Multi-century changes in land and ocean contributions to the climate-carbon feedback

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THE UNIVERSITY OF CALIFORNIA IRVINE

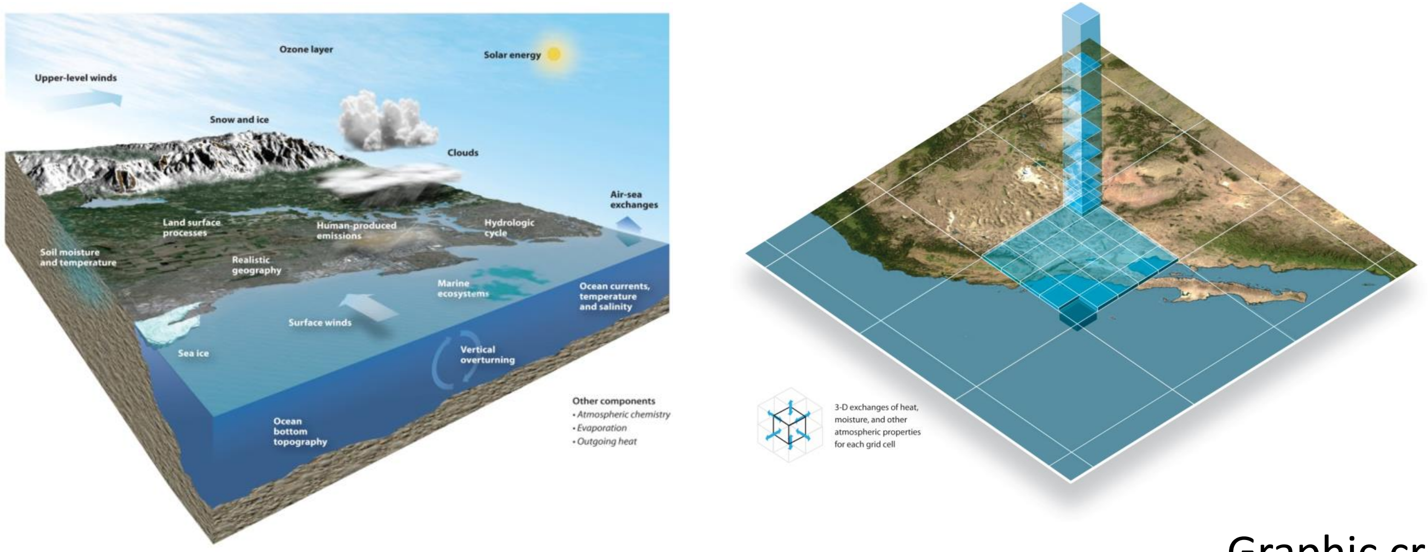
UCI DEPARTMENT OF EARTH SYSTEM SCIENCE

Biogeochemical Cycles Feedbacks
Science Focus Area

Science questions:

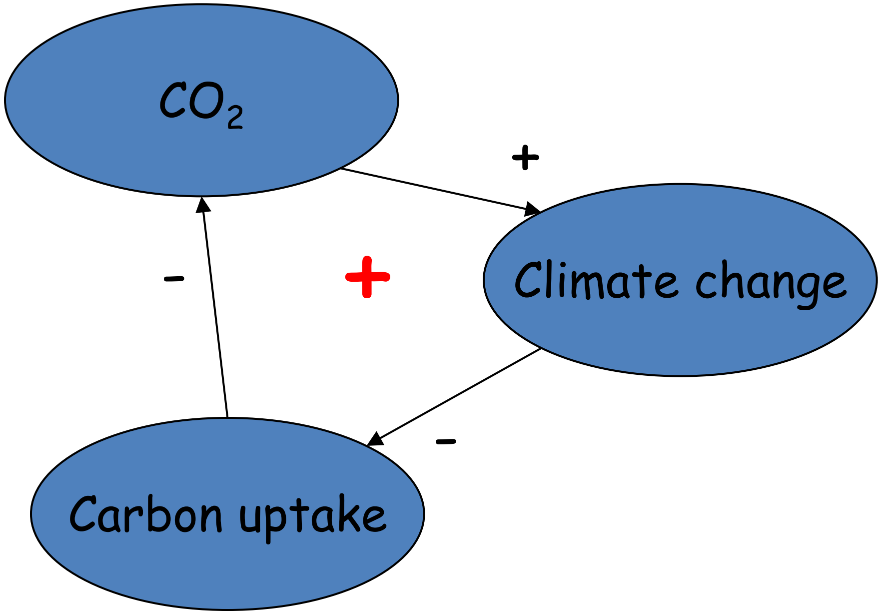
- How does the climate-carbon feedback evolve century by century to 2300?
- Do ocean and land feedbacks intensify over time?
- What are the implications of long-term changes in climate for land precipitation, disturbance regimes and terrestrial ecosystem function?

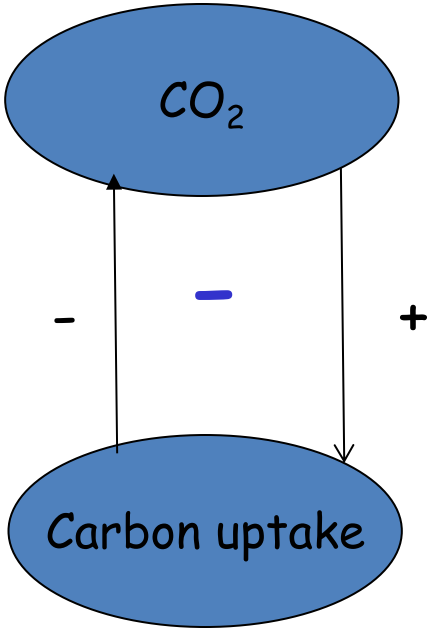
The Community Earth System Model



Graphic credit: UCAR

Two types of carbon cycle feedbacks influence the temporal evolution of atmospheric CO_2





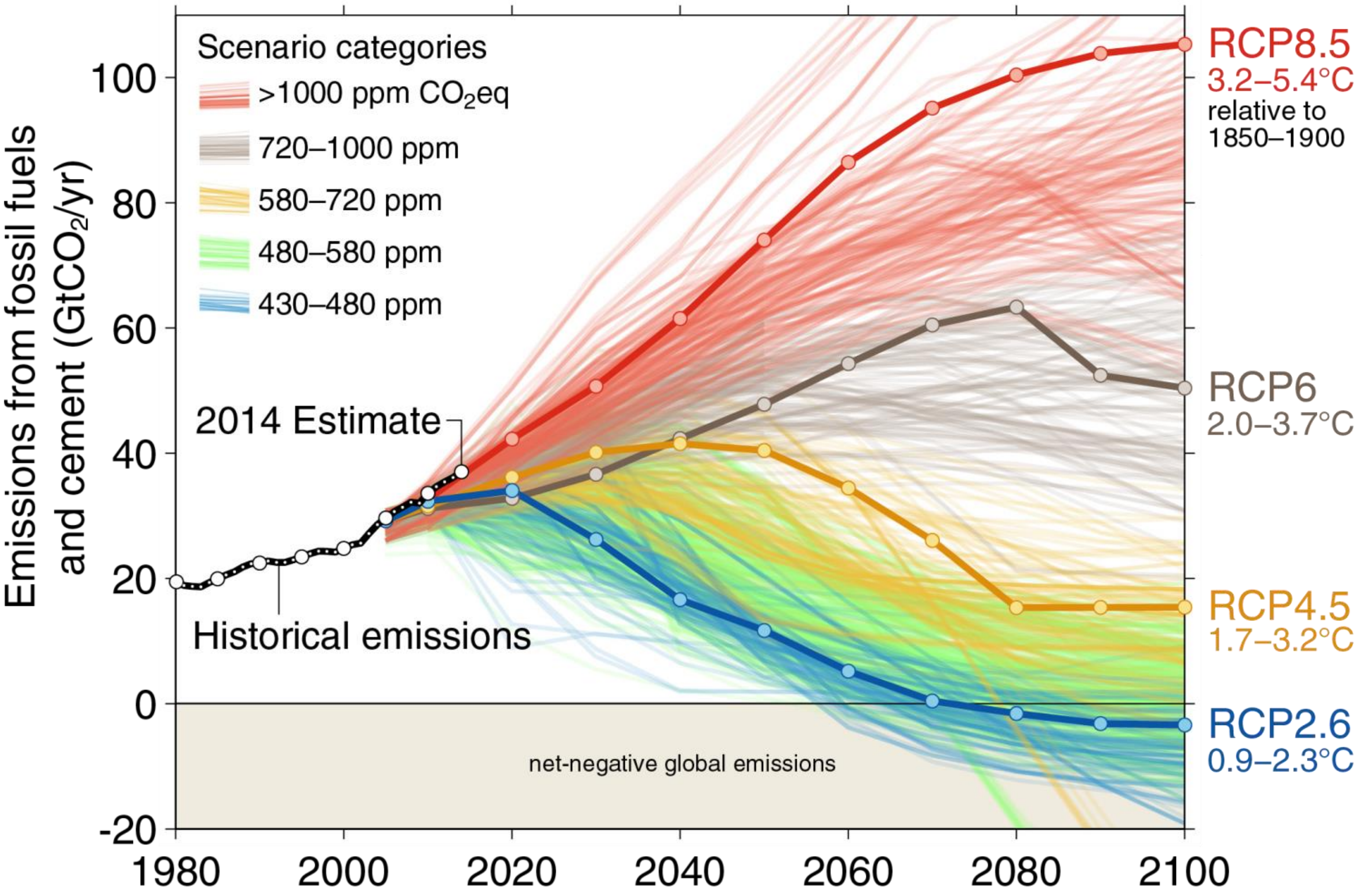
Climate–carbon feedback

γ

Concentration–carbon feedback

β

Simulation design: Prescribed atm. CO_2 from RCP8.5



The Global Carbon Project, 2014

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)

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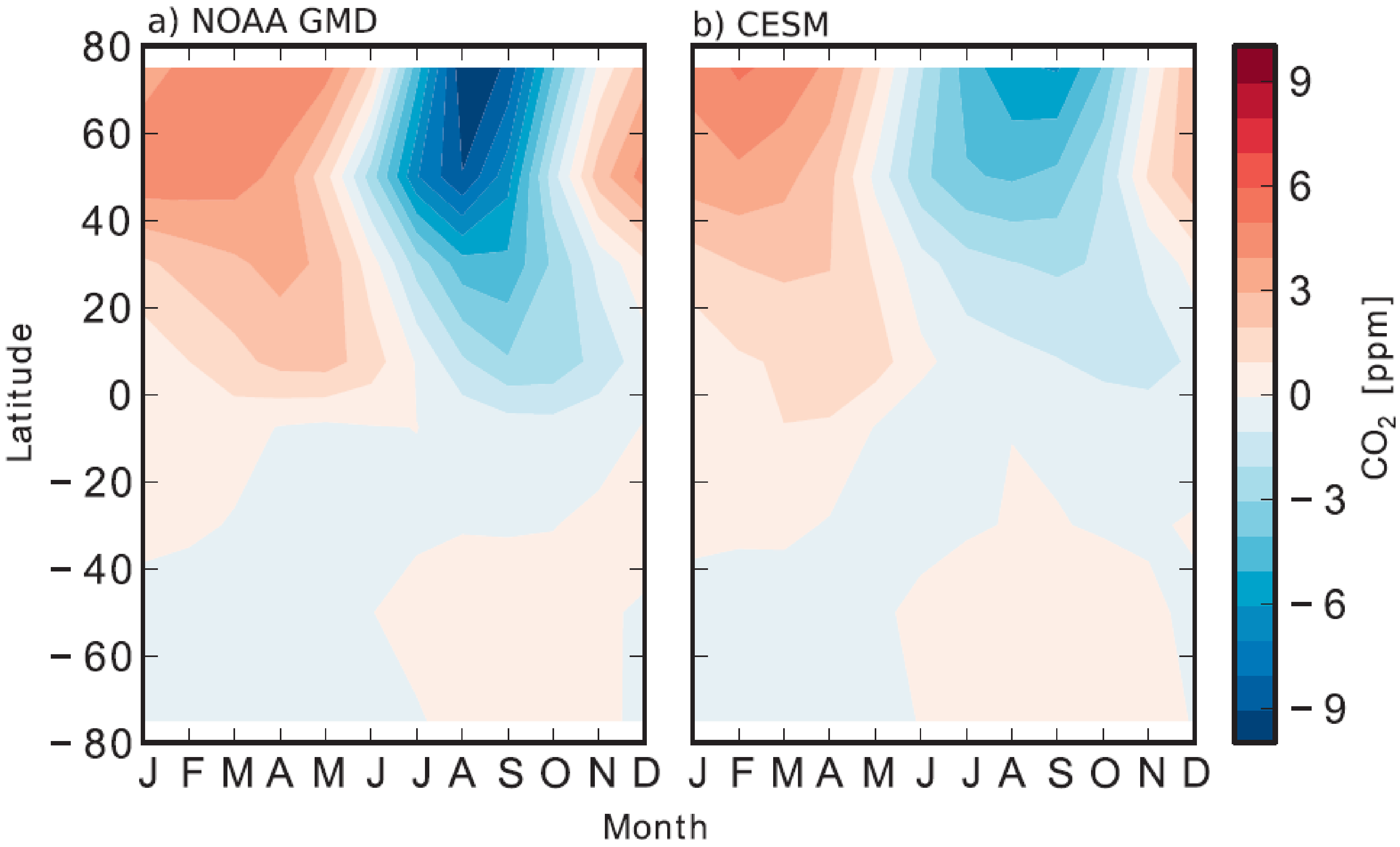
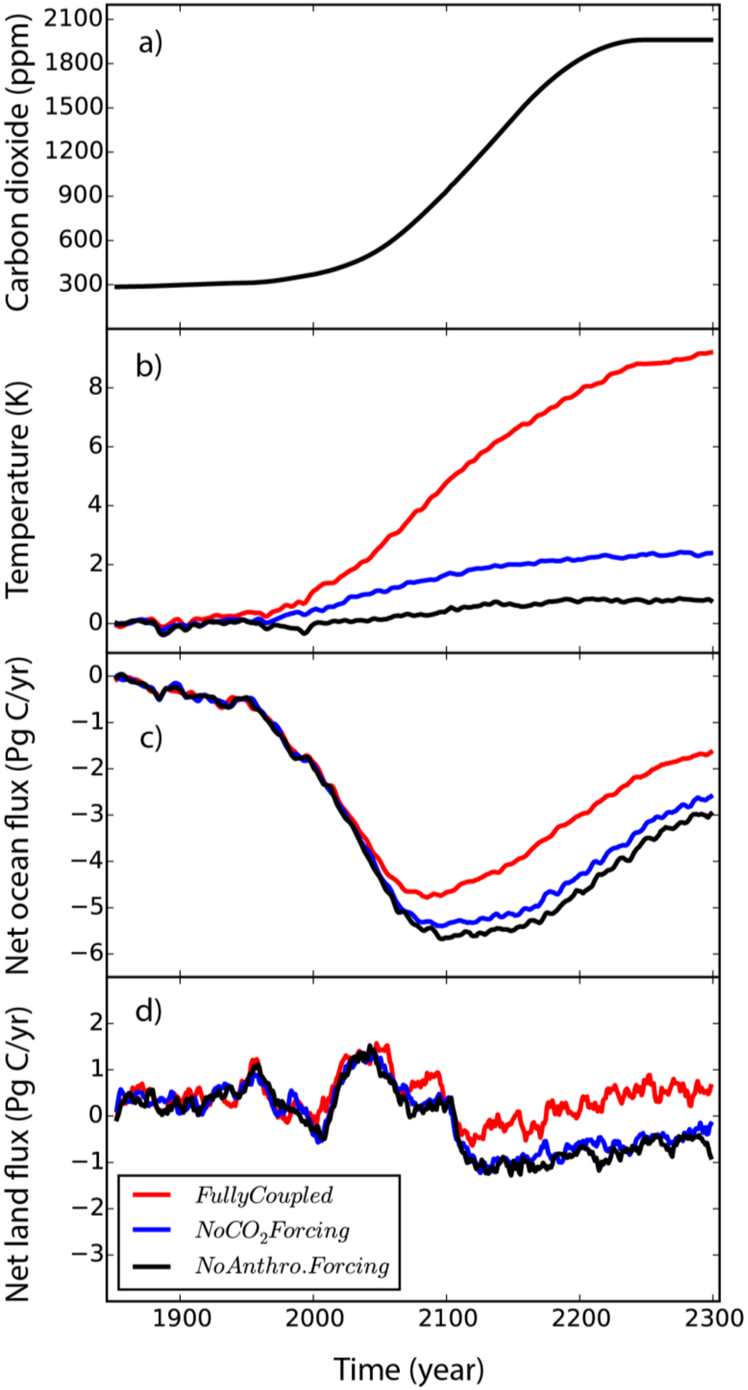
Lindsay et al. (2014), Keppel-Aleks et al. (2013), Moore et al. (2013), Long et al. (2013)

