Carbon uptake and feedbacks in CMIP

Matthew C. Long

Climate and Global Dynamics Laboratory
National Center for Atmospheric Research

Scott C. Doney

Marine Chemistry & Geochemistry
Woods Hole Oceanographic Institution

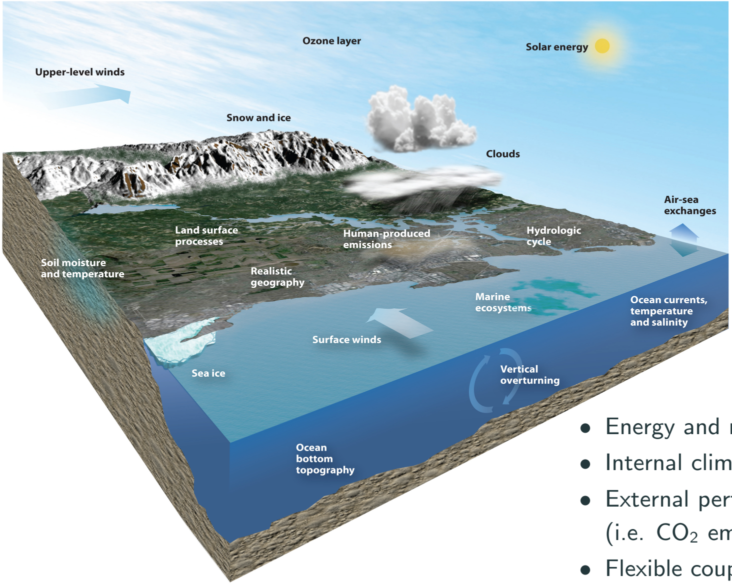
July 2016

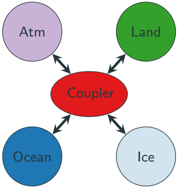
OCB Summer Workshop

Outline

- Characterize CMIP5 simulations of the carbon cycle:
    - carbon-concentration (β) and carbon-climate (γ) feedbacks;
    - separation of impacts on natural and anthropogenic CO_2;
    - prolonged timescale of ocean response to warming.
- How robust are the CMIP simulations?
    - Anthropogenic CO_2: circulation biases;
    - Natural CO_2: representing the biological pump.
- Emerging opportunities:
    - Decadal prediction experiments.

The Earth system modeling framework



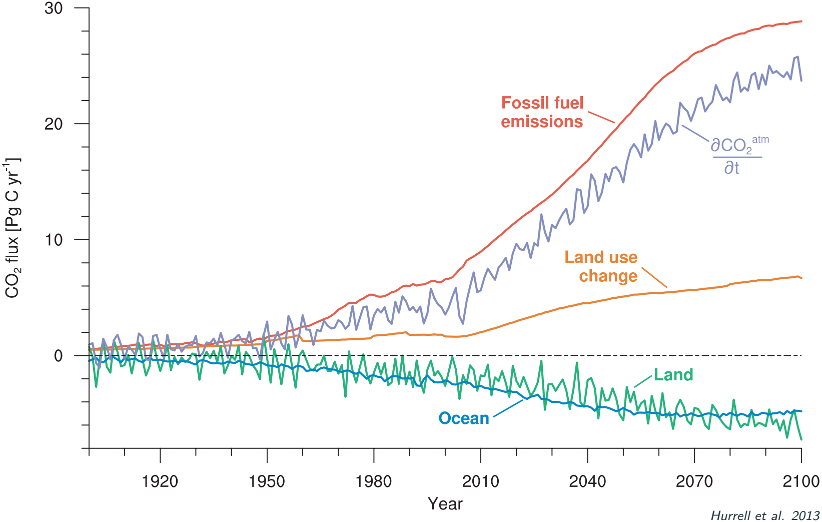


- Energy and mass conserving;
- Internal climate variability;
- External perturbations (i.e. CO_2 emissions);
- Flexible coupling infrastructure.

Earth System Models simulate a fully-coupled global carbon cycle

Emissions-forced prognostic carbon budget

CESM1(BGC): historial → RCP8.5

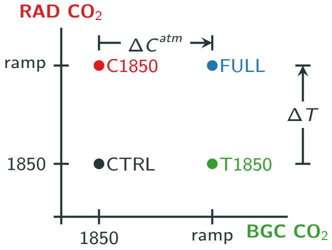


Hurrell et al. 2013

CMIP5 Idealized simulations: quantifying feedbacks

Linear decomposition of cumulative ocean carbon inventory

$$\Delta C^{ocn} = \int \phi_{as}\, dt = \int_V (C_t^{ocn} - C_0^{ocn}) dV$$
$$= \beta \Delta C^{atm} + \gamma \Delta T$$
$$= \Delta C^{\beta} + \Delta C^{\gamma}$$

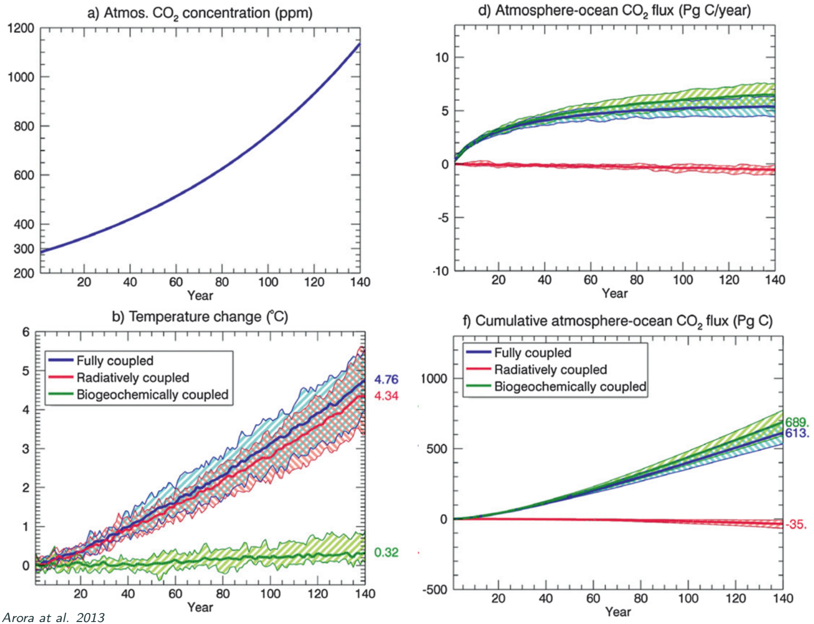


$$\underset{[\text{FULL} - \text{CTRL}]}{\Delta C^{ocn}} = \underset{[\text{T1850} - \text{CTRL}]}{\Delta C^{\beta}} + \underset{[\text{C1850} - \text{CTRL}]}{\Delta C^{\gamma}_{nat}} + \underset{(\text{residual})}{\Delta C^{\gamma}_{ant}}$$

