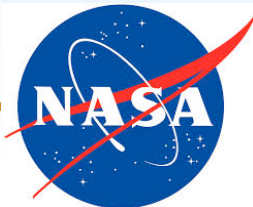
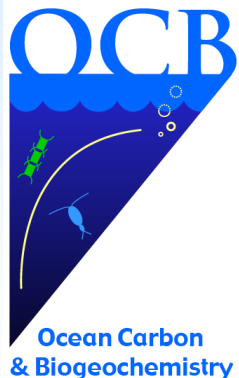


Model Biases & Uncertainties in CMIP5 Models: Ocean Carbon Uptake & Climate Feedbacks

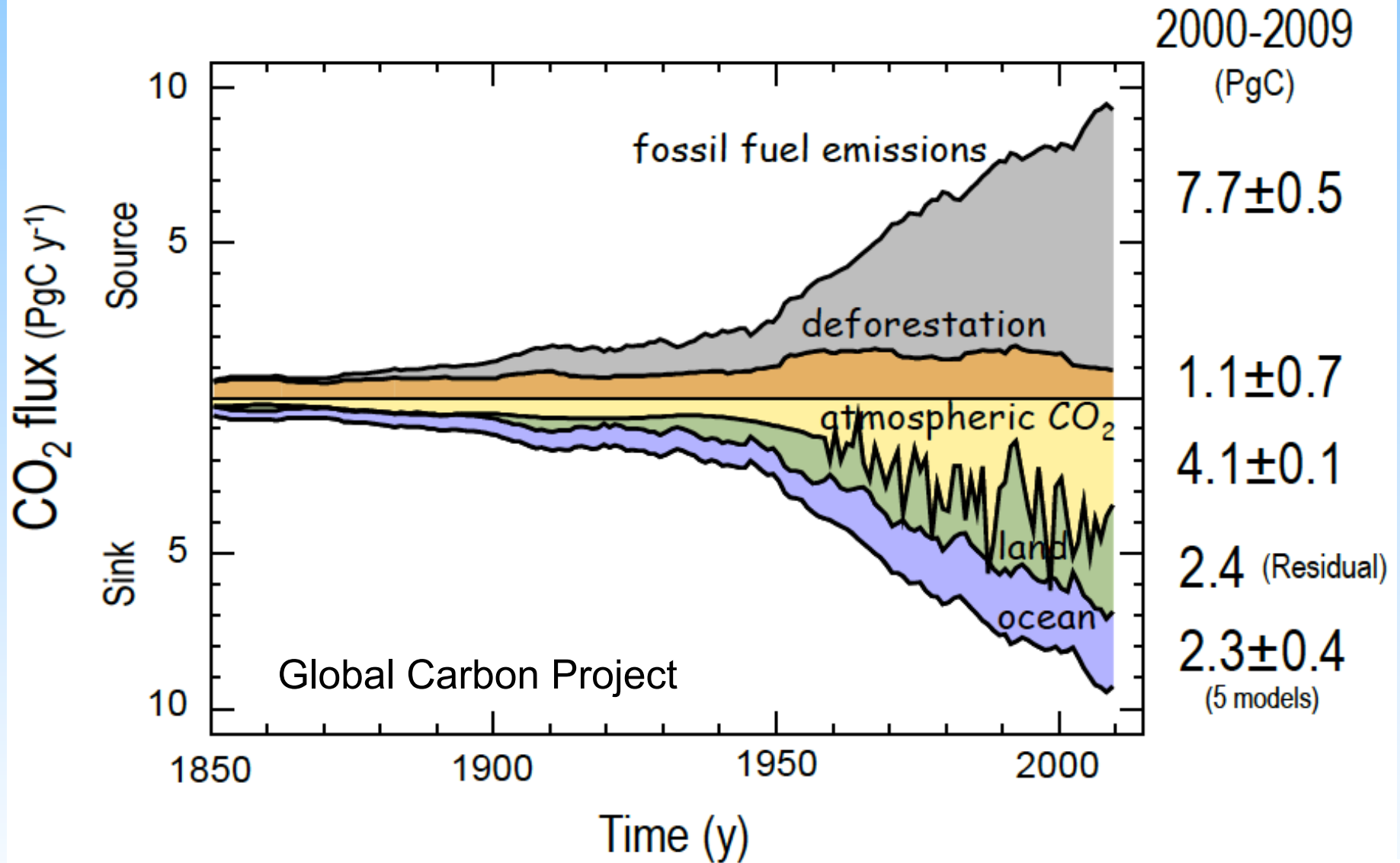
Scott Doney (WHOI), Matt Long & Keith Lindsay
(NCAR) & CESM-BGC Working Group

Useful References

- IPCC WG1 Chapter 6 (Cias, Sabine et al. 2013)
- J. Climate Special Collection "*Climate–Carbon Interactions in the CMIP5 Earth System Models*" (C4MIP)
- Biogeosciences Special Issue "*REgional Carbon Cycle Assessment and Processes (RECCAP)*"

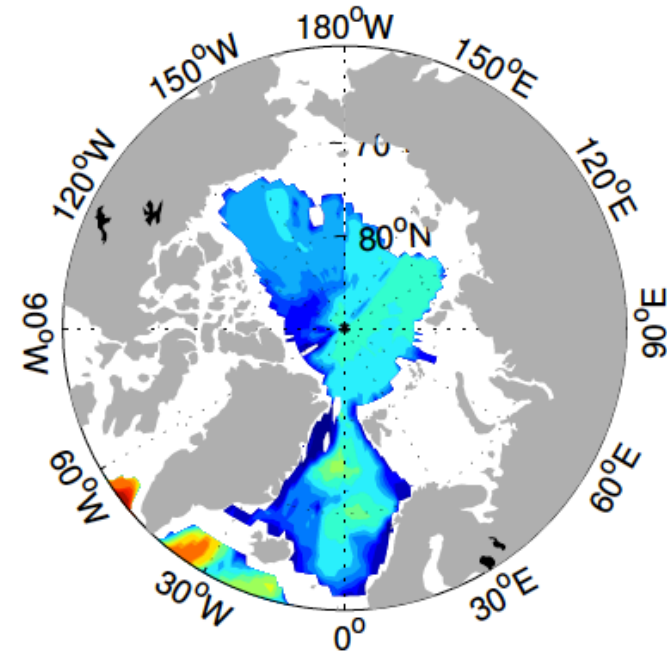
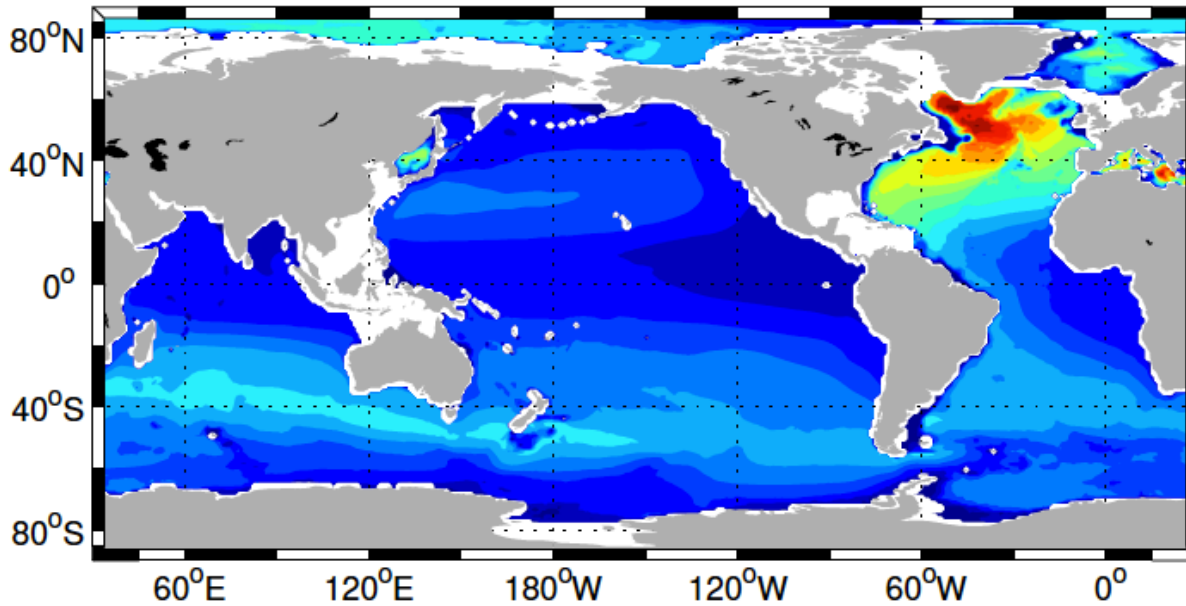


