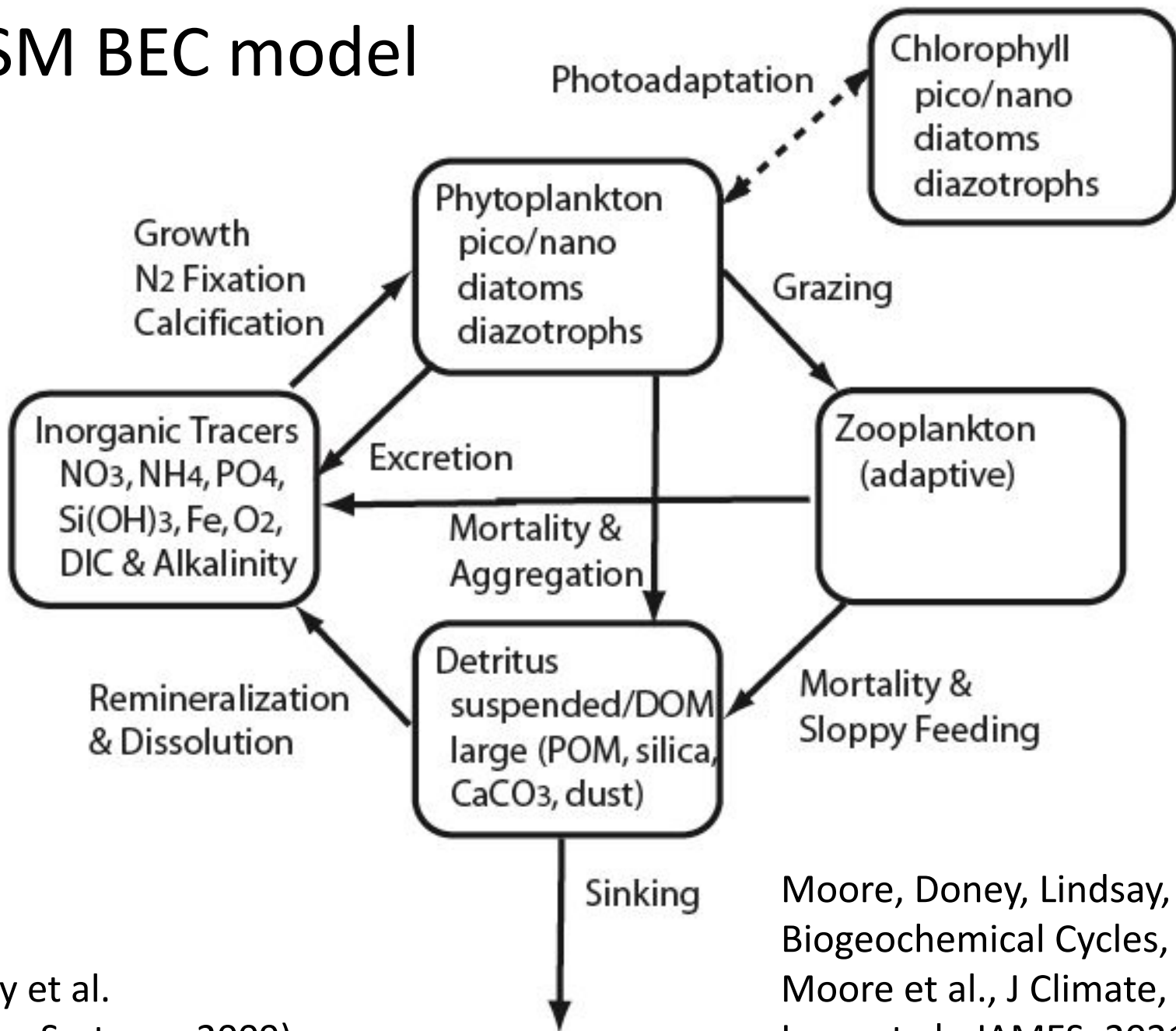
Assessment of skill and portability in regional marine biogeochemical models: Role of multiple planktonic groups, Friedrichs et al., *JGR-Oceans*, 2007.



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.  
Long et al., JAMES, 2021.