β: carbon-carbon feedback (PgC/ppm)

γ: carbon-climate feedback (PgC/K)

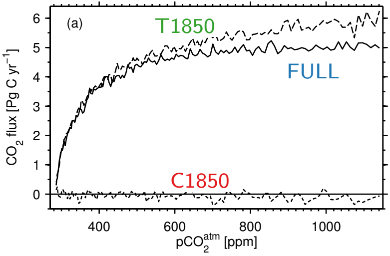
CMIP5 Idealized simulations



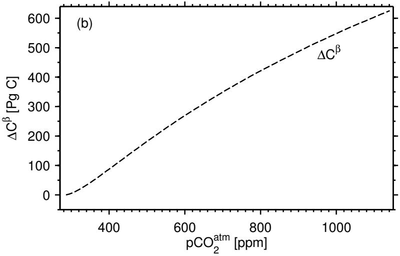
Arora at al. 2013

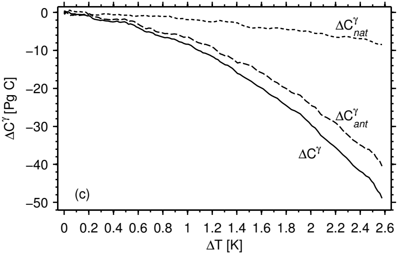
Ocean uptake under 1% y^{-1} ramping CO_2

Air-to-sea flux: anomaly timeseries



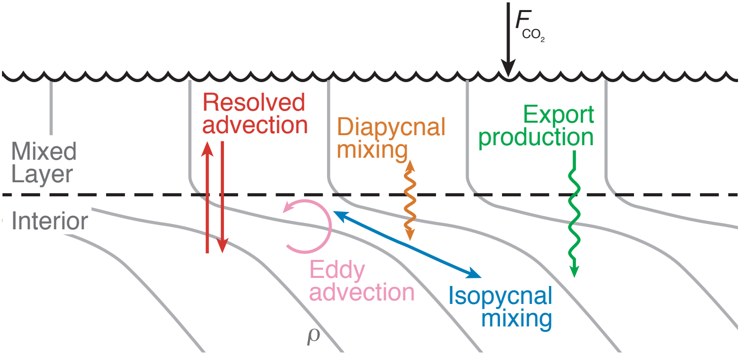
Carbon inventory changes





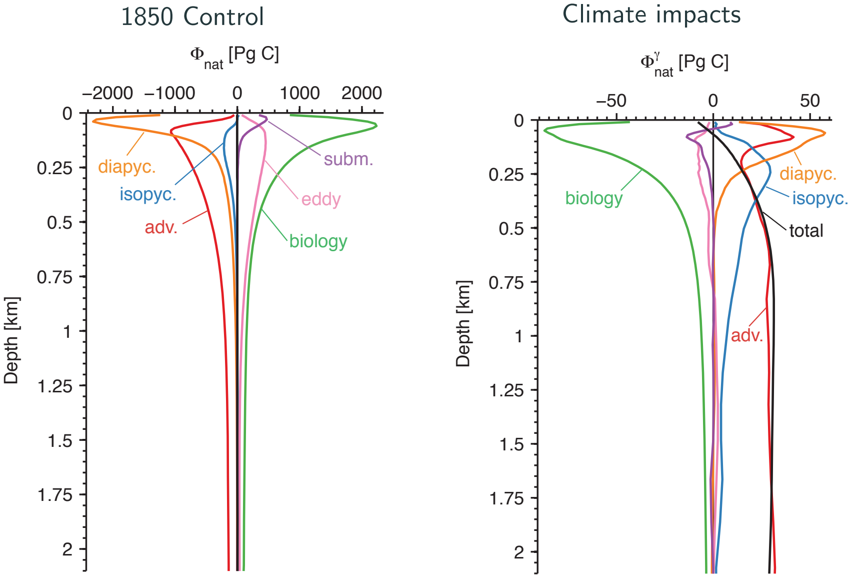
$$\Delta C^{ocn} = \Delta C^{\beta} + \Delta C^{\gamma}_{nat} + \Delta C^{\gamma}_{ant}$$

Processes controlling CO_2 uptake



$$\frac{\partial C}{\partial_t} + (\mathbf{u} + \mathbf{u}^*) \cdot \nabla C - \nabla \cdot (K \nabla C) = J_C$$

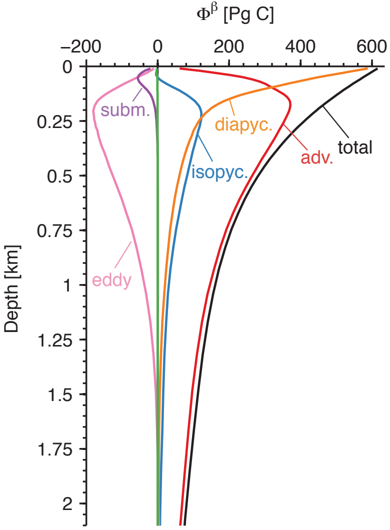
Globally-integrated vertical carbon fluxes: natural CO_2



positive := down

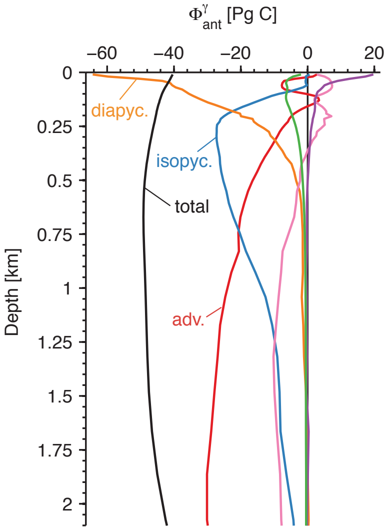
Globally-integrated vertical carbon fluxes: anthropogenic CO_2

