Climate-carbon feedbacks to 2100 and beyond

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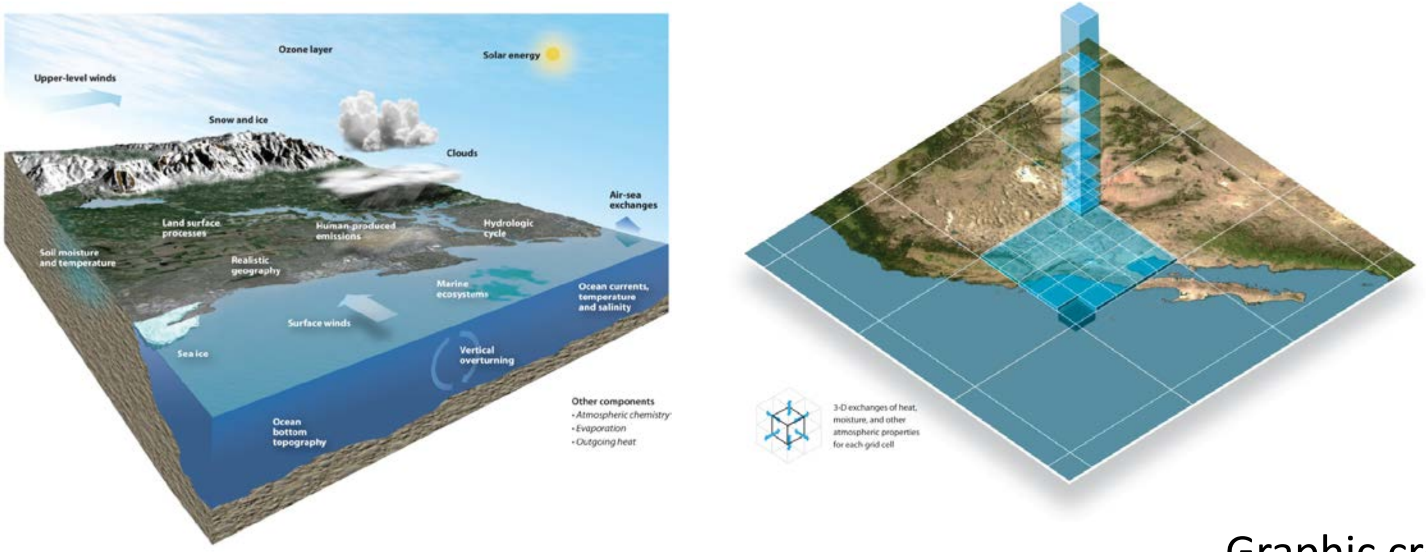
UCI DEPARTMENT OF EARTH SYSTEM SCIENCE

National Center for Atmospheric Research

Science questions:

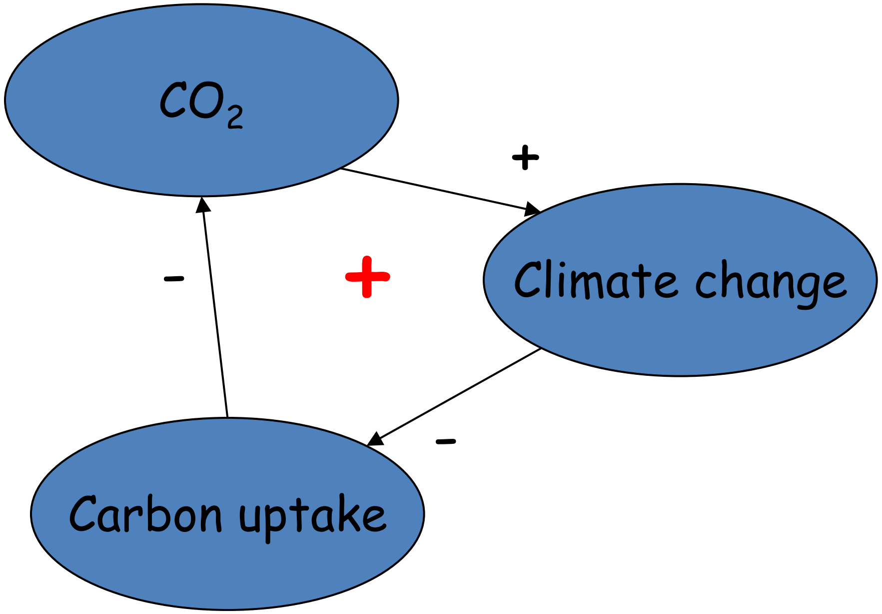
- How do climate-carbon feedbacks evolve century by century to 2300?
- What are the implications of long-term changes in climate for land precipitation, disturbance regimes and terrestrial ecosystem function?

The Community Earth System Model



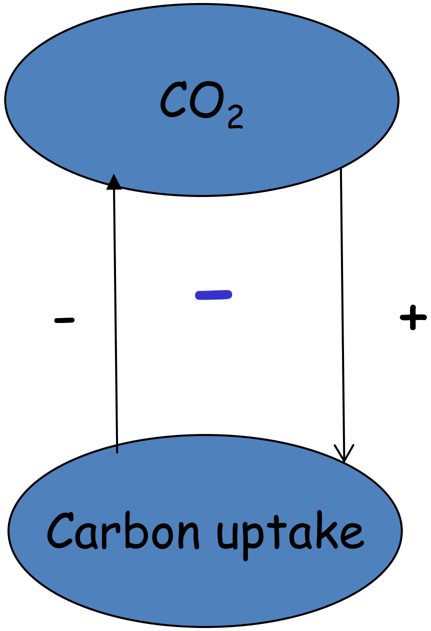
Graphic credit: UCAR

Two types of carbon feedback loops influence the temporal evolution of atmospheric CO_2



Positive climate–carbon feedback

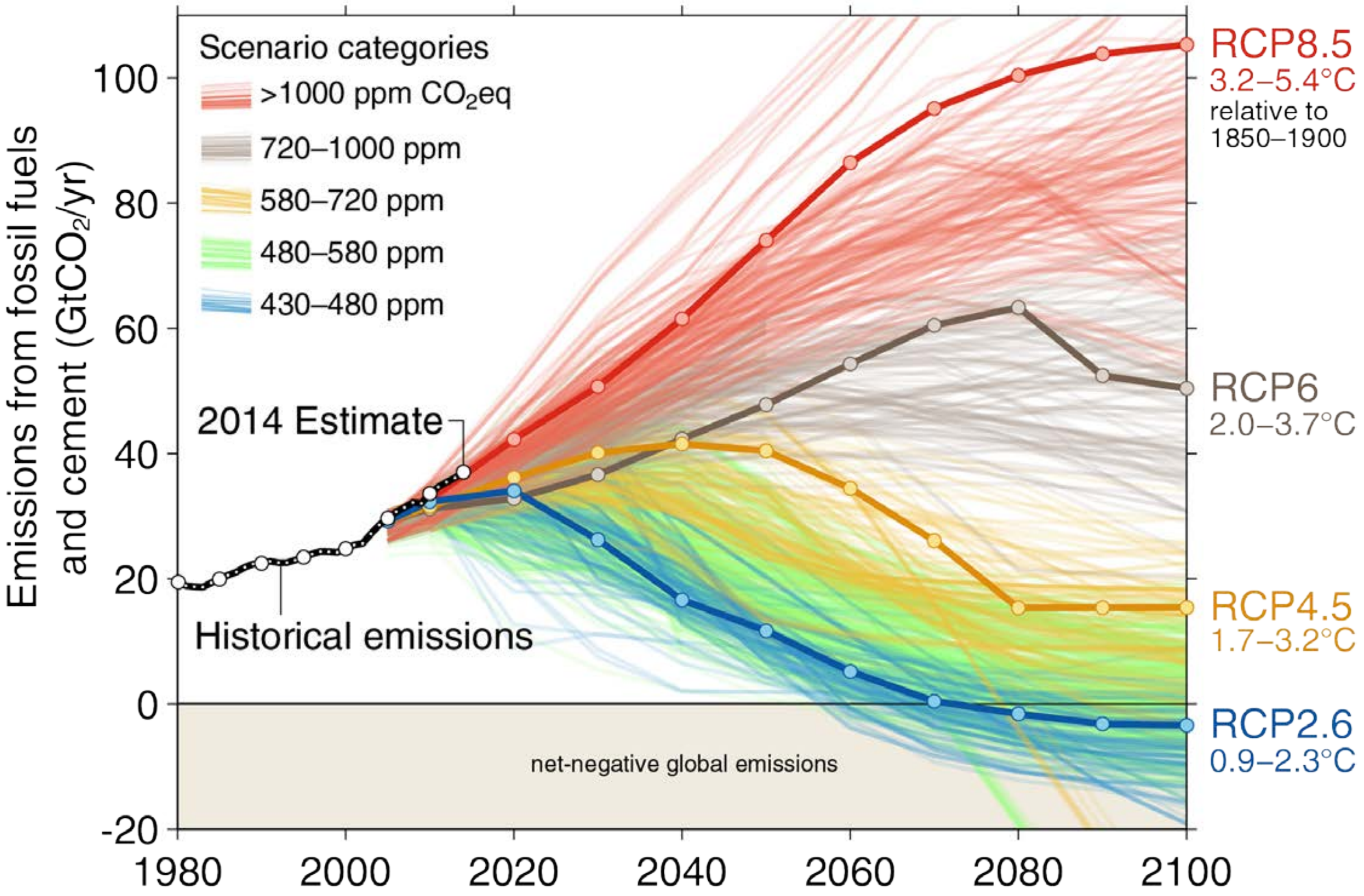
γ



Negative concentration–carbon feedback

β

Simulation design: Prescribed atm. CO_2 from RCP8.5



The Global Carbon Project, 2014

What are important climate-carbon processes and feedbacks?

Processes in CESM1(BGC):

- Ocean:
  - Increasing stratification with warming
  - Dissolved inorganic carbon sensitivity to temperature
  - Biological pump responses to stratification
- Land:
  - Drought & temperature effects on gross and net primary production
  - Soil decomposition increases in response to temperature
  - Response of fires to changes in fuels and drought
  - Land use change

Not yet in most ESMs:

- Species shifts
- Phosphorus limits on carbon uptake
- Permafrost dynamics
- Peatlands
- Insect-driven mortality
- Drought effects on tree mortality
- Climate effects on land use change

CESM1(BGC) experimental design

Simulation	Short name	Description
Fully coupled	Full	CO_2 and other atmospheric anthropogenic drivers influence radiative transfer, biogeochemistry responds to CO_2 increases
No CO_2 radiative forcing	No CO_2 forcing	Non-CO_2 anthropogenic drivers influence radiative transfer, biogeochemistry responds to CO_2 increases
No anthropogenic radiative forcing from greenhouse gases or aerosols	No anthro. forcing	No atmospheric anthropogenic climate change, biogeochemistry responds to CO_2 increases

Validation:
Lindsay et al. (2014), Moore et al. (2013), Long et al. (2013), Keppel-Aleks et al. (2013)

CESM1(BGC) experimental design

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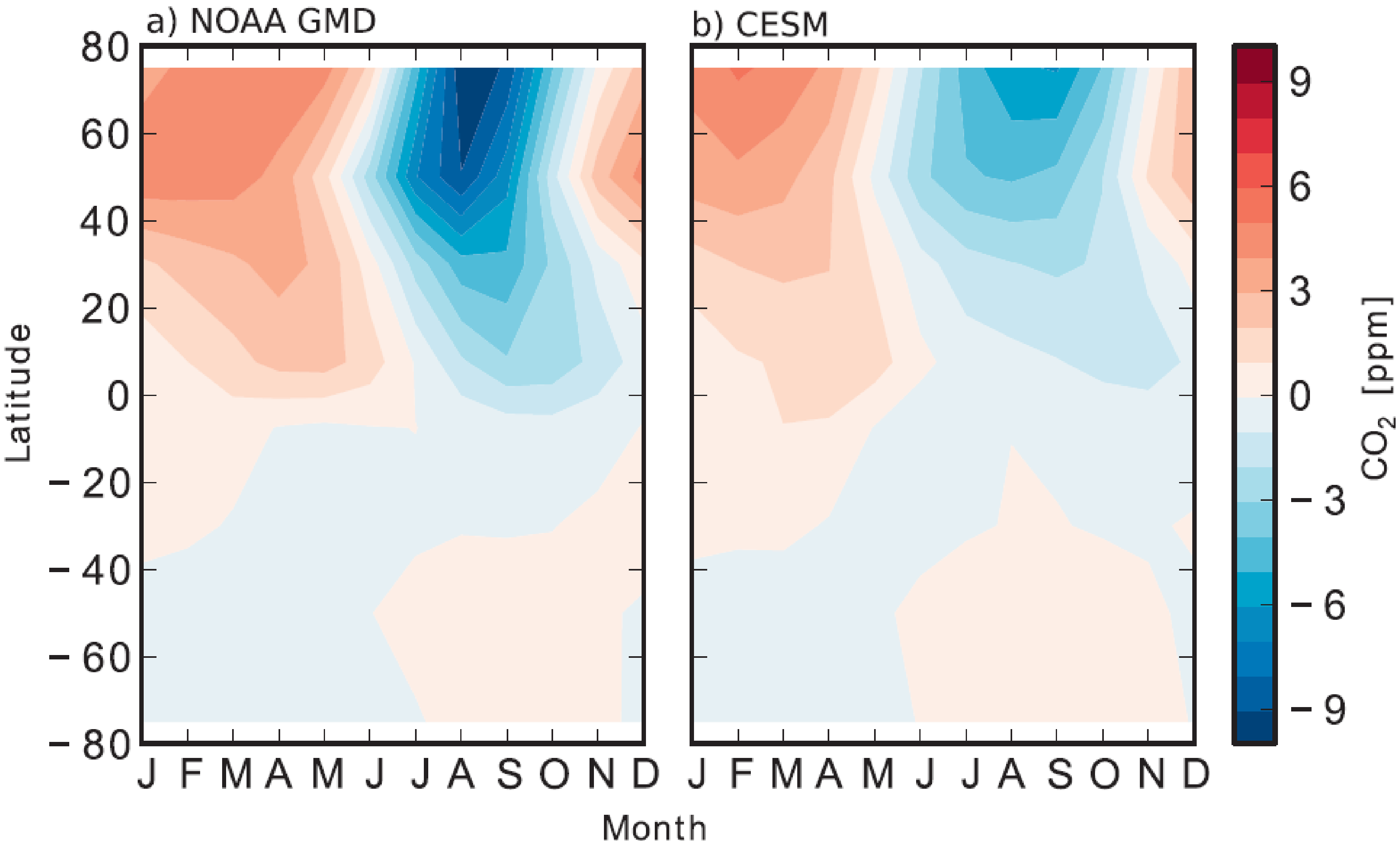
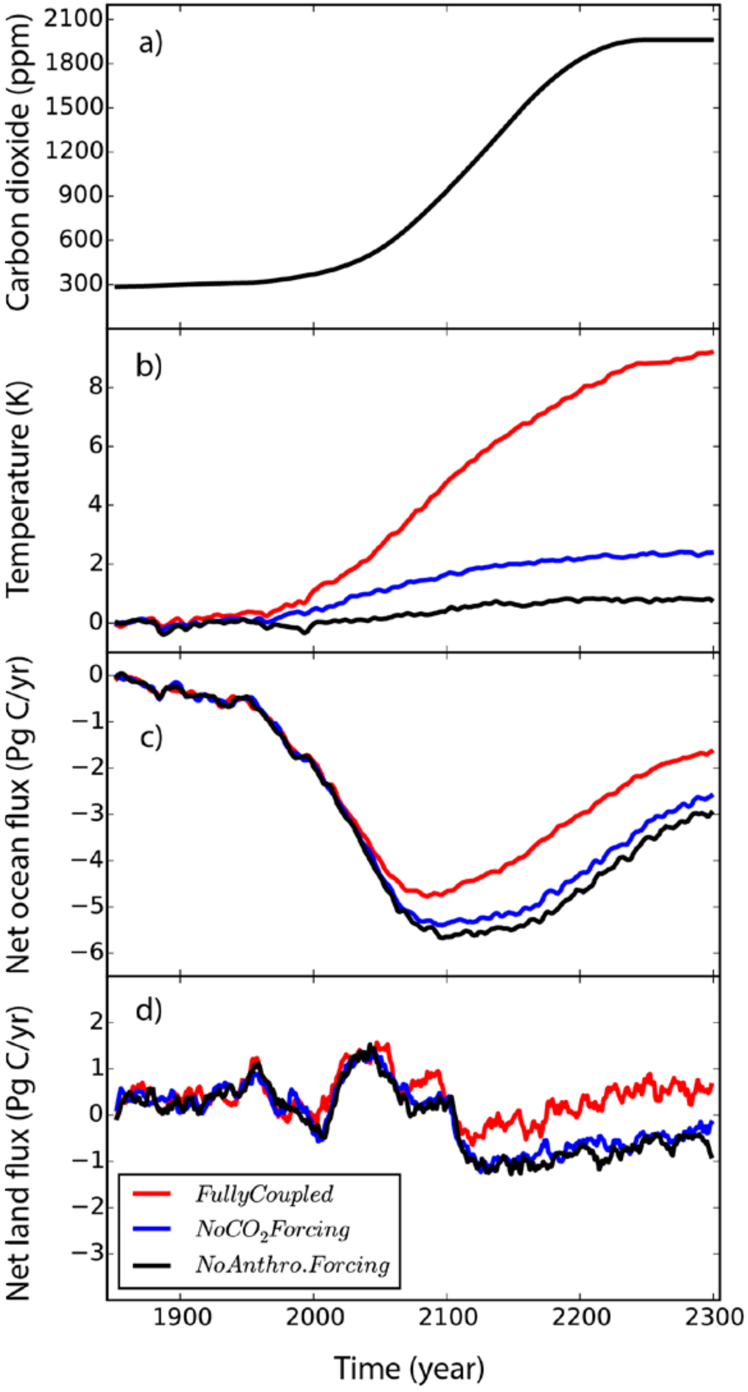
Lindsay et al. (2014), Keppel-Aleks et al. (2013), Moore et al. (2013), Long et al. (2013)