Human Perturbation to Global Carbon Cycle



Canadell et al. PNAS 2007; LeQuere et al. Nature Geosciences 2009

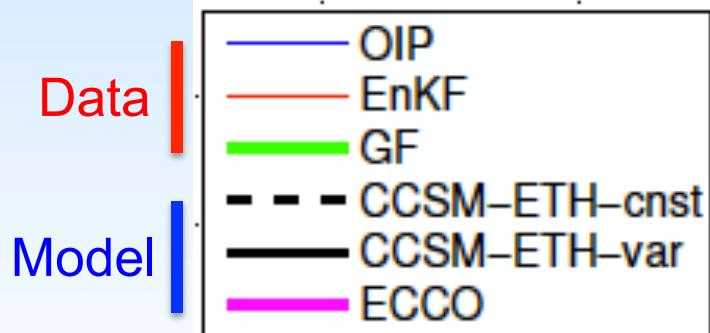
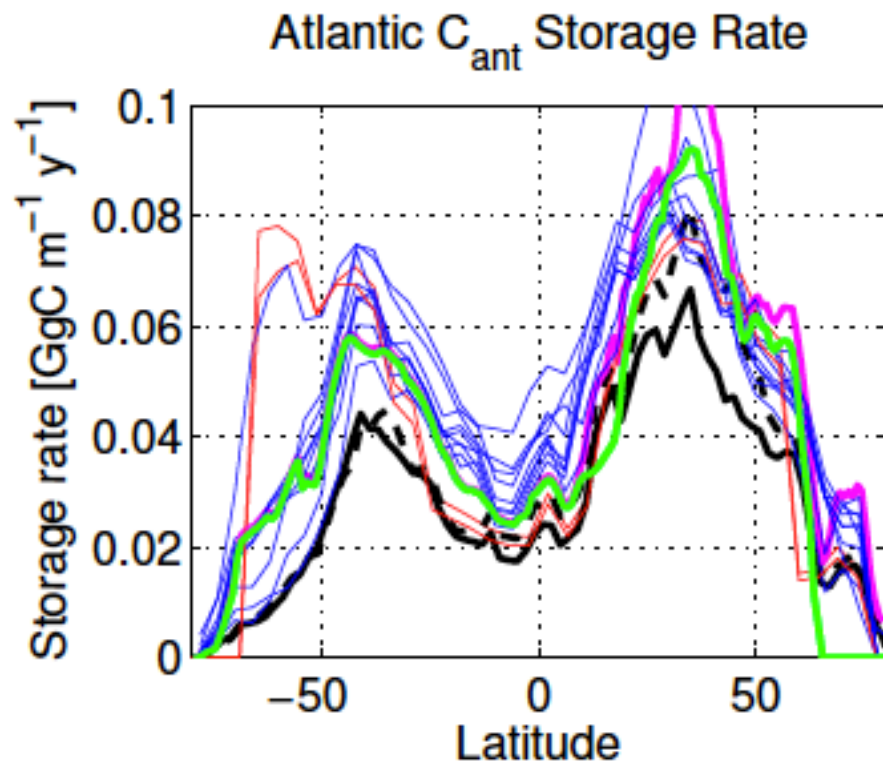
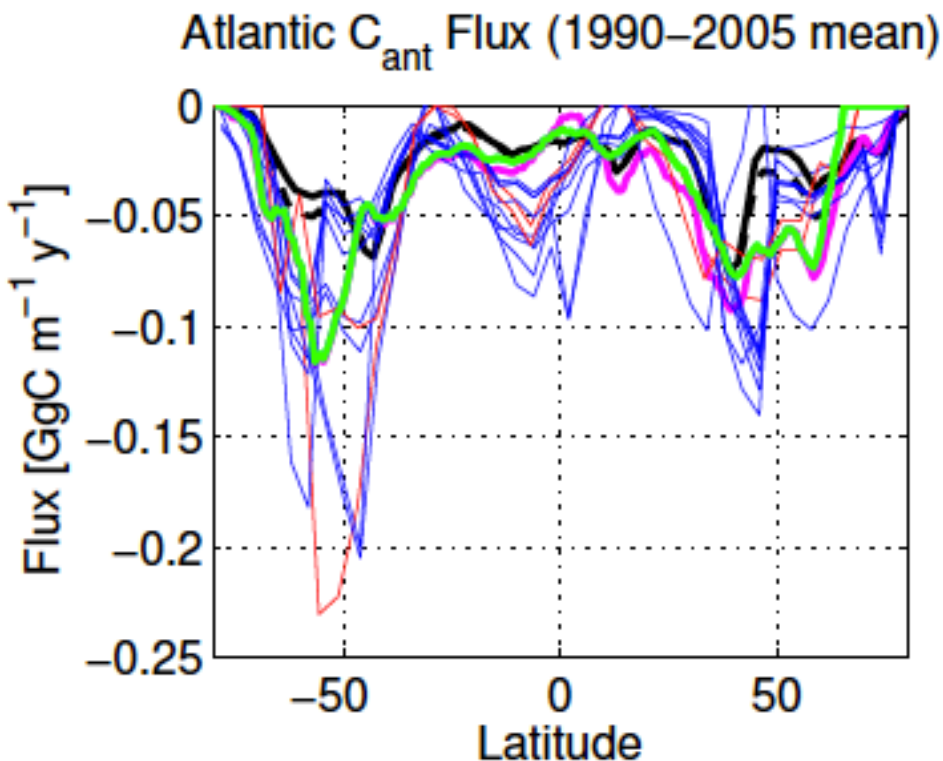
Data-based Ocean ΔC Inventory Patterns



WOCE/CLIVAR Repeat Hydrography & CO₂ Data
-multiple approaches based on analysis of CO₂
system, biogeochemical & transient tracer data
combined with diagnostic modeling

Khatiwala et al.
Biogeosciences
2013

Regional Variations in Data & Model Estimates



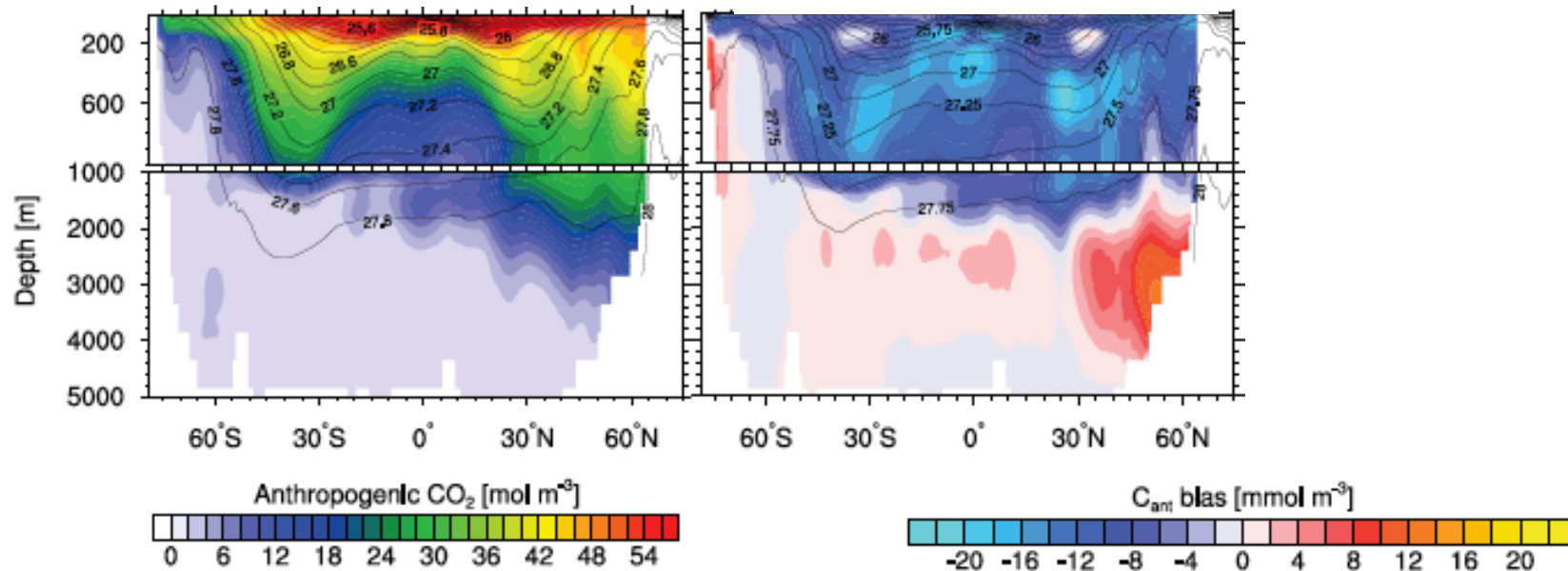
Khatiwala et al.
Biogeosciences
2013

Diagnosing Model Biases

Anthropogenic Carbon

Data (GLODAP)

