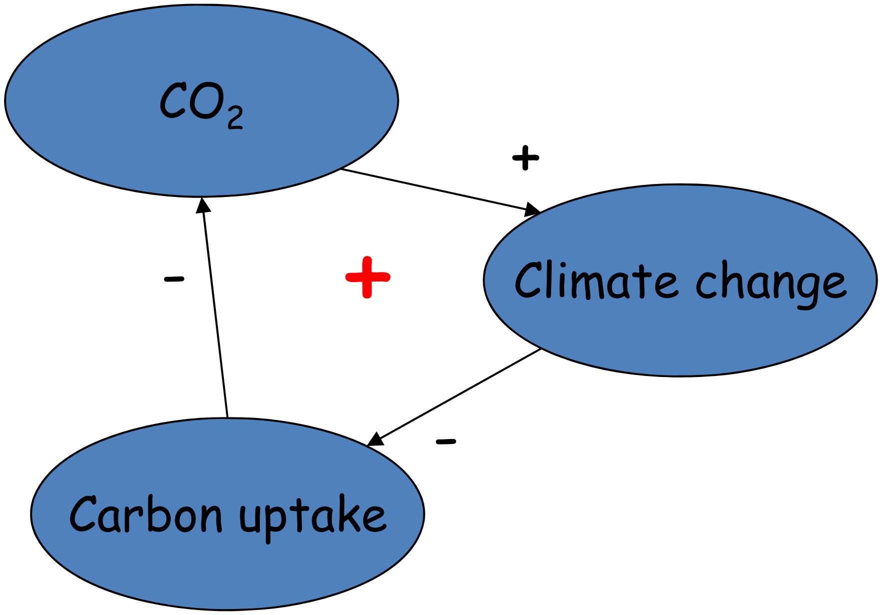
Improving our understanding of carbon cycle, drought and fire dynamics during the 21st century (and beyond!)

James Randerson
Chancellor's Professor
Earth System Science
UC Irvine

28 October 2015

U.S. Dept. of Energy
Biological and Environmental Research
Advisory Committee Meeting