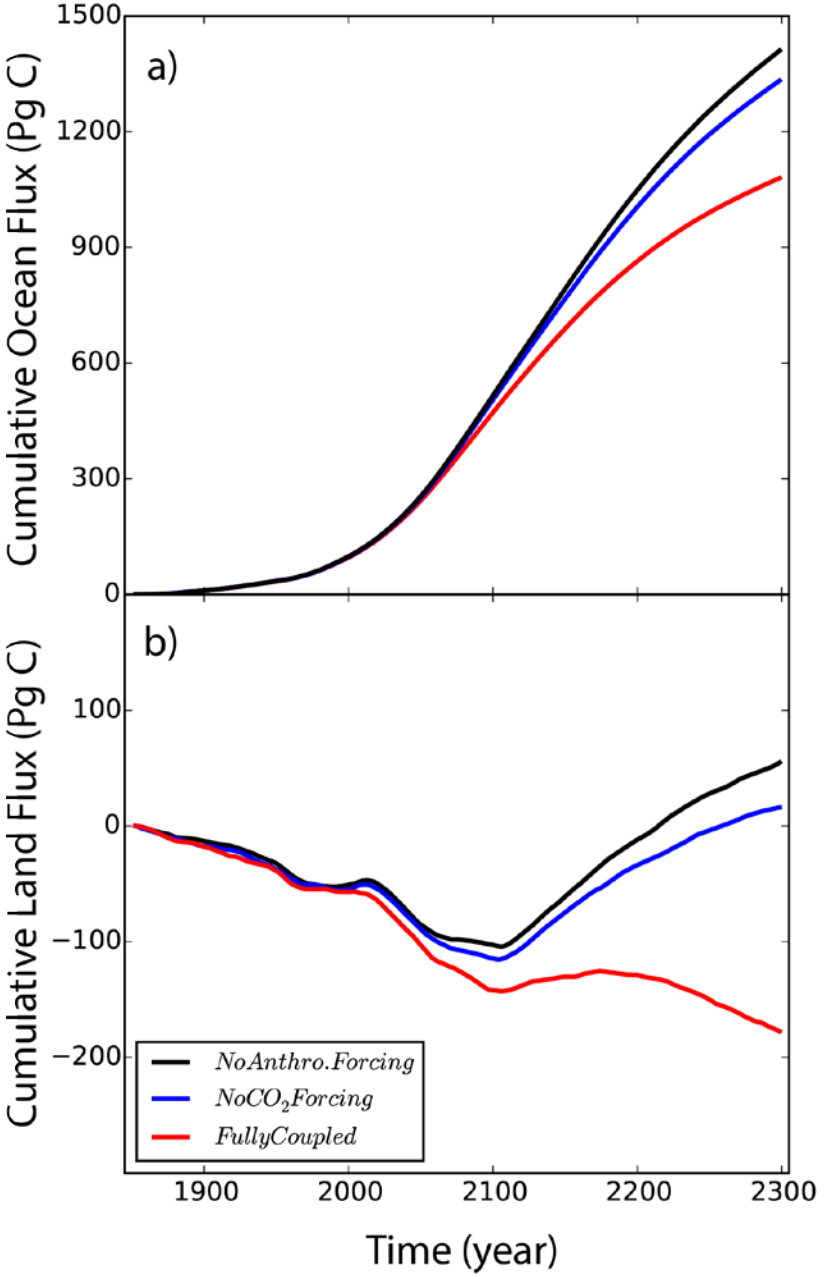
Validation of carbon cycle processes in CESM



Keppel Aleks et al., 2013, Journal of Climate



Randerson et al., GBC, submitted



Climate-carbon gain computed from compatible fossil fuel emissions from fully coupled and no CO_2 forcing simulations

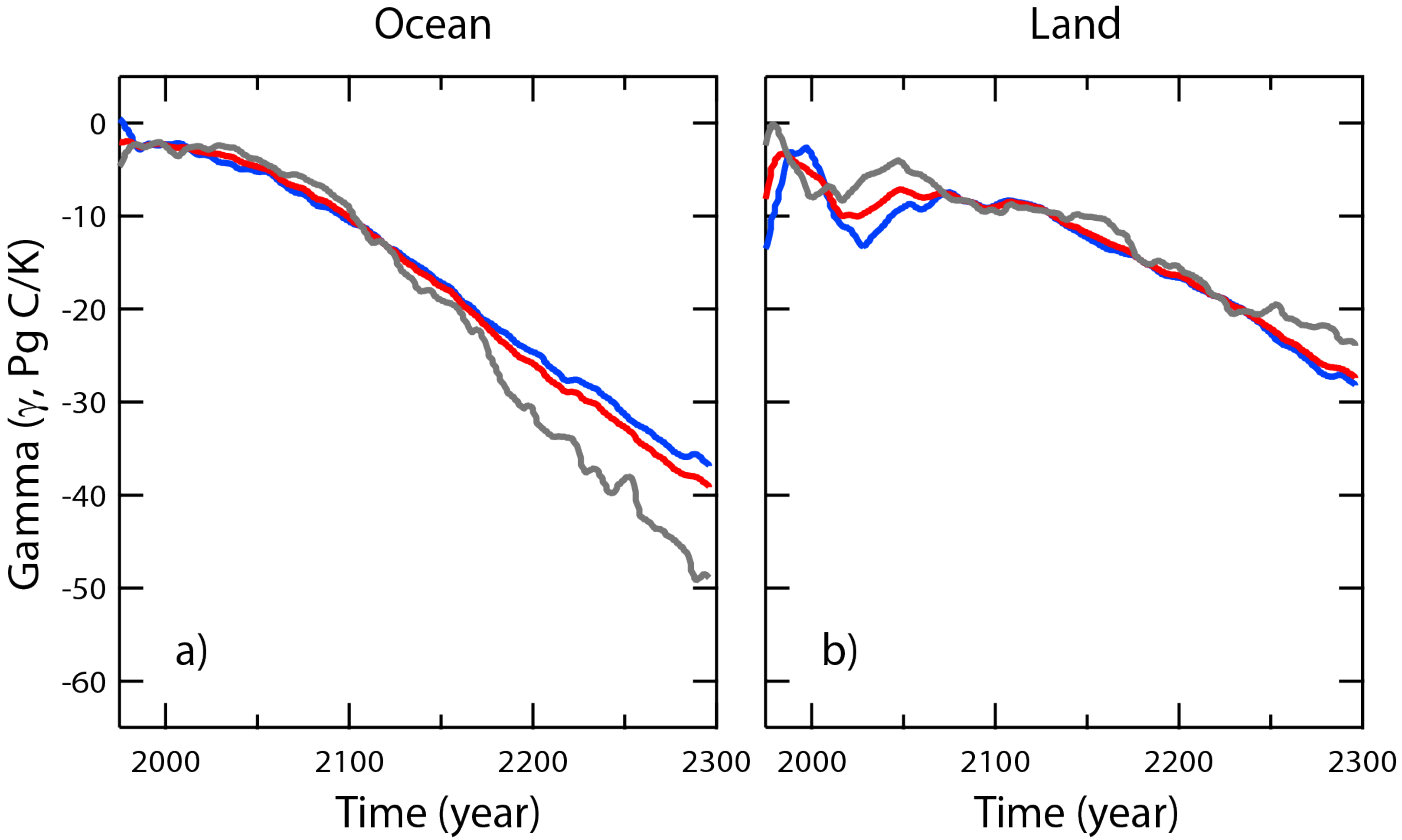
$$g = \frac{E_{noCO_2} - E_{FC}}{E_{noCO_2}}$$

Randerson et al., GBC, submitted

Climate-carbon feedback parameters

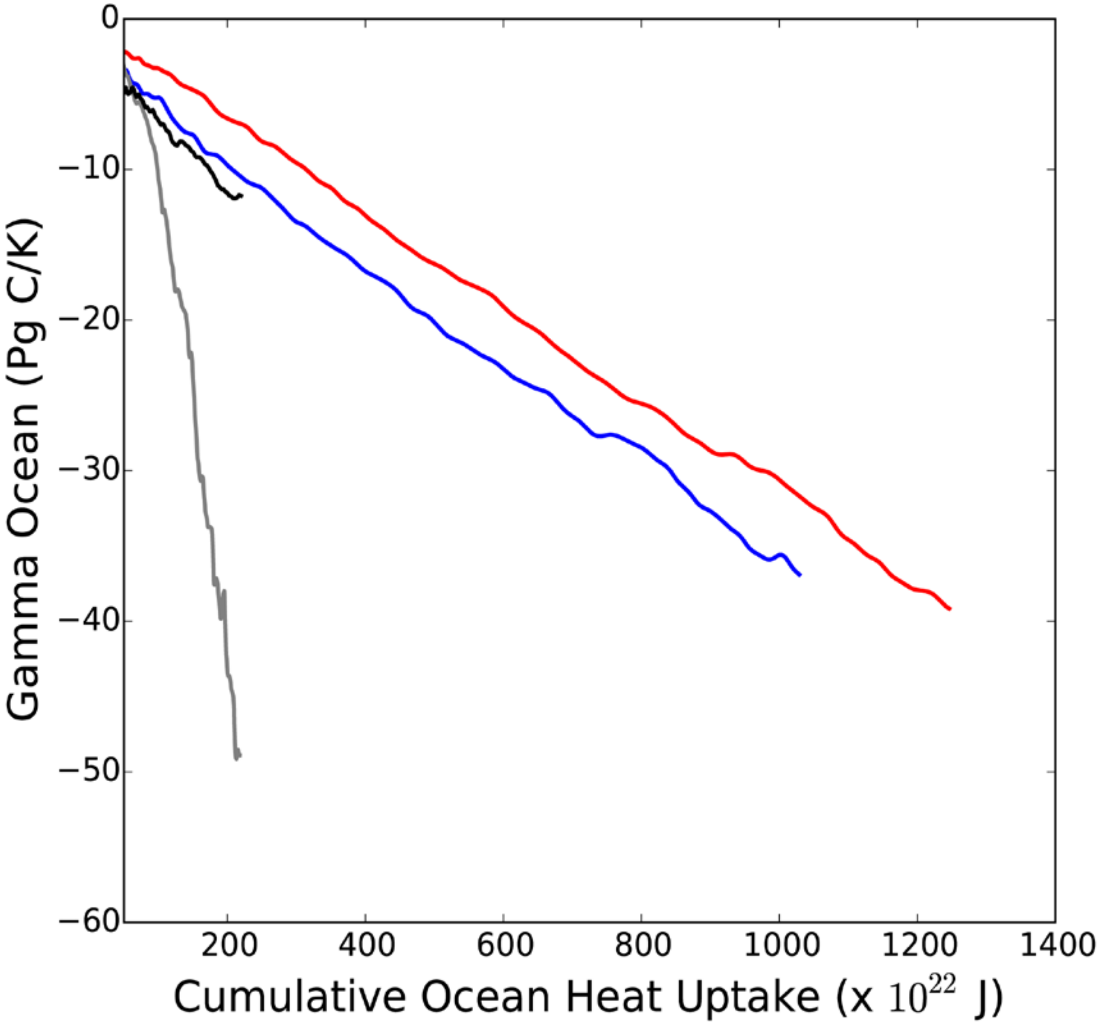
Parameter	Time Period			
	1850-1999	1850-2100	1850-2200	1850-2300
α (K/ppm)	0.0080	0.0048	0.0037	0.0041
β_L (Pg C/ppm)	-0.65	-0.18	-0.02	0.01
β_O (Pg C/ppm)	1.15	0.77	0.65	0.79
γ_L (Pg C/°C)	-2.9	-8.5	-16.4	-28.1
γ_O (Pg C/°C)	-1.5	-10.1	-24.4	-36.7
Gain	0.013	0.034	0.056	0.091

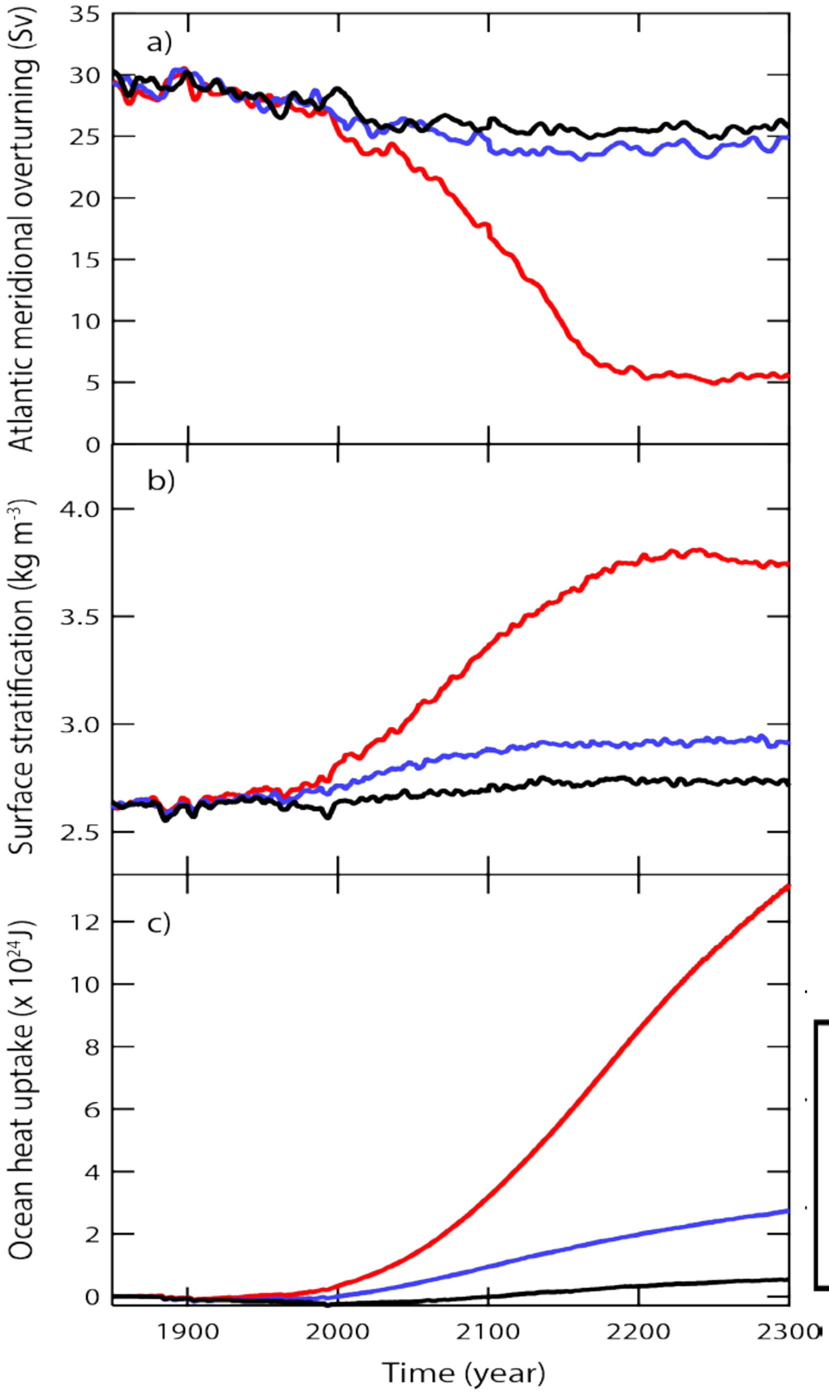
Cumulative Climate-Carbon Feedback Parameter Gamma