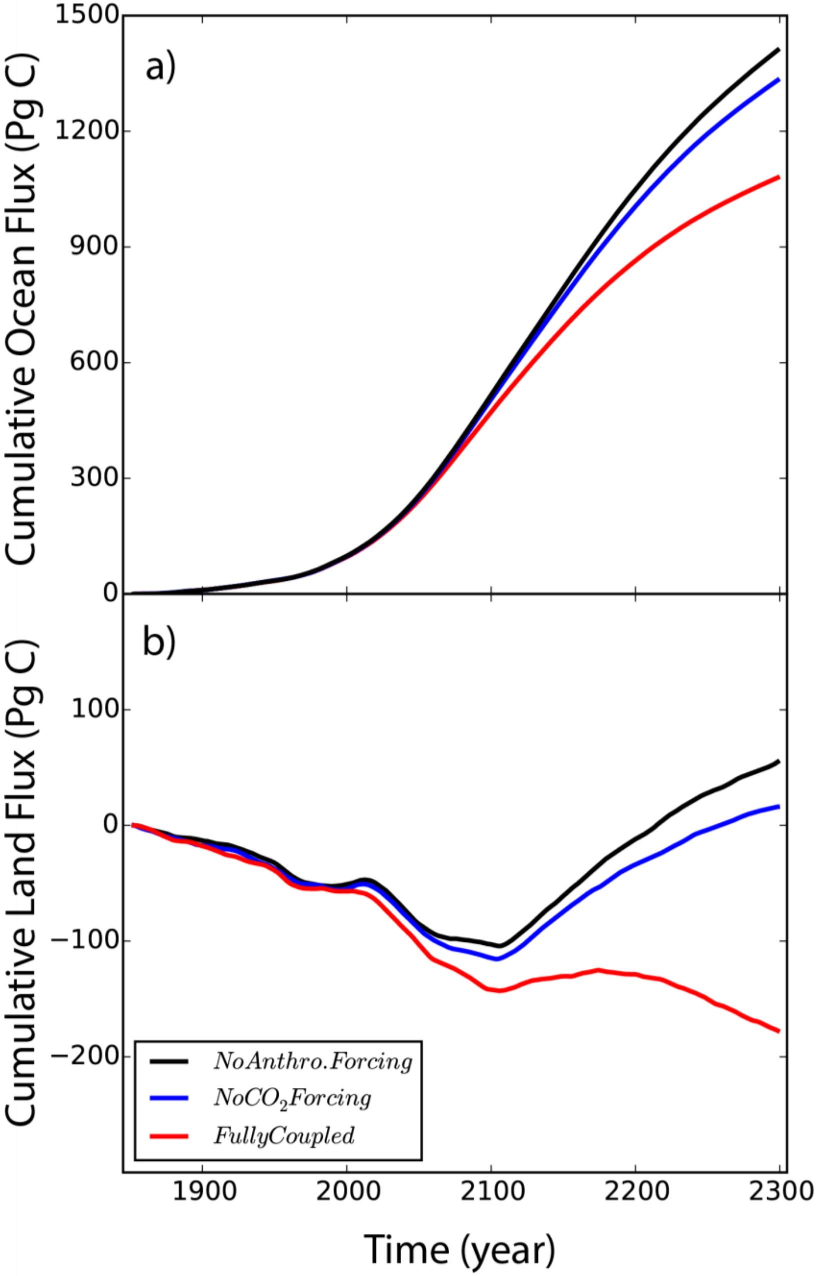
Validation of carbon cycle processes in CESM



Keppel Aleks et al., 2013, Journal of Climate



Randerson et al., In press



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

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

Climate feedbacks reduce possible emissions from 5020 Pg C to 4460 Pg C (11%)

Randerson et al., In press

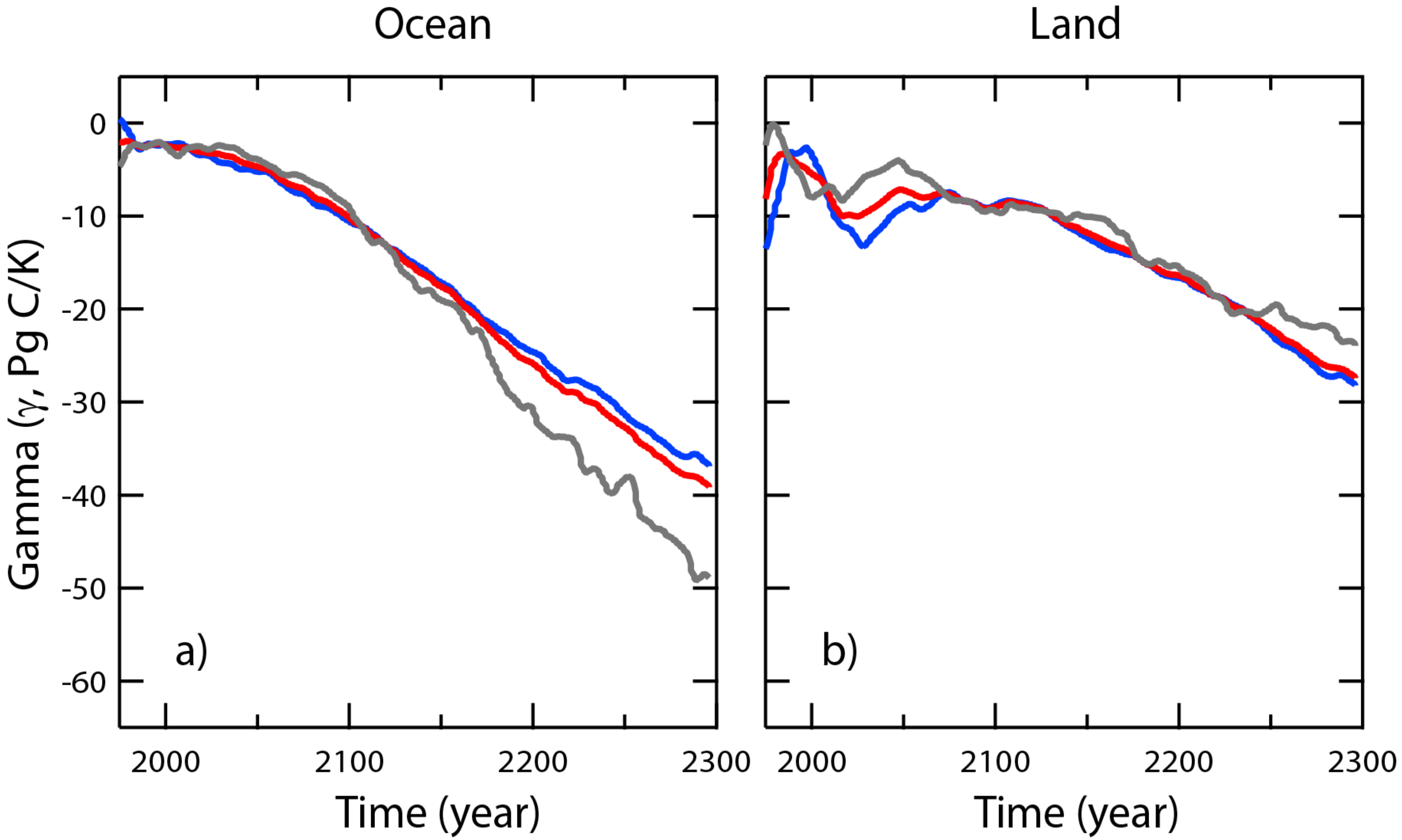
Climate-carbon feedback parameters

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 (g)	0.013	0.034	0.056	0.091

$$g = \alpha(\gamma_O + \gamma_L)/(m + \beta_O + \beta_L)$$

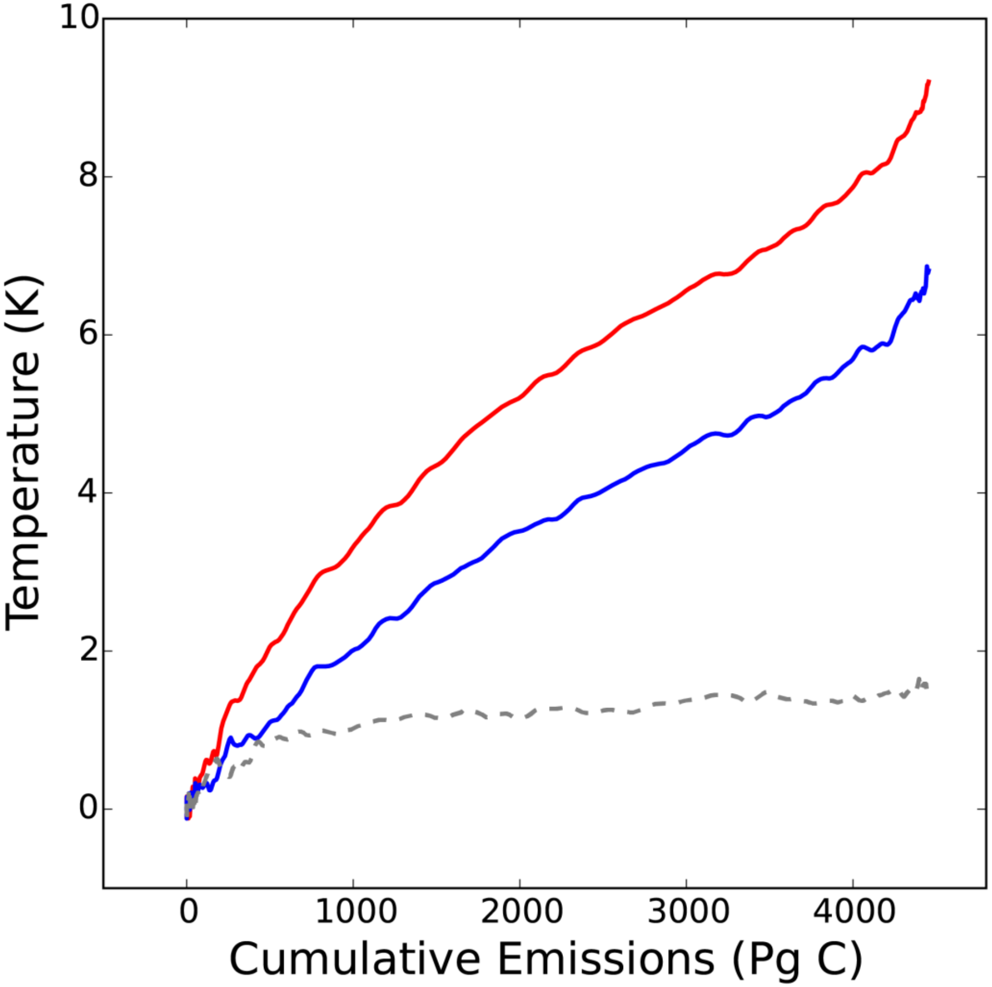
Randerson et al., In press

Cumulative Climate-Carbon Feedback Parameter Gamma



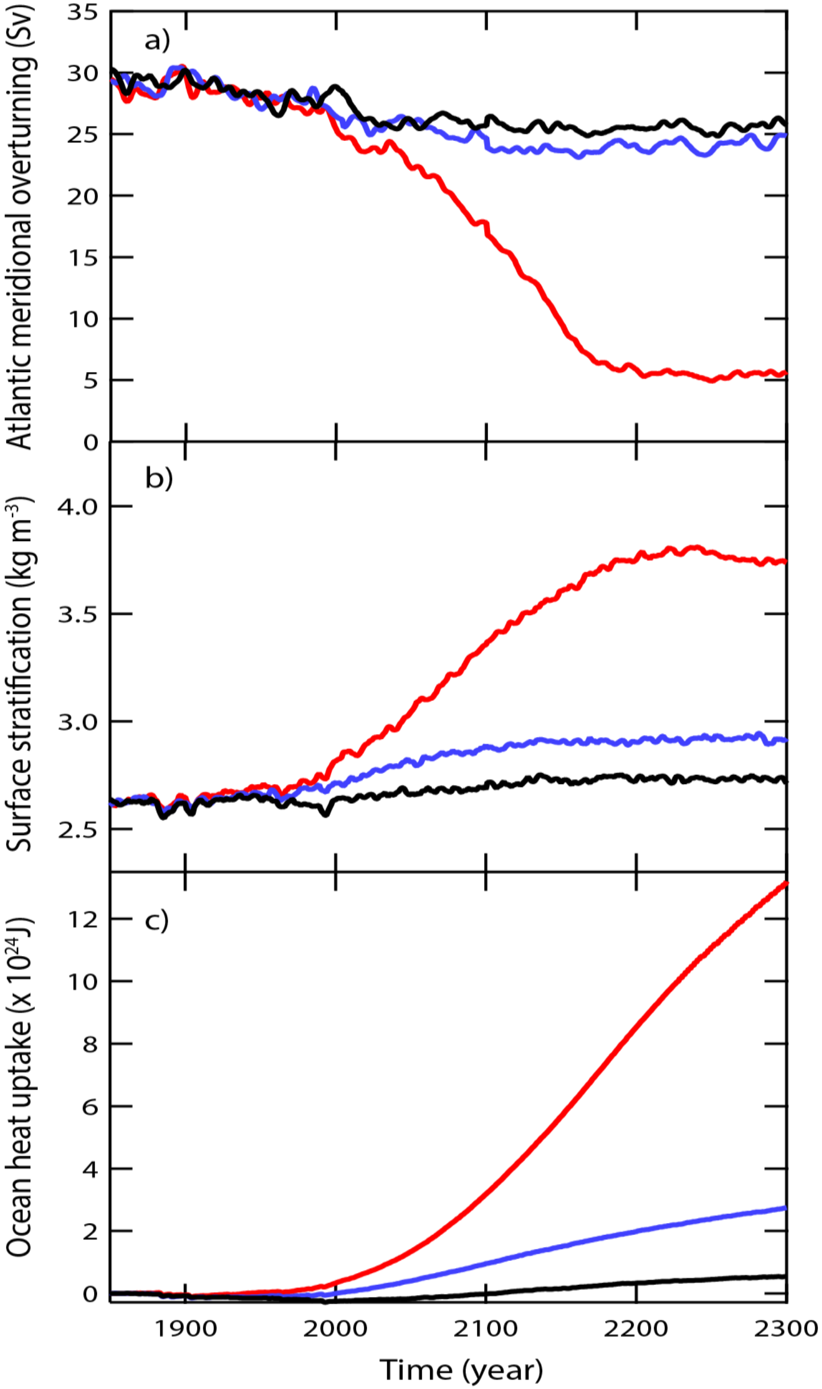
Blue = FC – no CO_2; **Red = FC – no anthro.**; **grey= no CO_2 – no anthro.**

Transient Climate Response to Cumulative Emissions (TCRE)



What are the mechanisms causing feedbacks to intensify?