# 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

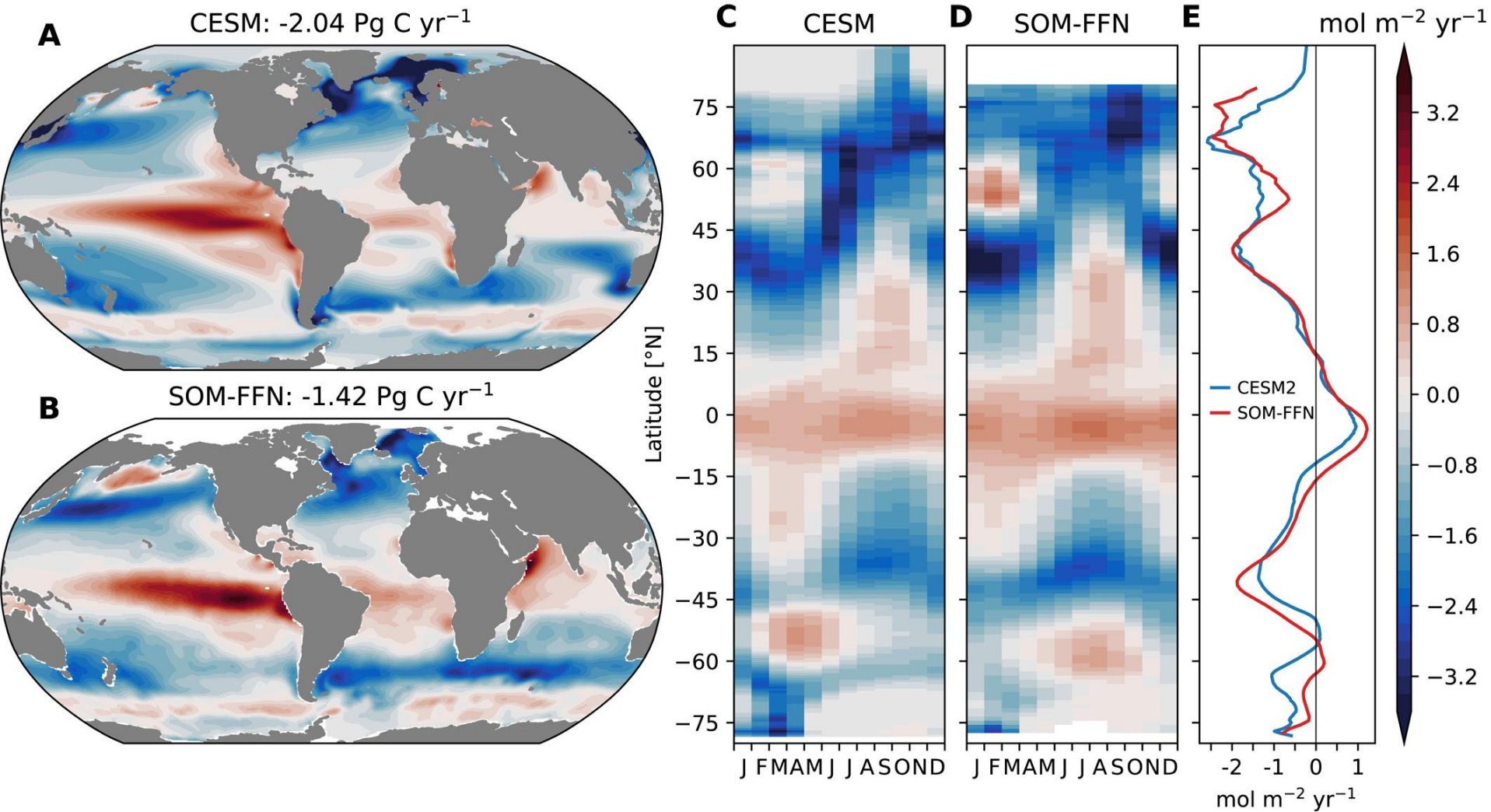
- Calcification & open ocean  $\text{CaCO}_3$  dissolution rates are independent of  $\text{CO}_3$  saturation state
- Riverine inputs of BGC tracers are prescribed
- C, N, P, Si,  $\text{CaCO}_3$  buried in sediments are lost from the system
- No treatment of BGC in sea-ice
- Focus in on lower trophic levels

# Model Validation: Examples of Data Sets

- Macronutrients ( $\text{PO}_4$ ,  $\text{NO}_3$ ,  $\text{SiO}_3$ ) and  $\text{O}_2$  from World Ocean Atlas
- DIC, ALK from GLODAP Analysis
- Surface Chl measured by satellite
- Productivity estimated from satellite
- $\text{pCO}_2$  and  $\text{CO}_2$  Flux, obs filled by neural net
- Fe, databases of obs