CO_2 anomaly



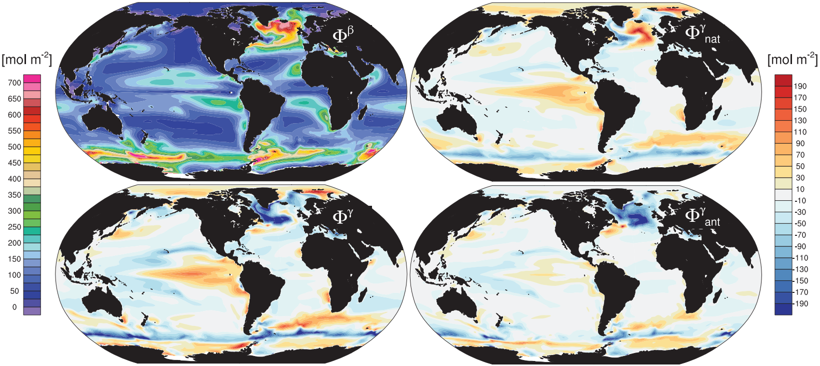
positive := down

Climate impacts



Spatially variable feedbacks

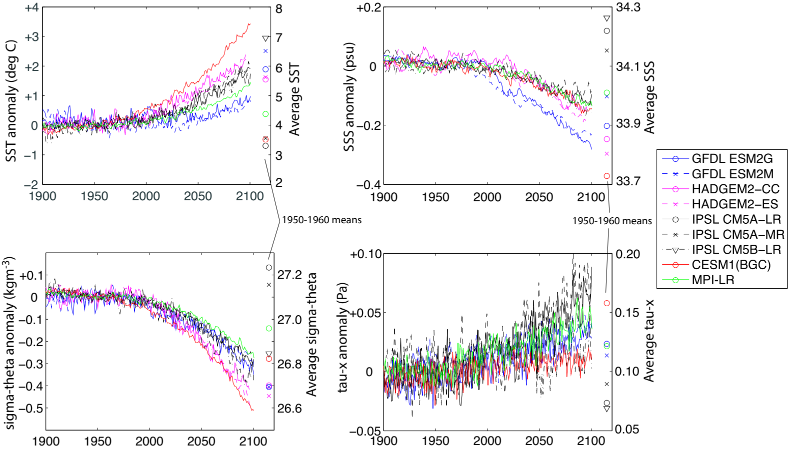
Time-integrated air-to-sea CO_2 flux components



positive := down

Changes in forcing under RCP8.5

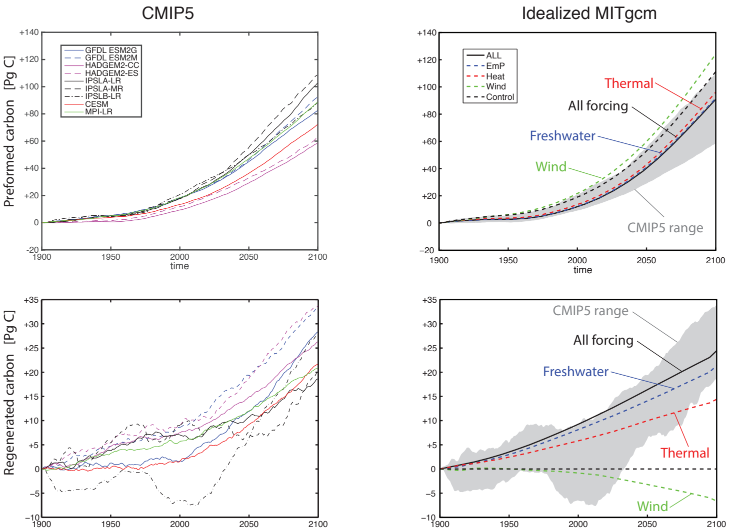
CMIP5 models: area-weighted surface properties SH extratropics (40-60°S)



Ito et al. 2015, GRL

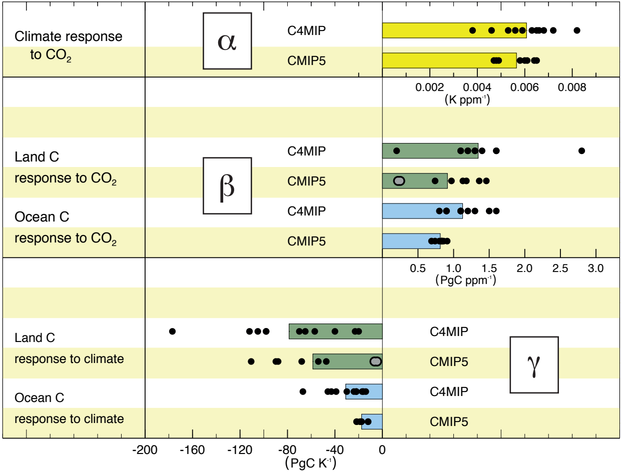
Complex response to transient forcing

Southern Ocean carbon inventory under RCP8.5 and idealized forcing



Ito et al., 2015, GRL

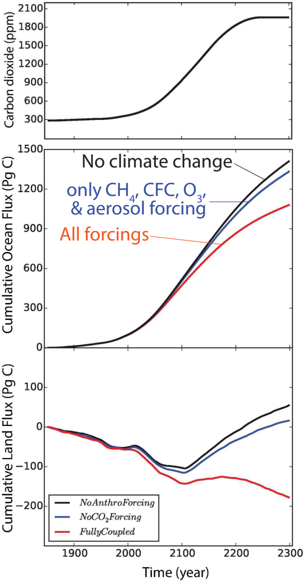
Feedback parameters: CMIP5 versus C4MIP

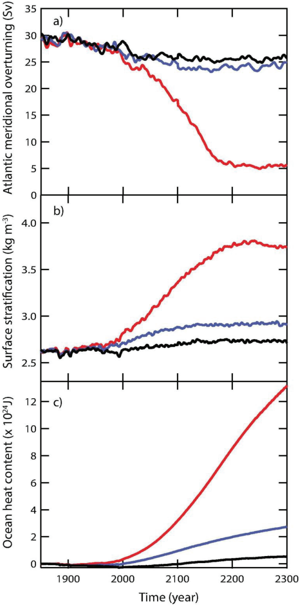


$$\left.\begin{array}{ll}\text{C4MIP:} & \sim 0.5\%\,\text{yr}^{-1} \\ \text{CMIP5:} & 1\%\,\text{yr}^{-1}\end{array}\right\} \rightarrow \beta^{\text{CMIP5}} < \beta^{\text{C4MIP}}$$