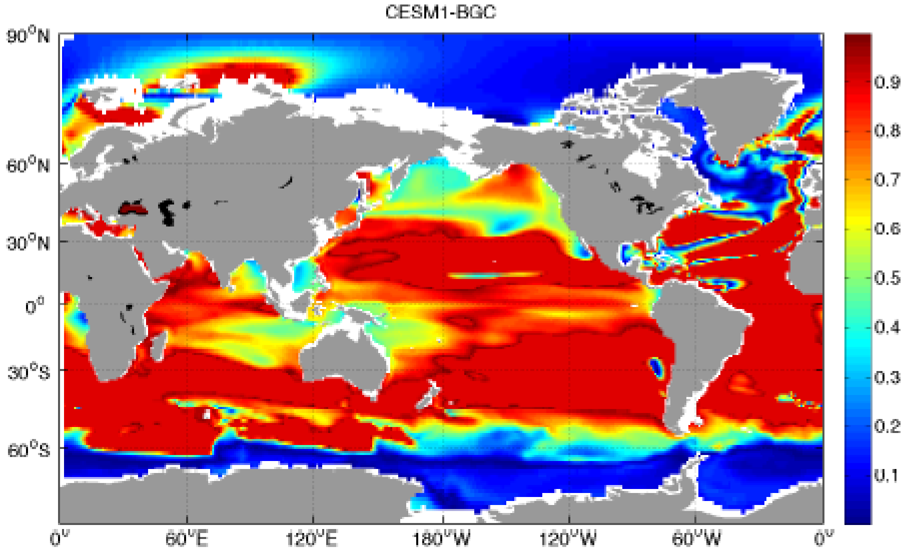


Blue = FC – no CO_2; **Red = FC – no anthro.**; **grey= no CO_2 – no anthro.**

The strength of the ocean climate-carbon feedback is closely related to ocean heat content

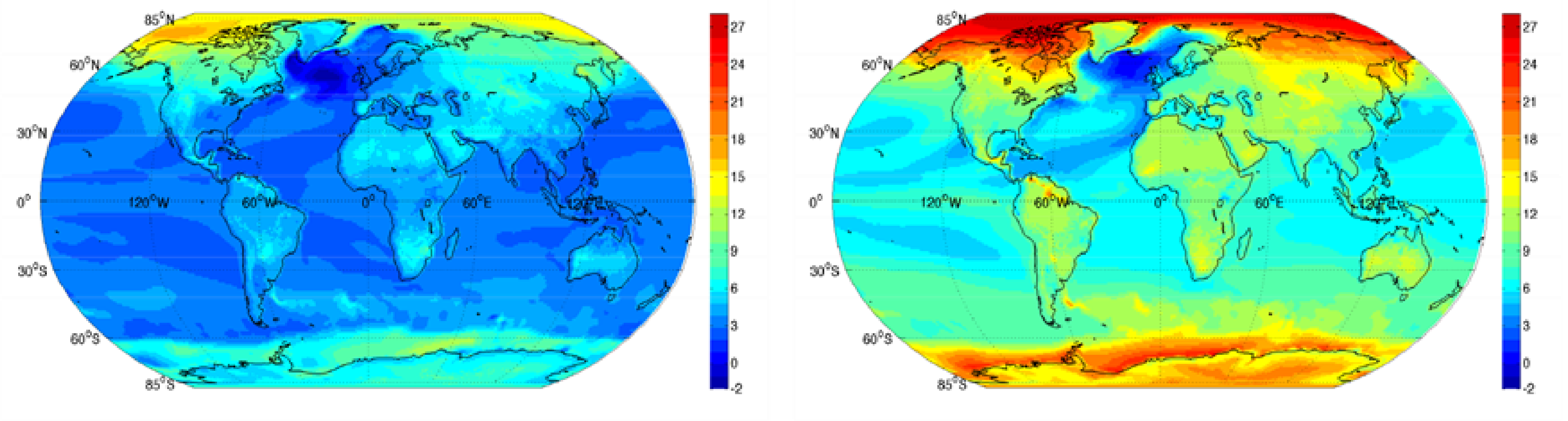






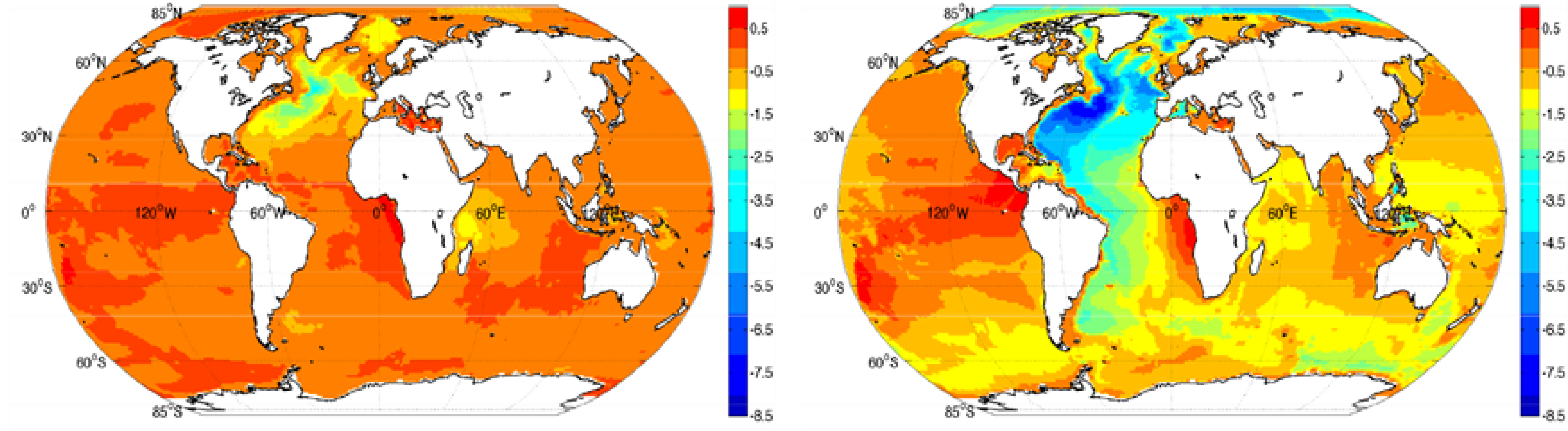
CESM1(BGC) temperature and salinity drivers of stratification at 2100

Shutdown in Atlantic Meridional Overturning Reduces Carbon Uptake in CESM



(a) T_{AS}: 2100-1850

(b) T_{AS}: 2300-1850



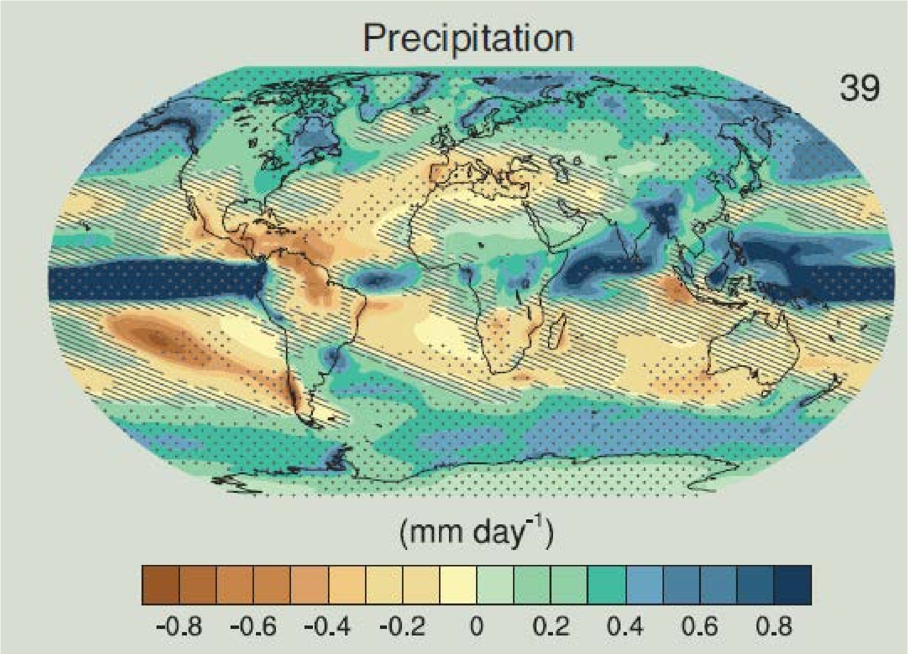
(c) ocean carbon: 2100-1850

(d) ocean carbon: 2300-1850

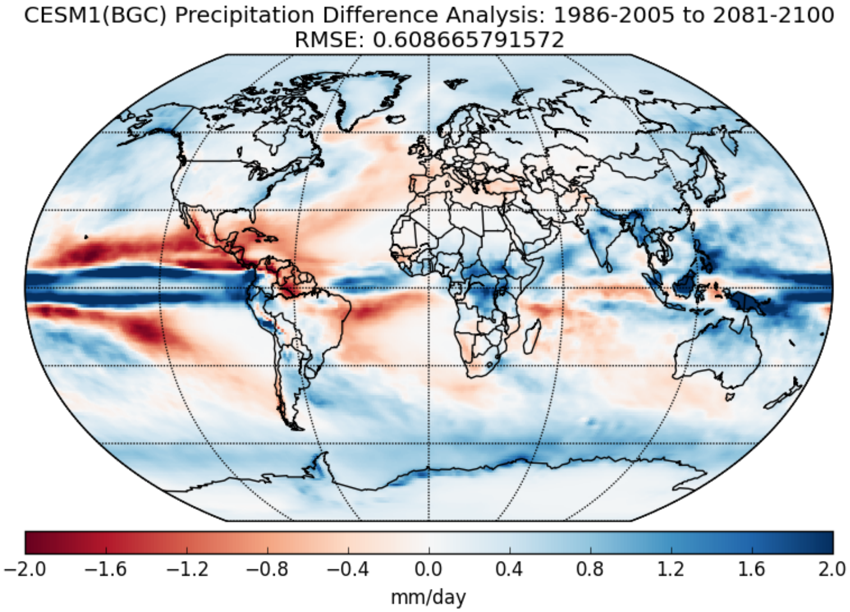
Changing vulnerability of the Amazon to drought

Precipitation changes for Representative Concentration Pathway 8.5
(2081-2100) – (1986-2005)

CMIP5 multi-model mean, IPCC AR1 TS



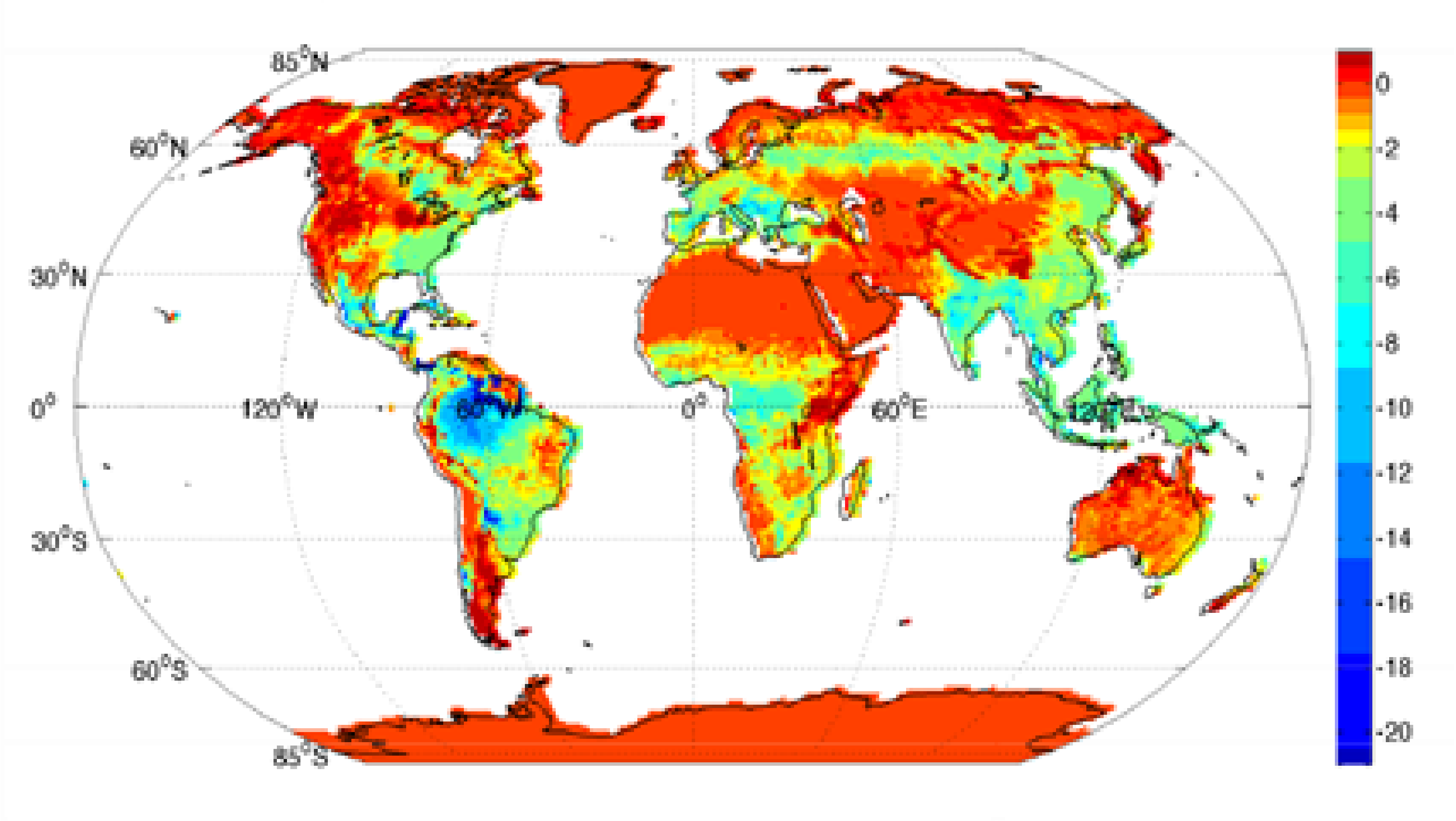
CESM1(BGC)



mm/day

Hydrological cycle changes are not uniform across tropical land, with most models drying more in South America than in Africa or Asia

Forests in Central and South America exhibit a high degree of vulnerability to climate change-induced carbon losses


(f) land carbon: 2300-1850

Reduced AMOC

→

Cooling

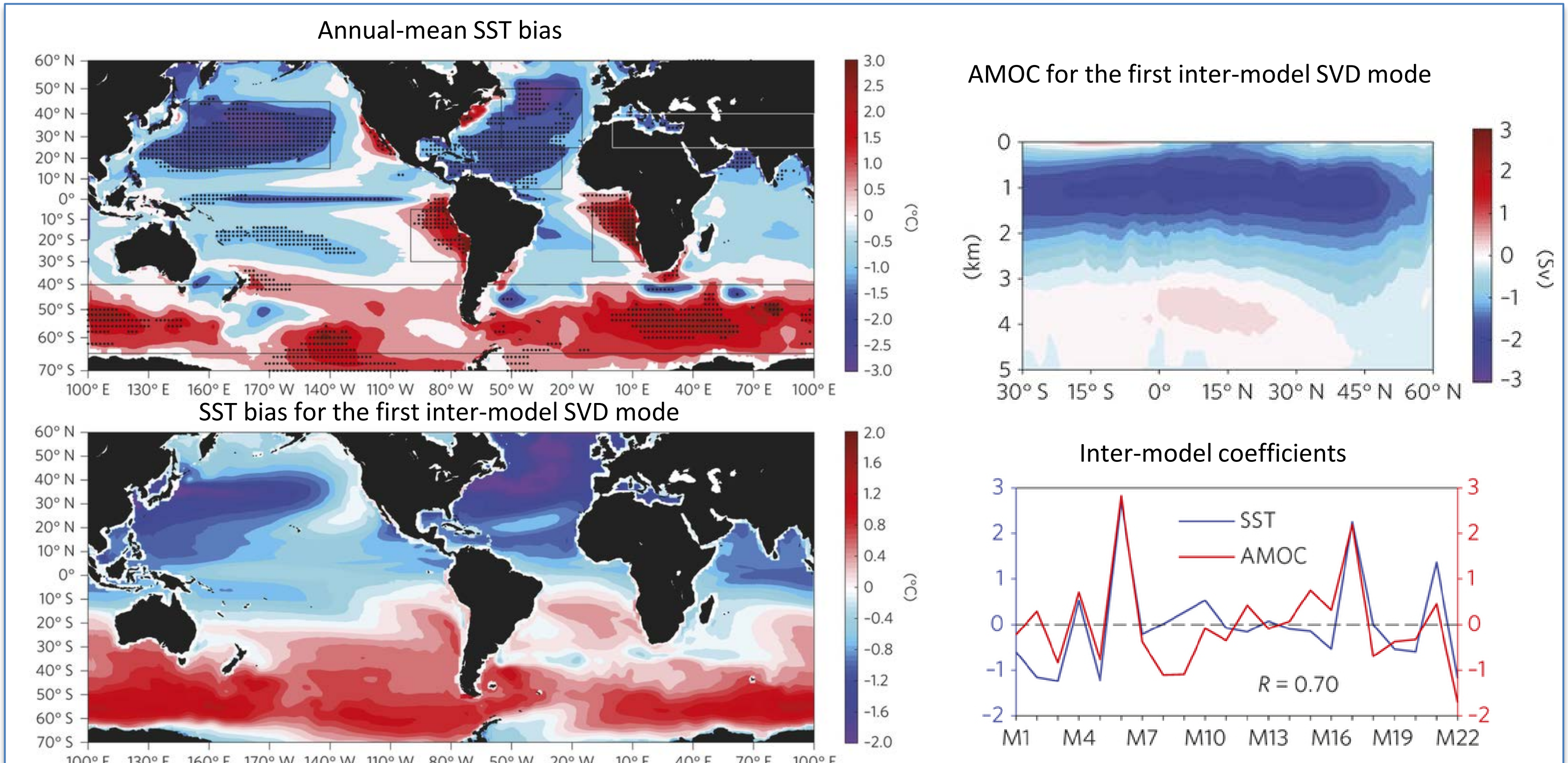
North Atlantic Ocean
Tropical North Atlantic
North Pacific
Mediterranean Sea