# Air-sea CO<sub>2</sub> 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

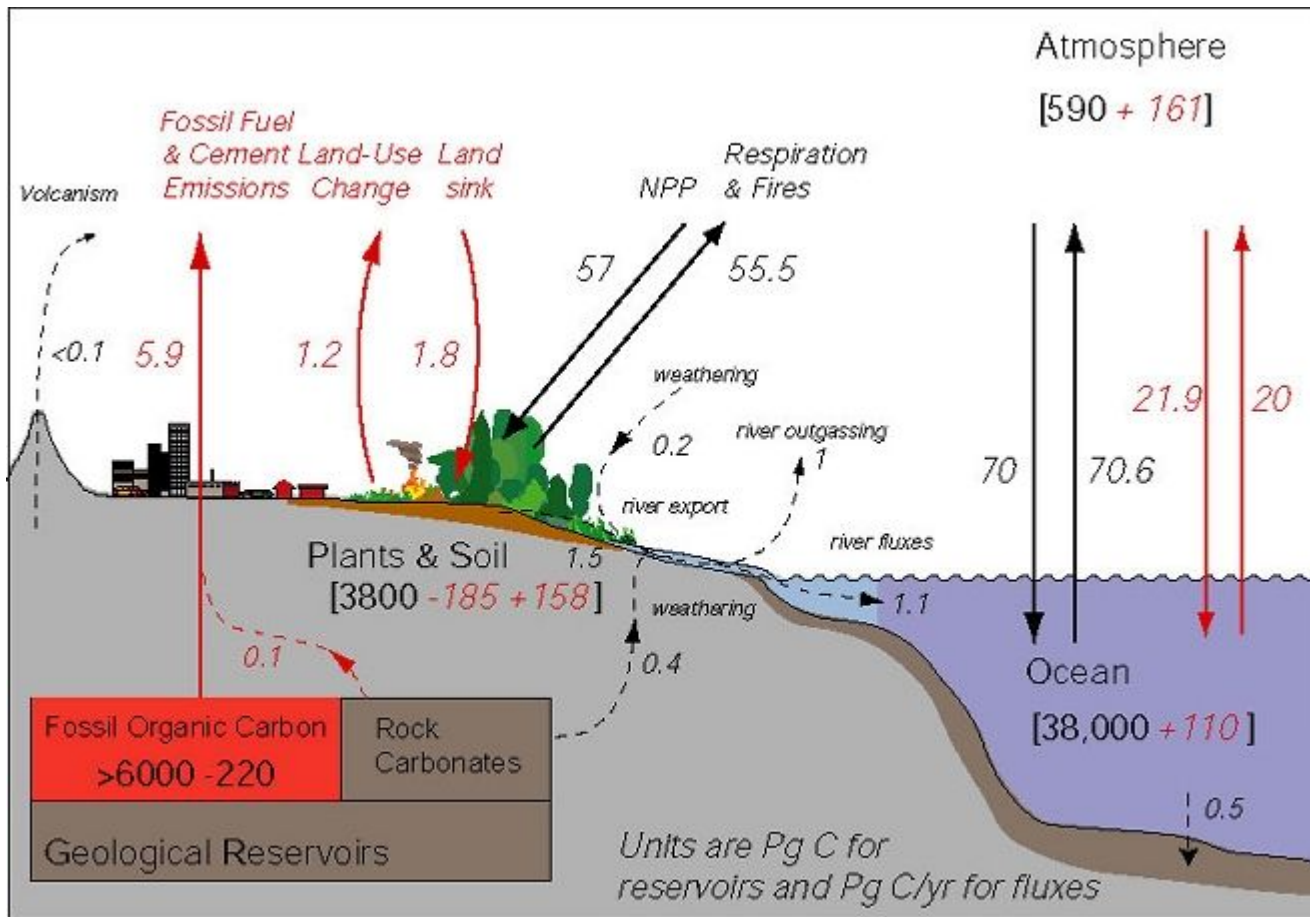
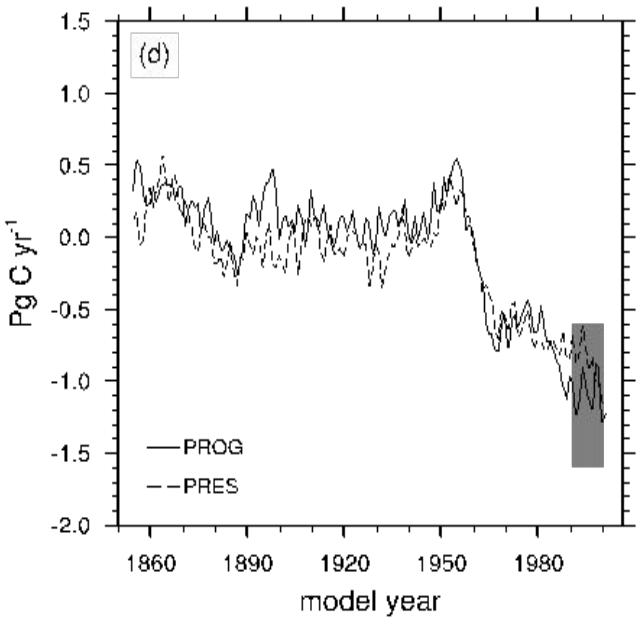