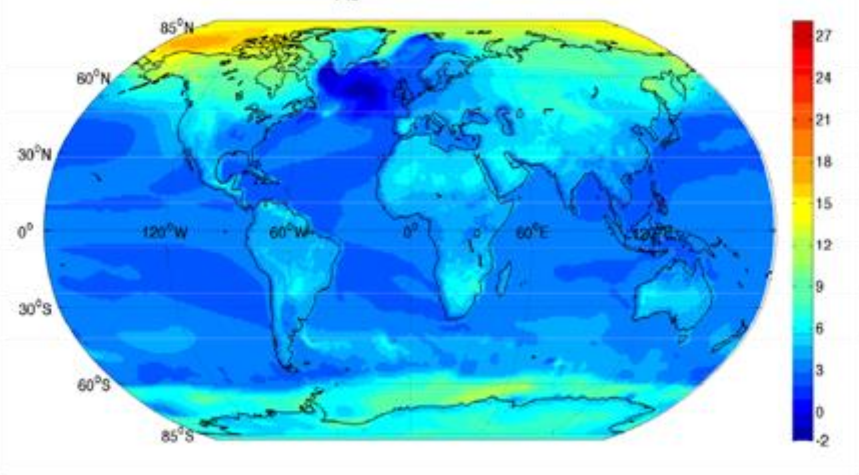
How is the ocean changing?



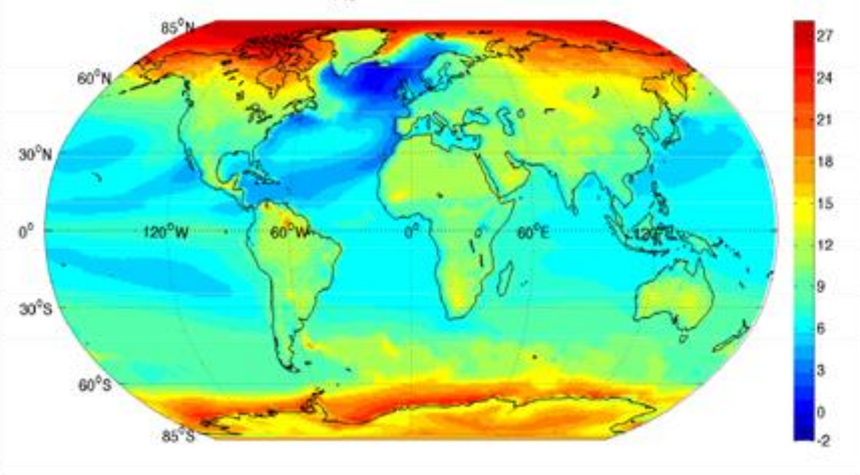
Randerson et al., In press

Shutdown in Atlantic Meridional Overturning Reduces Carbon Uptake in CESM

(a) T_{AS}: 2100-1850

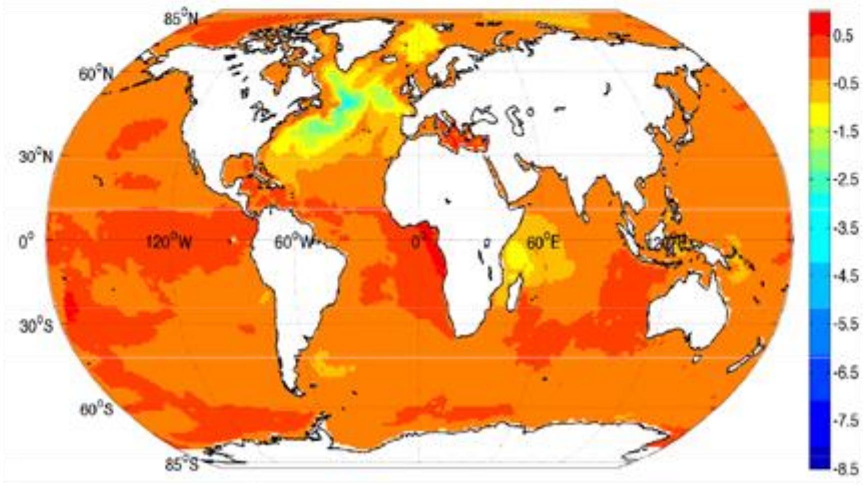


(b) T_{AS}: 2300-1850

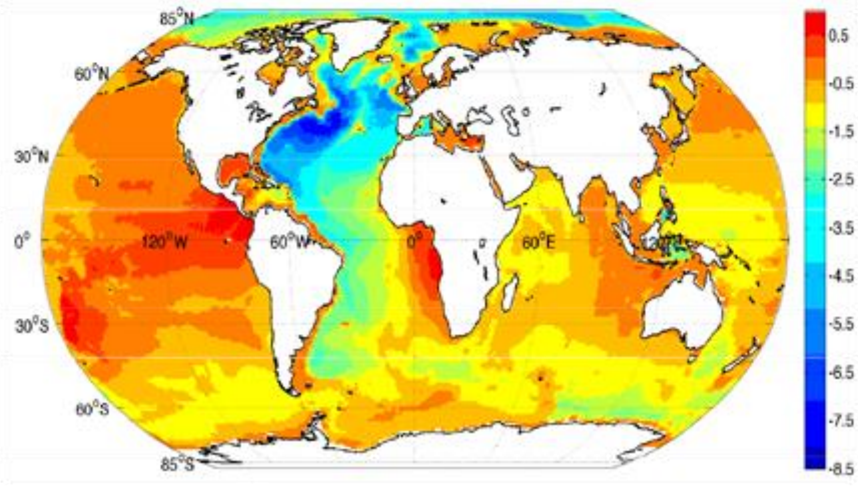


Kg C per m^2

(c) ocean carbon: 2100-1850



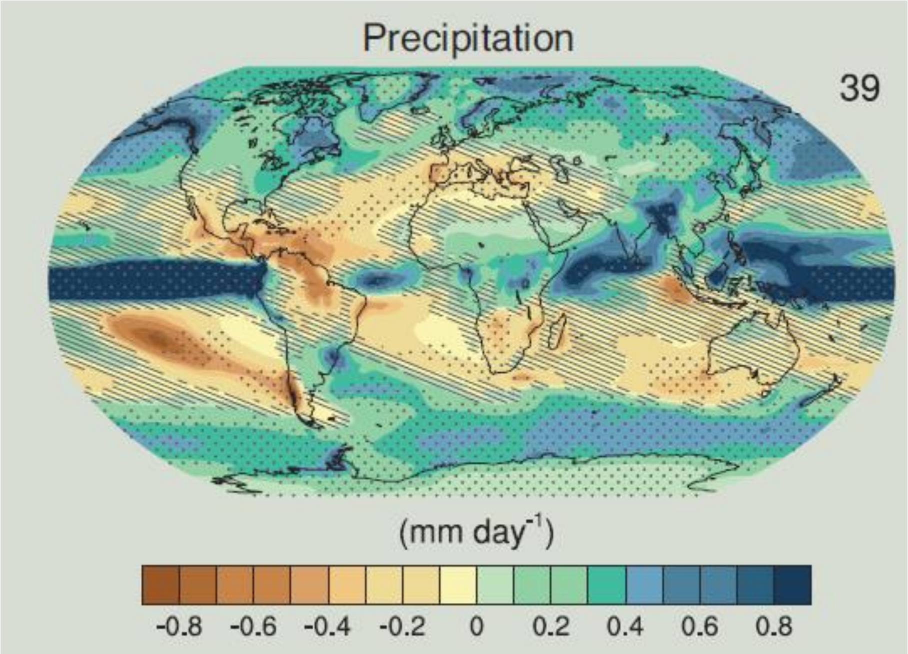
(d) ocean carbon: 2300-1850



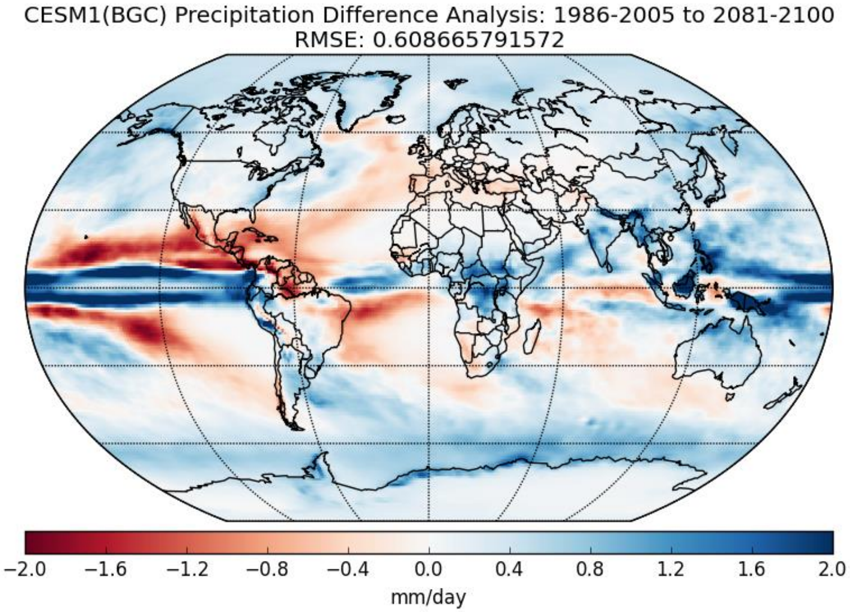
Changing vulnerability of the Amazon to drought

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

CMIP5 multi-model mean, IPCC AR1 TS



CESM1(BGC)

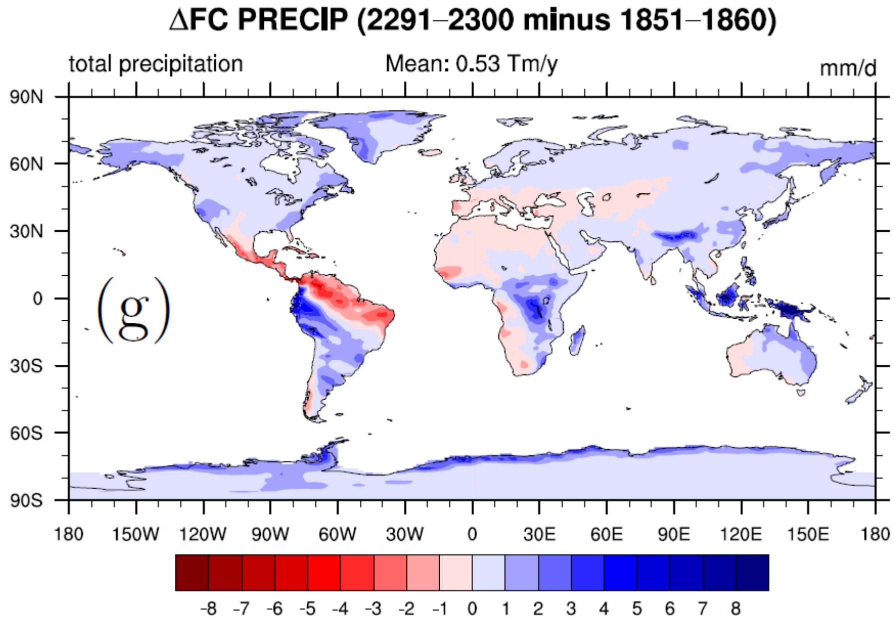


mm/day

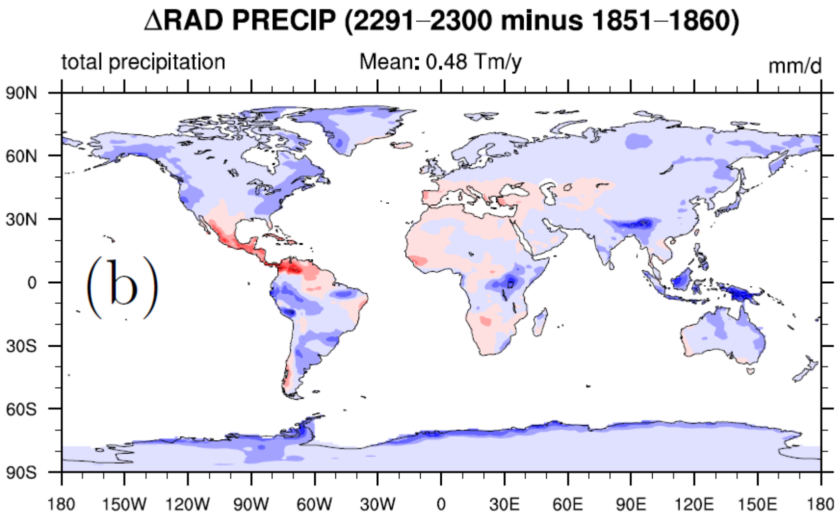
Hydrological cycle changes are not uniform across tropical land, with most models drying more in South America than in Africa or Asia

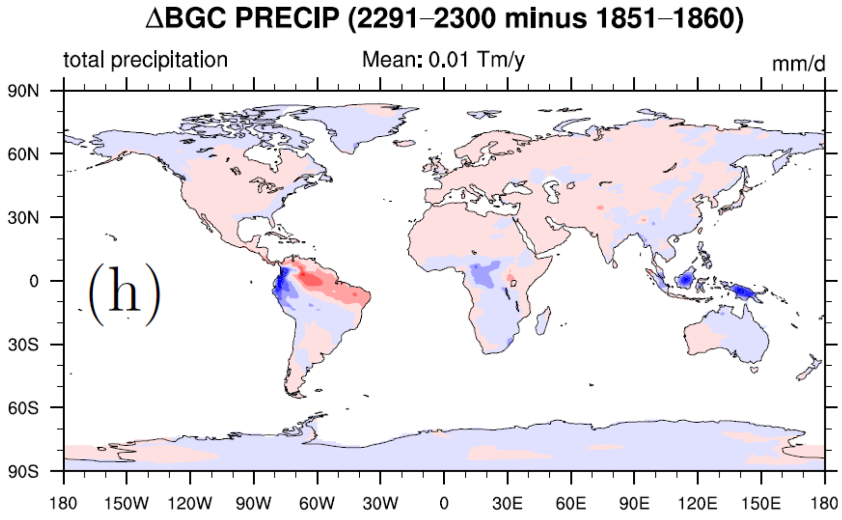
Precipitation reductions in neotropical forests driven equally by radiative and physiological effects of CO_2