Ocean-ice Hindcast
Model - Data



Atlantic Zonal Mean

Global ΔC Inventory in 1994
CESM1-BGC 90 Pg C
GLODAP data 118 \pm 19 Pg C

Long et al.
J. Climate 2013

Diagnosing Model Biases

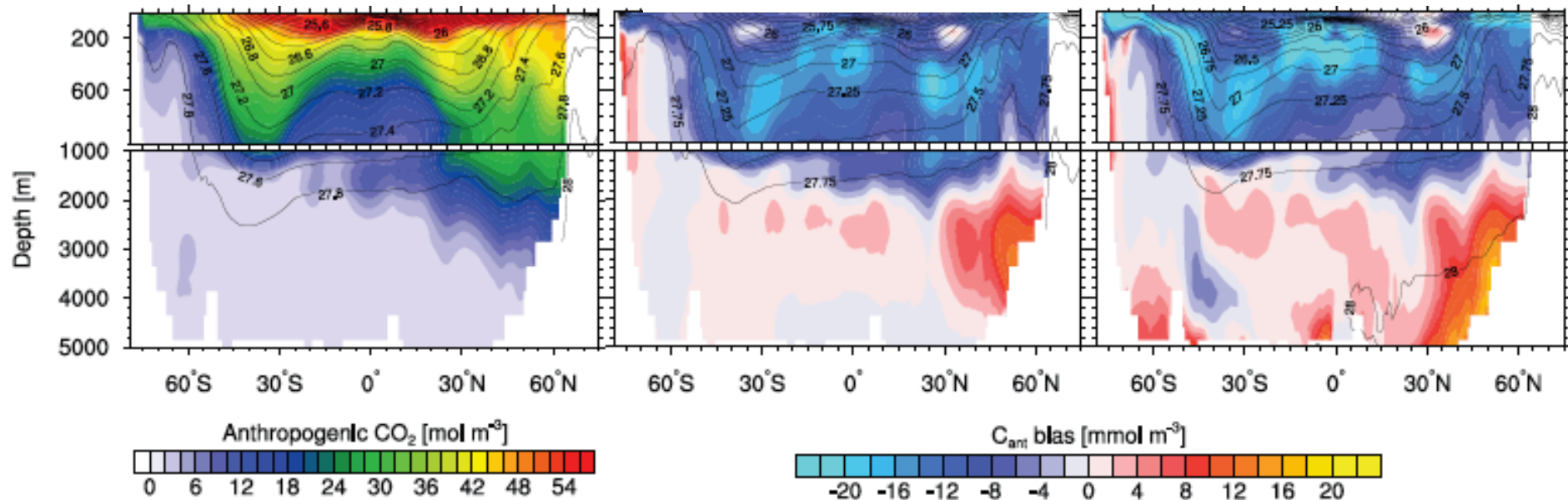
Anthropogenic Carbon

Chlorofluorocarbons

Data (GLODAP)