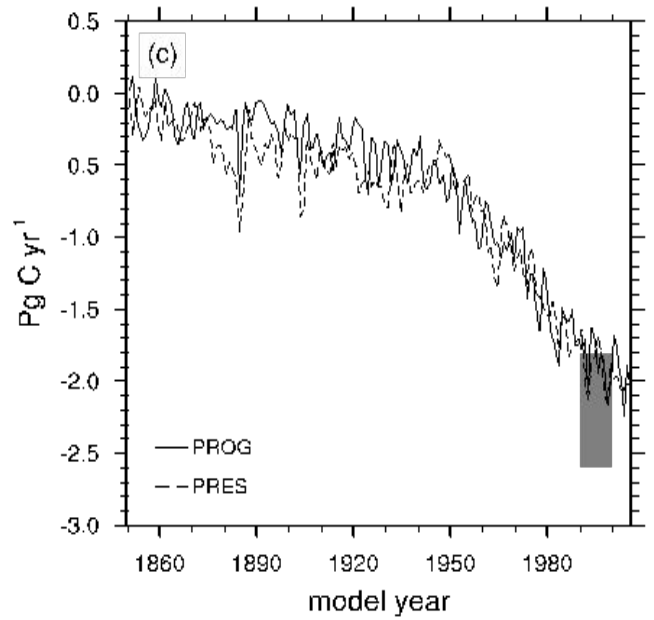
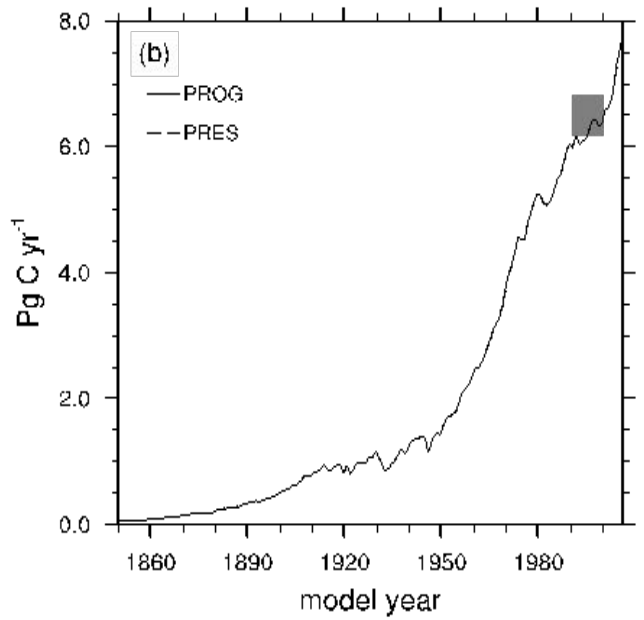
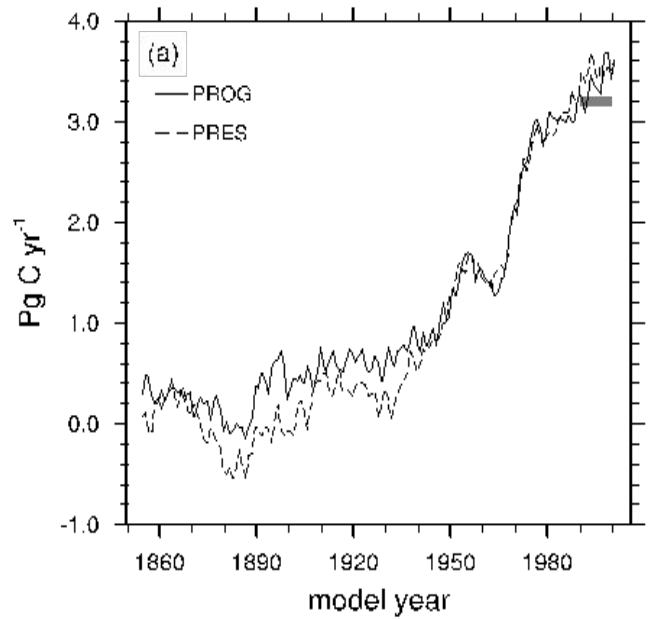