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



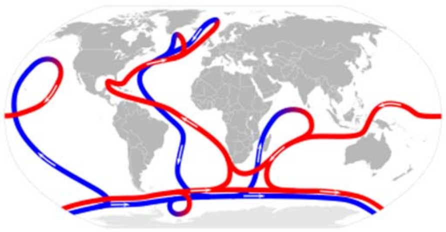
CO_2

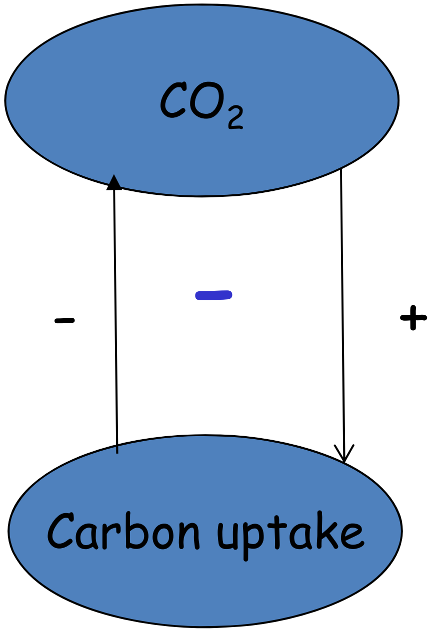
Climate change

Carbon uptake

Climate–carbon feedback

γ





CO_2

Carbon uptake

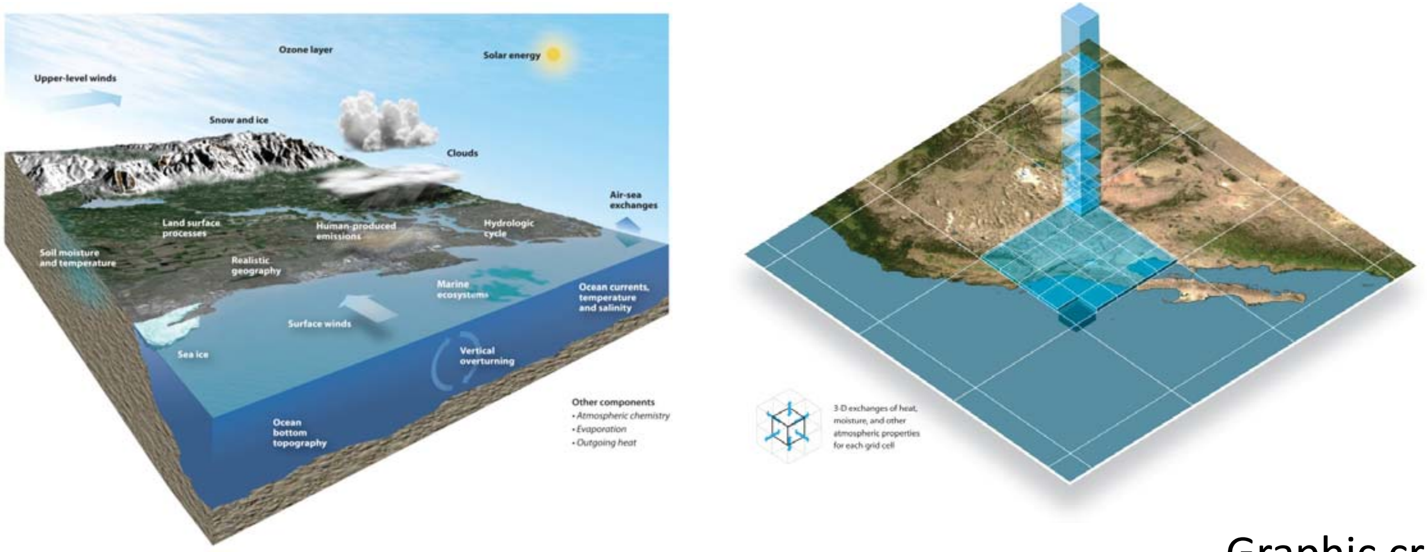
Concentration–carbon feedback

β

Science questions:

- How are ocean and land contributions to the climate-carbon feedback likely to evolve over time?
- How can we use isotope observations to reduce uncertainties in future projections of the soil carbon sink?
- How will climate change influence drought and fire dynamics?