Warming

Southeastern Pacific
Southeastern Atlantic
Southern Ocean

→

Increasing of global SST bias



Annual-mean SST bias

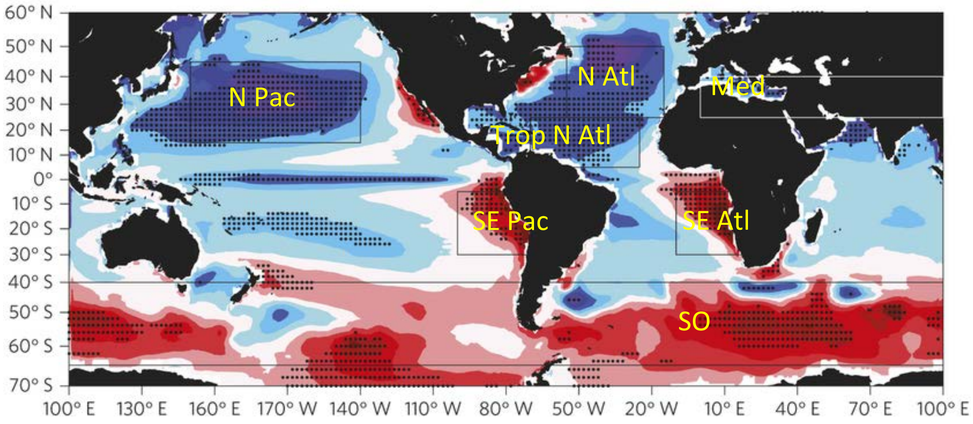
SST bias for the first inter-model SVD mode

AMOC for the first inter-model SVD mode

Inter-model coefficients

Source: Wang et al., 2014, Nature Climate Change

Using SST transregional index (TRi) to approximate AMOC



Southern-Northern difference (SND):

$$SND = \frac{(\overline{SST}_{SE.Atl} + \overline{SST}_{SE.Pac} + \overline{SST}_{SO}) - (\overline{SST}_{N.Atl} + \overline{SST}_{Trop.N.Atl} + \overline{SST}_{N.Pac} + \overline{SST}_{Med})}{7}$$

Transregional index (TRi)

$TRi = SND_{mod} - SND_{obs}$

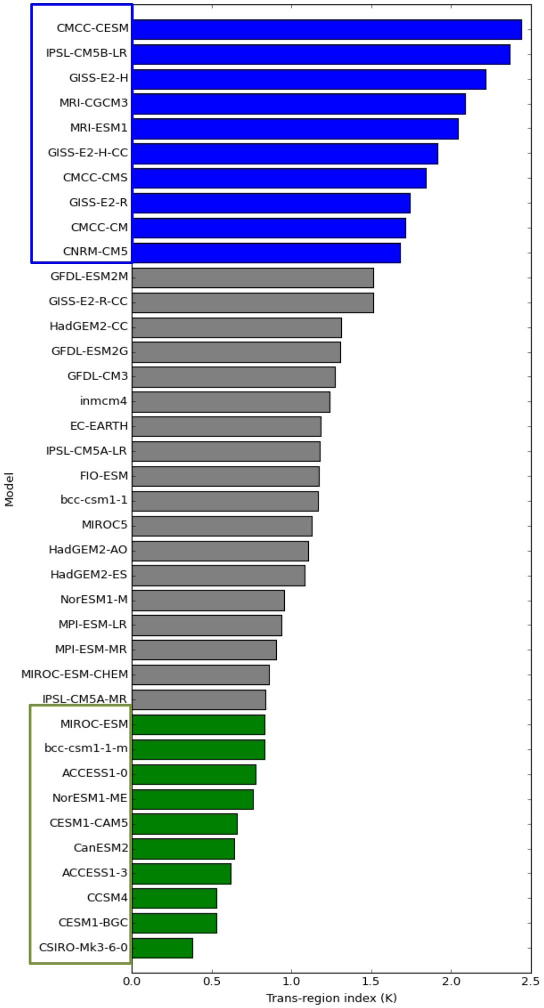
Change in Transregional index (dTRi)

$dTRi = SND_{mod\text{-}rcp85} - SND_{mod\text{-}historical}$

Small TRi	Large TRi
Low SH SSTs High NH SSTs Small global bias Strong AMOC	High SH SSTs Low NH SSTs Large global bias Weak AMOC

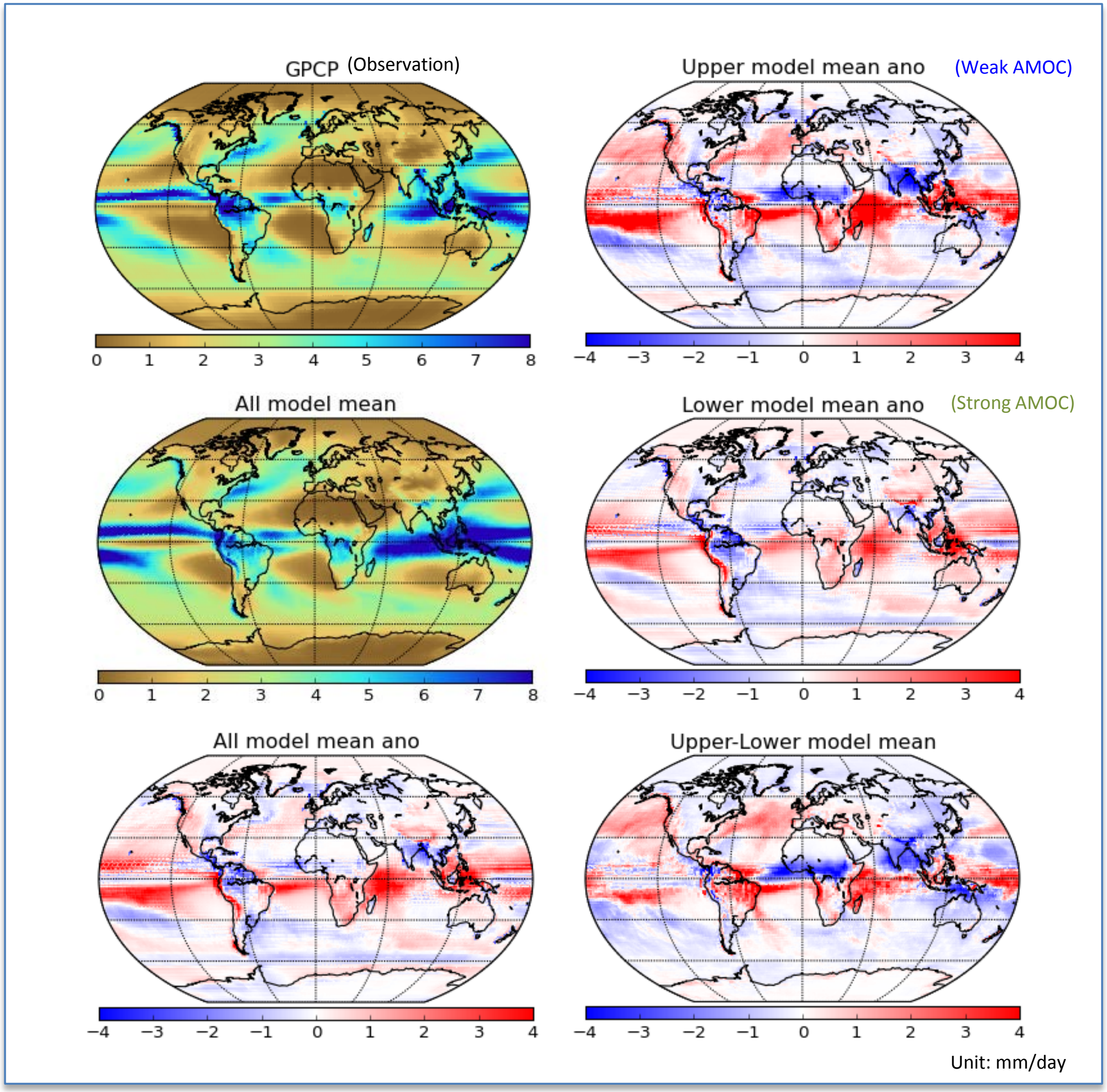
All models are underestimating AMOC!

“Upper models”, “low AMOC models”, “models with highest SST bias”



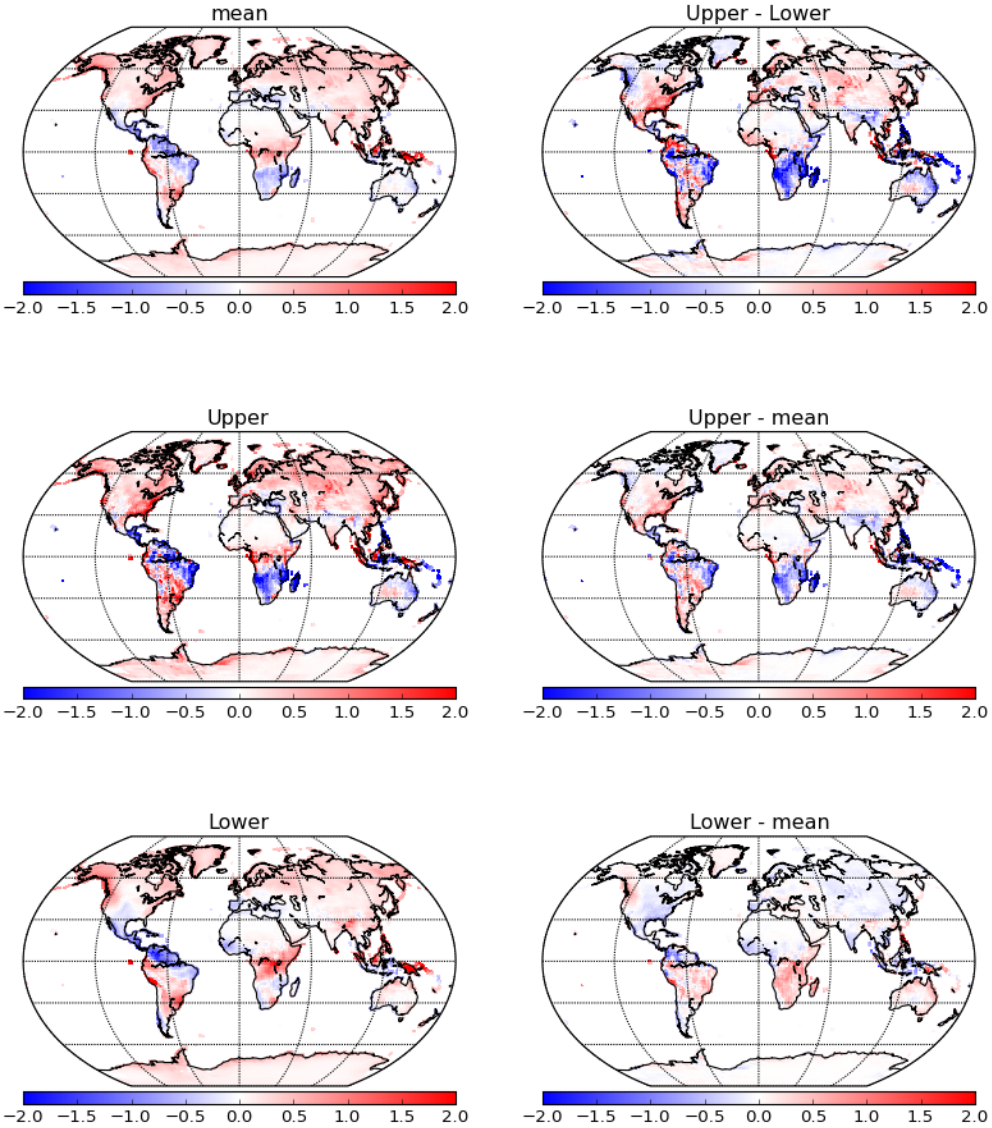
“Lower models”, “high AMOC models”, “models with lowest SST bias”