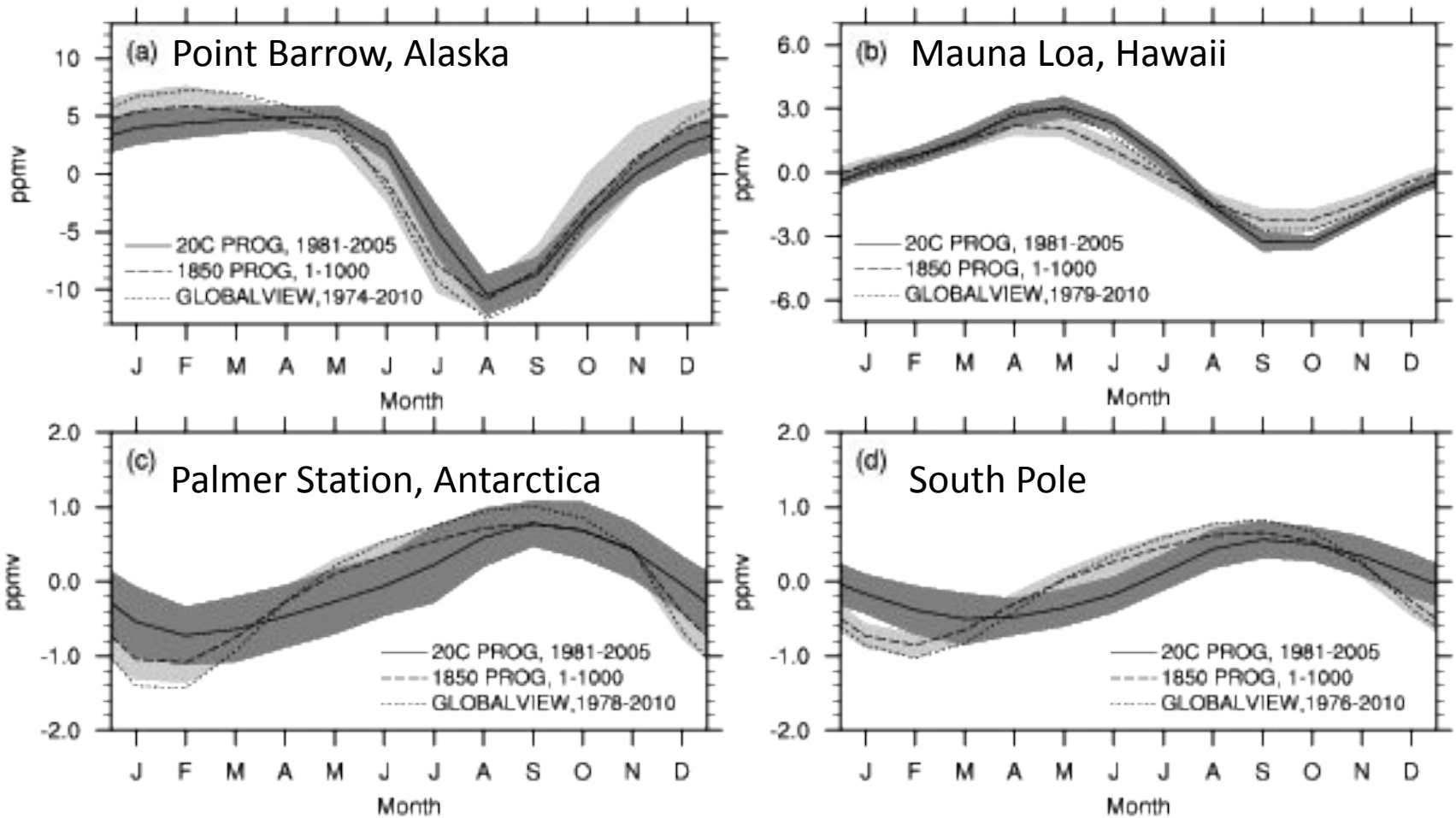
Figure courtesy PMEL

# 20<sup>th</sup> Century CO<sub>2</sub> Fluxes into Atmosphere in CESM1.2+(BGC)

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



# Seasonal Cycle of CO<sub>2</sub>, 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<sub>2</sub> Concentrations
  - Jones et al., J Clim, 2013
- Feedbacks in 1% CO<sub>2</sub> 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