IPCC AR5, 2013

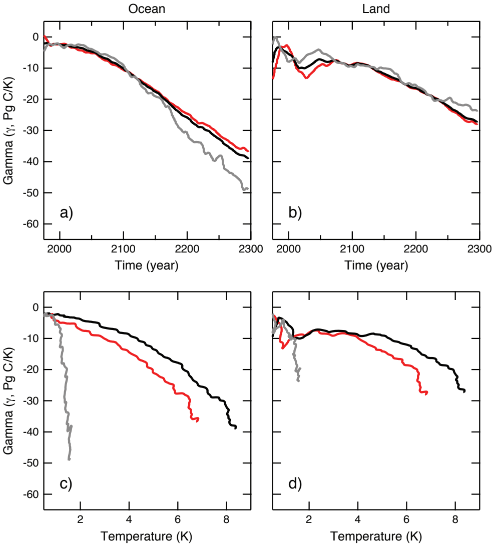
Feedbacks grow as warming continues: extended RCP8.5 simulations

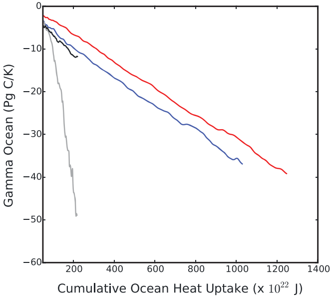




Randerson et al. 2015

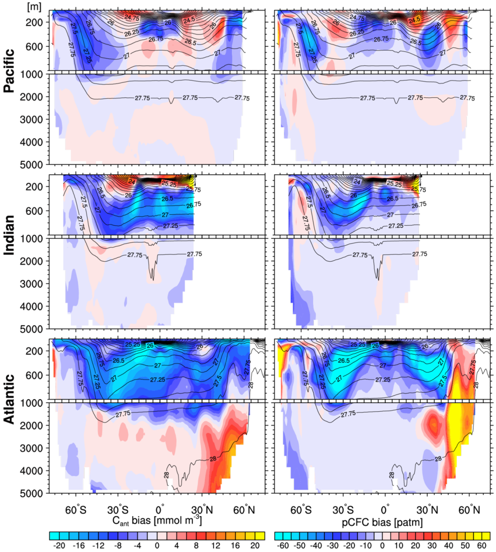
Feedbacks grow as warming continues





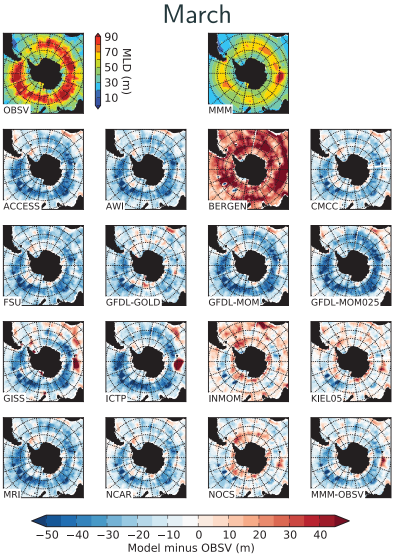
Randerson et al. 2015

Biases relative to GLODAP

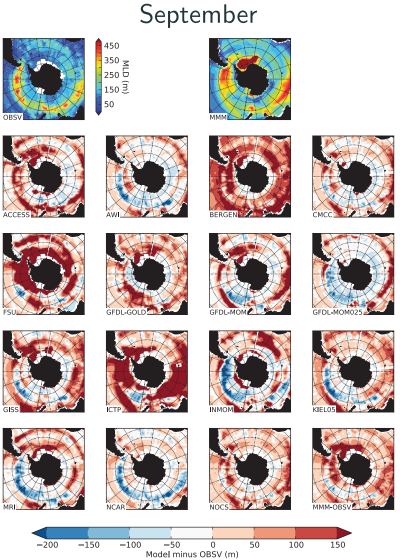


Long et al. 2013

Mixed layers depth biases in hindcast runs: Missing physics?