Most of the world is wetter and there is much higher water availability globally by 2300 – with the exception of Central America, Europe, and western Africa

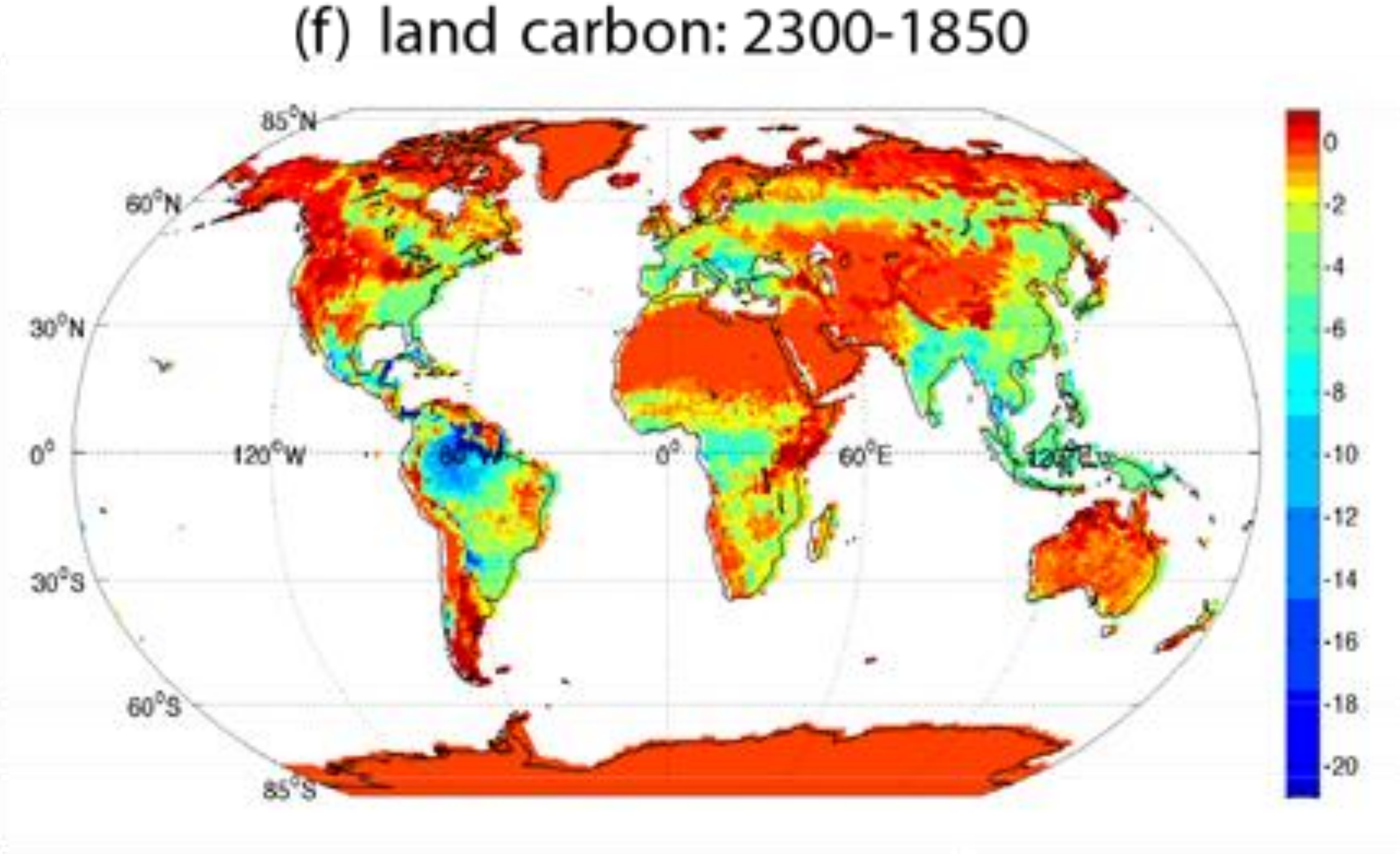


Hoffman et a. (in prep.)



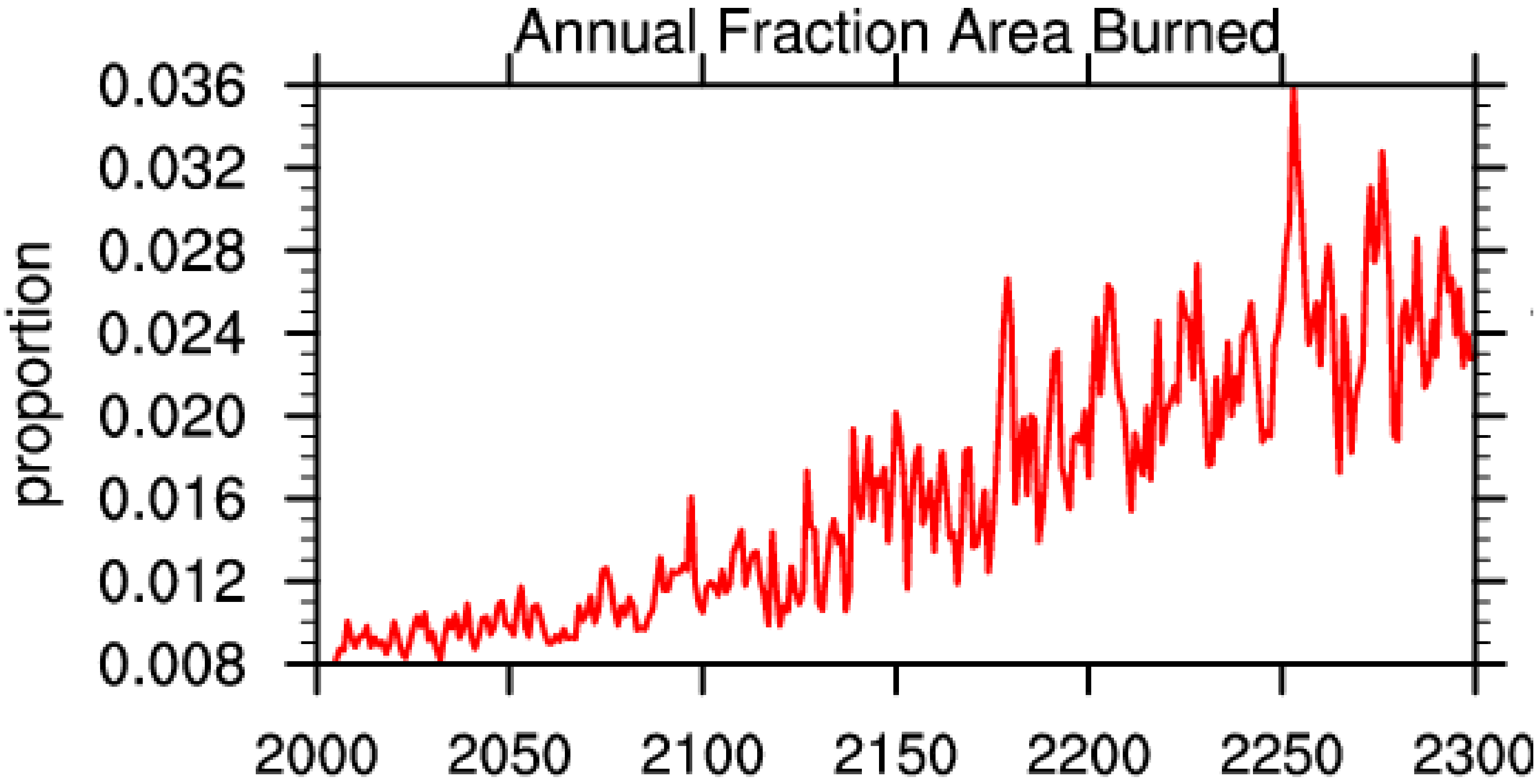


Forests in Central and South America exhibit a high degree of vulnerability to climate change-induced carbon losses

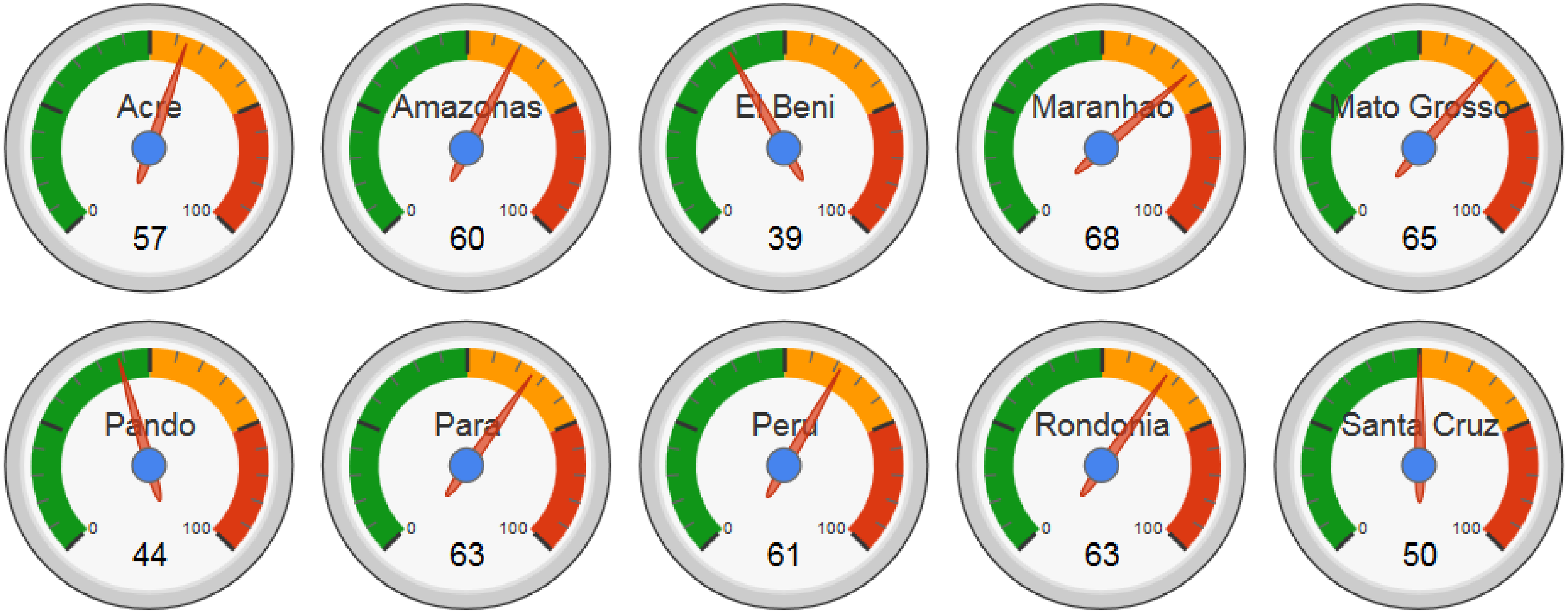


Kg C per m^2

Amazon broadleaf forest burned area from the fully coupled simulation



2015 Amazon fire season forecast
Using SSTs through March for a fire season that spans July-October



https://webfiles.uci.edu/ychen17/data/SAMFSS2015.html

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 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

Next Steps

- Repeat the experimental design with CESM1.2(BGC) that has improvements in ocean physics and biogeochemistry from Keith, permafrost from Charlie, and GPP from Gordon Bonan
  - Document improvements from CESM1 to 1.2 using ILAMB
  - Conduct emissions forced experiments
  - Track the CO_2 pulse and impacts to year 2300

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

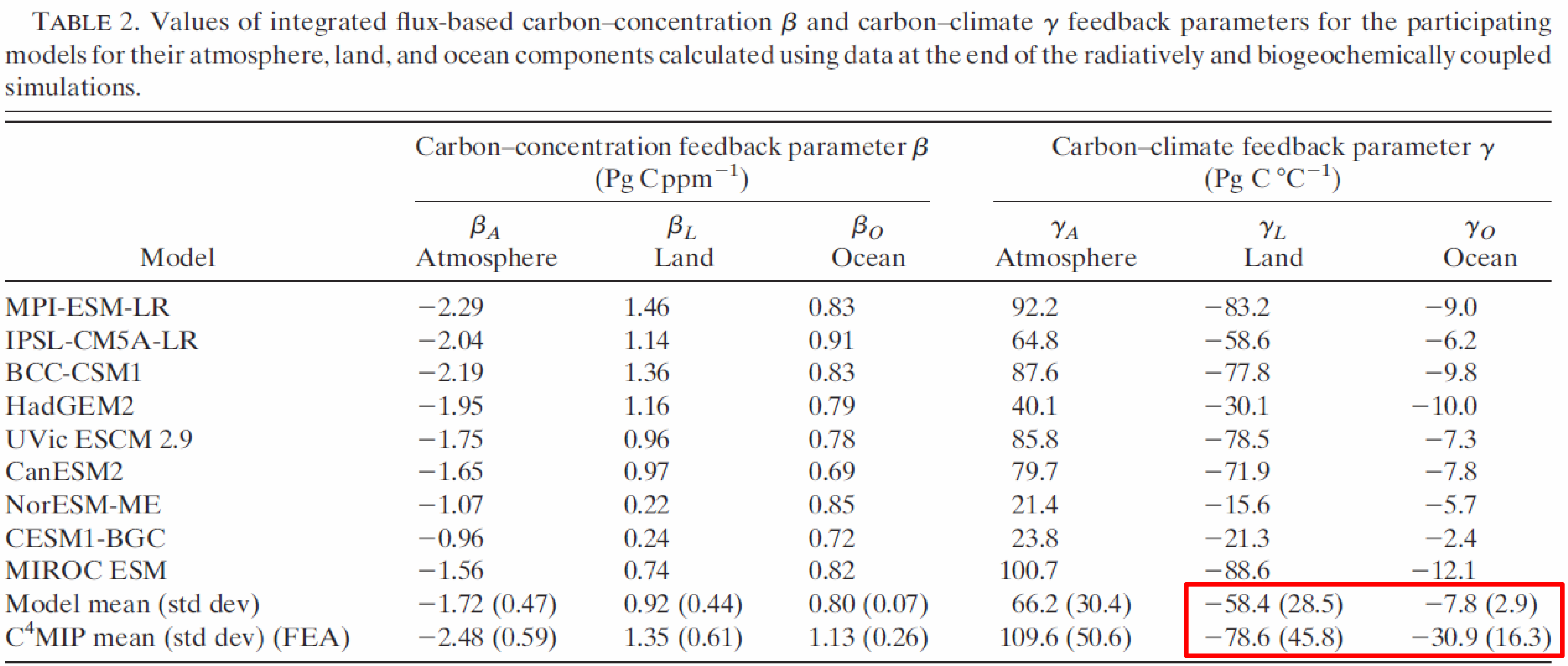


TABLE 2. Values of integrated flux-based carbon–concentration β and carbon–climate γ feedback parameters for the participating models for their atmosphere, land, and ocean components calculated using data at the end of the radiatively and biogeochemically coupled simulations.