Ocean-ice Hindcast
Model - Data

Model - Data

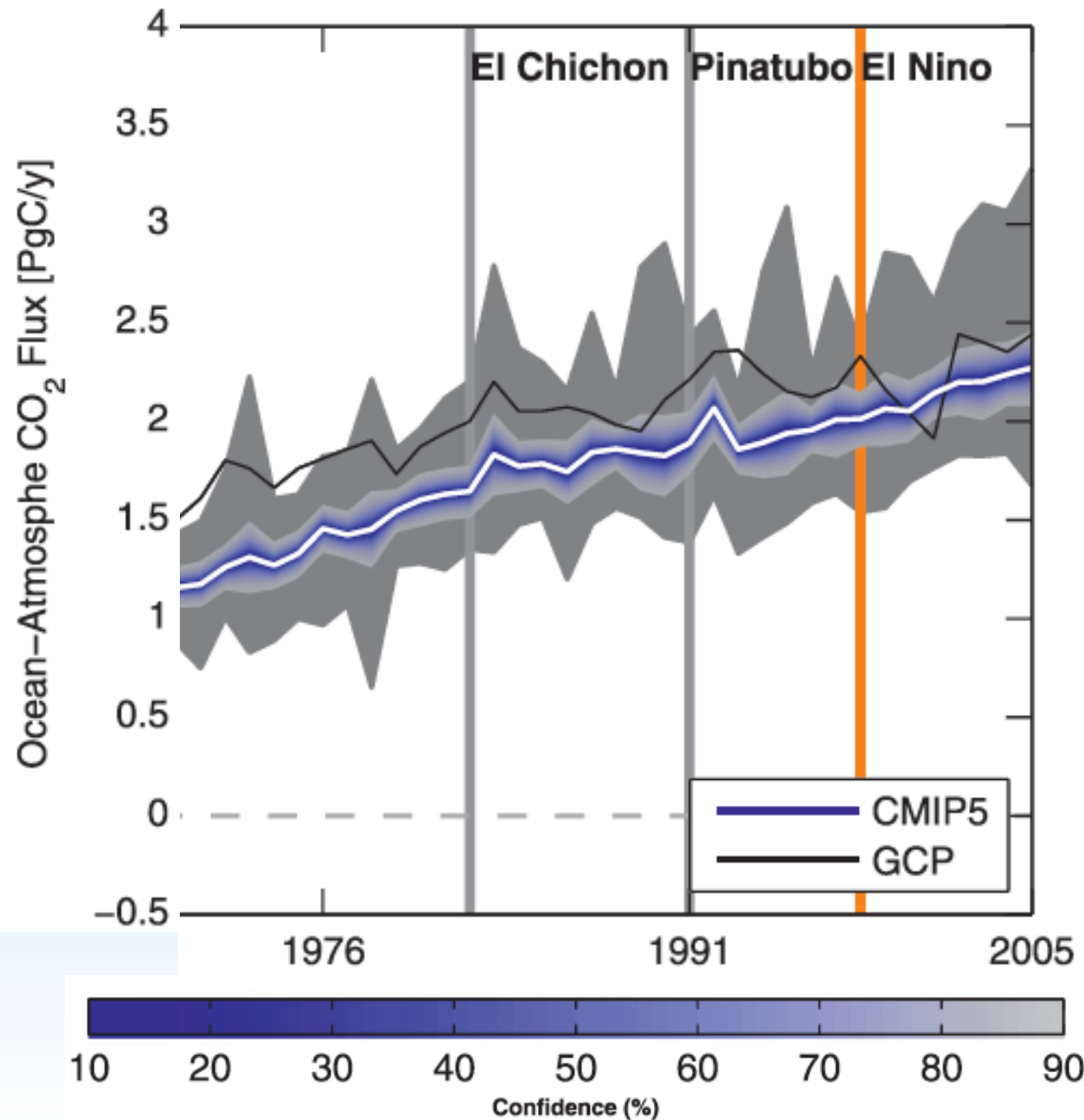


Atlantic Zonal Mean

Global ΔC Inventory in 1994
 CESM1-BGC 90 Pg C
 GLODAP data 118 ± 19 Pg C

Long et al.
 J. Climate 2013

Ocean Uptake Trends & Variability

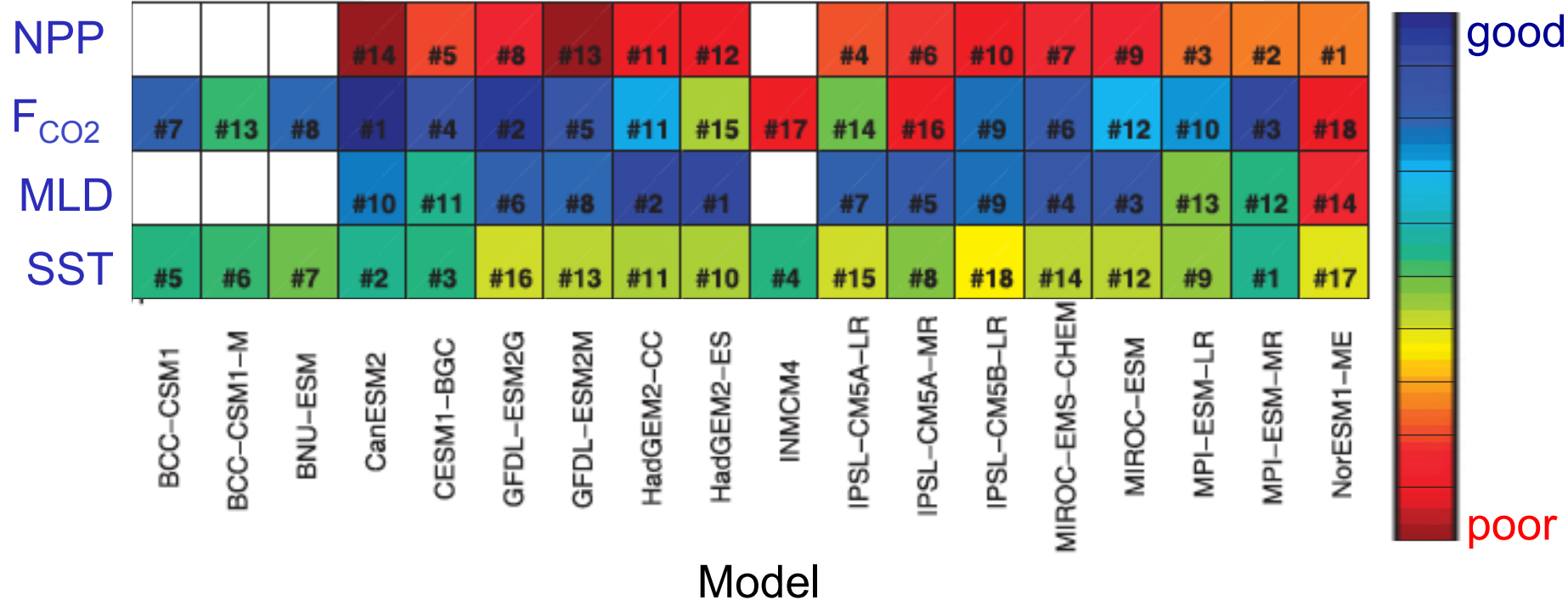


Anav et al.
J. Climate 2013

CMIP5 Ocean Model Skill

Variable

Skill Metric of Bias & Interannual Variability

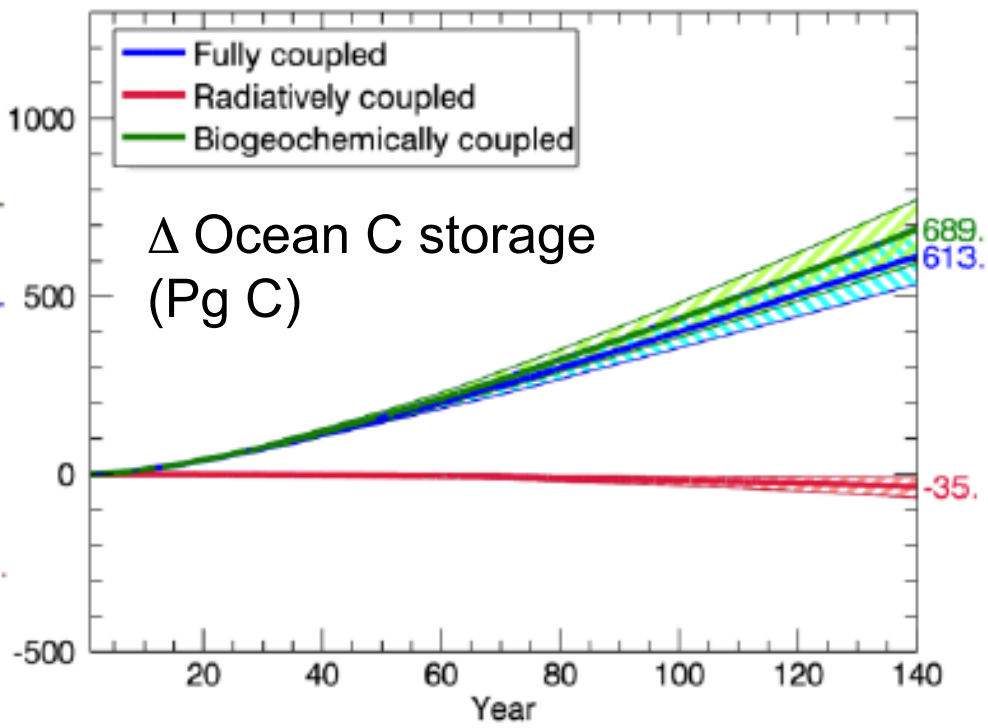
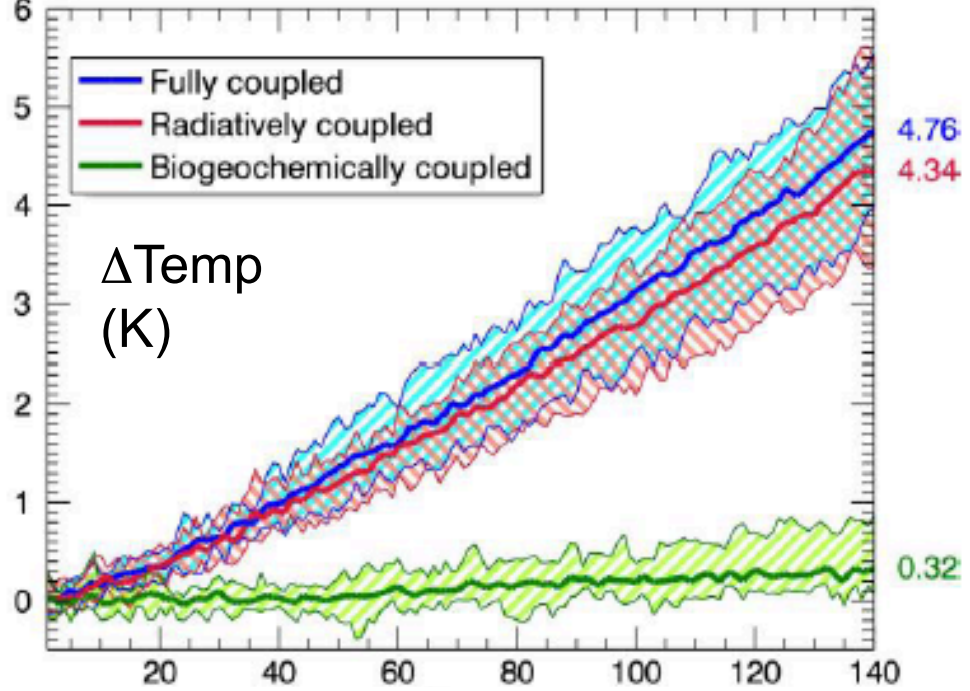


- Seasonal cycle amplitude & phase
- Spatial bias
- Interannual Variability (spread of probability distribution)

Anav et al.
J. Climate 2013

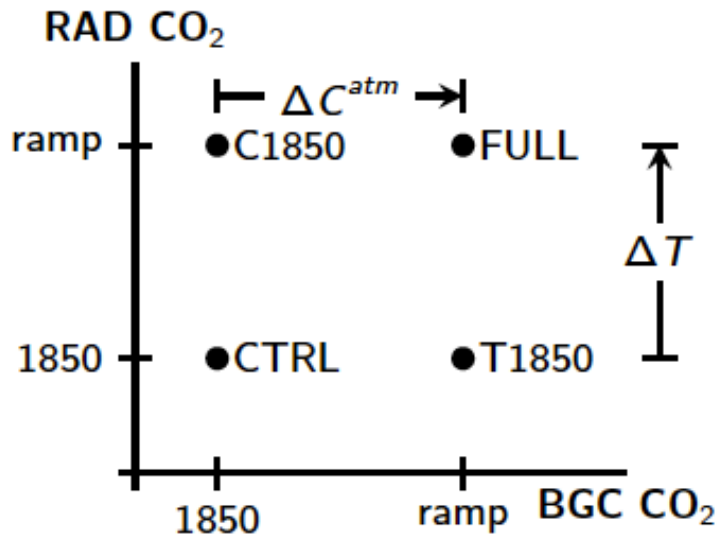
CMIP5 Idealized Simulations

Sensitivity experiments with prescribed atmospheric CO₂ increasing at 1%/y



Arora et al.
J. Climate
2013

Ramping CO₂ experiments



Atmospheric CO₂ & Climate-Carbon Feedbacks

Friedlingstein et al. J. Climate 2006
 Arora et al. J. Climate 2013
 Long et al. in prep.