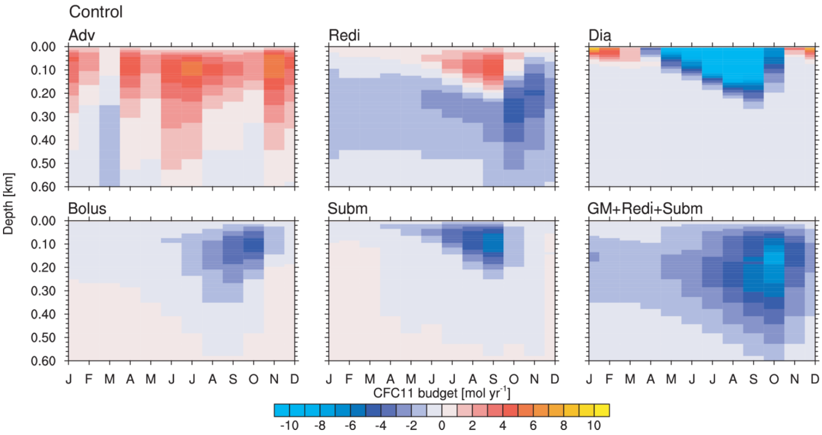


Downes et al. 2015

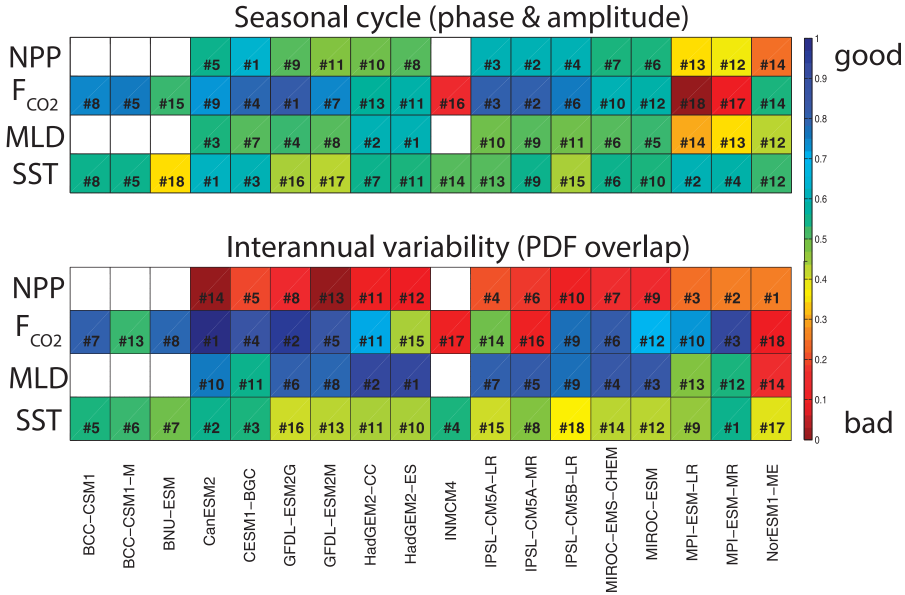


Seasonal handoff: boundary layer to isopycnal mixing

Vertical fluxes in ACC

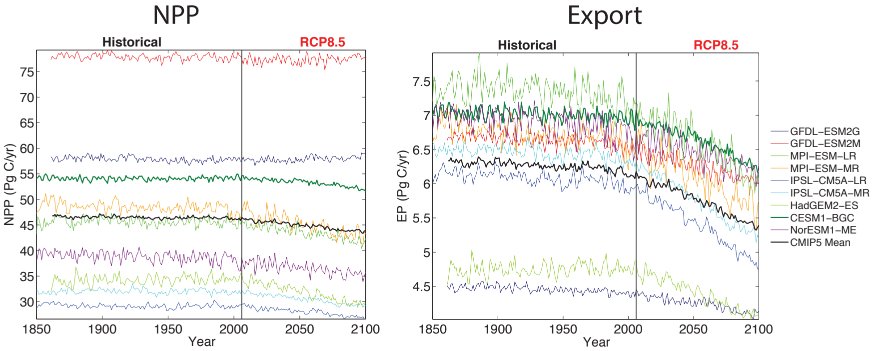


CMIP5 model skill metrics



Anav et al. 2015

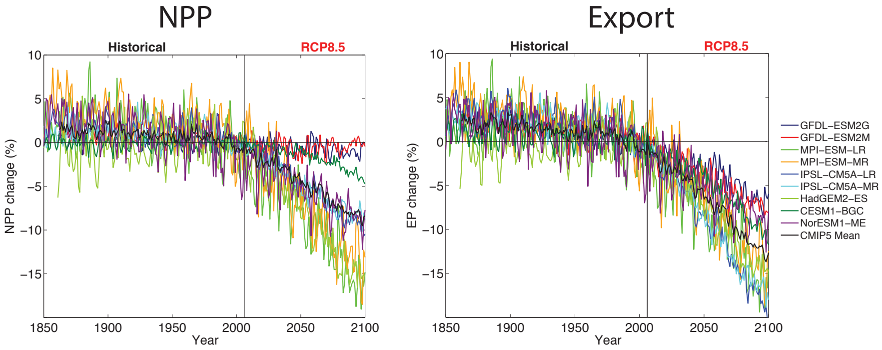
CMIP5: Changes in NPP and export production



- Large spread in simulated NPP.

Fu et al. 2015

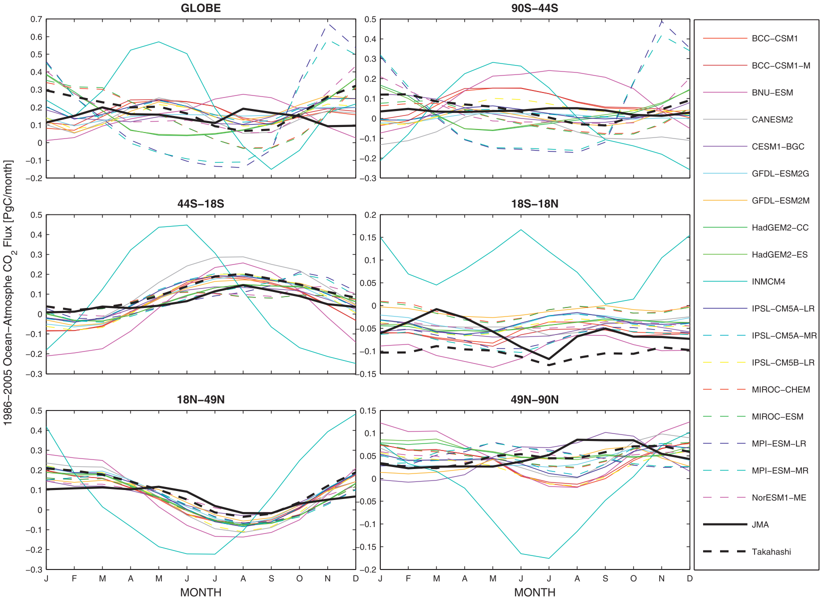
CMIP5: Changes in NPP and export production



- Less NPP decline in models (CESM, GFDL) simulating changes in phytoplankton community (diatoms→small phytoplankton);
- Changes in export production somewhat more robust: constrained by physically-mediate nutrient supply.