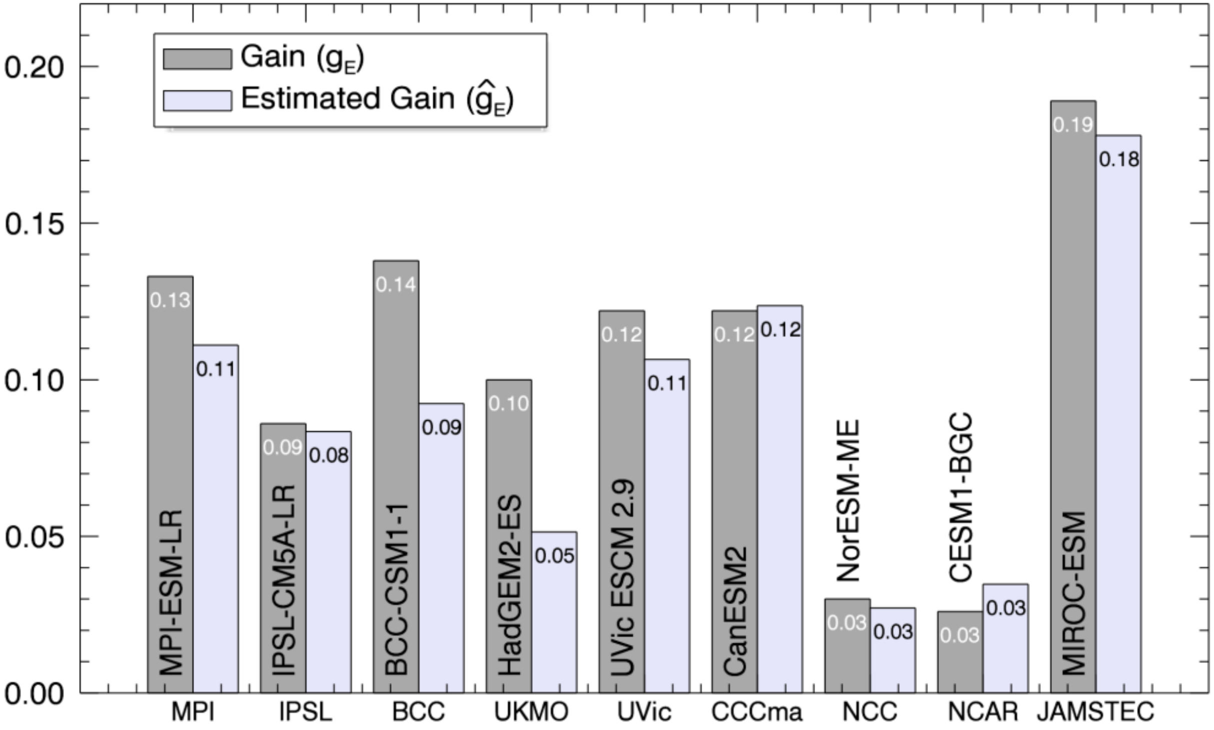
	Carbon–concentration feedback parameter β (Pg C ppm^{-1})			Carbon–climate feedback parameter γ (Pg C °C^{-1})		
Model	β_A Atmosphere	β_L Land	β_O Ocean	γ_A Atmosphere	γ_L Land	γ_O Ocean
MPI-ESM-LR	−2.29	1.46	0.83	92.2	−83.2	−9.0
IPSL-CM5A-LR	−2.04	1.14	0.91	64.8	−58.6	−6.2
BCC-CSM1	−2.19	1.36	0.83	87.6	−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)

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

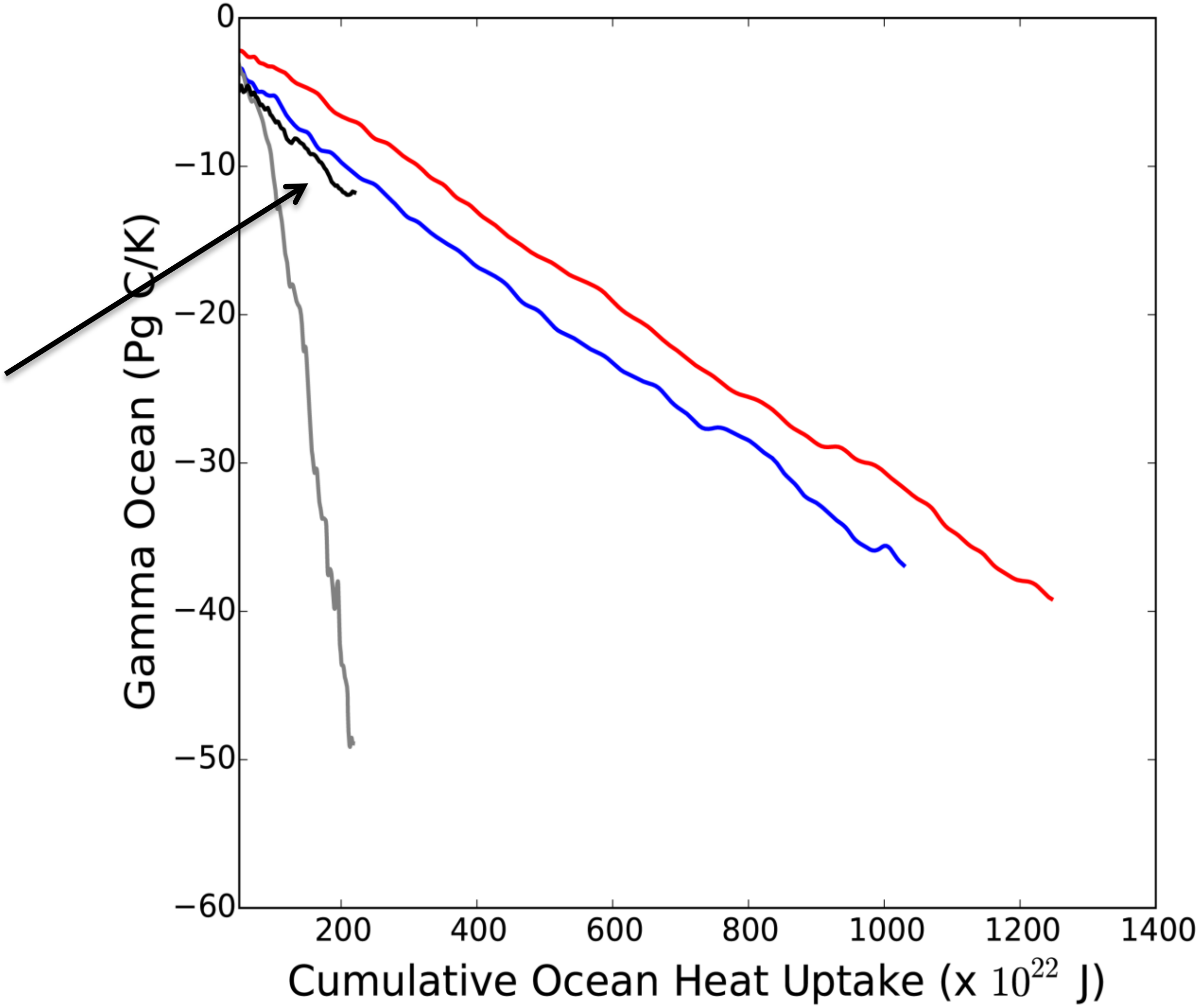
$$g = \frac{E_{BGC} - E_{FC}}{E_{BGC}}$$

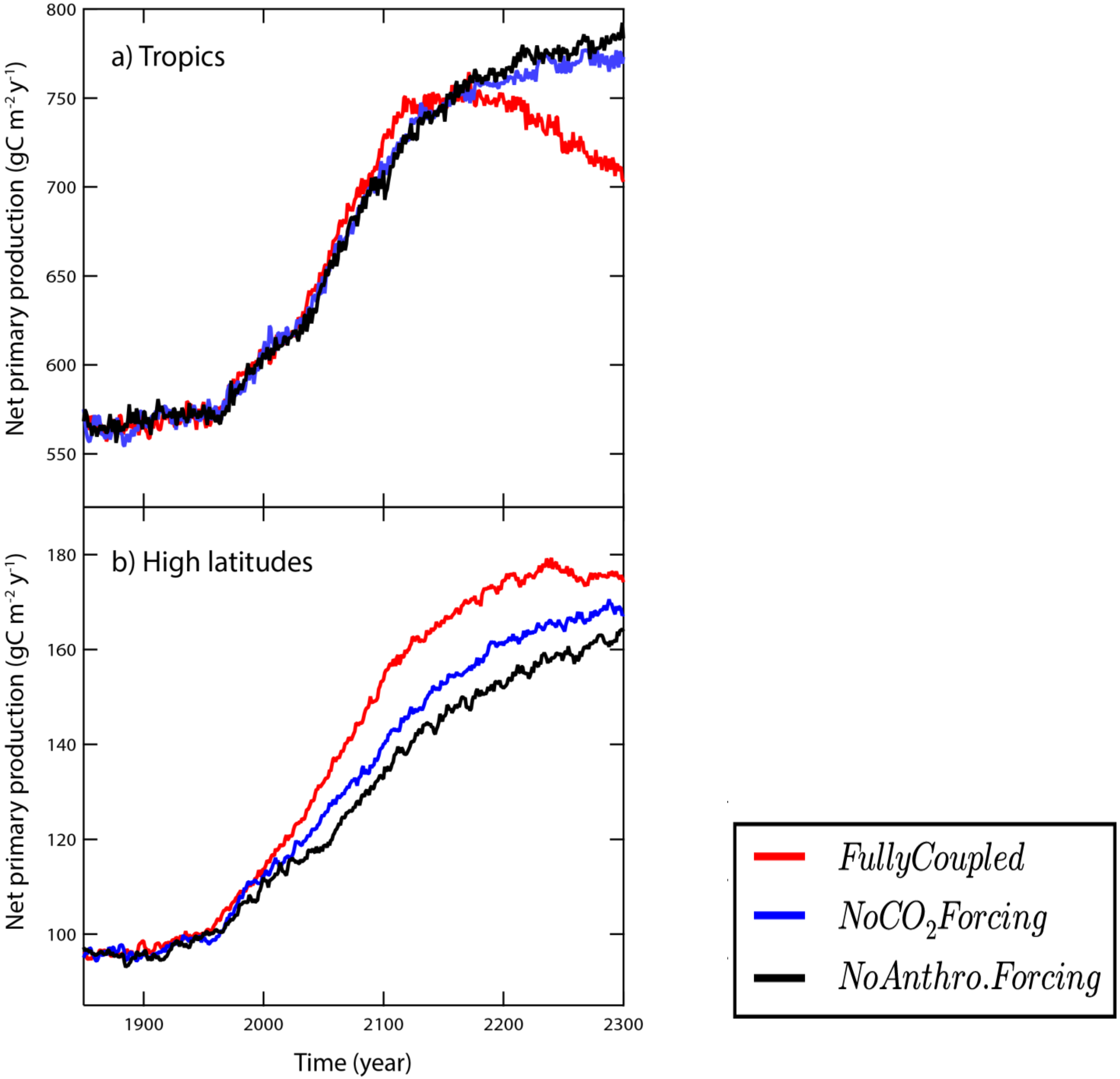
- Mean gain of the C4MIP ESMs was 0.15 (all were positive)
- Mean gain of the CMIP5 ESMs was a little lower:



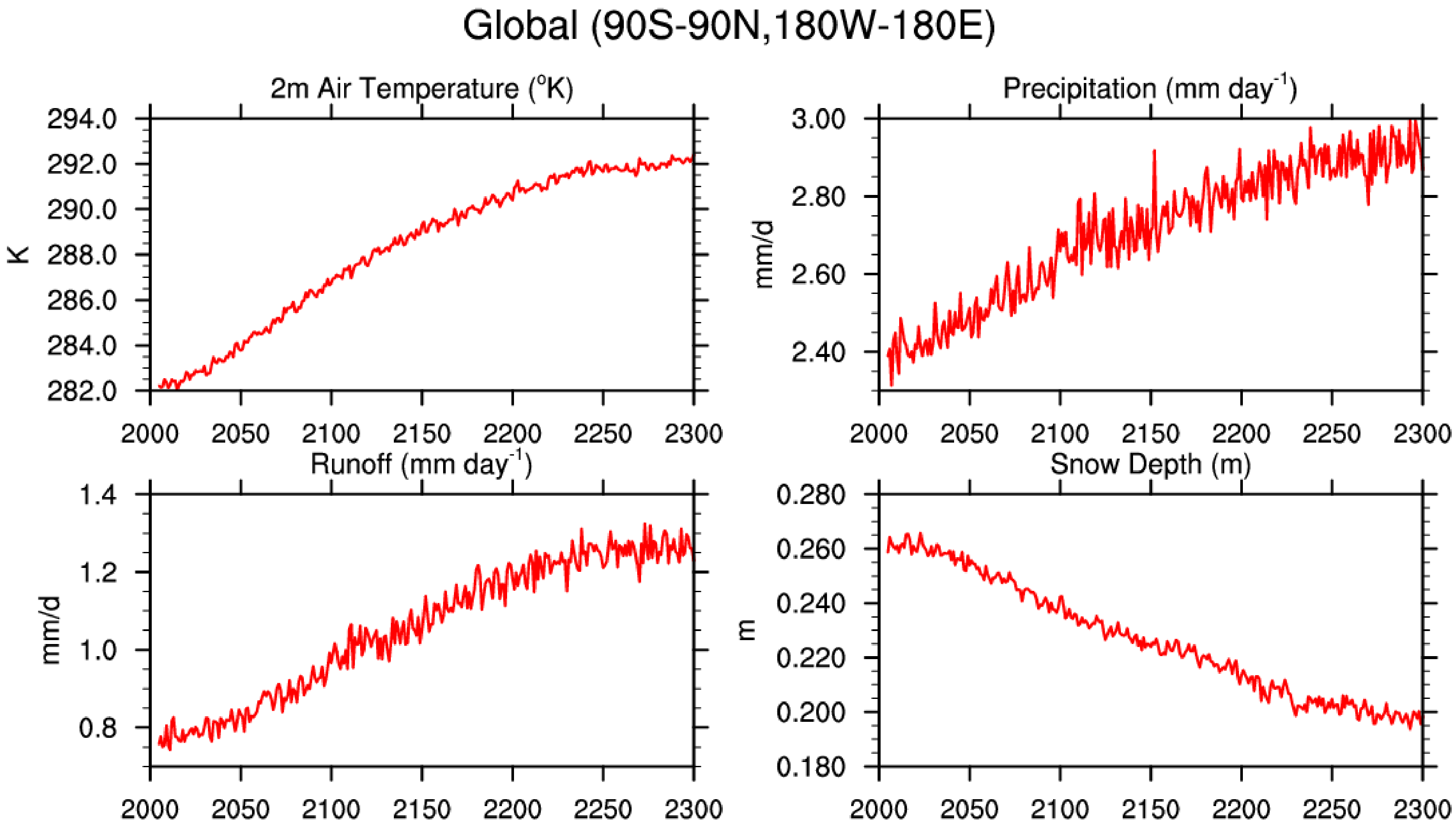
The strength of the ocean climate-carbon feedback is closely related to ocean heat content