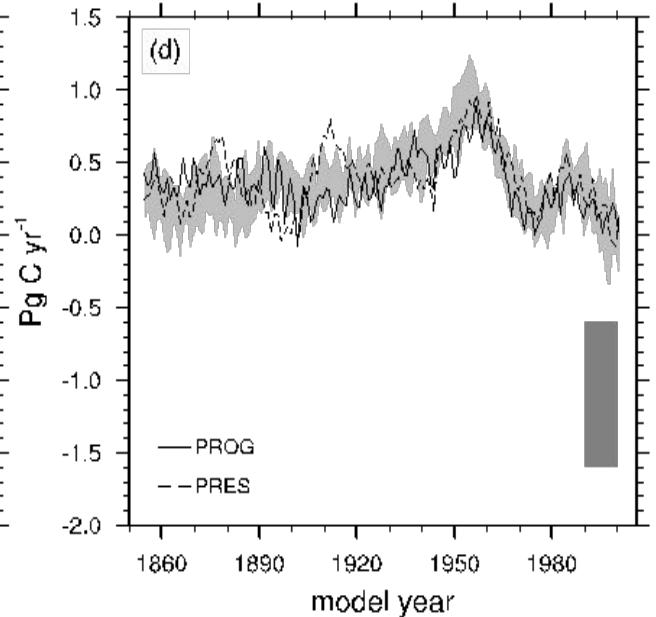
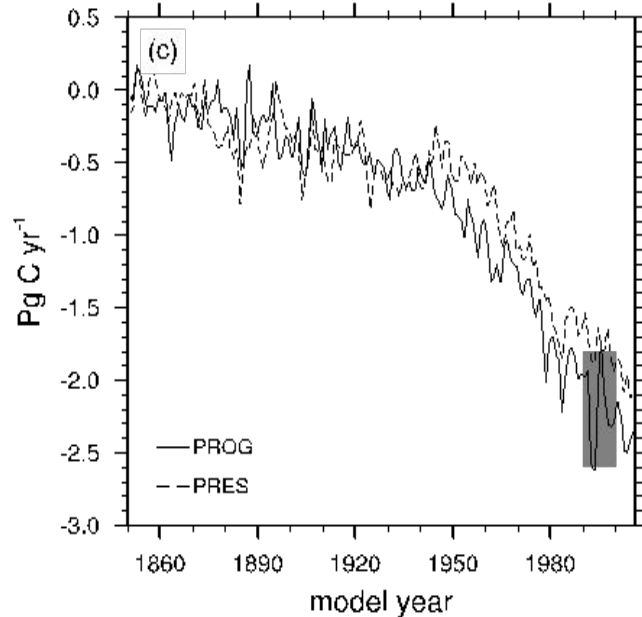
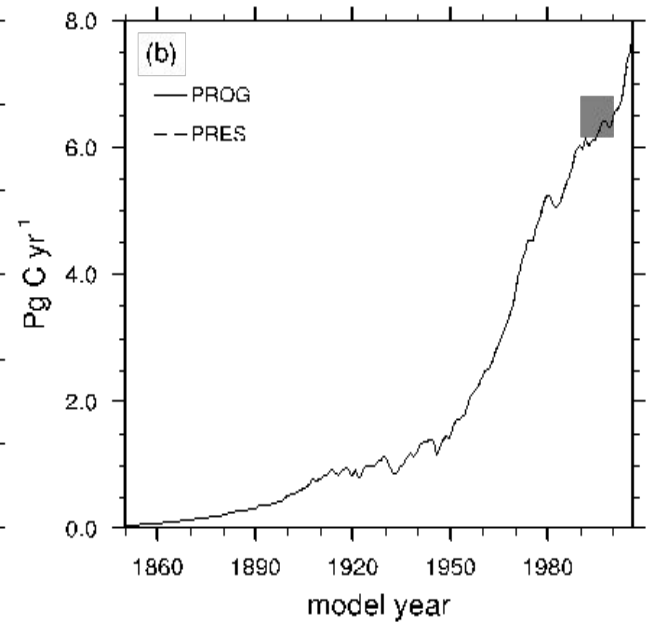
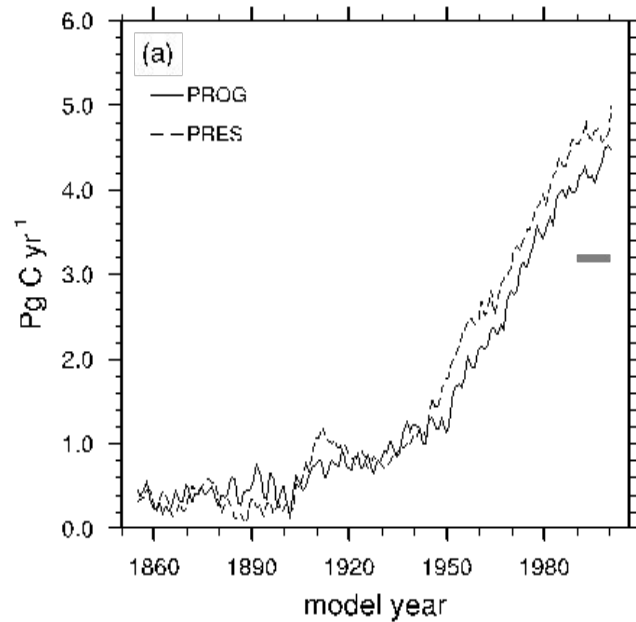
- Large scale ocean biogeochemical features are determined by handful of processes
- ‘Perfect’ ecosystem model doesn’t exist, many simplifications need to be made. Improving models is ongoing research. Scientific questions and observational constraints guide this process.
- Global carbon cycle is now present in numerous CMIP class models (ESMs). Observations of atmospheric CO<sub>2</sub>, on multiple timescales, are valuable constraint on models.
- Land & ocean uptake of anthropogenic CO<sub>2</sub>, 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