Fu et al. 2015

CMIP5 model skill metrics: Seasonal cycle in air-sea CO_2 flux



Anav et al. 2015

FeMIP: Large intermodel differences in iron cycling

Table 2. A Summary of the Magnitude of the Fe Sources, the Total and Average Fe Inventories, and the Residence Time of Fe Across the FeMIP Models

	Fe Sources (Gmol yr^{-1})							
Model	Dust	Sediment	Hydrothermal	Rivers	Total	Fe Inventory ($\times 10^{11}$ mol)	Average Fe (nmoles L^{-1})	Residence Time (years)
BEC	21.9	84.6	17.7	0.34	124.5	10.1	0.74	8.1
BFM	1.4	0	0	0.06	1.4	8.8	0.65	626.3
BLING	3.3	9.1	0	0	12.4	5.3	0.37	42.4
COBALT	32.5	155	0	0	182.5	6.8	0.50	3.7
GENIE	1.8	0	0	0	1.8	10.1	0.48	560.0
MEDUSA1	2.7	0	0	0	2.7	6.3	0.46	232.0
MEDUSA2	3.4	2.9	0	0	6.8	4.8	0.35	69.9
MITecco	3.5	104	0	0	107.5	8.8	0.65	8.2
MITigsm	1.4	194	0	0	195.4	9.0	0.66	4.6
PISCES1	32.7	26.6	11.3	2.5	71.0	8.1	0.59	11.5
PISCES2	32.7	26.6	11.3	2.5	71.0	11.2	0.81	15.7
REcoM	3.7	0.6	0	0	4.3	12.5	0.73	291.6
TOPAZ	13.8	74.8	0	0	88.6	6.8	0.50	7.6
				Mean	66.9	8.3	0.58	144.7
				Standard deviation	67.1	2.2	0.14	175.8

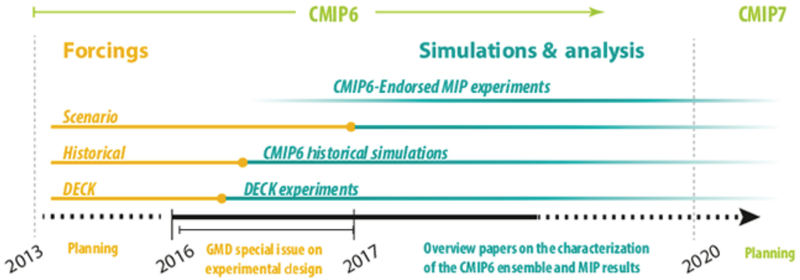
- Total Fe inputs vary widely;
- Mean oceanic Fe concentrations are similar;
- Scavenging compensates: Fe residence time varies widely.

Tagliabue et al. 2015

Summary

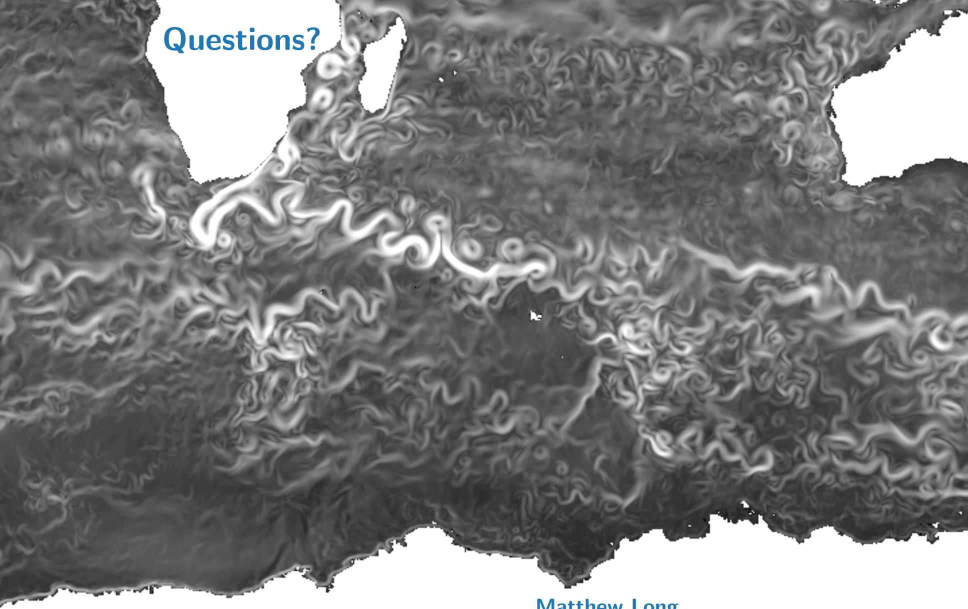
- CMIP5 simulations show:
    - C_{ant} transfer into the ocean interior is dominated by resolved advection (mid-latitudes) and diapycnal mixing (high-latitudes); warming-induced stratification weakens these fluxes.
    - Stratification limits C_{nat} outgassing, but also curtails surface nutrient supply, thereby weakening the biological pump (reduced efficiency) and yielding net release of natural carbon.
    - Southern Ocean shows particularly intricate behavior.
- How robust are the CMIP simulations?
    - Southern Ocean mixed layer depths and overturning circulation remain problematic.
    - Wide divergence in model representations of the biological pump.
- Emerging opportunities:
    - Initialized prediction experiments represent interesting framework for model-observation fusion.

CMIP6 Timeline



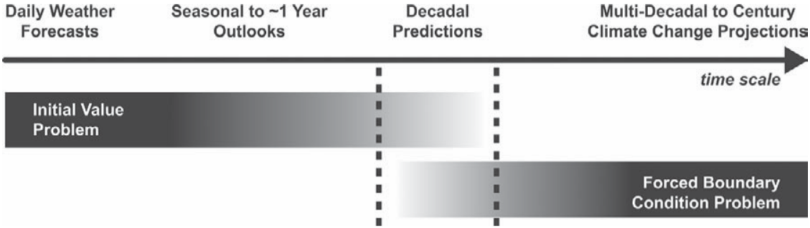
Eyring et al. 2016

Questions?