The Community Earth System Model



Graphic credit: UCAR

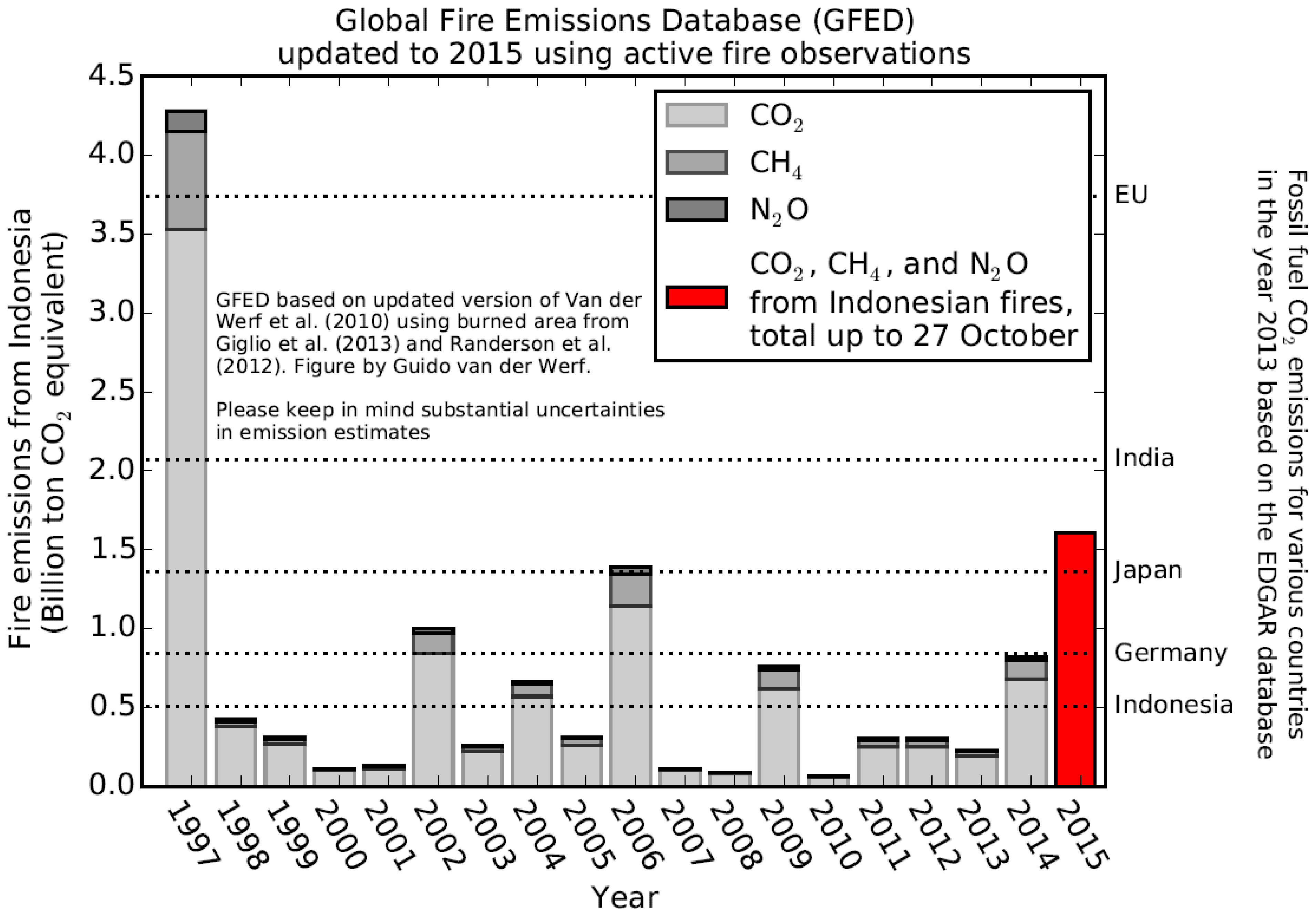
What are important climate-carbon processes and feedbacks?

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 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 CMIP ESMs:

- Species range shifts
- Phosphorus limits on land carbon uptake (integration underway into ACME)
- Permafrost dynamics (now in CLM4.5)
- Peatlands
- Fires
- Insect-driven mortality
- Drought effects on tree mortality
- Climate effects on land use change


Global Fire Emissions Database (GFED) updated to 2015 using active fire observations