The black line is the ocean heat content change and γ in the runs analyzed for climate-carbon feedbacks by Arora et al. (2013) (1pctCO2 & ESMfixclim1)




a) Tropics
Net primary production (gC m^{-2} y^{-1})
800
750
700
650
600
550
b) High latitudes
Net primary production (gC m^{-2} y^{-1})
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



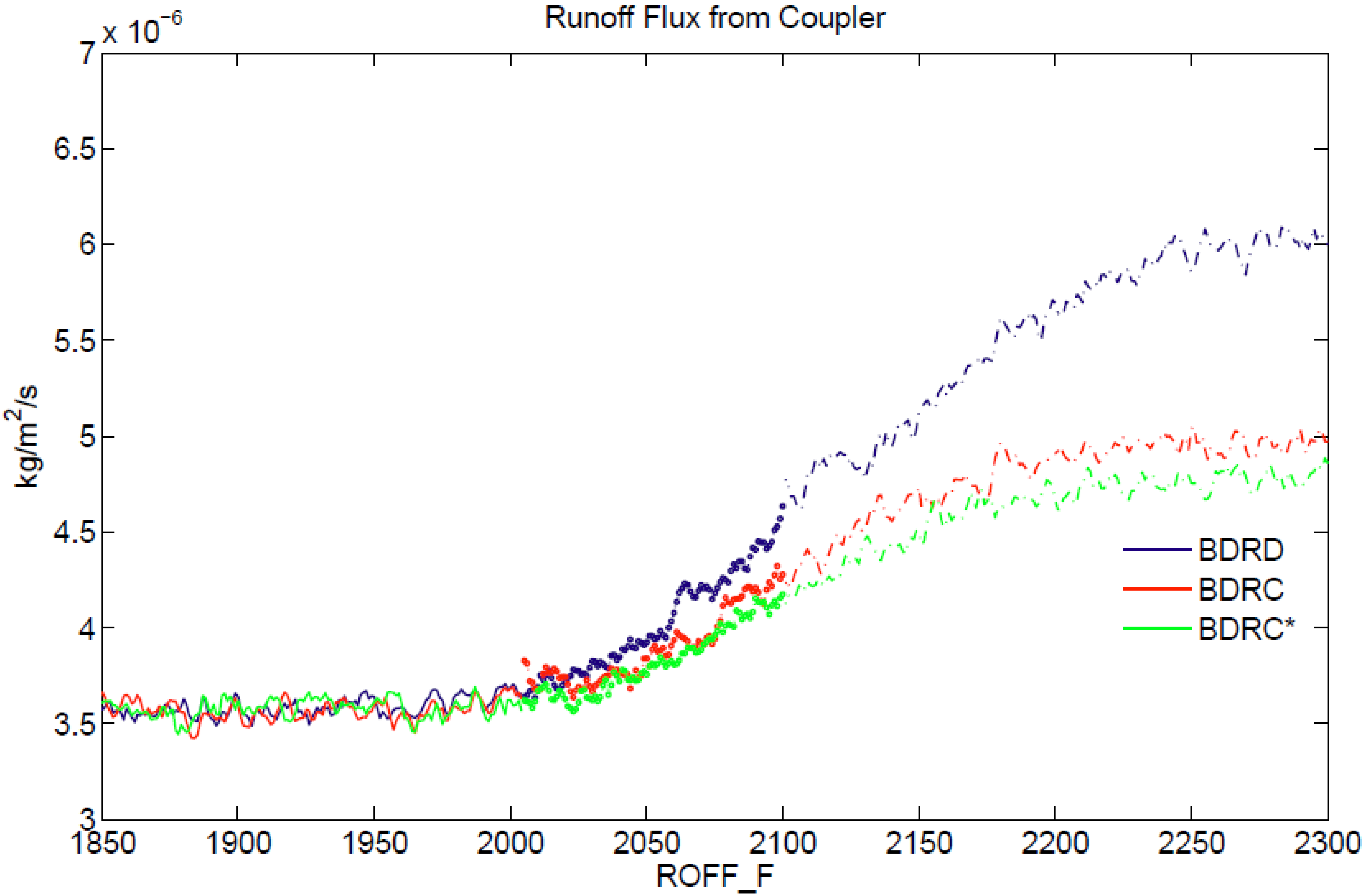
Global (90S-90N,180W-180E)

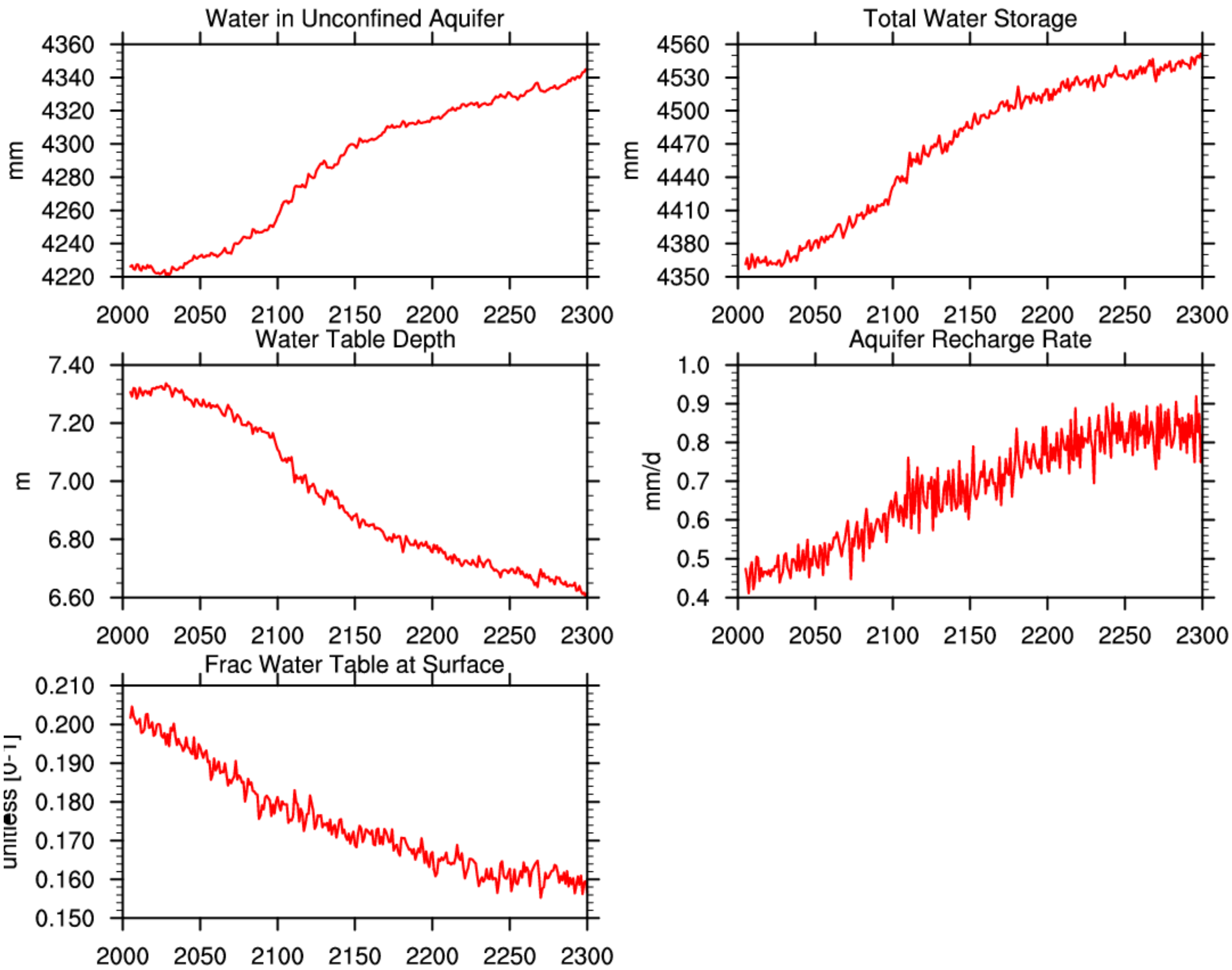
2m Air Temperature (^{o}K)

Precipitation (mm day^{-1})

Runoff (mm day^{-1})

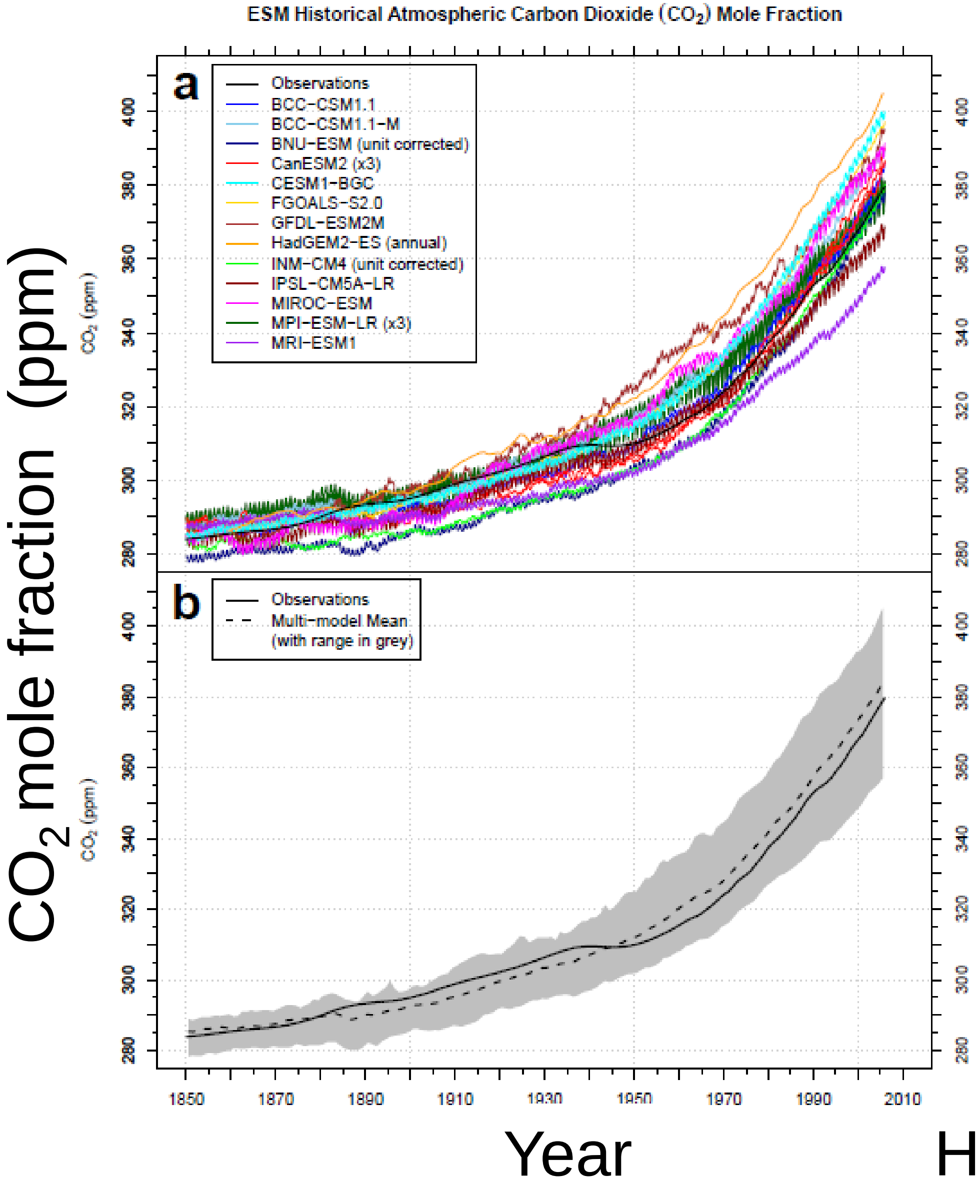
Snow Depth (m)

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)

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



Hoffman et al. 2014

What are important climate-carbon processes and feedbacks?

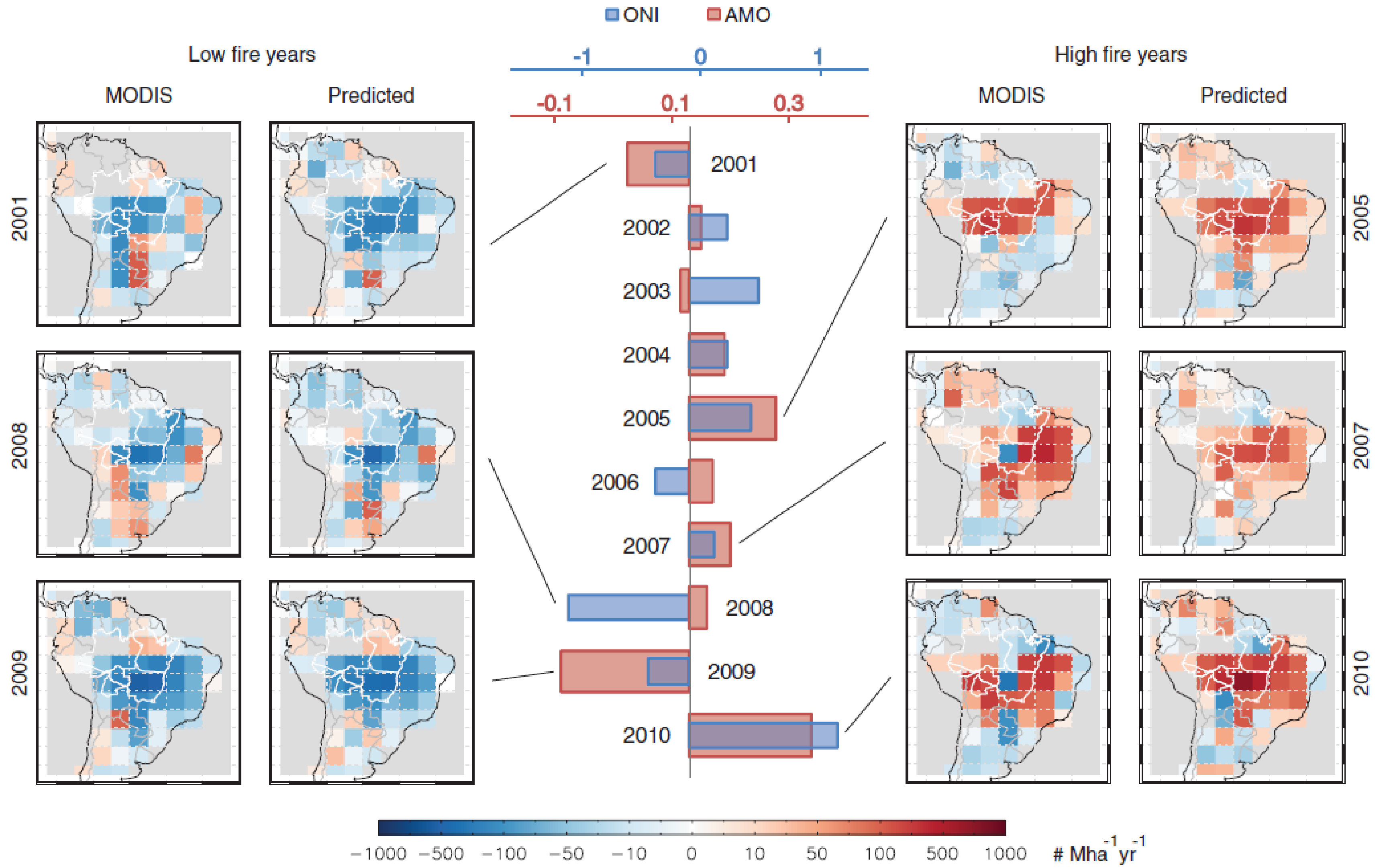
Processes in CESM1(BGC):