Linear decomposition of cumulative ocean carbon inventory

$$\Delta C = \beta \Delta \text{CO}_2^{\text{atm}} + \gamma \Delta T \quad \beta (\text{PgC/ppm}); \gamma (\text{Pg C/K})$$

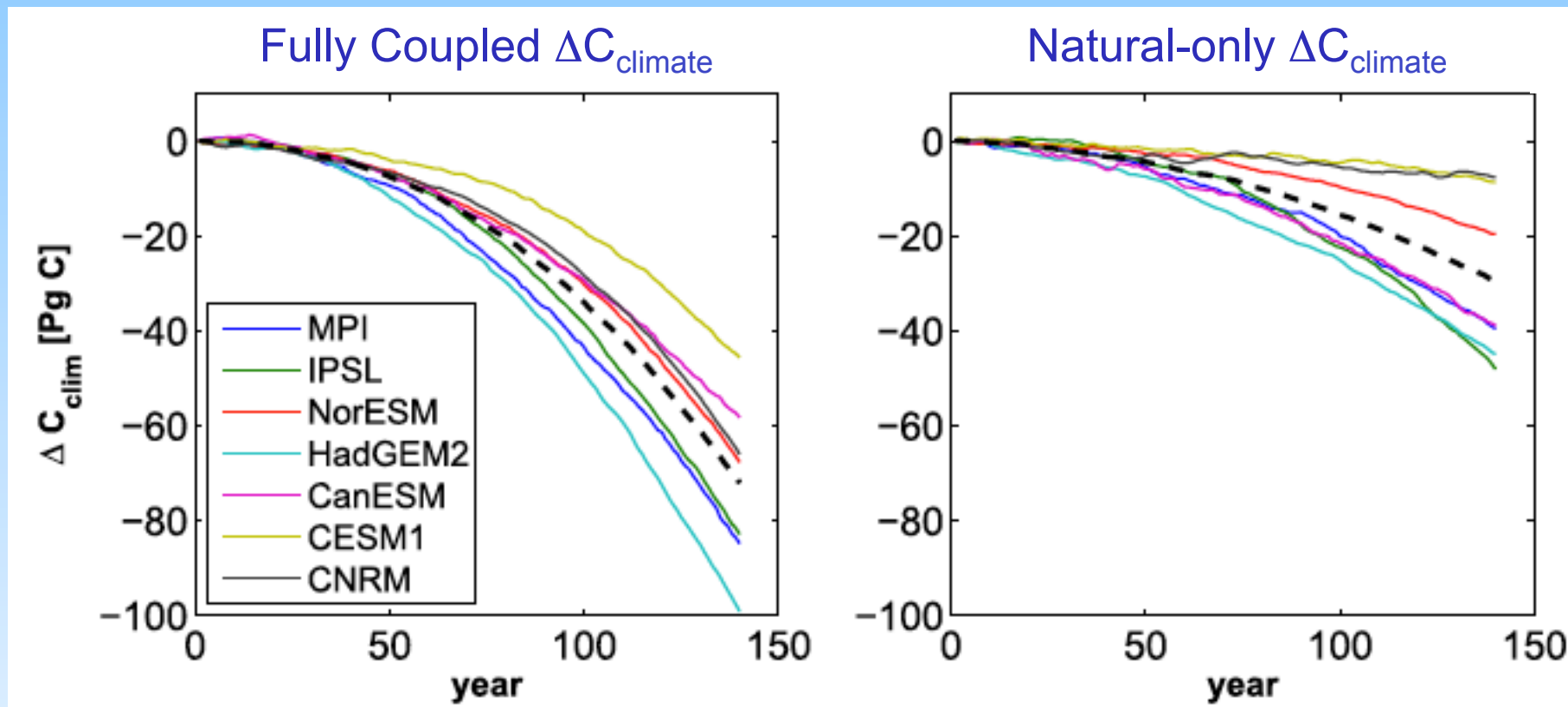
$$\Delta C_{\text{coupled}} = \Delta C^{\beta} + \Delta C^{\gamma}$$

Full-CTRL T1850-CTRL Full-T1850

$$\Delta C_{\text{coupled}} = \Delta C^{\beta} + \Delta C^{\gamma}_{\text{nat}} + \Delta C^{\gamma}_{\text{anthro}}$$

Full-CTRL T1850-CTRL C1850-CTRL residual

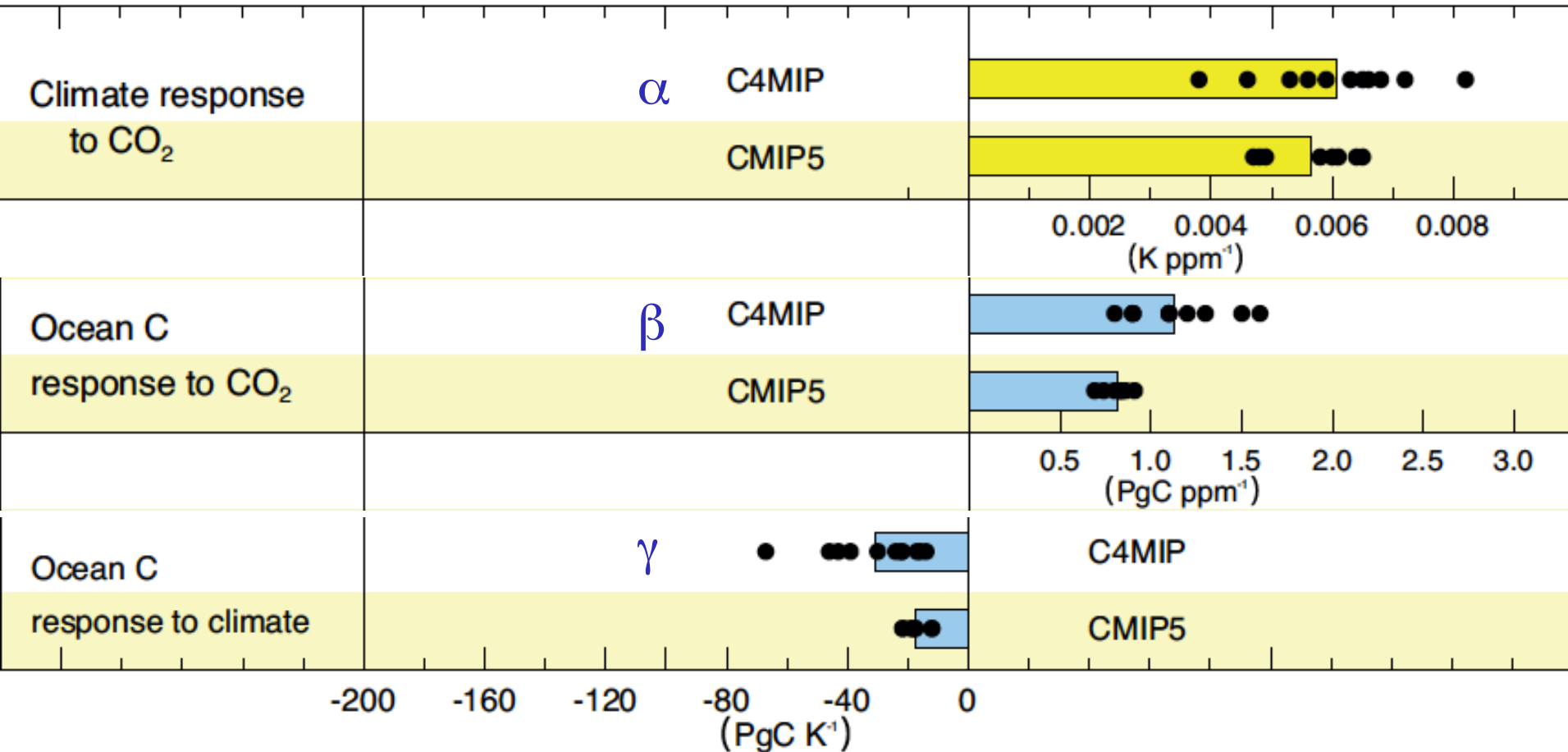
Climate Feedbacks on Natural & Anthropogenic C



Proper accounting for “non-linear” climate terms on both natural & anthropogenic carbon fields