Matthew Long
Climate & Global Dynamics Laboratory
National Center for Atmospheric Research
mclong@ucar.edu

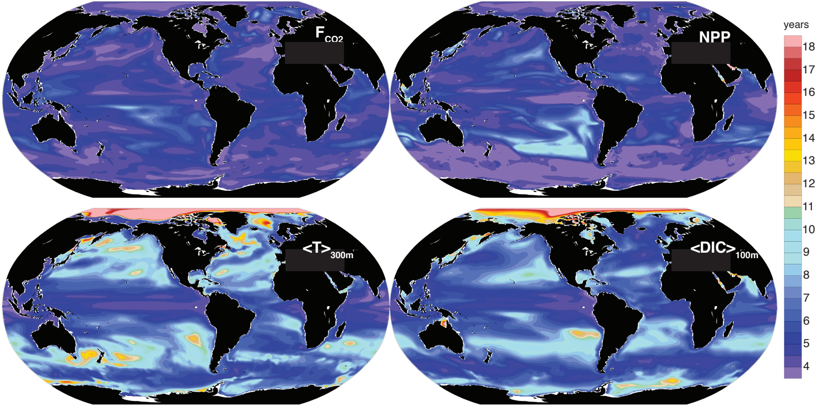
Decadal timescale: initial value + boundary value problem



Meehl et al. 2009

Dominant timescales of intrinsic variability

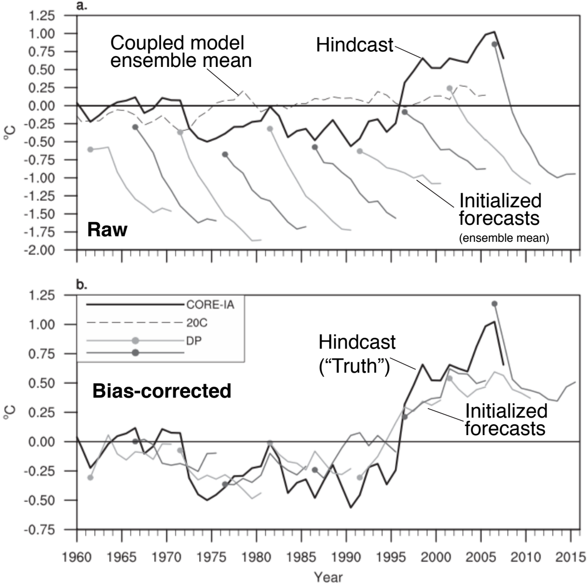
Variance-weighted mean frequency (period)



$$T_x = \sum_k V(f_k, x) \Big/ \sum_k f_k V(f_k, x)$$

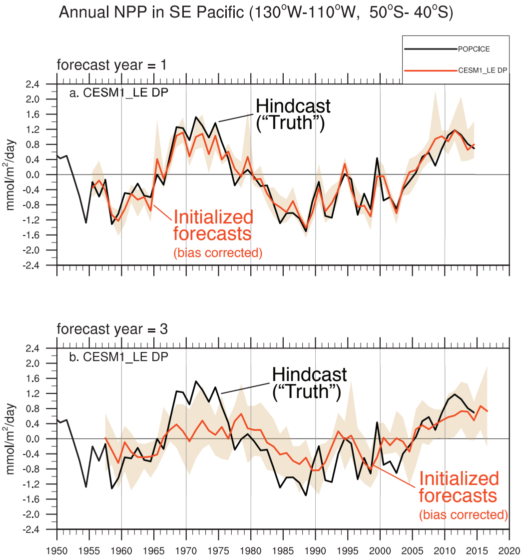
Skillful forecasts of upper ocean heat content on decadal timescale

Heat content anomaly, N. Atlantic Subpolar gyre $(z > -275\,\mathbf{m})$



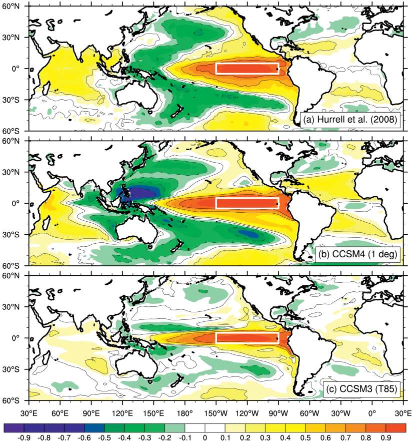
Yeager et al. 2012

Biogeochemical predictions on multi-annual timescales: possible?



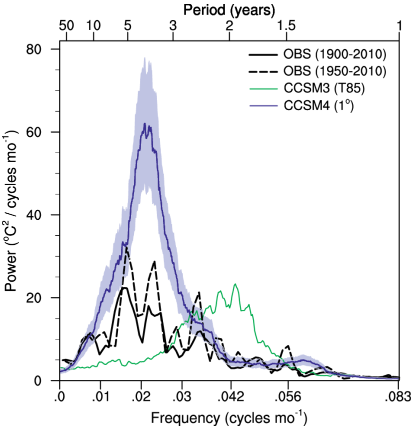
Long, Yeager et al., in prep

El Niño-Southern Oscillation



Correlation of SST with Niño3.4 index

Gent et al. 2011

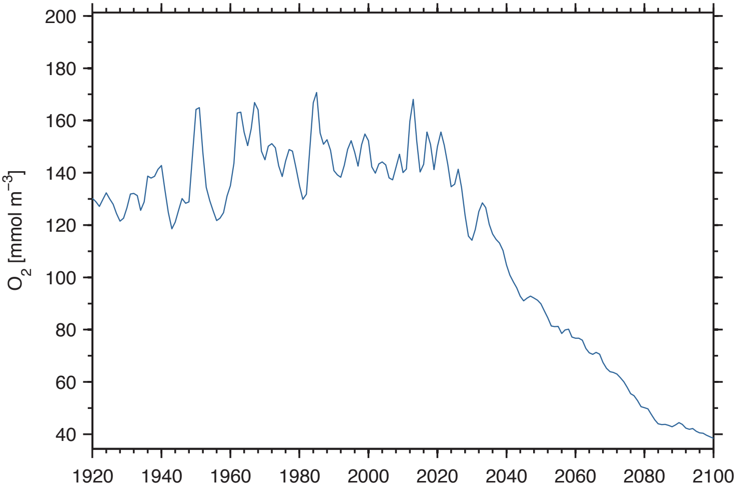


Power spectrum of the Niño3.4 index

Deser et al. 2012

Natural variability can reinforce or oppose trends

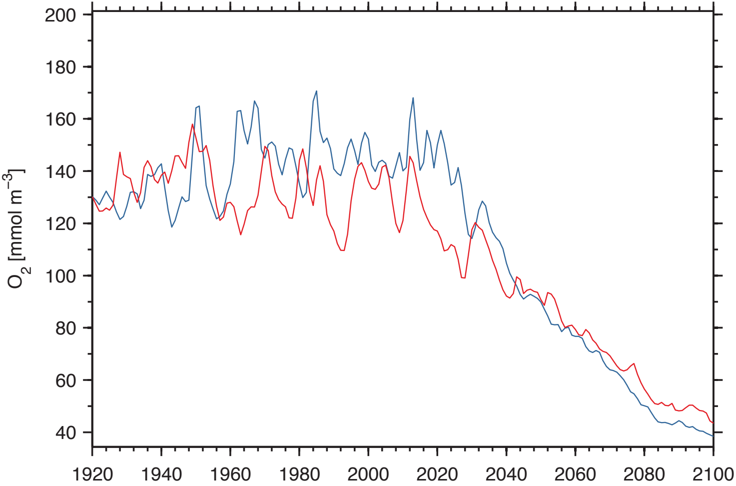
CESM simulation of dissolved oxygen at Station P ($\sigma_\theta = 26.5$)