20-year Mean PPT during the historical period



Model simulations of PPT change

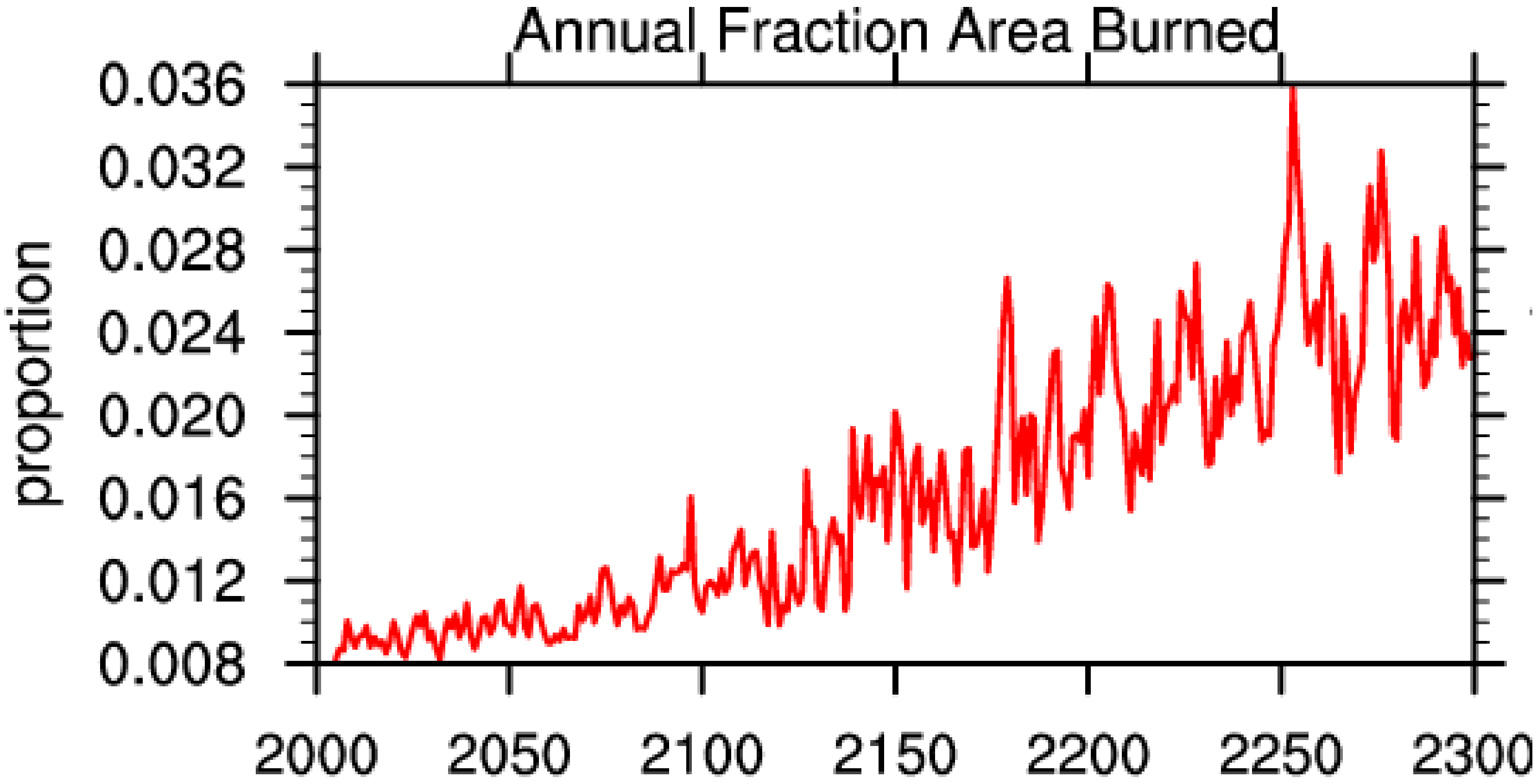
Land



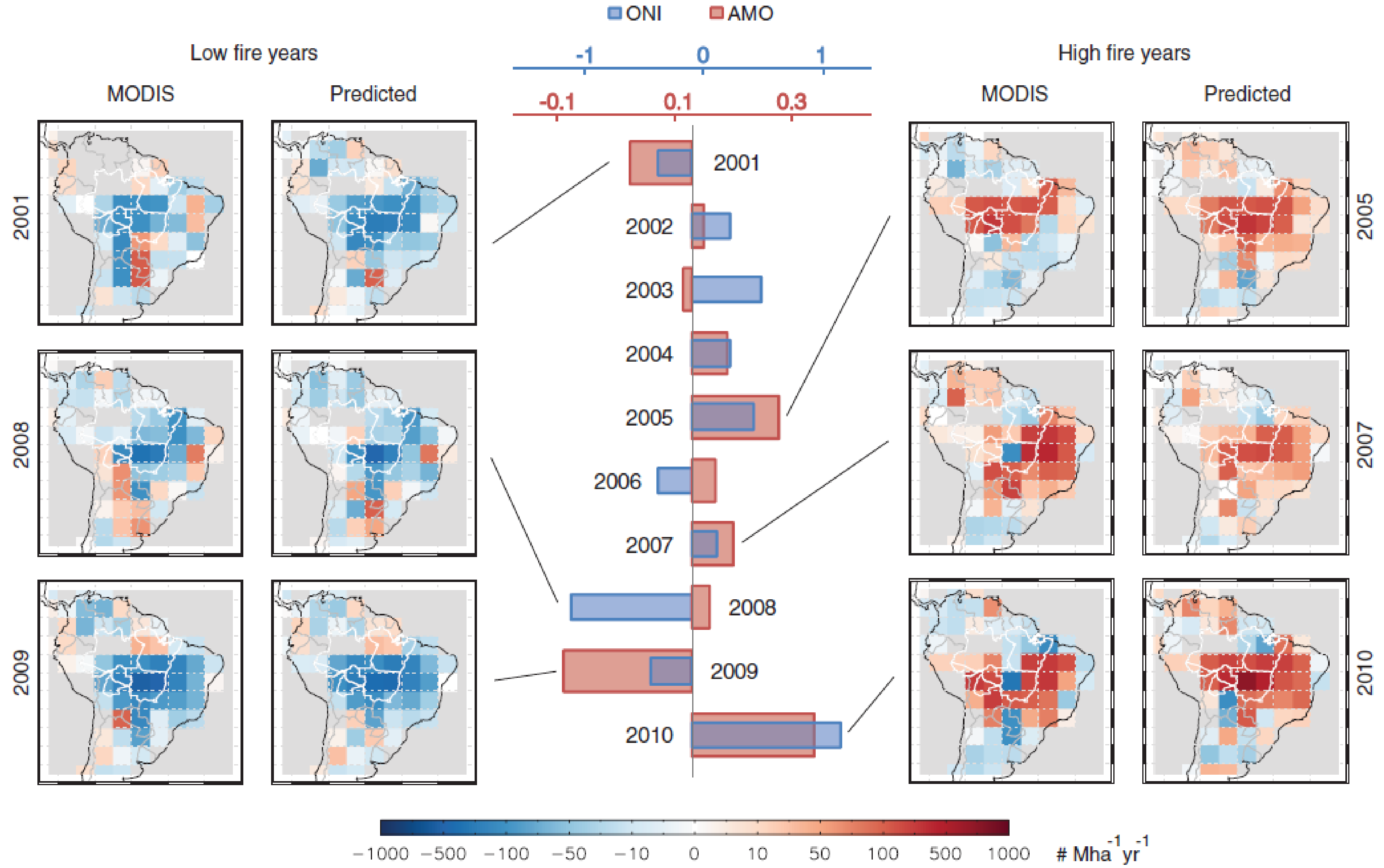
(Weak AMOC)

(Strong AMOC)

Amazon broadleaf forest burned area from the fully coupled simulation



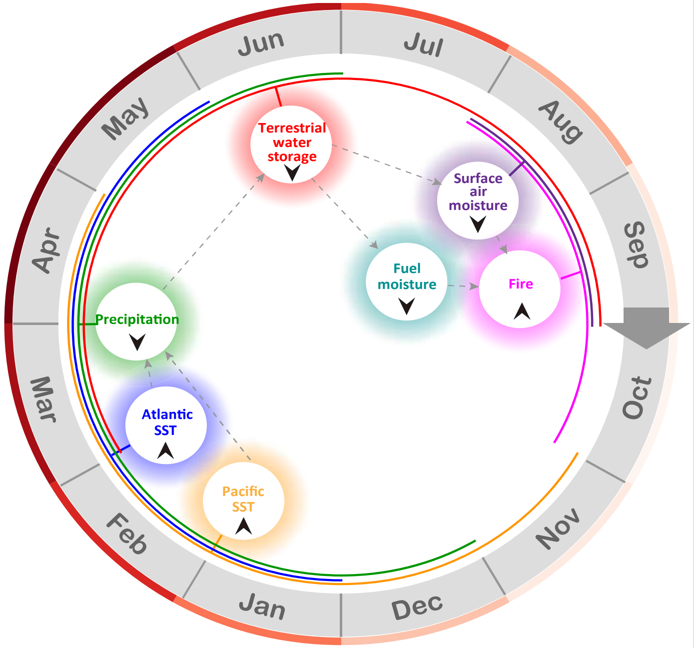
Fire Forecasting Model Performance



Terra satellite number of fires

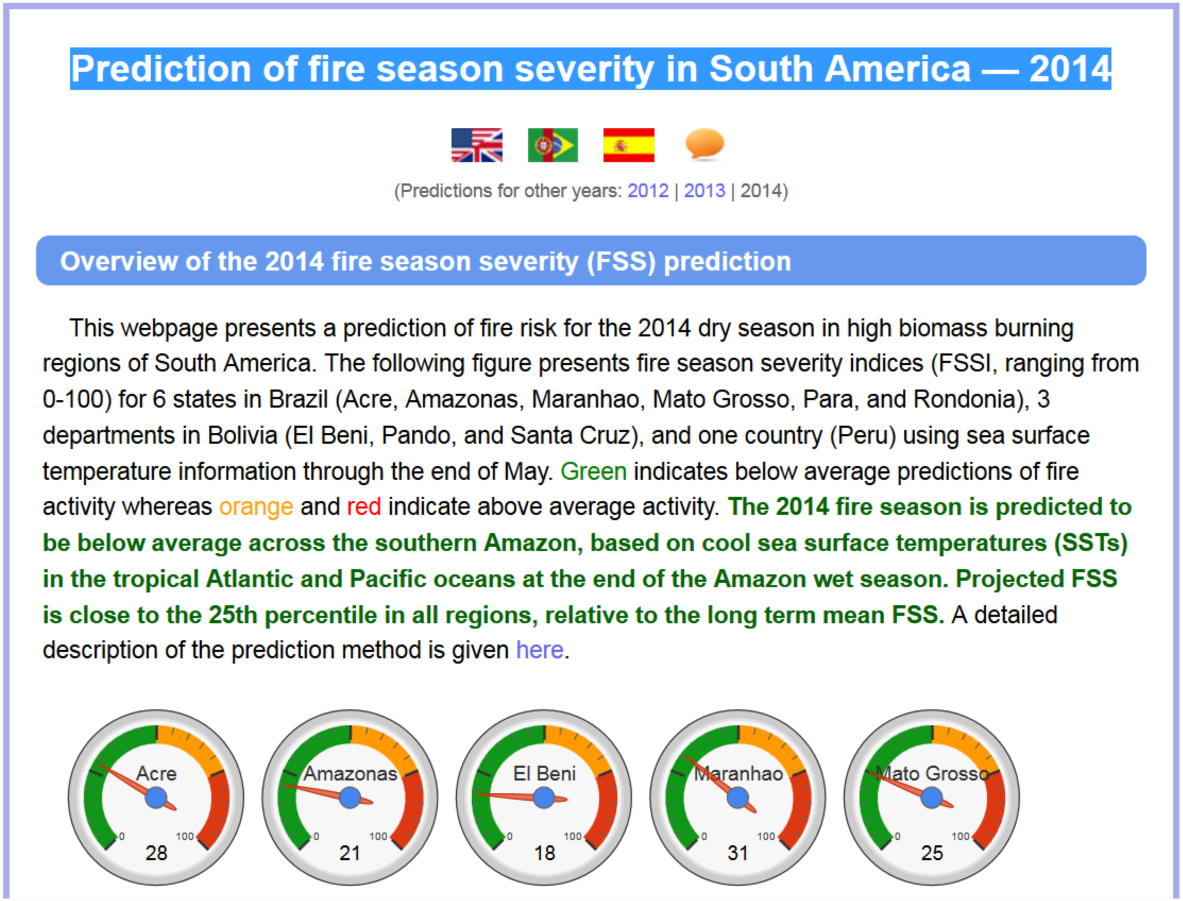
Chen et al. (2011) Science

Tropical forest soil water recharge acts as a capacitor



Chen et al. 2013

2014 fire season forecast:



Prediction of fire season severity in South America — 2014

(Predictions for other years: 2012 | 2013 | 2014)

Overview of the 2014 fire season severity (FSS) prediction

This webpage presents a prediction of fire risk for the 2014 dry season in high biomass burning regions of South America. The following figure presents fire season severity indices (FSSI, ranging from 0-100) for 6 states in Brazil (Acre, Amazonas, Maranhao, Mato Grosso, Para, and Rondonia), 3 departments in Bolivia (El Beni, Pando, and Santa Cruz), and one country (Peru) using sea surface temperature information through the end of May. Green indicates below average predictions of fire activity whereas orange and red indicate above average activity. **The 2014 fire season is predicted to be below average across the southern Amazon, based on cool sea surface temperatures (SSTs) in the tropical Atlantic and Pacific oceans at the end of the Amazon wet season. Projected FSS is close to the 25th percentile in all regions, relative to the long term mean FSS.** A detailed description of the prediction method is given here.

Conclusions

- Carbon cycle feedback processes can be quantitatively assessed for a representative concentration pathway simulation that includes non-CO_2 anthropogenic forcing agents

- Forcing from non-CO_2 agents for the RCP8.5 scenario is almost enough to surpass the 2 °C dangerous interference limit (i.e., Hansen et al. (2013))

- Ocean contribution to the climate-carbon feedback increases considerably over time for the RCP8.5 scenario, and exceeds contributions from land after 2100
  - Land feedback strength likely reduced from land use change
  - Ocean feedback strength closely related to ocean heat content and AMOC shutdown

- Tropical forests in Central and South America have a higher vulnerability to climate change than other tropical regions

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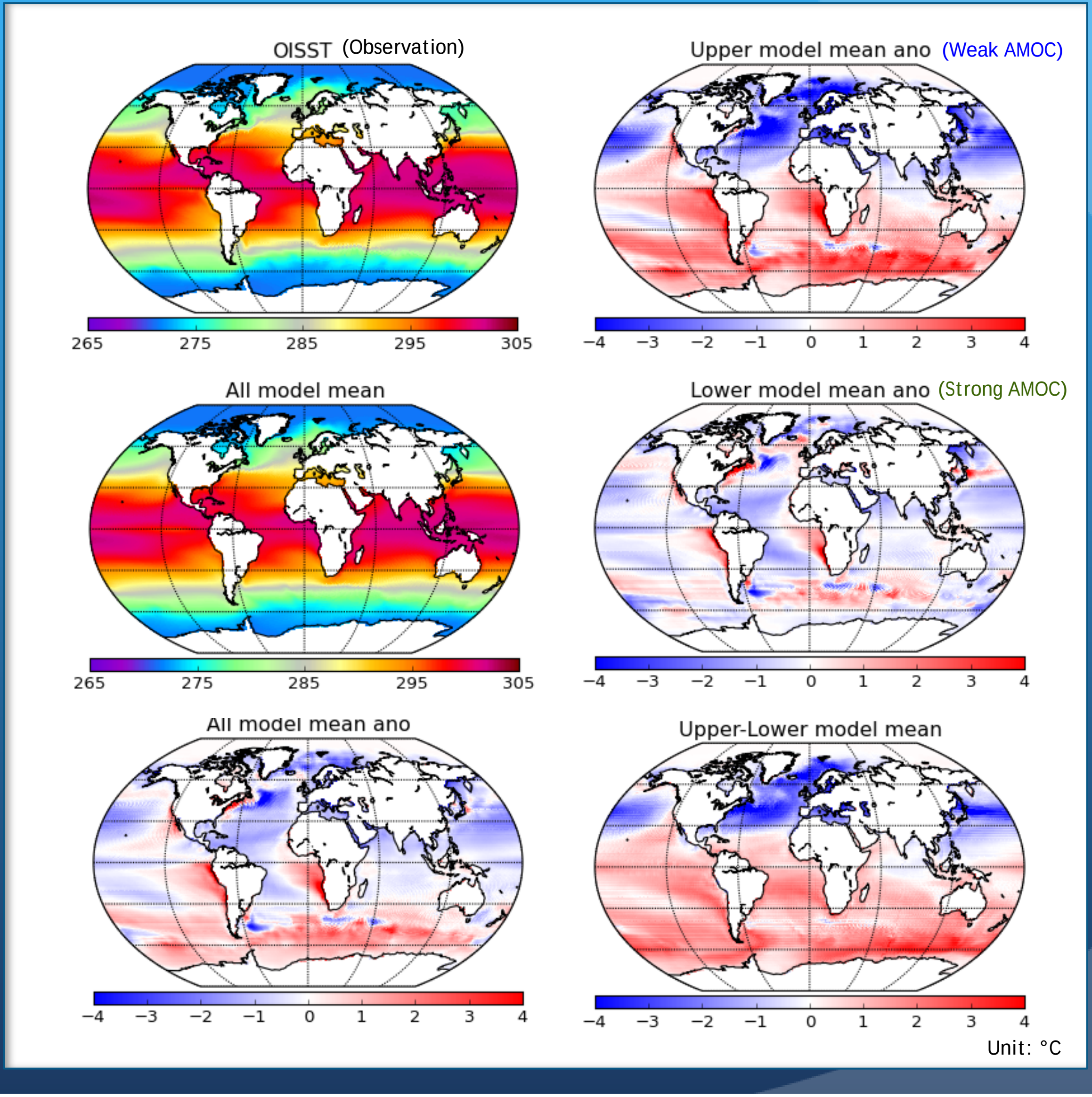
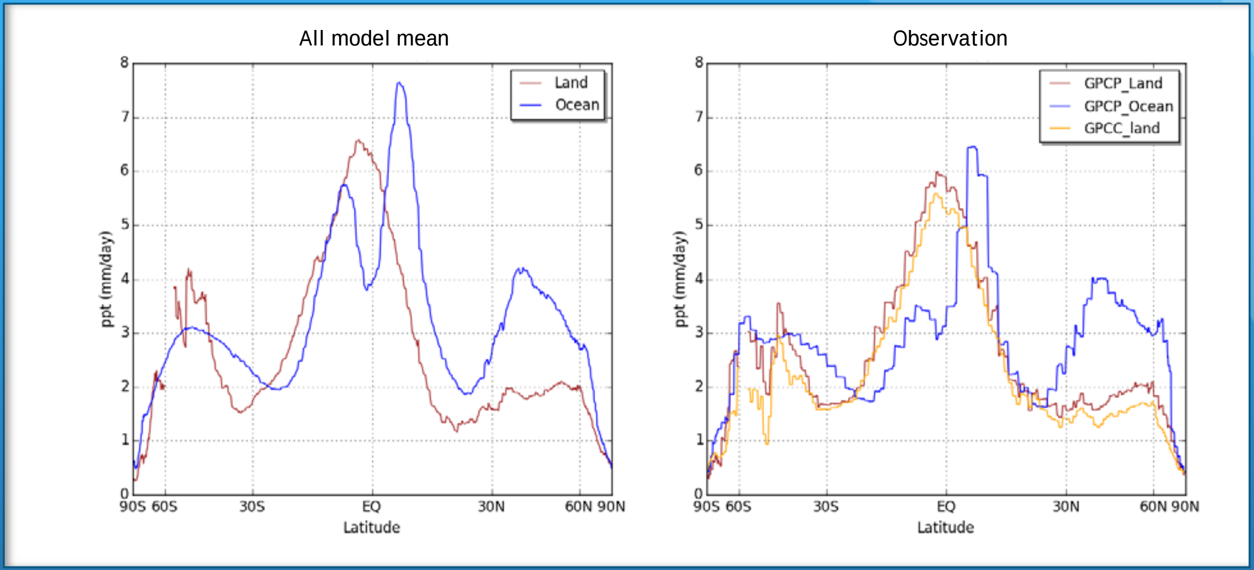
20-year Mean SSTs during the historical period