Schwinger et al.
J. Climate 2014

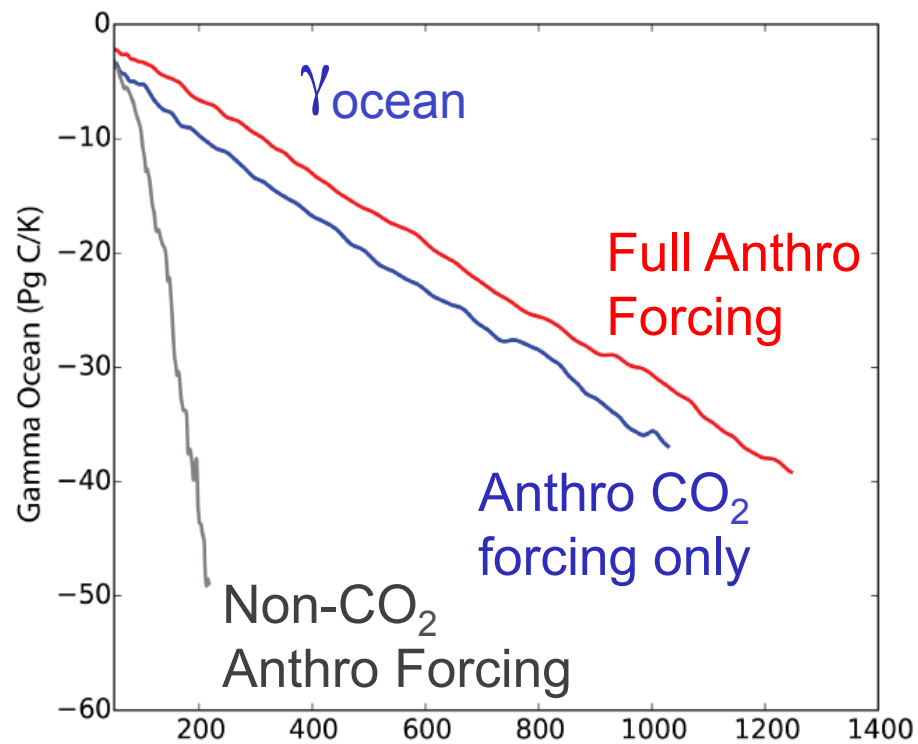
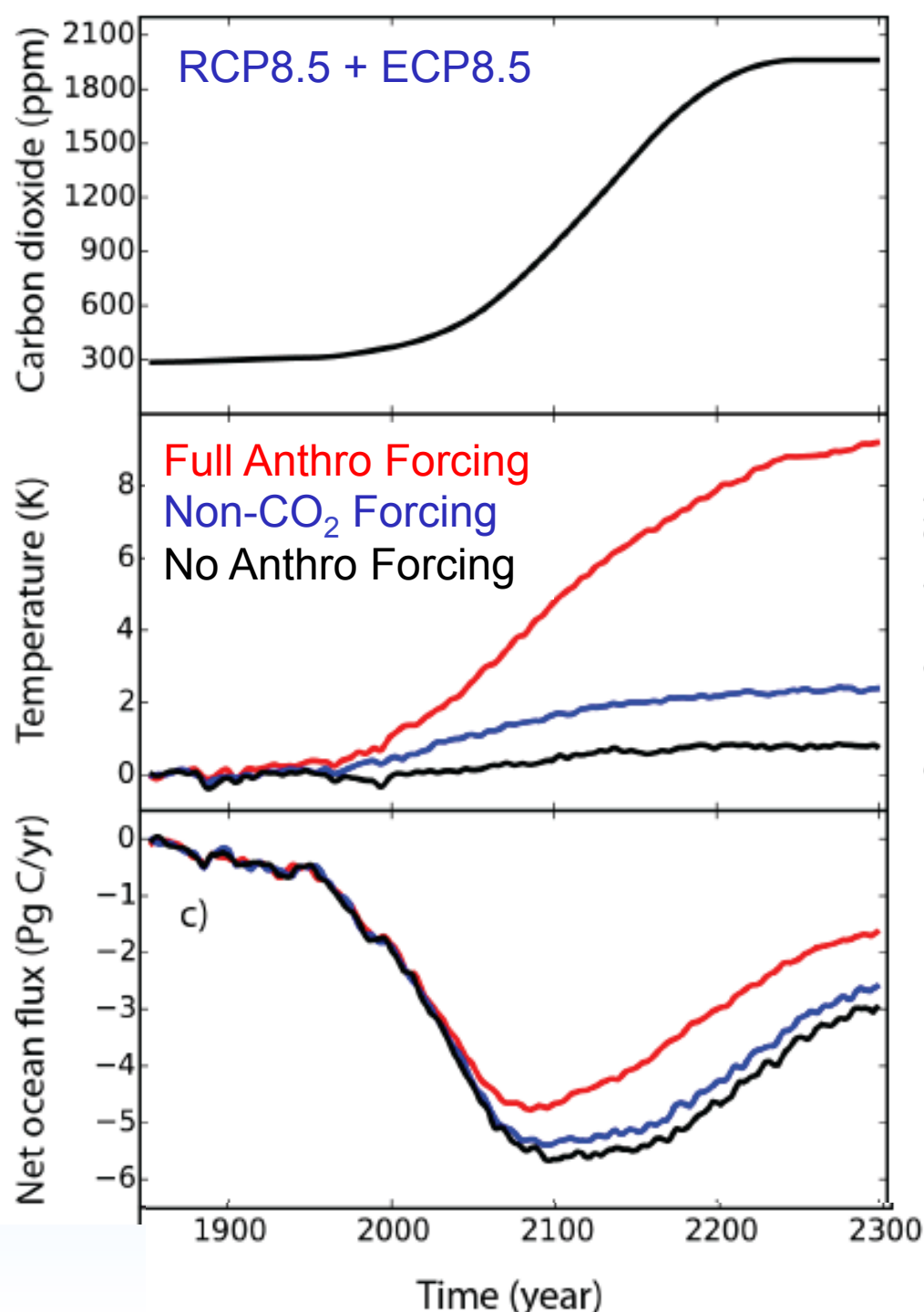
CMIP5 Feedback Term Summary



Feedback parameters sensitive to scenarios
 -rate of change of atmospheric CO_2
 -prescribed concentration vs. emissions

IPCC 2013
 WG1 Chapter 6

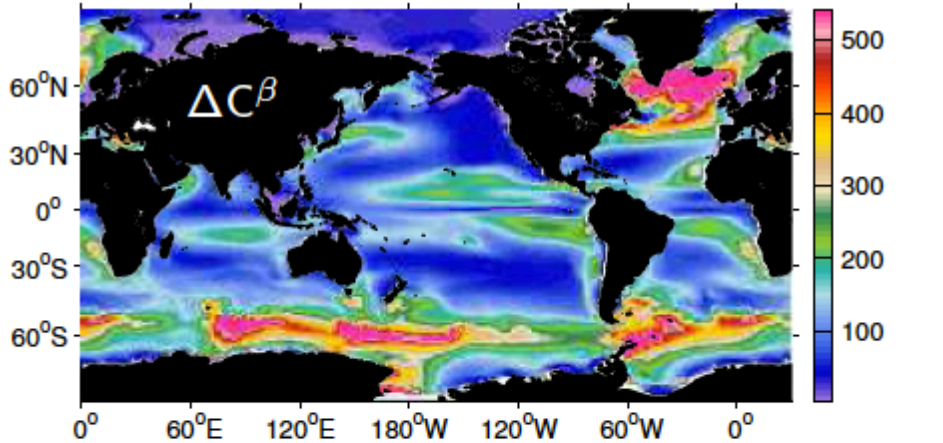
Scenario & Time Dependence of Climate Feedback



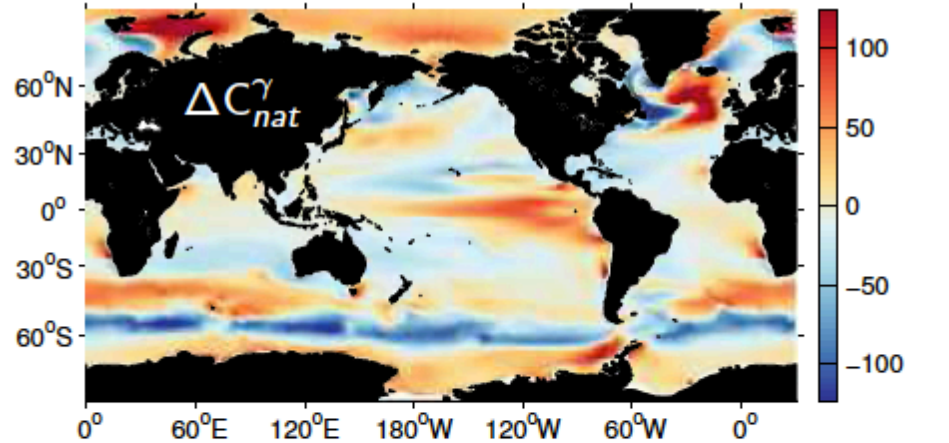
Randerson et al. in prep.