Long et al. 2016

Natural variability can reinforce or oppose trends

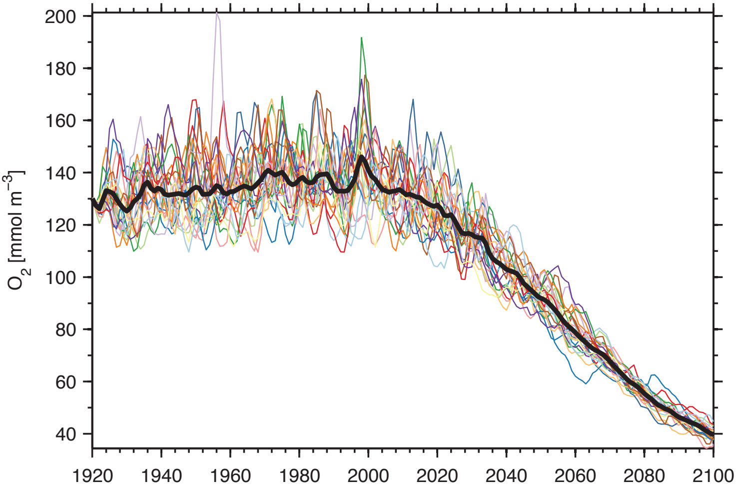
CESM simulation of dissolved oxygen at Station P ($\sigma_\theta = 26.5$)



Long et al. 2016

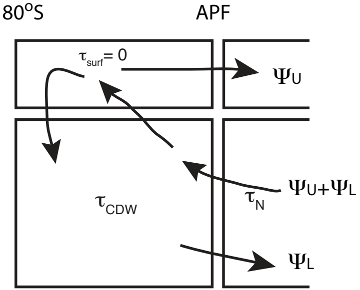
Natural variability can reinforce or oppose trends

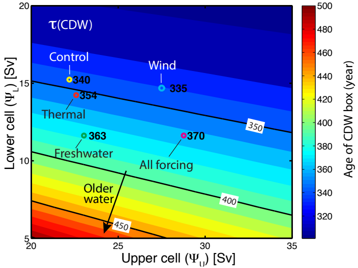
CESM simulation of dissolved oxygen at Station P ($\sigma_\theta = 26.5$)

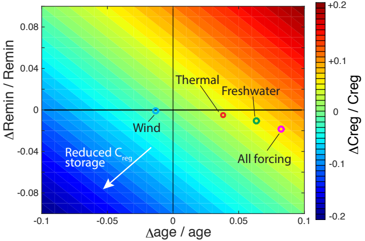


Long et al. 2016

Southern Ocean box model



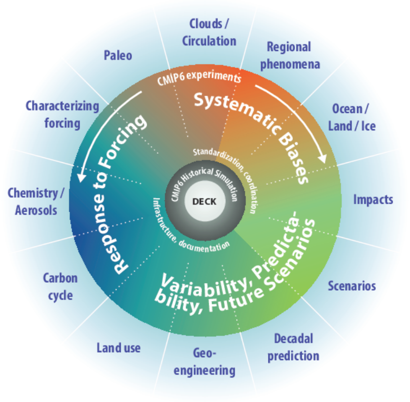




- Weaker lower cell (Ψ_L): ventilation age (τ) increases; stronger upper cell (Ψ_U) partially compensates.
- Increased age (τ): greater C_{reg} storage; decrease in respiration rates (R) weakly opposes.

Ito et al., 2015, GRL

CMIP6 Overview



DECK := Diagnostic, Evaluation and Characterization of Klima

Eyring et al. 2016

Continuous and distributed organization

- Common experiments:
  - DECK
    1. AMIP historical (1979–2014)
    2. Pre-industrial control
    3. 1%/yr CO_2 increase
    4. Abrupt 4×CO_2
  - CMIP6 historical simulation
    5. 1850–2014 under CMIP6 forcings
- CMIP-Endorsed modeling intercomparison projects

CMIP6 Endorsed MIPs

1	AerChemMIP	Aerosols and Chemistry Model Intercomparison Project
2	C4MIP	Coupled Climate Carbon Cycle Model Intercomparison Project
3	CFMIP	Cloud Feedback Model Intercomparison Project
4	DAMIP	Detection and Attribution Model Intercomparison Project
5	DCPP	Decadal Climate Prediction Project
6	FAFMIP	Flux-Anomaly-Forced Model Intercomparison Project
7	GeoMIP	Geoengineering Model Intercomparison Project
8	GMMIP	Global Monsoons Model Intercomparison Project
9	HighResMIP	High Resolution Model Intercomparison Project
10	ISMIP6	Ice Sheet Model Intercomparison Project for CMIP6
11	LS3MIP	Land Surface, Snow and Soil Moisture
12	LUMIP	Land-Use Model Intercomparison Project
13	OMIP	Ocean Model Intercomparison Project
14	PMIP	Palaeoclimate Modelling Intercomparison Project
15	RFMIP	Radiative Forcing Model Intercomparison Project
16	ScenarioMIP	Scenario Model Intercomparison Project
17	VolMIP	Volcanic Forcings Model Intercomparison Project
18	CORDEX*	Coordinated Regional Climate Downscaling Experiment
19	DynVar*	Dynamics and Variability of the Stratosphere-Troposphere System
20	SIMIP*	Sea-Ice Model Intercomparison Project
21	VIACS AB*	VIACS Advisory Board for CMIP6

* "Diagnostic MIPs"