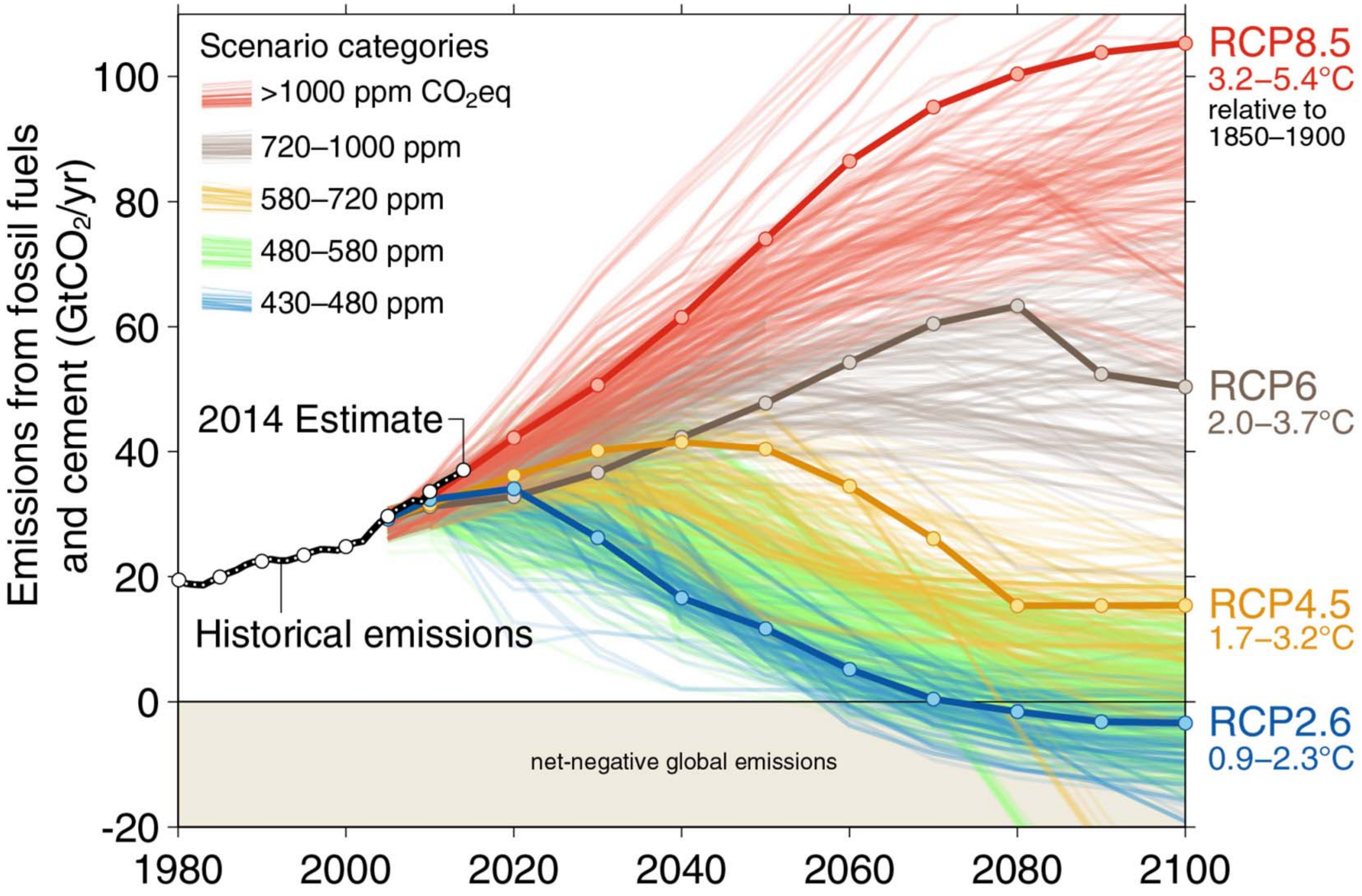
GFED based on updated version of Van der Werf et al. (2010) using burned area from Giglio et al. (2013) and Randerson et al. (2012). Figure by Guido van der Werf.

Please keep in mind substantial uncertainties in emission estimates

http://www.globalfiredata.org/_plots/updates/emissions.pdf

Guido van der Werf

Experimental design: All three simulations have 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)

CESM1(BGC) experimental design

Simulation	Short name	Description
Fully coupled	Full	CO_2 and other atmospheric anthropogenic drivers force radiative forcing, biogeochemistry responds to CO_2 increases
No CO_2 radiative forcing	No CO_2 forcing	Non-CO_2 anthropogenic drivers influence radiative forcing, 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