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

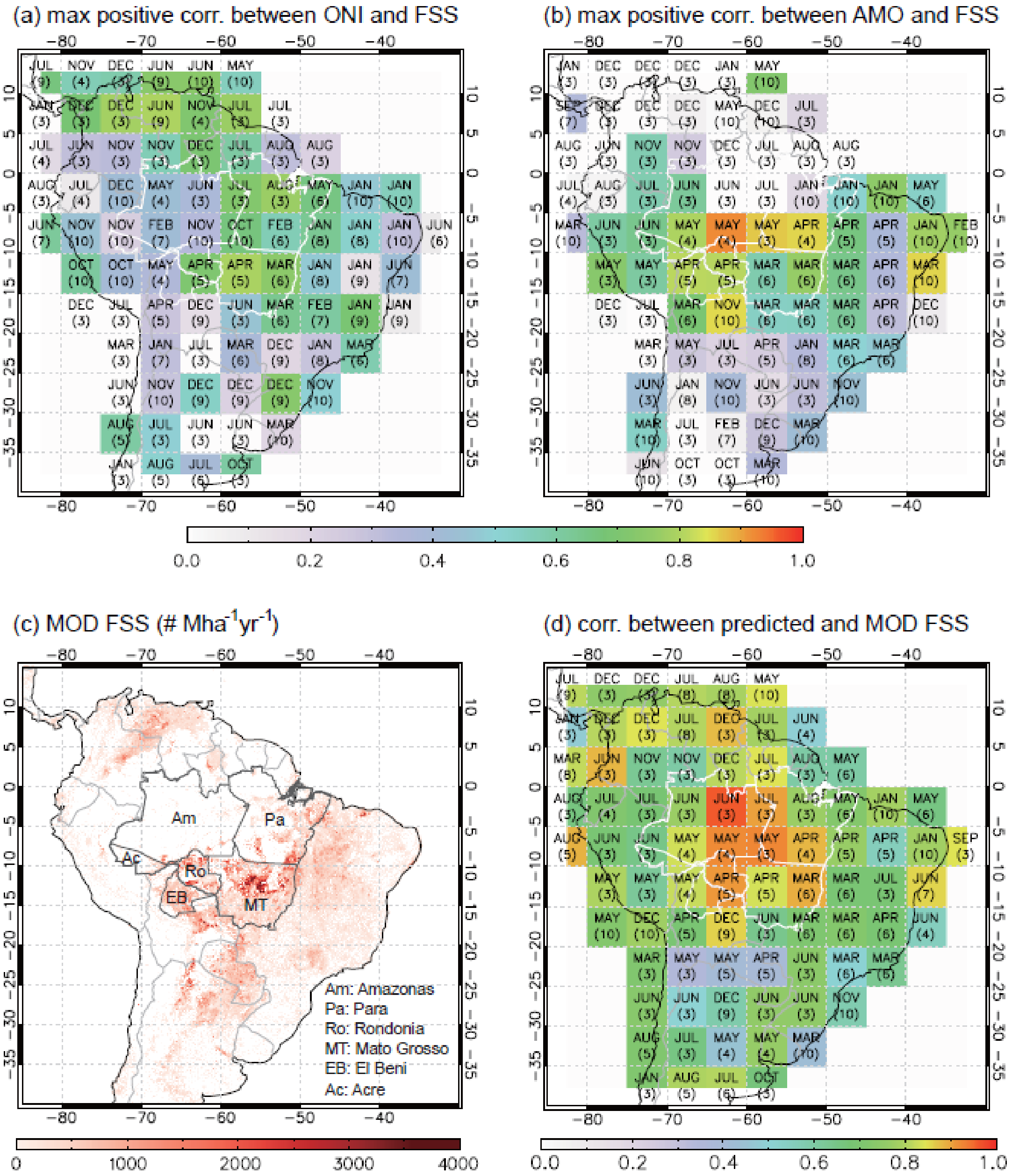
Fire Forecasting Model Performance



Terra satellite number of fires

Chen et al. (2011) Science

$$FSS_{predicted}(x,t) = a(x) \times ONI[i(x)] + b(x) \times AMO[j(x)] + c(x)$$


(a) max positive corr. between ONI and FSS

(b) max positive corr. between AMO and FSS

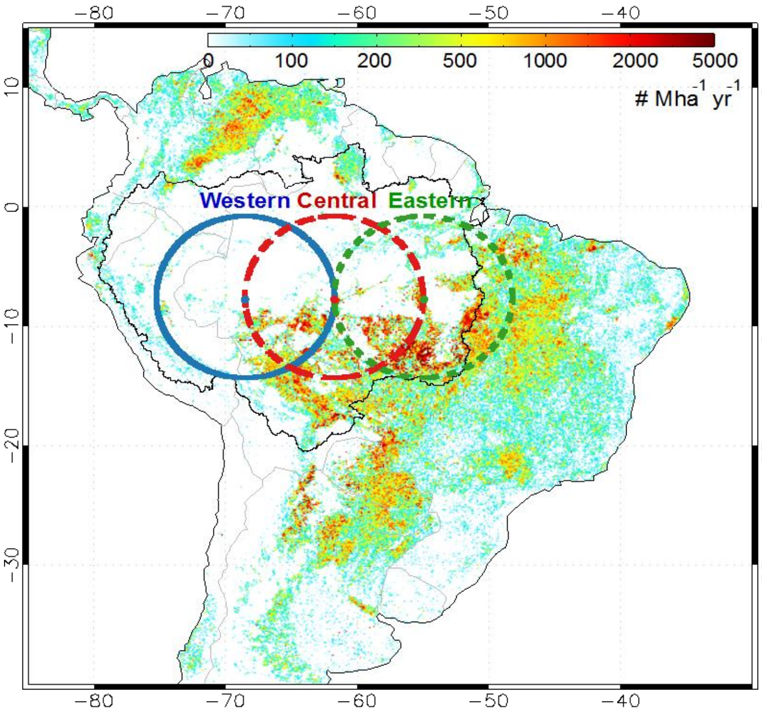
(c) MOD FSS (# $Mha^{-1}yr^{-1}$)

(d) corr. between predicted and MOD FSS

By combining information from Pacific and Atlantic sea surface temperatures a considerable amount of year to year variations in the number of fires in South America can be explained.

Chen et al. (2011) Science

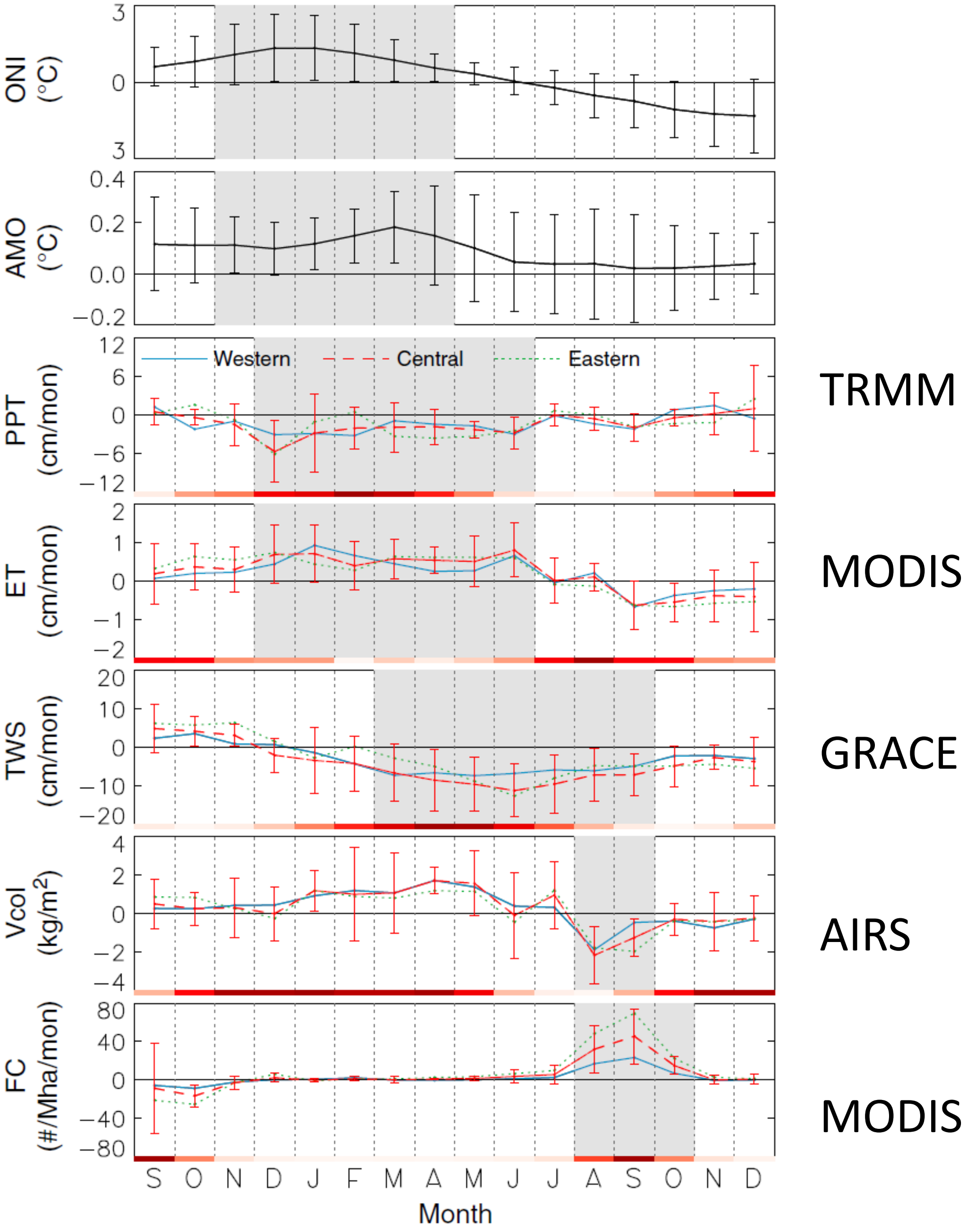
Test of the forest – soil moisture capacitor hypothesis for fire season predictions using satellite observations



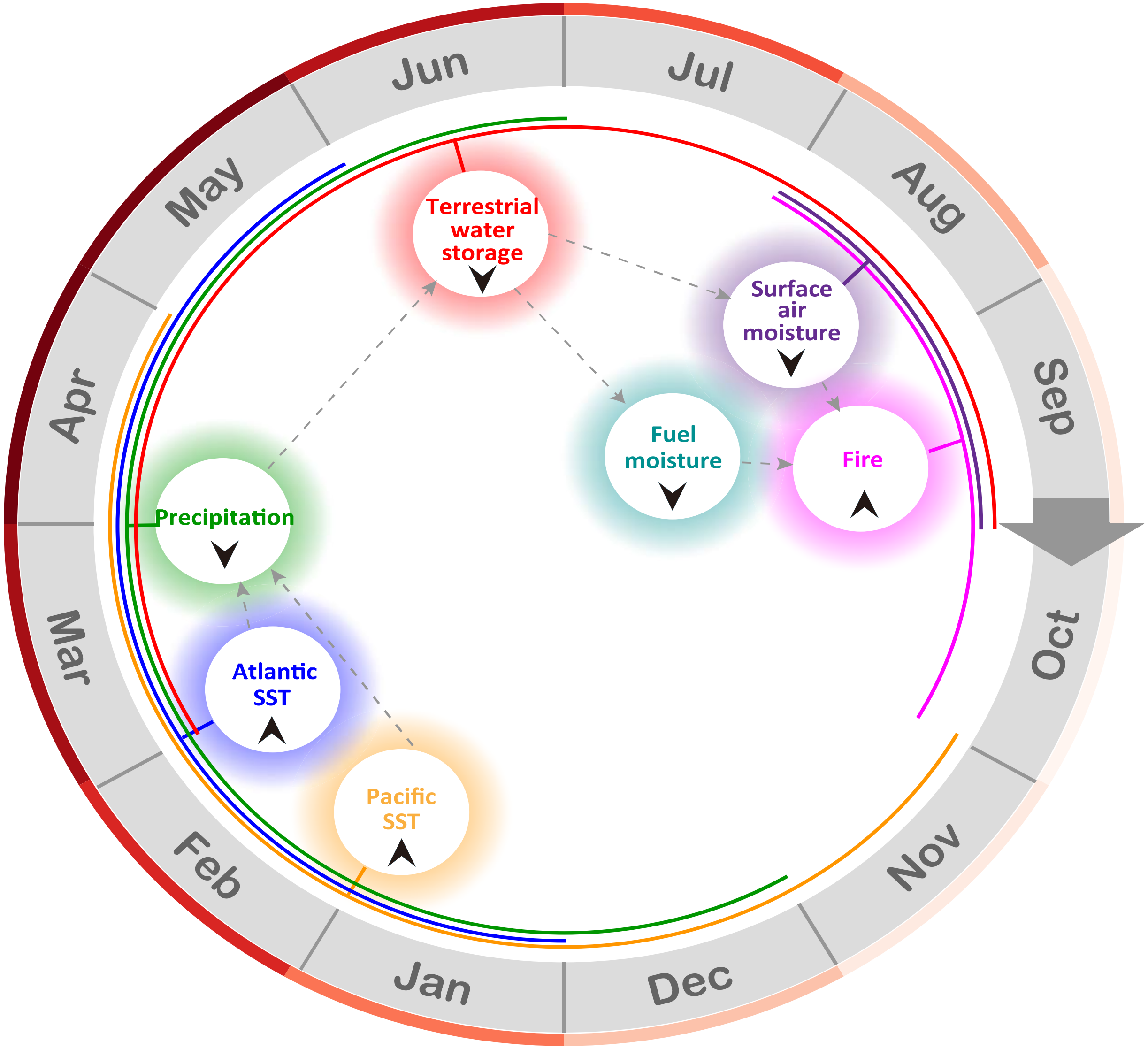
High fire years: 2004, 2005, 2007, and 2010
Low fire years: 2006, 2008, 2009, and 2011