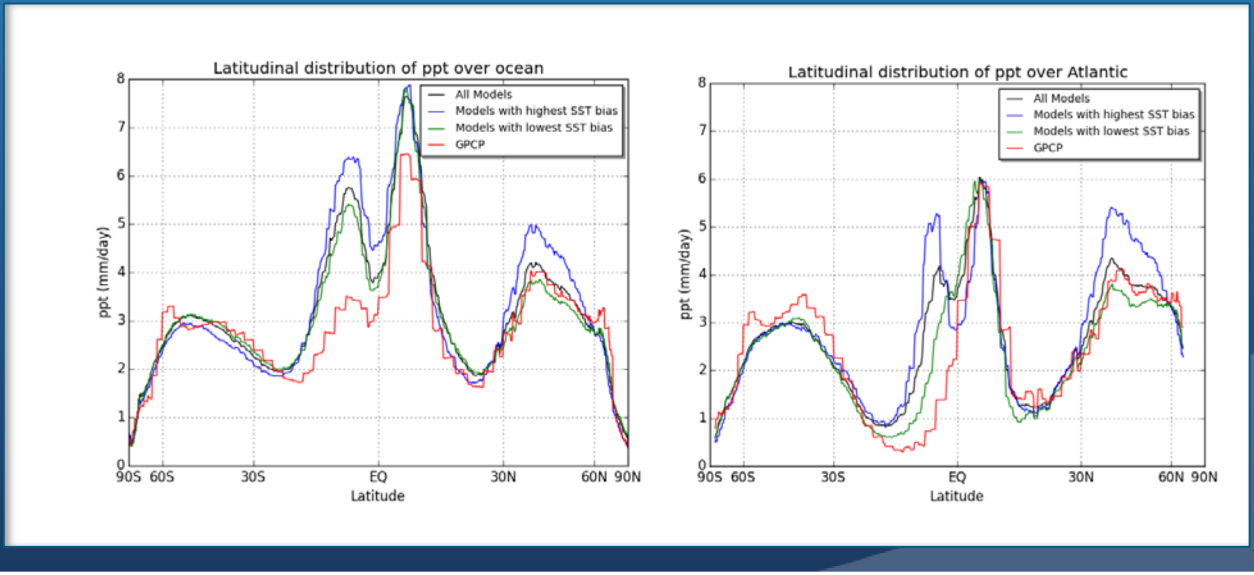


Latitudinal distribution of PPT over ocean

land vs. ocean



Global ocean vs. Atlantic



Earth System Model Climate-Carbon Feedbacks

γ – the sensitivity of carbon stocks to temperature change (Pg C °C^{-1})

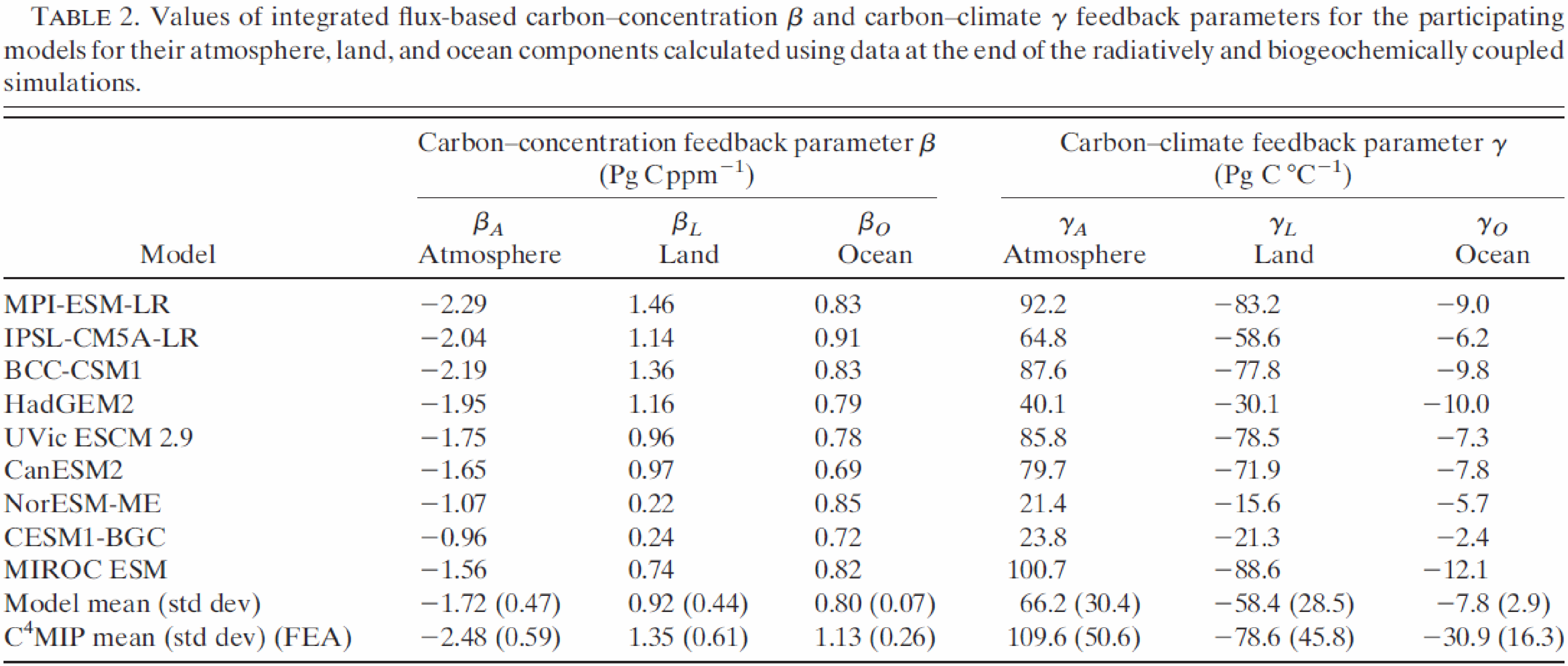


TABLE 2. Values of integrated flux-based carbon–concentration β and carbon–climate γ feedback parameters for the participating models for their atmosphere, land, and ocean components calculated using data at the end of the radiatively and biogeochemically coupled simulations.

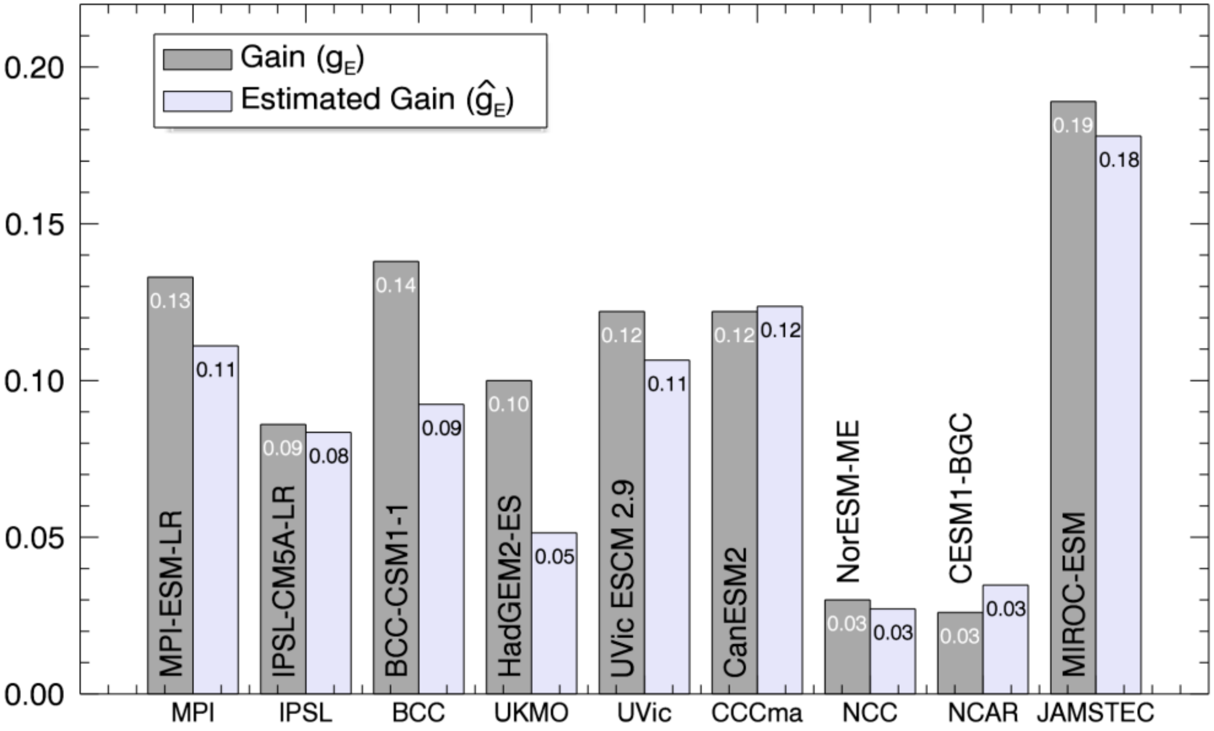
	Carbon–concentration feedback parameter β (Pg C ppm^{-1})			Carbon–climate feedback parameter γ (Pg C °C^{-1})		
Model	β_A Atmosphere	β_L Land	β_O Ocean	γ_A Atmosphere	γ_L Land	γ_O Ocean
MPI-ESM-LR	−2.29	1.46	0.83	92.2	−83.2	−9.0
IPSL-CM5A-LR	−2.04	1.14	0.91	64.8	−58.6	−6.2
BCC-CSM1	−2.19	1.36	0.83	87.6	−77.8	−9.8
HadGEM2	−1.95	1.16	0.79	40.1	−30.1	−10.0
UVic ESCM 2.9	−1.75	0.96	0.78	85.8	−78.5	−7.3
CanESM2	−1.65	0.97	0.69	79.7	−71.9	−7.8
NorESM-ME	−1.07	0.22	0.85	21.4	−15.6	−5.7
CESM1-BGC	−0.96	0.24	0.72	23.8	−21.3	−2.4
MIROC ESM	−1.56	0.74	0.82	100.7	−88.6	−12.1
Model mean (std dev)	−1.72 (0.47)	0.92 (0.44)	0.80 (0.07)	66.2 (30.4)	−58.4 (28.5)	−7.8 (2.9)
C^{4}MIP mean (std dev) (FEA)	−2.48 (0.59)	1.35 (0.61)	1.13 (0.26)	109.6 (50.6)	−78.6 (45.8)	−30.9 (16.3)

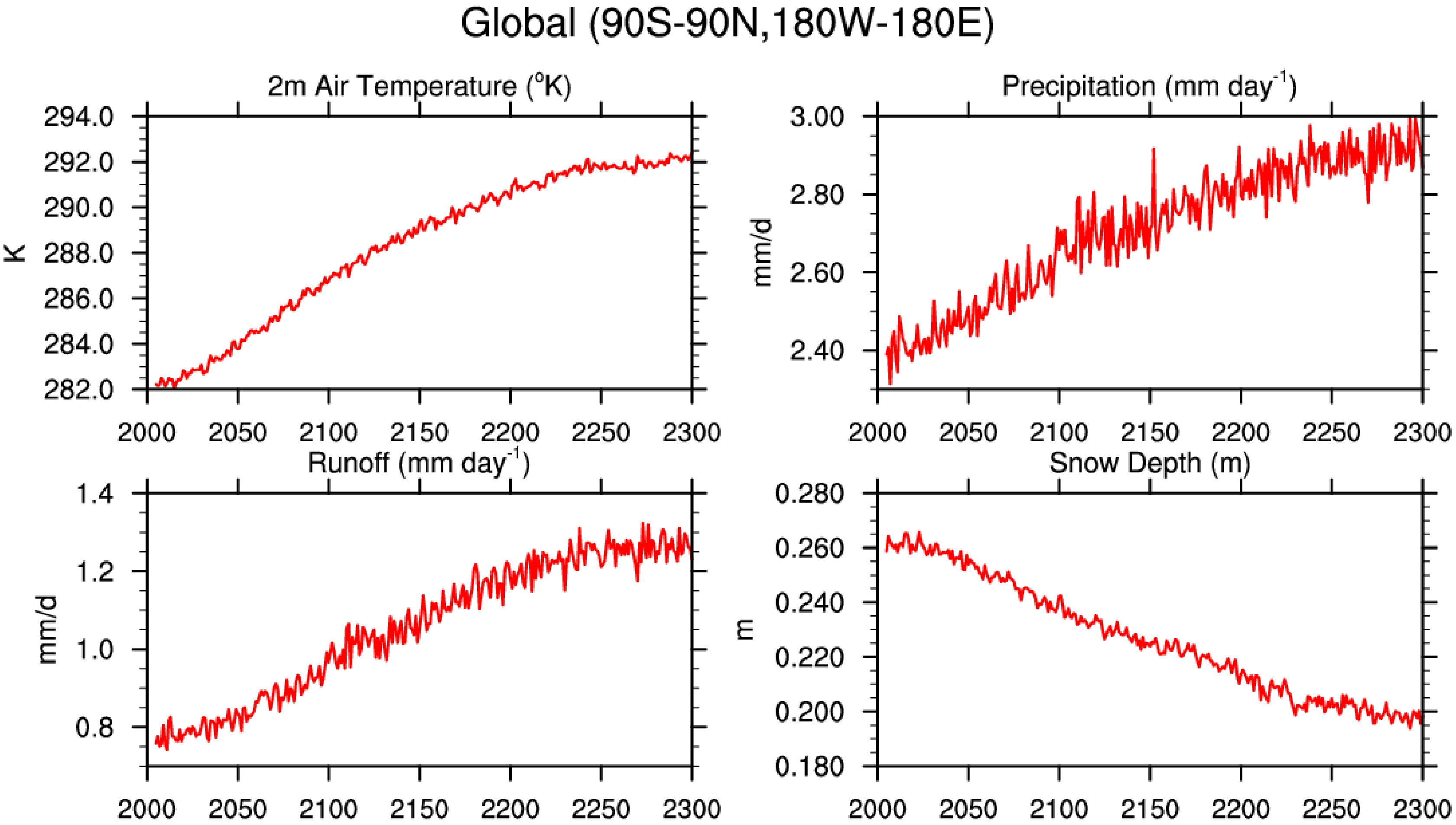
From Arora et al. (2013)

For most models, the gain of the climate carbon feedback is positive

$$g = \frac{E_{BGC} - E_{FC}}{E_{BGC}}$$

- Mean gain of the C4MIP ESMs was 0.15 (all were positive)
- Mean gain of the CMIP5 ESMs was a little lower:





Global (90S-90N,180W-180E)