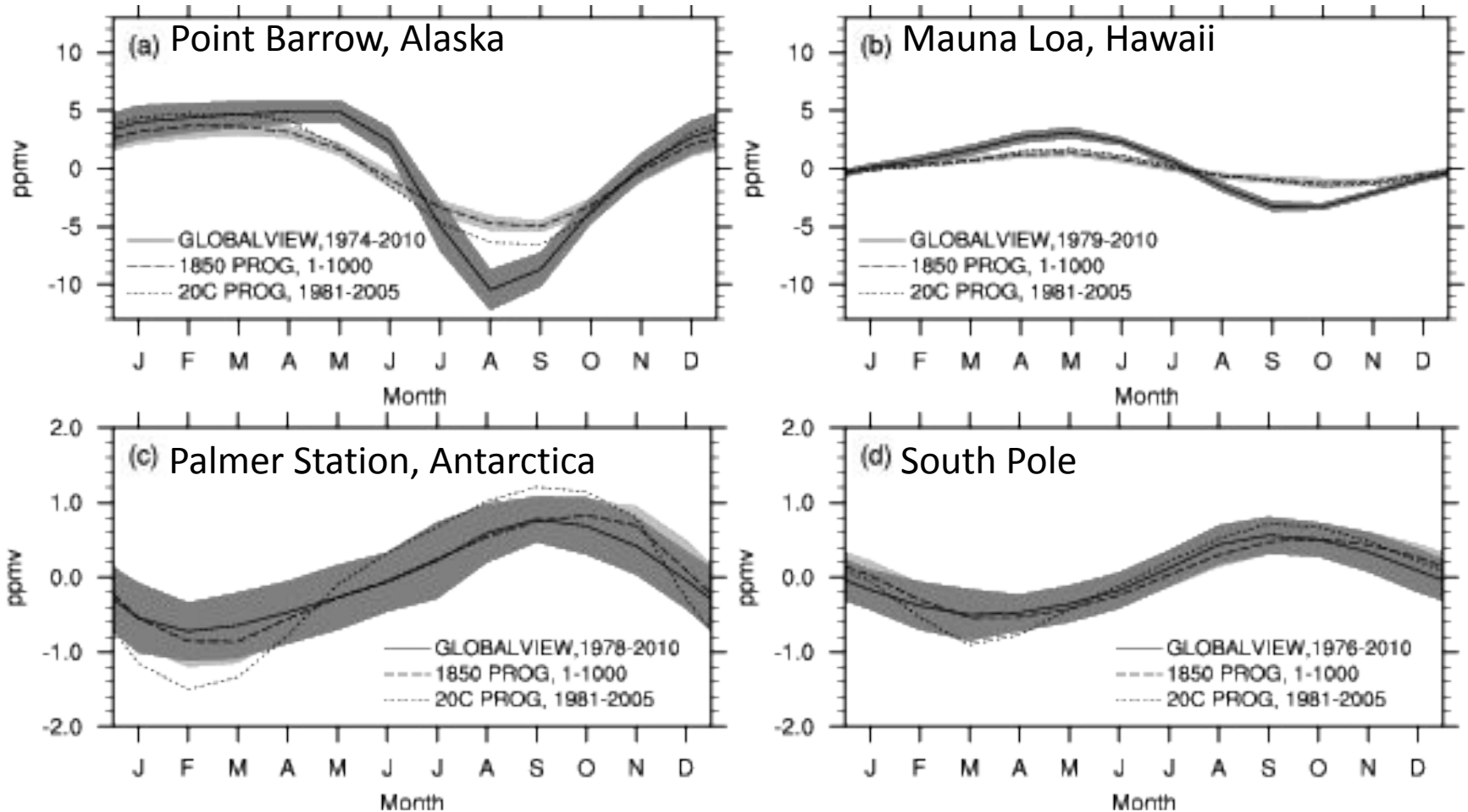


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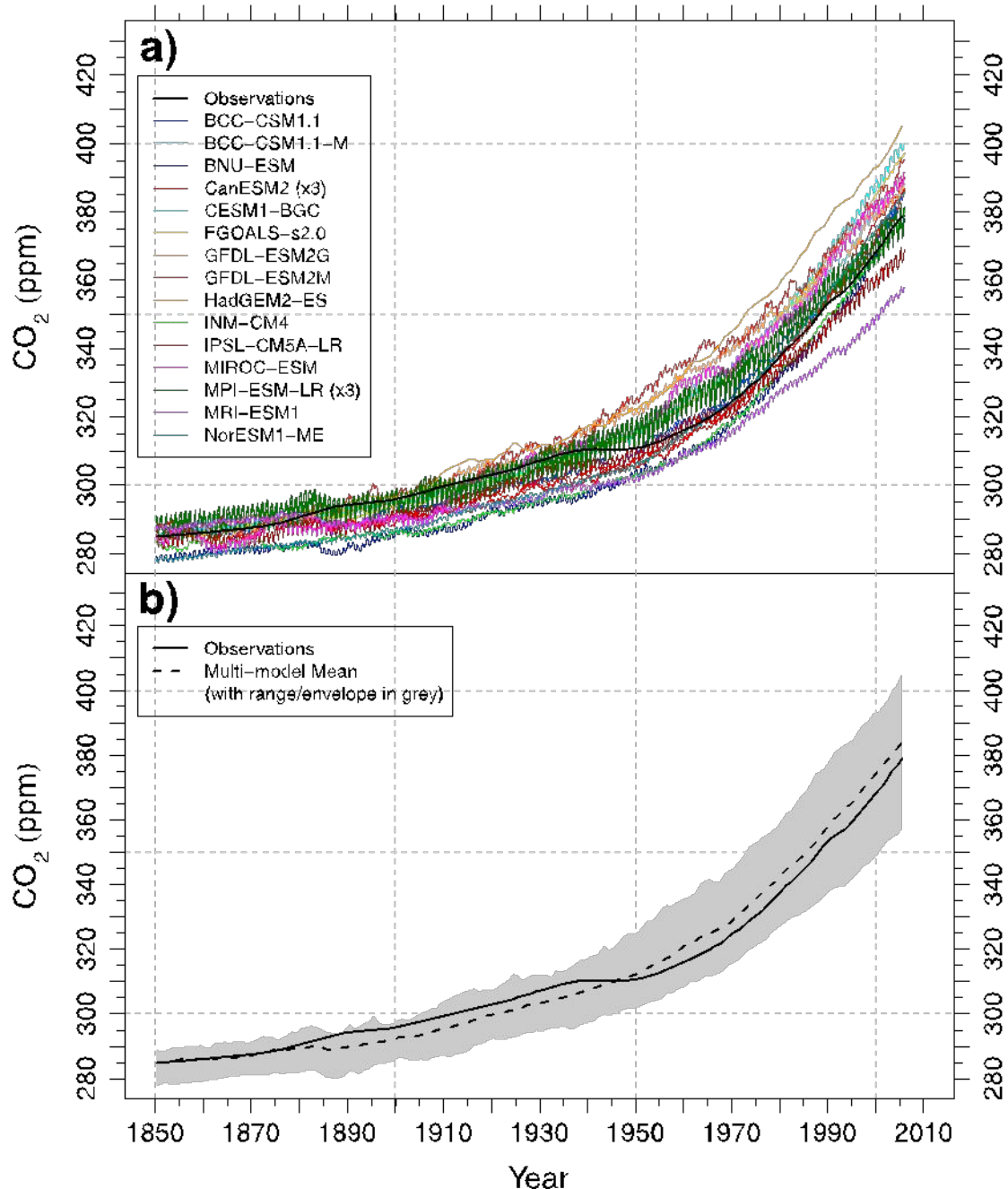


# Seasonal Cycle of CO<sub>2</sub>, CESM1(BGC)



# Atmospheric CO<sub>2</sub> in CMIP5 Earth System Models

ESM Historical Atmospheric CO<sub>2</sub> Mole Fraction



# Ocean and Land Carbon Accumulation in CMIP5 Earth System Models

ESM Historical Ocean and Land Carbon Accumulation