Chen et al. (2013) JGR

Mean of high – low fire years

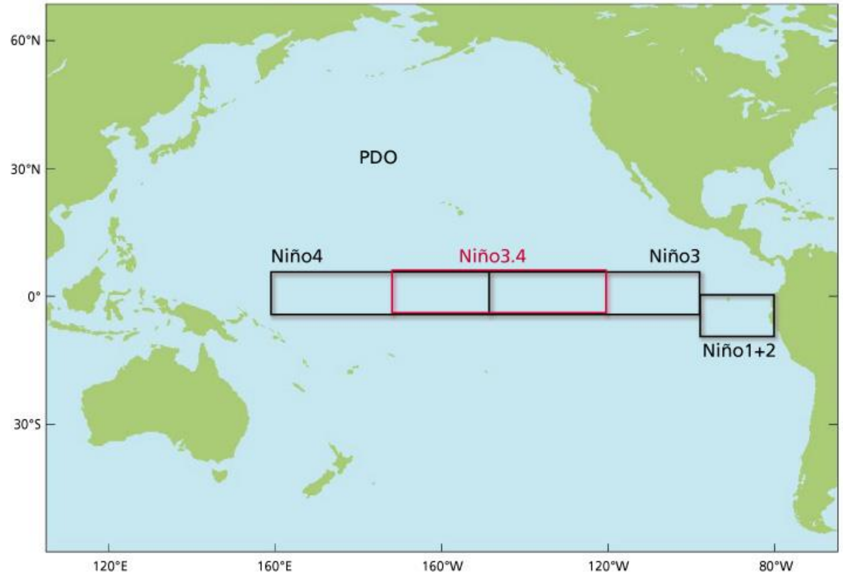


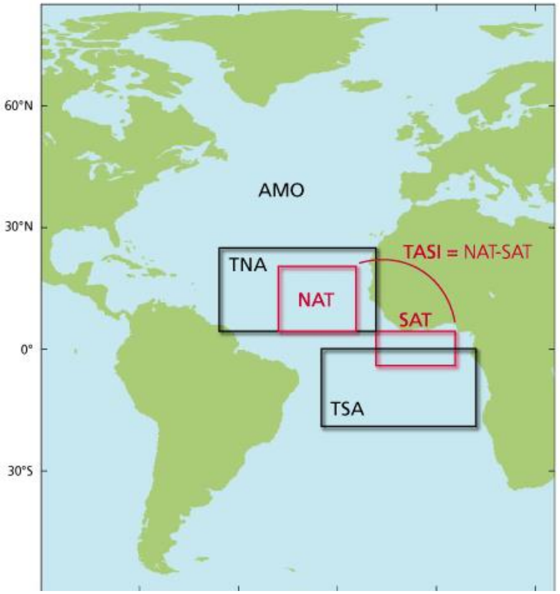
A conceptual model for fire predictability is based on a forest soils capacitor mechanism

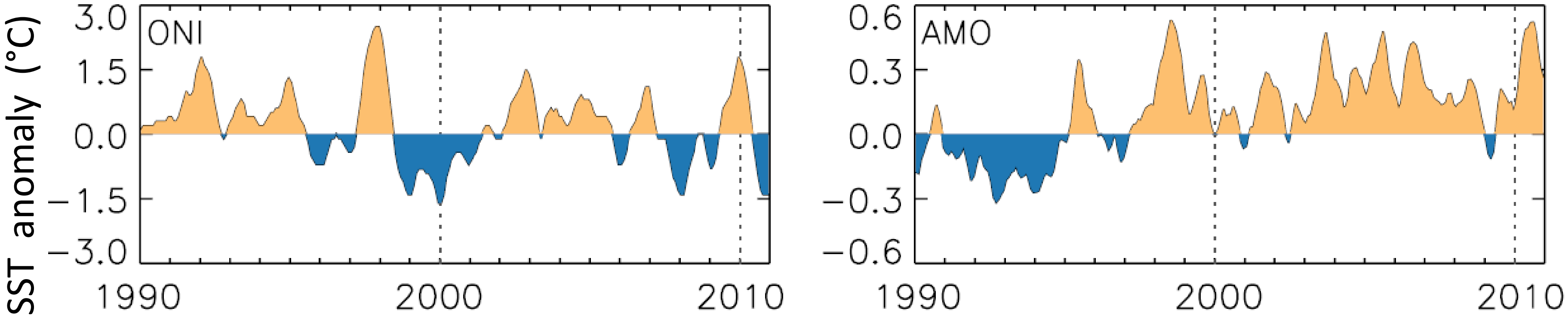


Important index regions for climate in South America

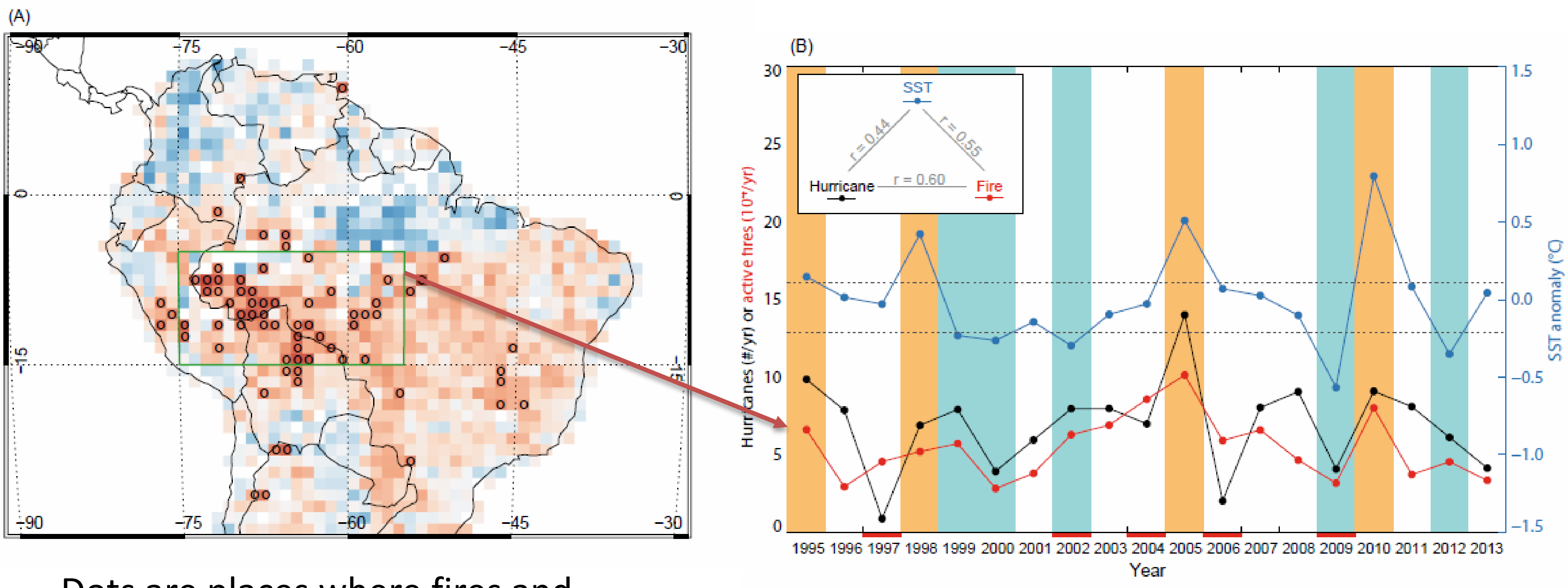
Oceanic Nino Index (ONI) and Atlantic Multi-decadal Oscillation (AMO) climate indices are well established regulators of drought in South America



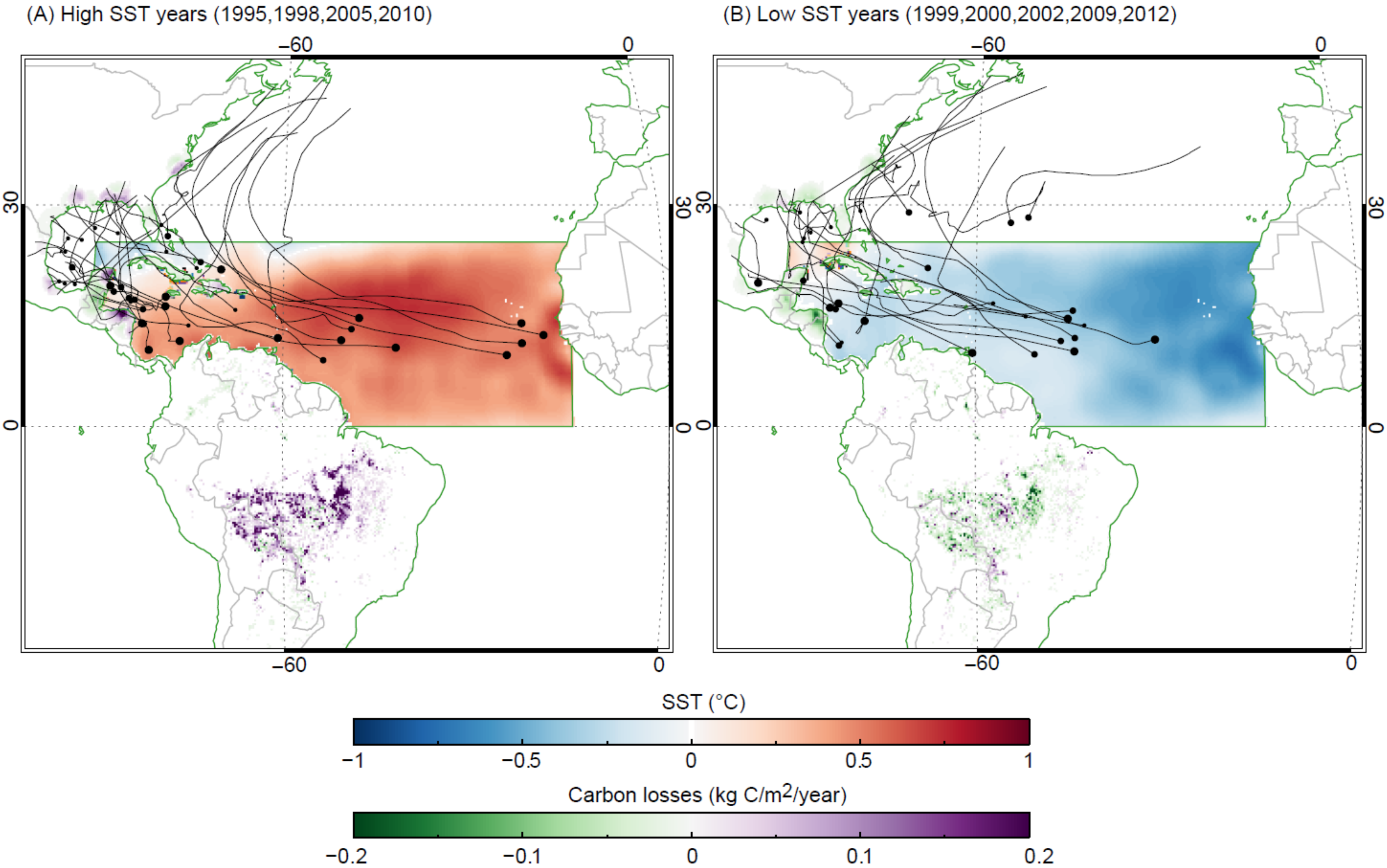




Hurricanes and Amazon fires covary by linkages to tropical North Atlantic sea surface temperatures

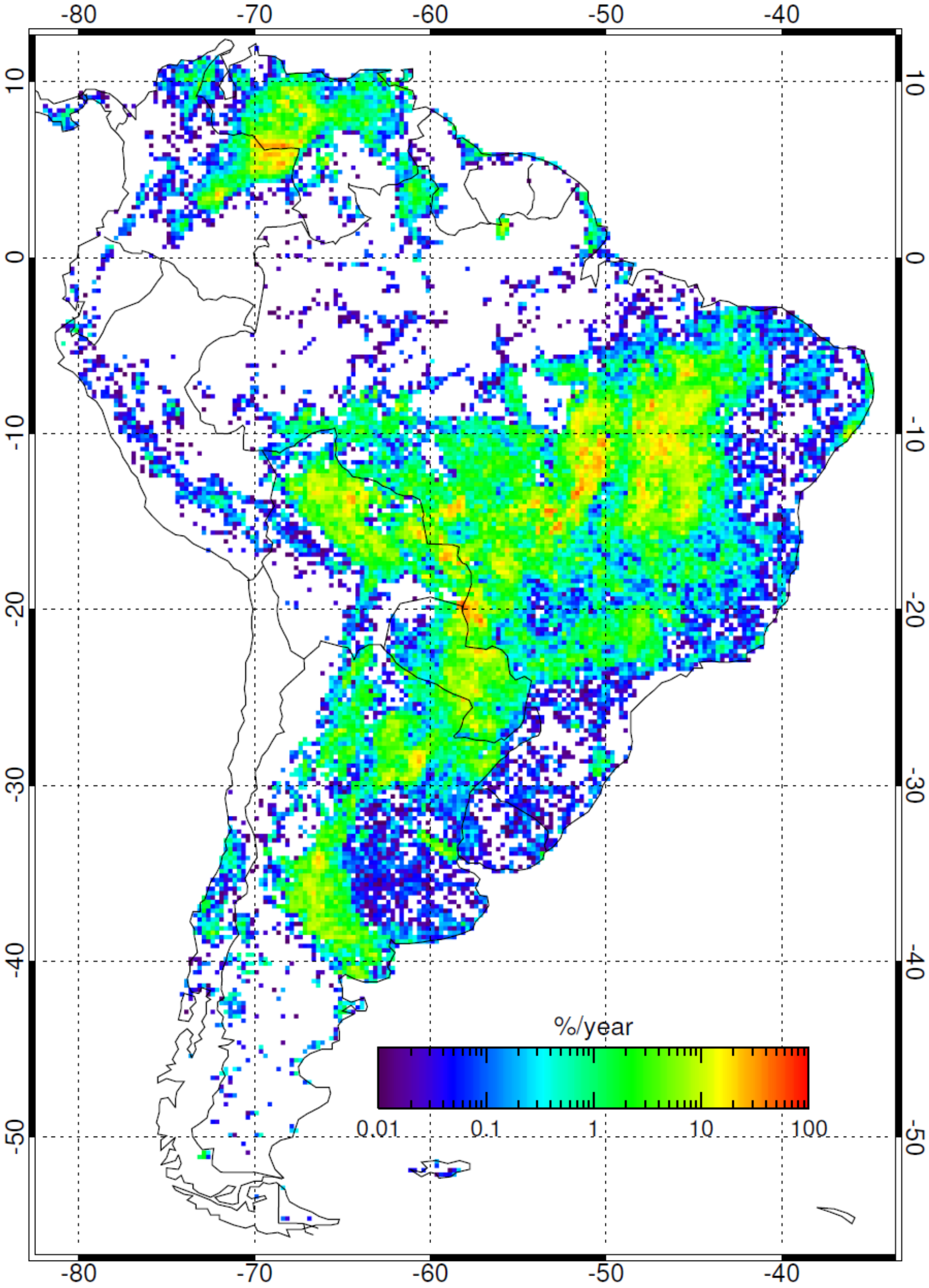


Dots are places where fires and hurricanes are significantly correlated from year to year


(A) High SST years (1995,1998,2005,2010)
(B) Low SST years (1999,2000,2002,2009,2012)
−60
0
30
0
−60
0
SST (°C)
−1
−0.5
0
0.5
1
Carbon losses (kg C/m2/year)
−0.2
−0.1
0
0.1
0.2

GFED4 burned area

- 1996-present
- Derived almost entirely from 500m MODIS surface reflectance from 2001 - present
- Regression with TRMM and ATSR fire thermal anomalies for the pre-MODIS era
- 0.25 spatial resolution, daily time step during 2001-present
- Publicly available in 2013 (www.globalfiredata.org/)
- Led by Louis Giglio and the GFED team, including Guido van der Werf, Doug Morton, Ruth DeFries, etc.



Giglio et al., JGR-B 2013