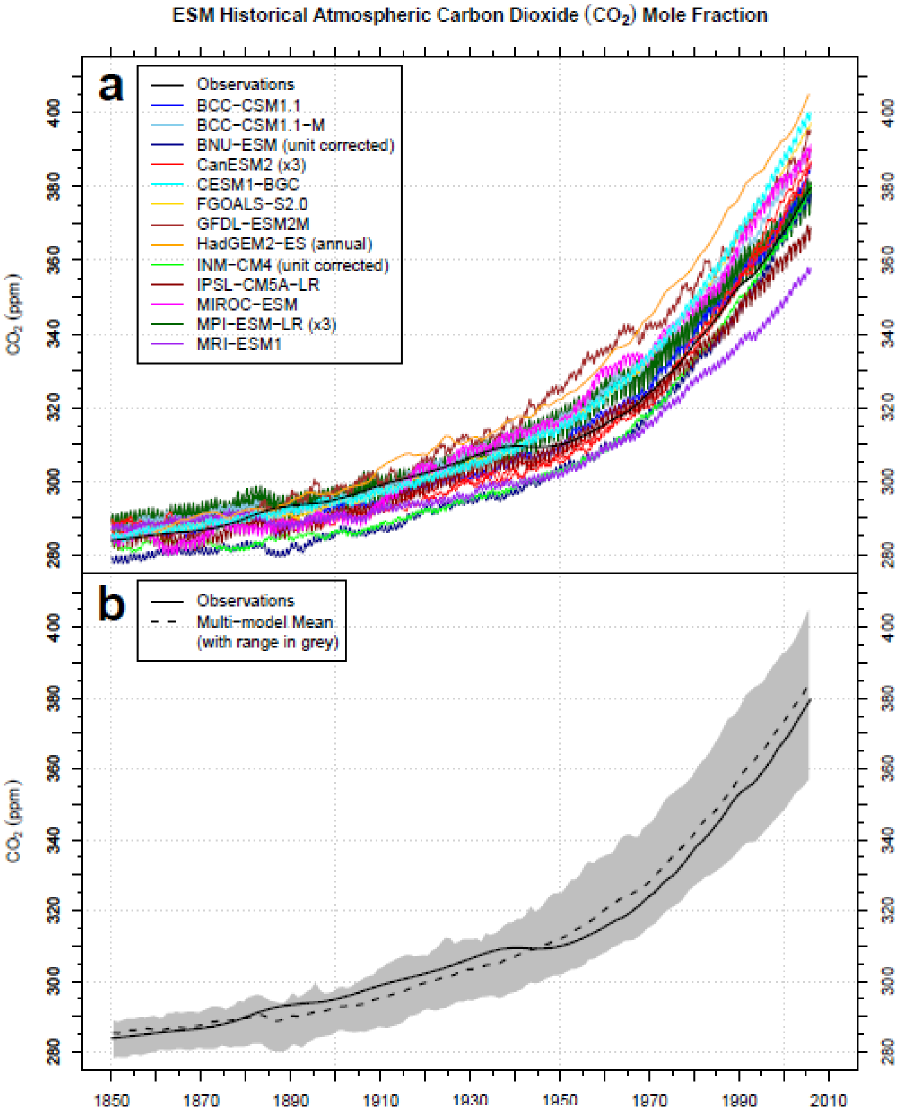
2m Air Temperature (^oK)

Precipitation (mm day^{-1})

Runoff (mm day^{-1})

Snow Depth (m)

Most CMIP5 ESMs have a positive bias in atmospheric CO_2 by the end of the observational era

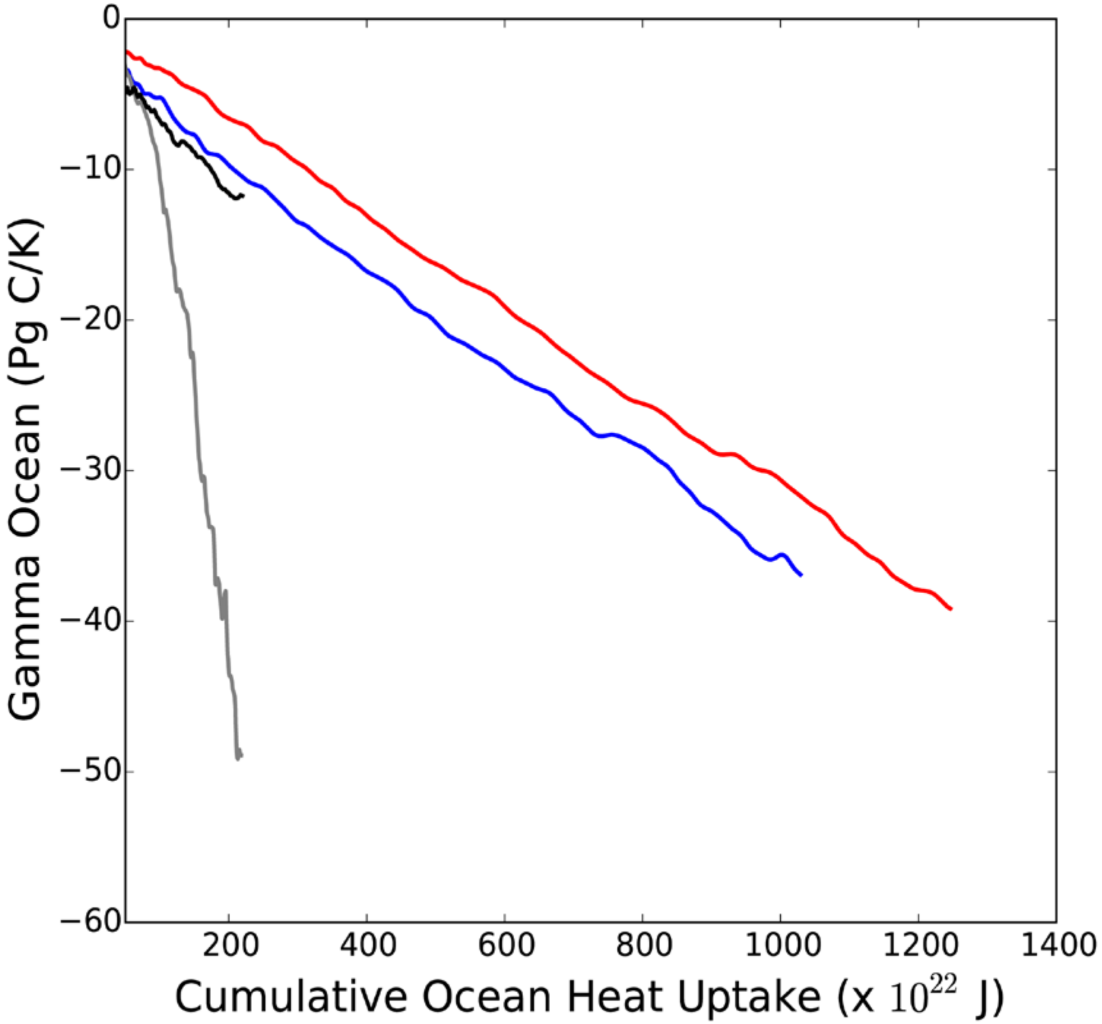


CO_2 mole fraction (ppm)

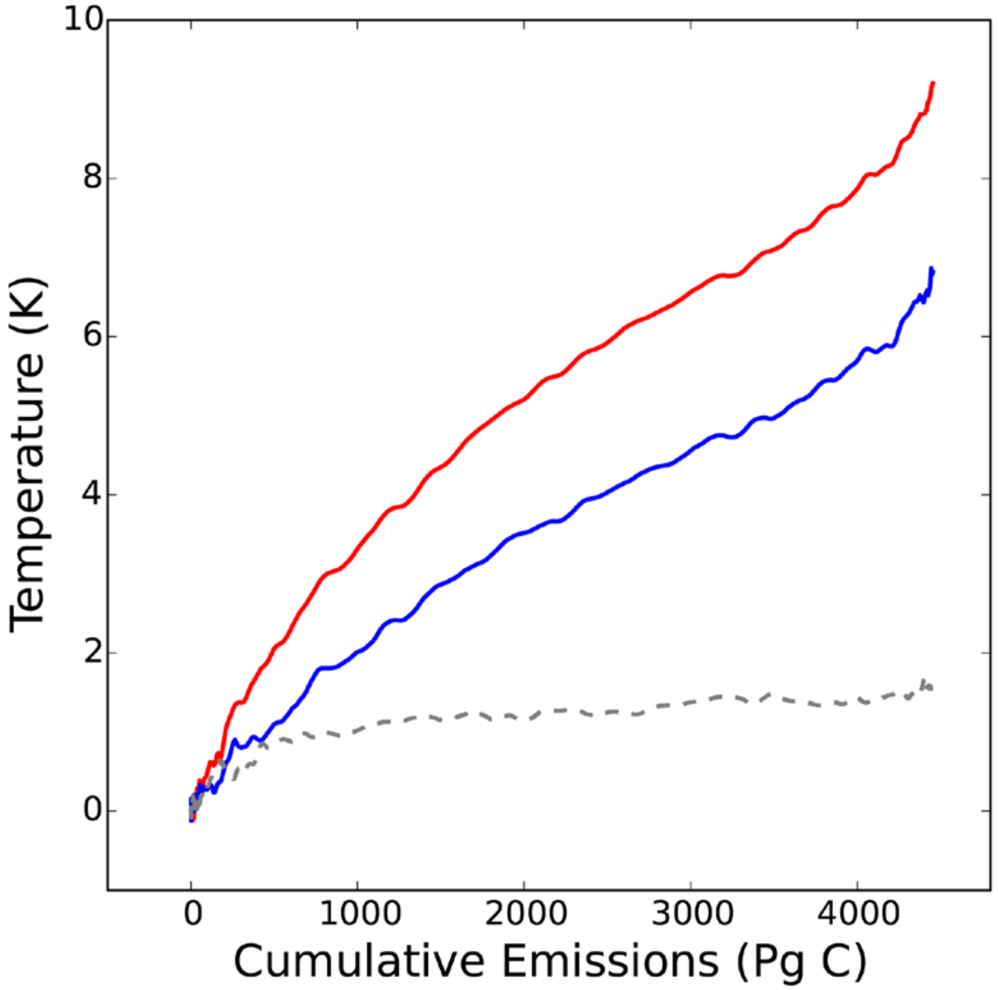
Year

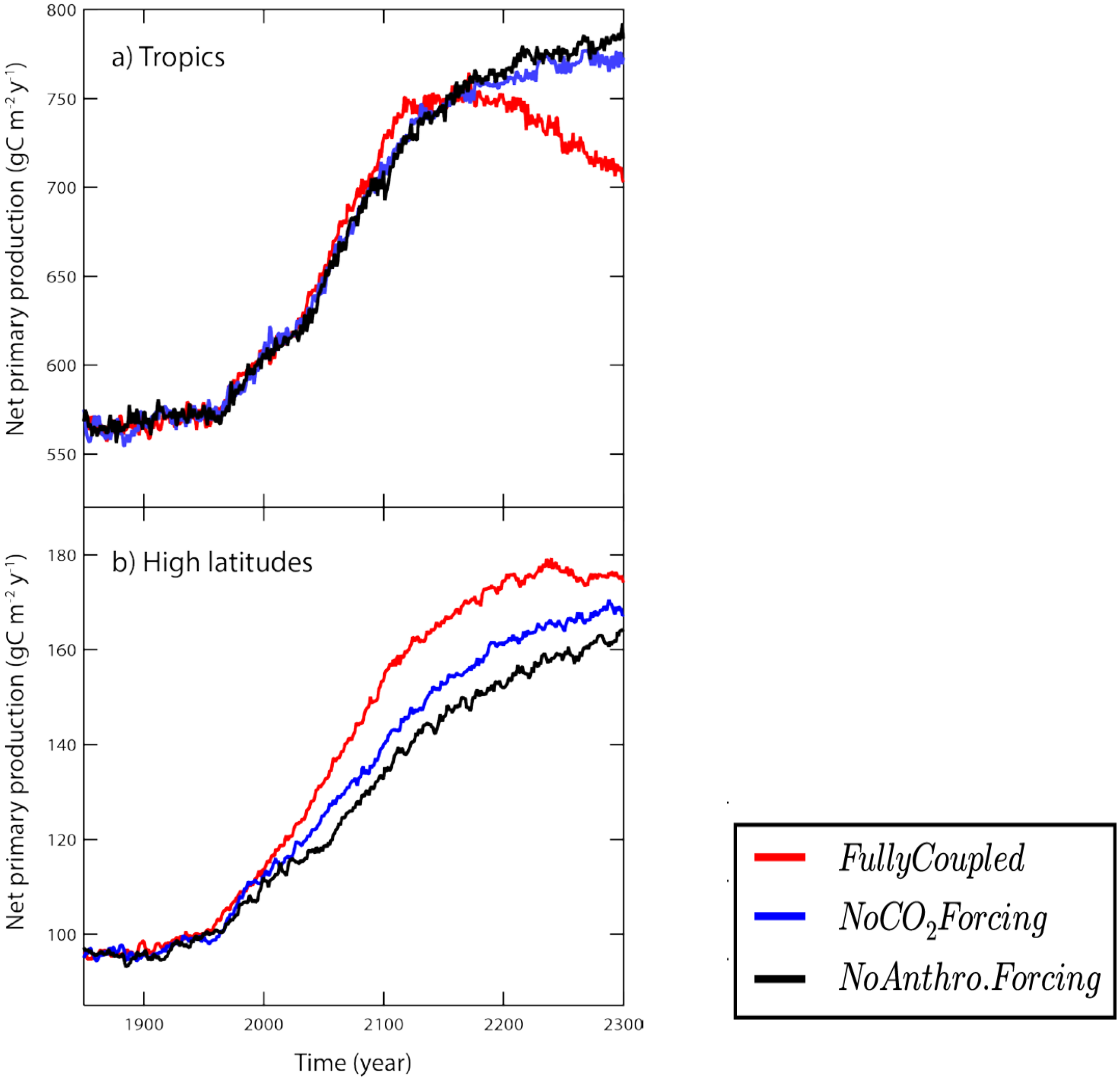
Hoffman et al. 2014

The strength of the ocean climate-carbon feedback is closely related to ocean heat content

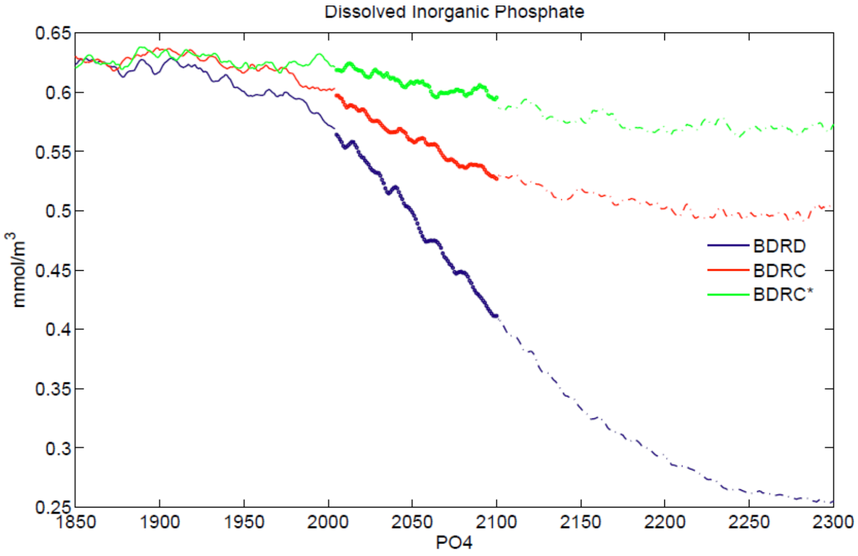


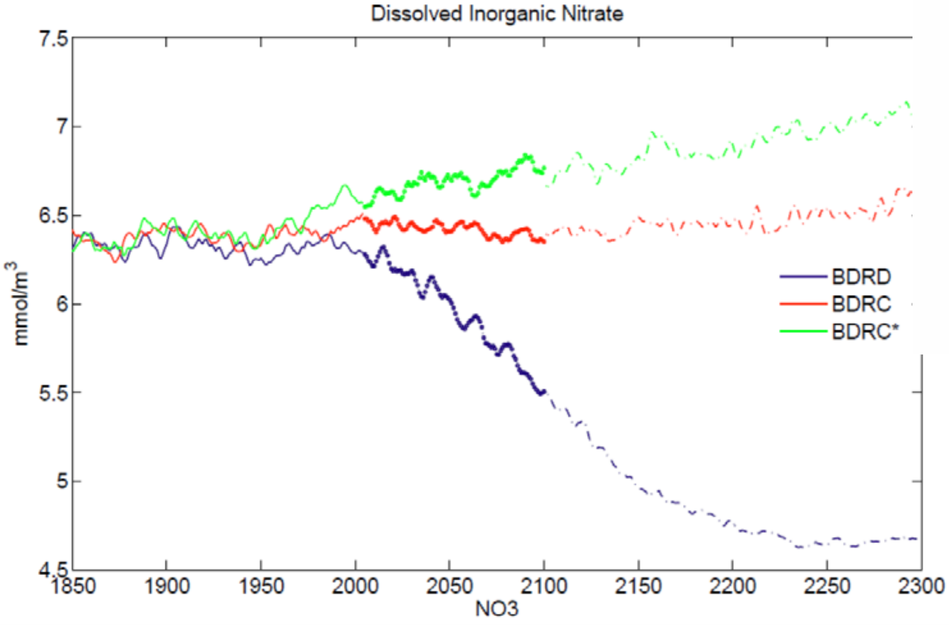
Transient Climate Response to Cumulative Emissions (TCRE)