Time-Integrated Air-Sea Flux Components

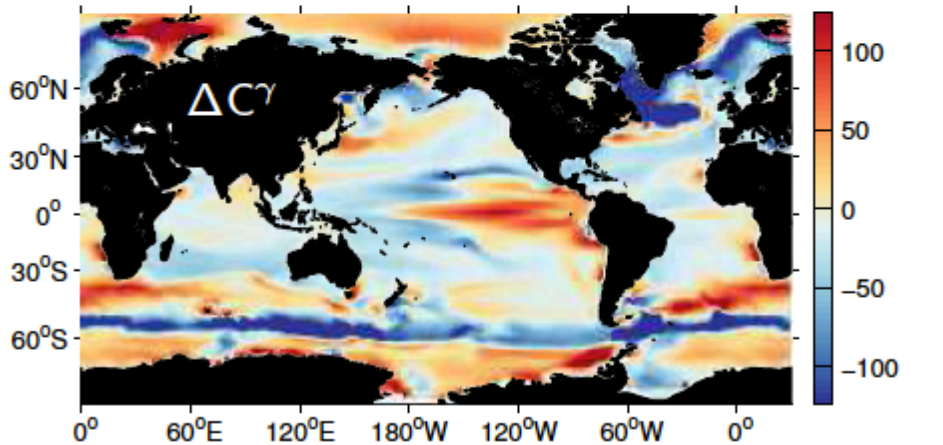
Φ^β Air-sea CO_2 flux



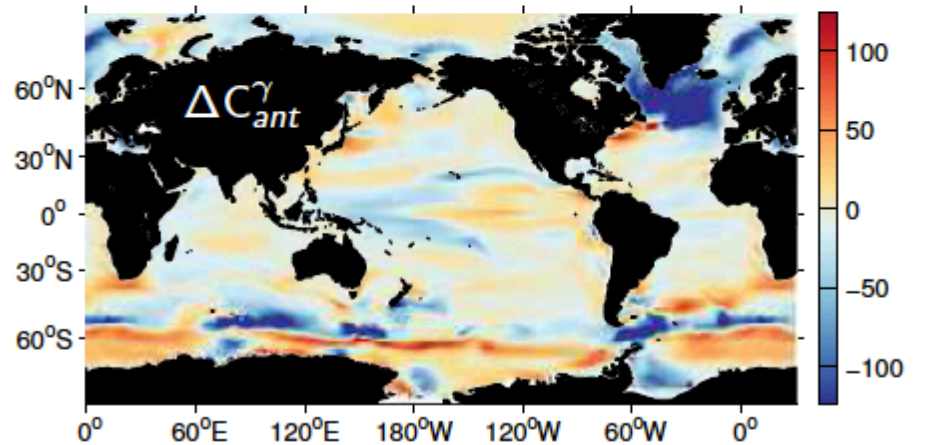
Φ_{nat}^γ Air-sea CO_2 flux



Φ^γ Air-sea CO_2 flux



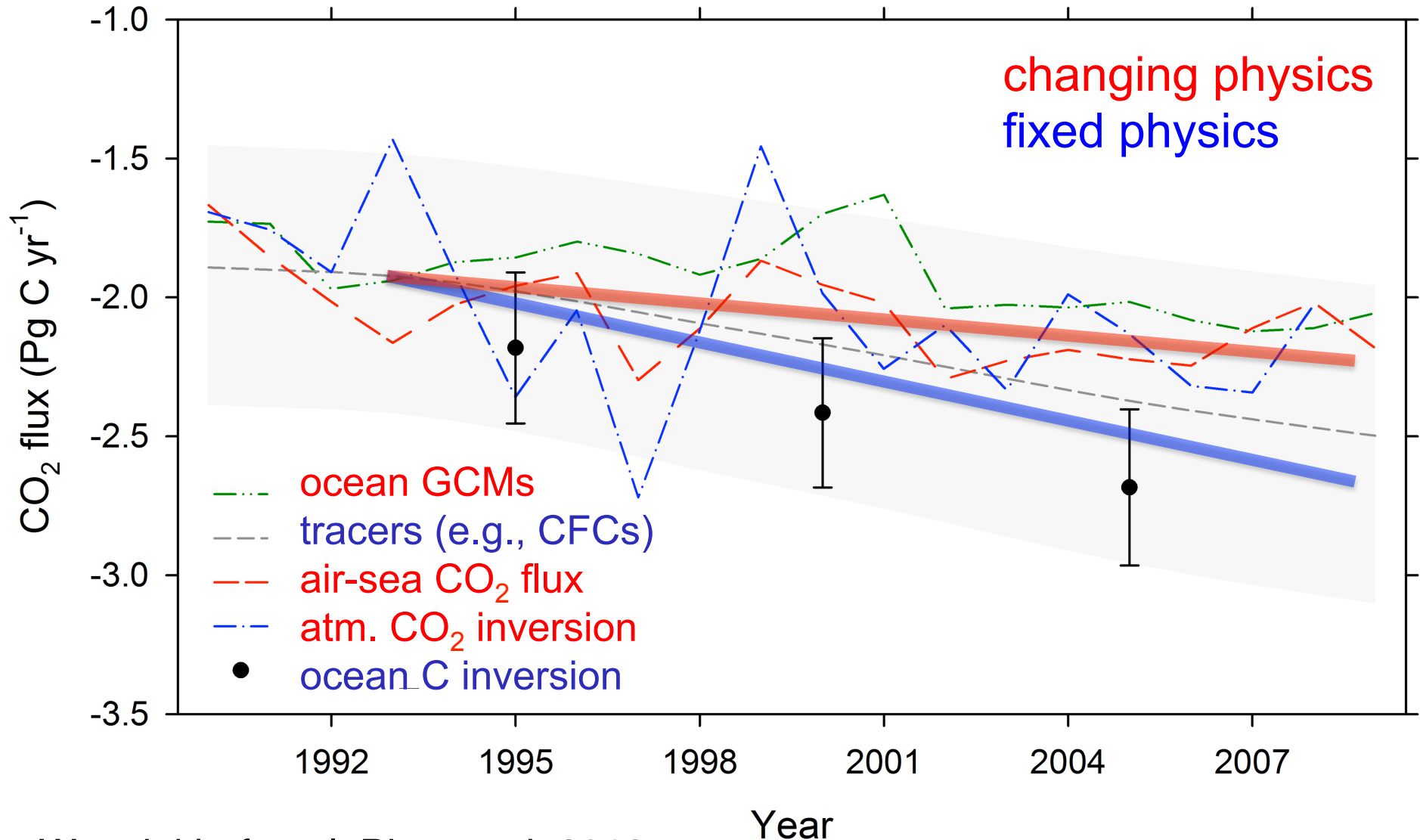
Φ_{ant}^γ Air-sea CO_2 flux



positive := downward

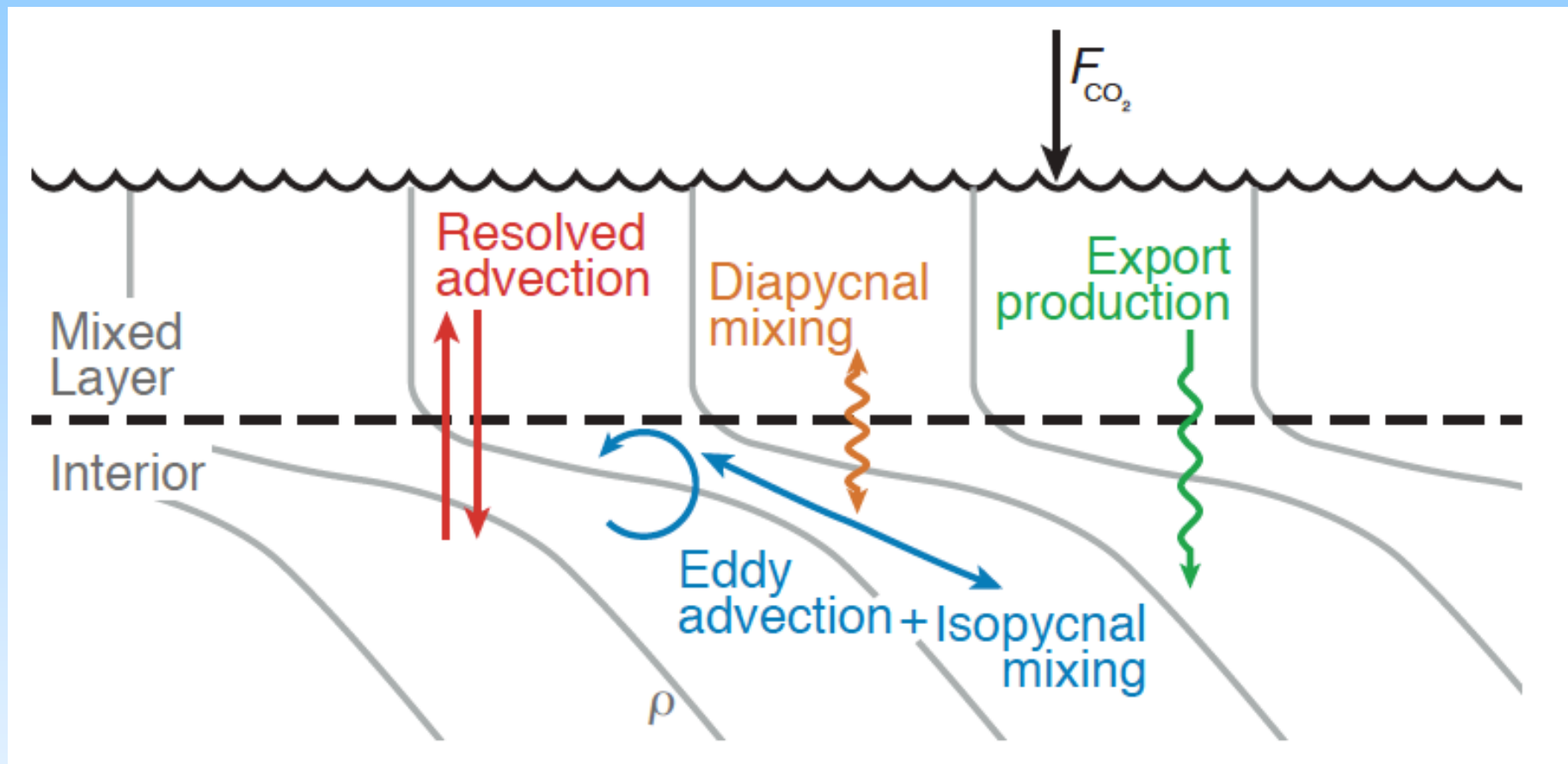
Long et al. in prep.

Ocean CO₂ Uptake Trends



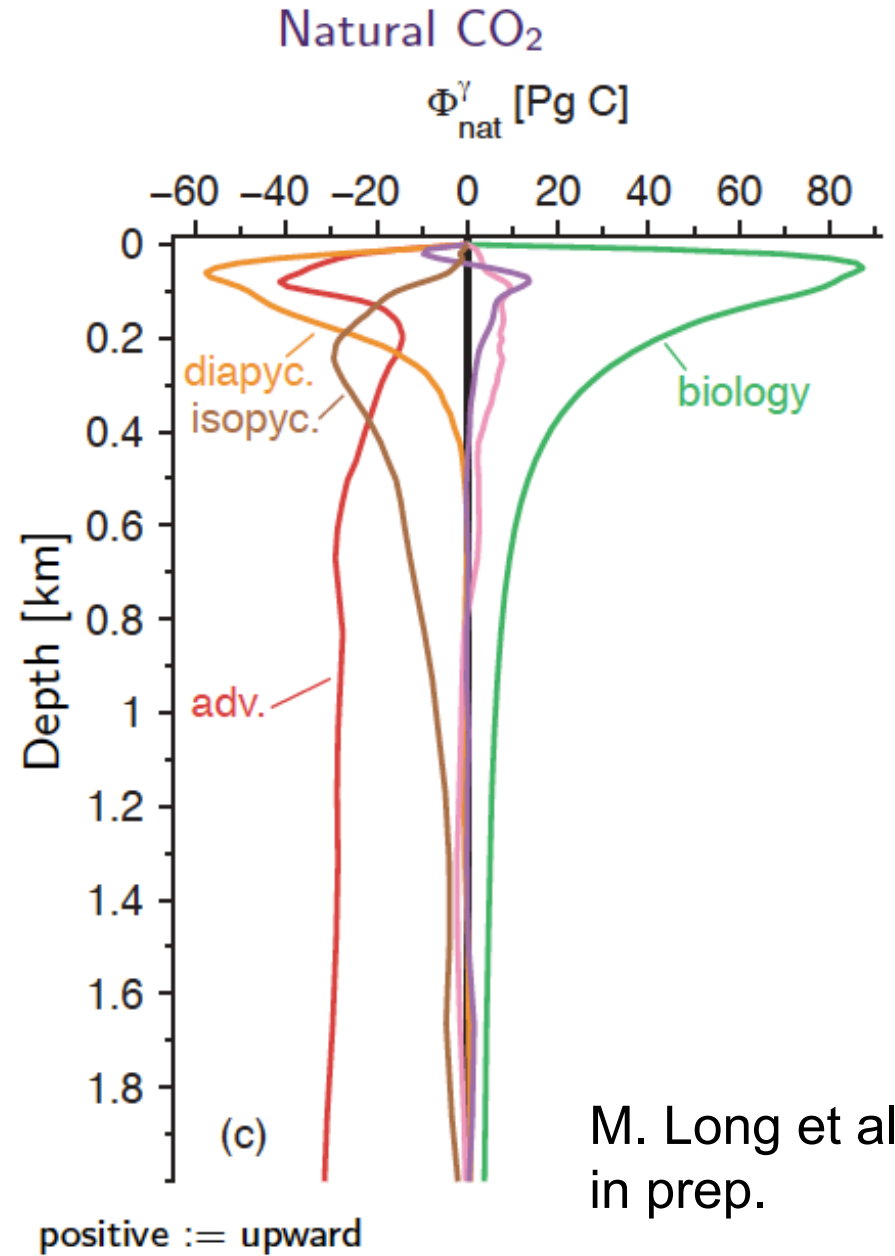
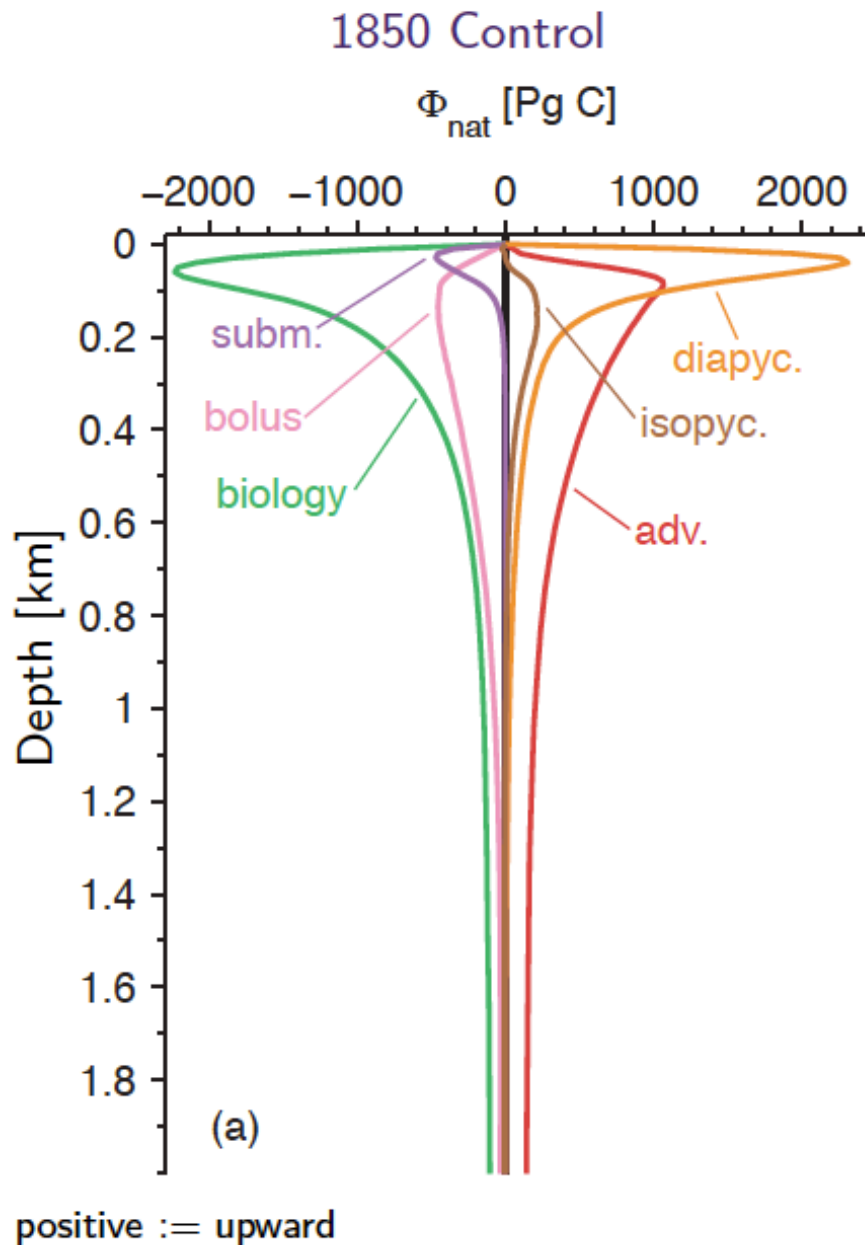
Wanninkhof et al. Biogeosci. 2013
Khatiwala et al. Biogeosci. 2013

Diagnosing Processes Controlling CO₂ Uptake



M. Long et al. in prep.

Diagnosing Vertical Transport Terms



M. Long et al.
in prep.

Ocean Carbon Uptake Biases & Uncertainties

-Skill Metrics Against Contemporary Observations

- Coupled ocean-atmosphere model biases
- Joint physical-biogeochemical errors
- Southern Ocean biases
- Detection & attribution of climate change signal

-Model Derived Atmospheric CO₂ & Climate Feedbacks

- Scenario dependence
- Southern Ocean & North Atlantic hotspots
- Diagnosing physical transport terms
- Unaccounted for biogeochemistry