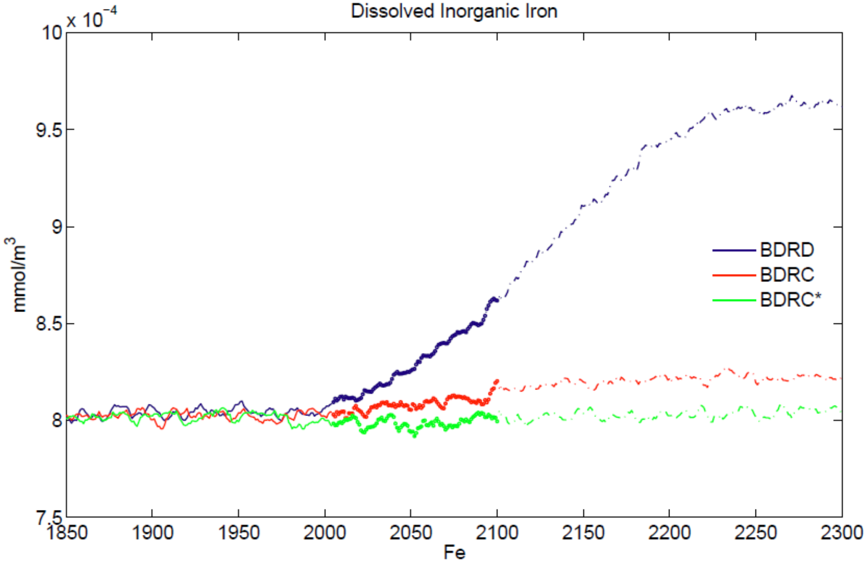


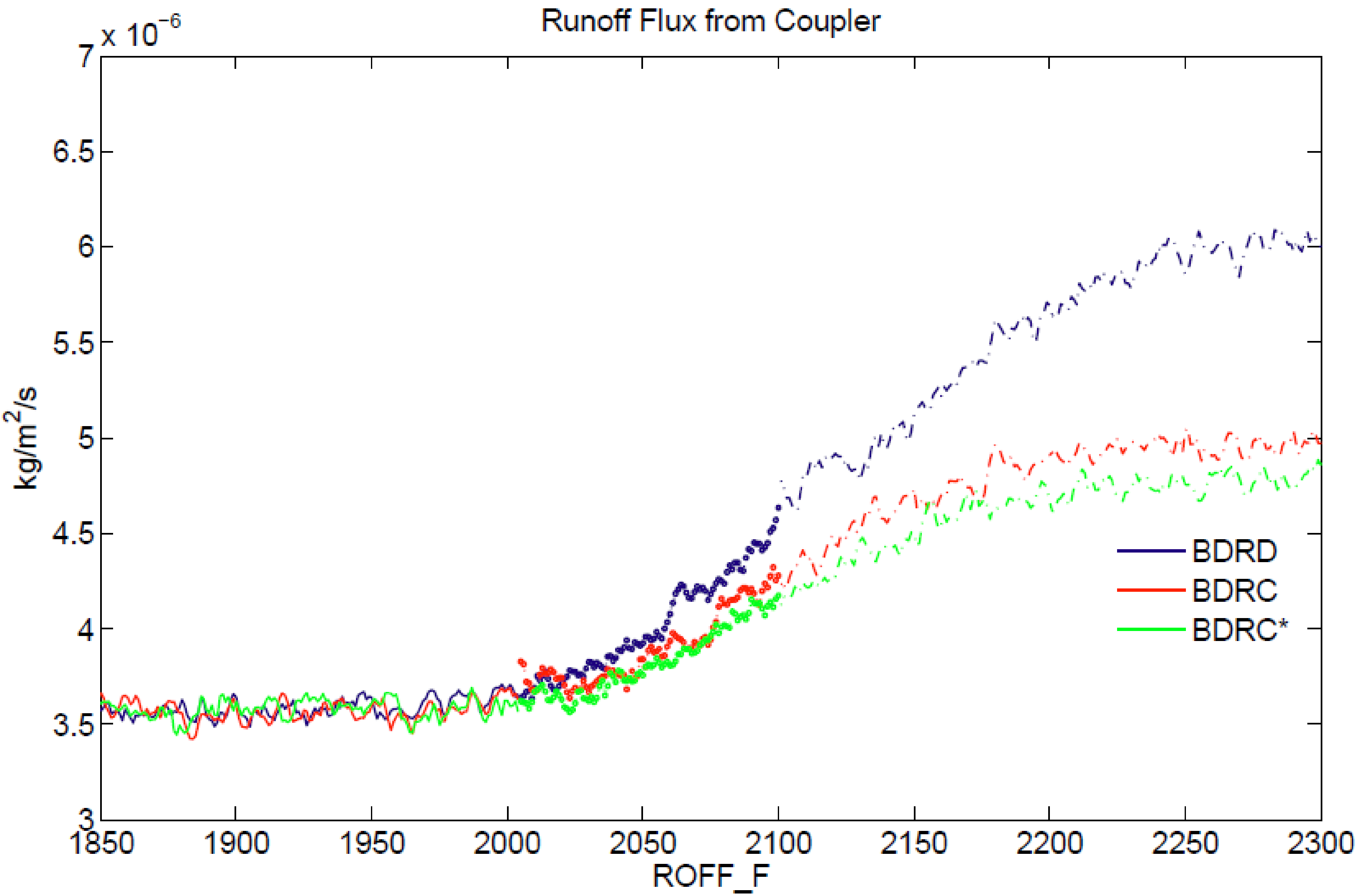

a) Tropics
b) High latitudes
Net primary production (gC m^{-2} y^{-1})
800
750
700
650
600
550
180
160
140
120
100
1900
2000
2100
2200
2300
Time (year)
FullyCoupled
NoCO$_2$Forcing
NoAnthro.Forcing

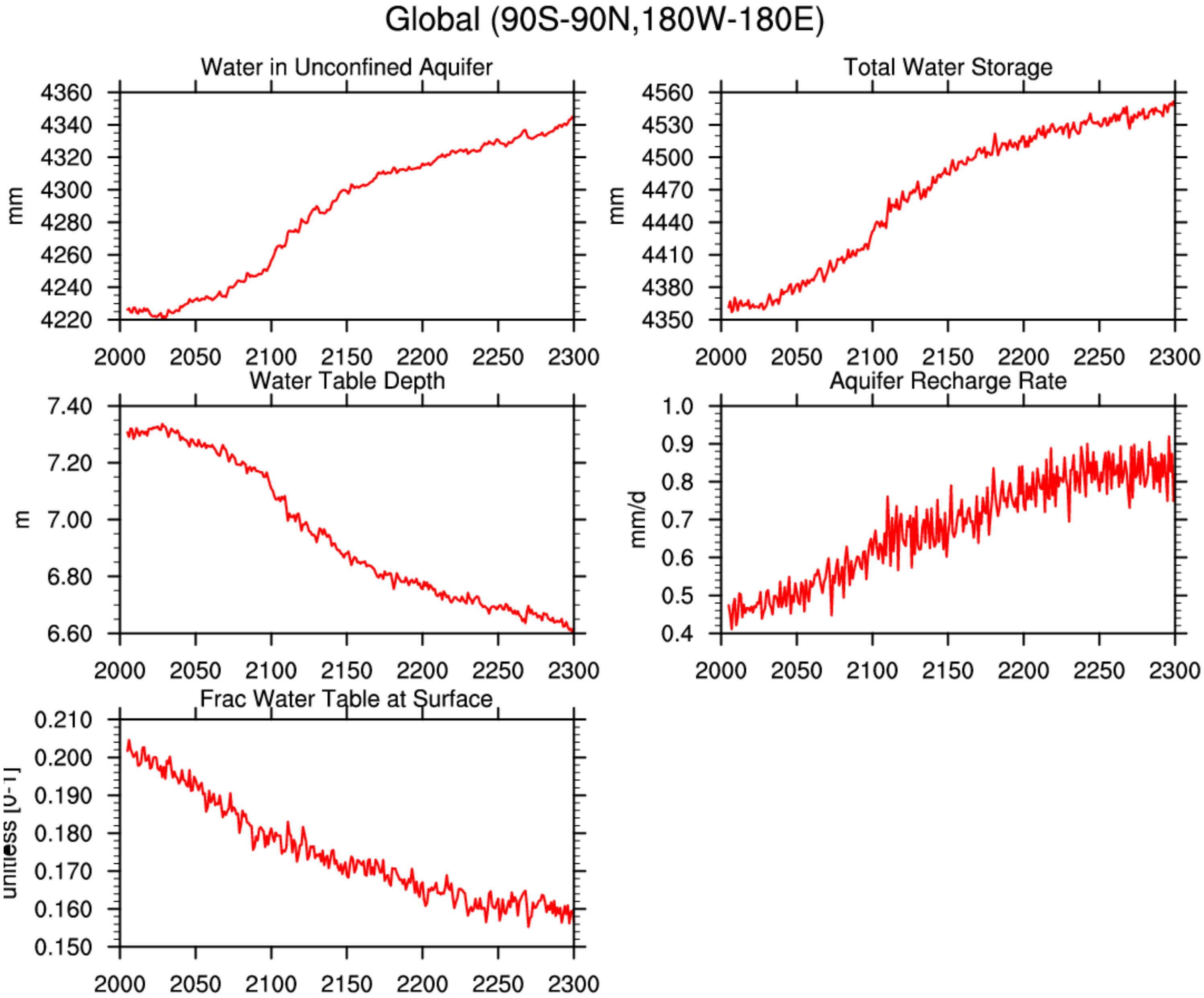
Model state variable	Time (year)			
	1999	2099	2199	2300
Atmospheric CO_2 (ppm)[1]	370	940	1831	1961
Temperature change, Fully coupled (K)	1.18	4.88	7.98	9.27
Temperature change, No CO_2 forcing (K)	0.50	1.71	2.19	2.41
Temperature change, No anth. forcing (K)	-0.03	0.43	0.74	0.76
Compatible fossil emissions, Fully coupled (Pg C)	220	1721	4014	4455
Compatible fossil emissions, No CO_2 forcing (Pg C)	223	1781	4250	4900
Compatible fossil emissions, No anth. forcing (Pg C)	229	1805	4317	5018
Ocean cumulative uptake, Fully coupled (Pg C)	97	475	866	1080
Ocean cumulative uptake, No CO_2 forcing (Pg C)	98	507	1007	1332
Ocean cumulative uptake, No anth. forcing (Pg C)	100	519	1051	1410
Land cumulative uptake, Fully coupled (Pg C)	-57	-142	-129	-178
Land cumulative uptake, No CO_2 forcing (Pg C)	-55	-115	-34	15
Land cumulative uptake, No anth. forcing (Pg C)	-51	-103	-12	54


Dissolved Inorganic Phosphate


Dissolved Inorganic Nitrate


Dissolved Inorganic Iron


Runoff Flux from Coupler
x 10^-6
7
6.5
6
5.5
5
4.5
4
3.5
3
kg/m^2/s
1850
1900
1950
2000
2050
2100
2150
2200
2250
2300
ROFF_F
BDRD
BDRC
BDRC*


Global (90S-90N,180W-180E)
Water in Unconfined Aquifer
mm
4360
4340
4320
4300
4280
4260
4240
4220
2000
2050
2100
2150
2200
2250
2300
Total Water Storage
mm
4560
4530
4500
4470
4440
4410
4380
4350
Water Table Depth
m
7.40
7.20
7.00
6.80
6.60
Aquifer Recharge Rate
mm/d
1.0
0.9
0.8
0.7
0.6
0.5
0.4
Frac Water Table at Surface
unitless [0-1]
0.210
0.200
0.190
0.180
0.170
0.160
0.150

IPCC AR5 reports that the land carbon-climate feedback is typically 4-5 times larger than the ocean feedback

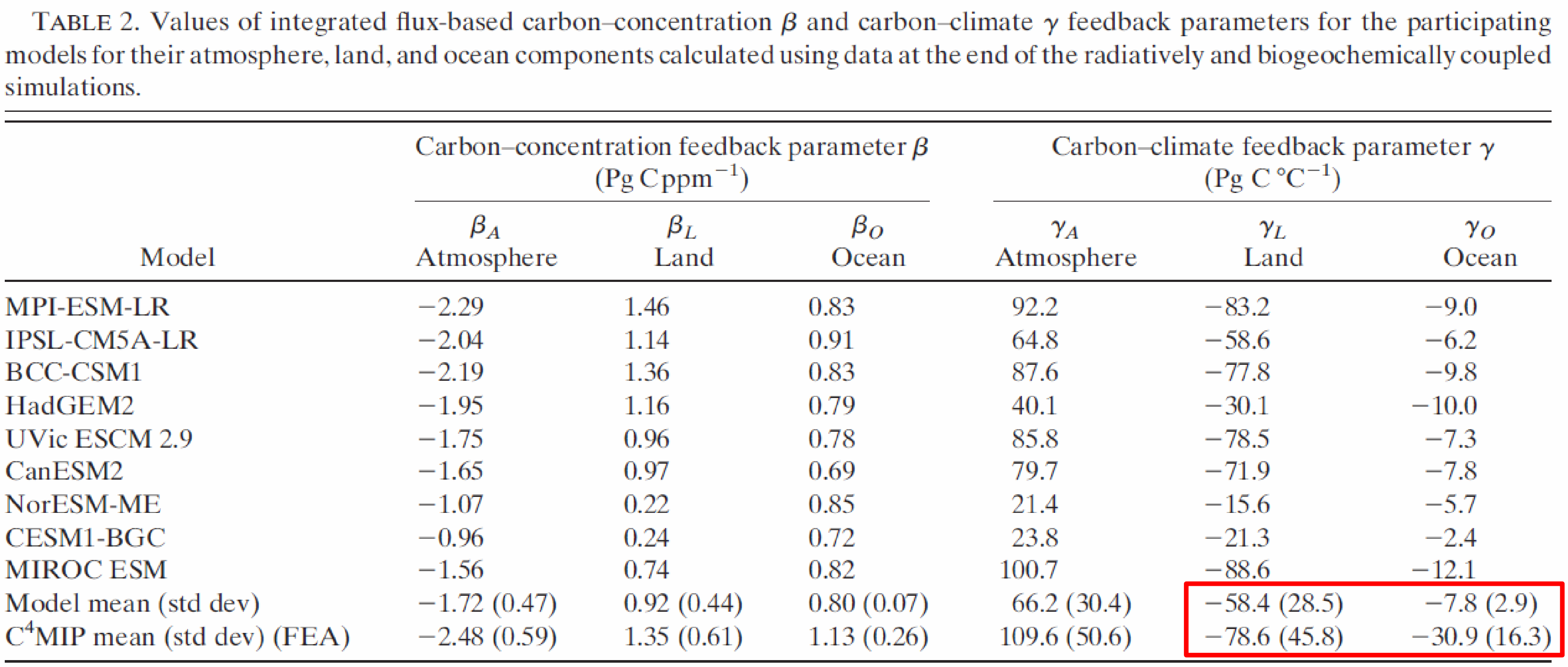


TABLE 2. Values of integrated flux-based carbon–concentration β and carbon–climate γ feedback parameters for the participating models for their atmosphere, land, and ocean components calculated using data at the end of the radiatively and biogeochemically coupled simulations.

	Carbon–concentration feedback parameter β (Pg C ppm^{-1})			Carbon–climate feedback parameter γ (Pg C °C^{-1})		
Model	β_A Atmosphere	β_L Land	β_O Ocean	γ_A Atmosphere	γ_L Land	γ_O Ocean
MPI-ESM-LR	−2.29	1.46	0.83	92.2	−83.2	−9.0
IPSL-CM5A-LR	−2.04	1.14	0.91	64.8	−58.6	−6.2
BCC-CSM1	−2.19	1.36	0.83	87.6	−77.8	−9.8
HadGEM2	−1.95	1.16	0.79	40.1	−30.1	−10.0
UVic ESCM 2.9	−1.75	0.96	0.78	85.8	−78.5	−7.3
CanESM2	−1.65	0.97	0.69	79.7	−71.9	−7.8
NorESM-ME	−1.07	0.22	0.85	21.4	−15.6	−5.7
CESM1-BGC	−0.96	0.24	0.72	23.8	−21.3	−2.4
MIROC ESM	−1.56	0.74	0.82	100.7	−88.6	−12.1
Model mean (std dev)	−1.72 (0.47)	0.92 (0.44)	0.80 (0.07)	66.2 (30.4)	−58.4 (28.5)	−7.8 (2.9)
C^{4}MIP mean (std dev) (FEA)	−2.48 (0.59)	1.35 (0.61)	1.13 (0.26)	109.6 (50.6)	−78.6 (45.8)	−30.9 (16.3)

From Arora et al. (2013)