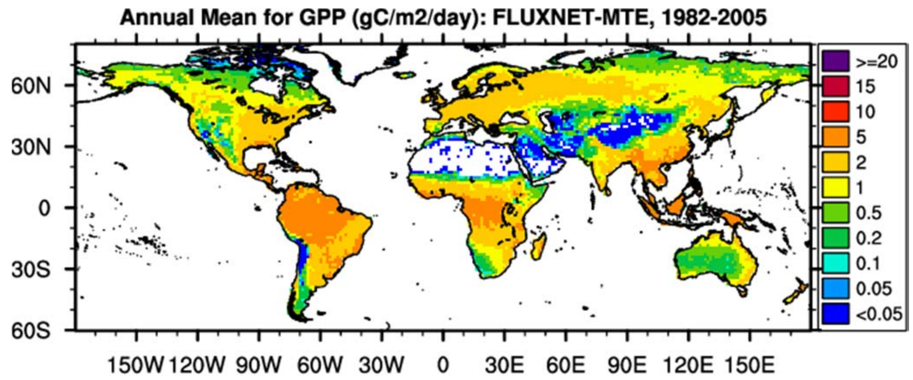
Lindsay et al. (2014), Keppel-Aleks et al. (2013), Moore et al. (2013), Long et al. (2013)

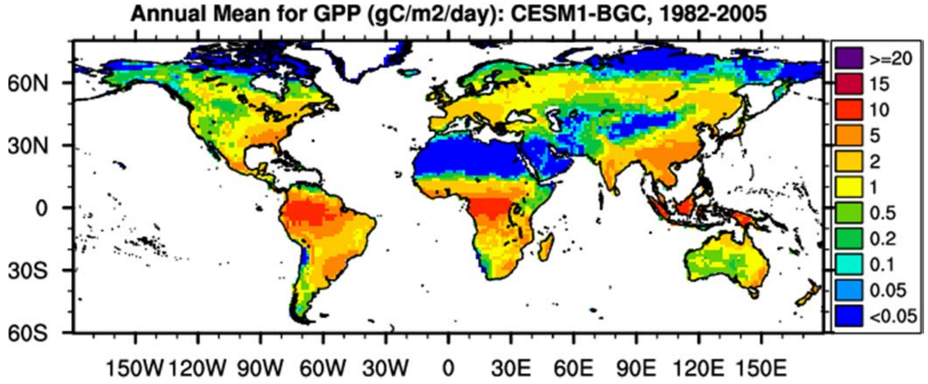
CESM1(BGC) experimental design

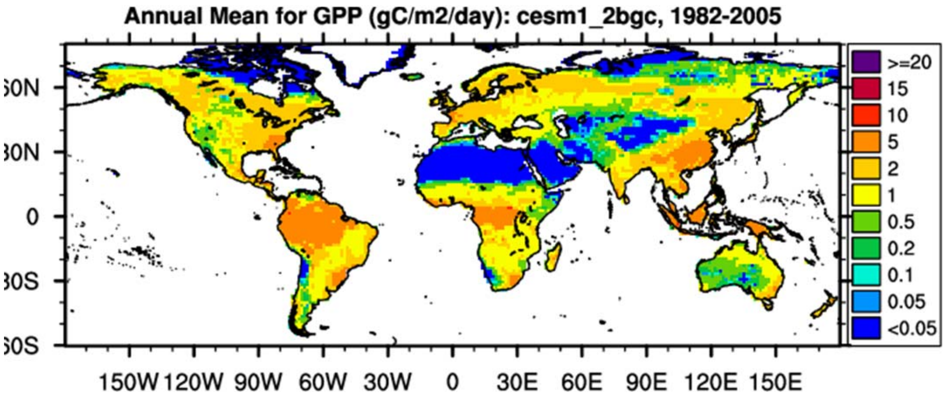
Simulation	Short name	Description
Fully coupled	Full	CO_2 and other atmospheric anthropogenic drivers force radiative forcing, biogeochemistry responds to CO_2 increases
No CO_2 radiative forcing	No CO_2 forcing	Non-CO_2 anthropogenic drivers influence radiative forcing, biogeochemistry responds to CO_2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

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

Validation of carbon cycle processes in CESM with the International Land Model Benchmarking System

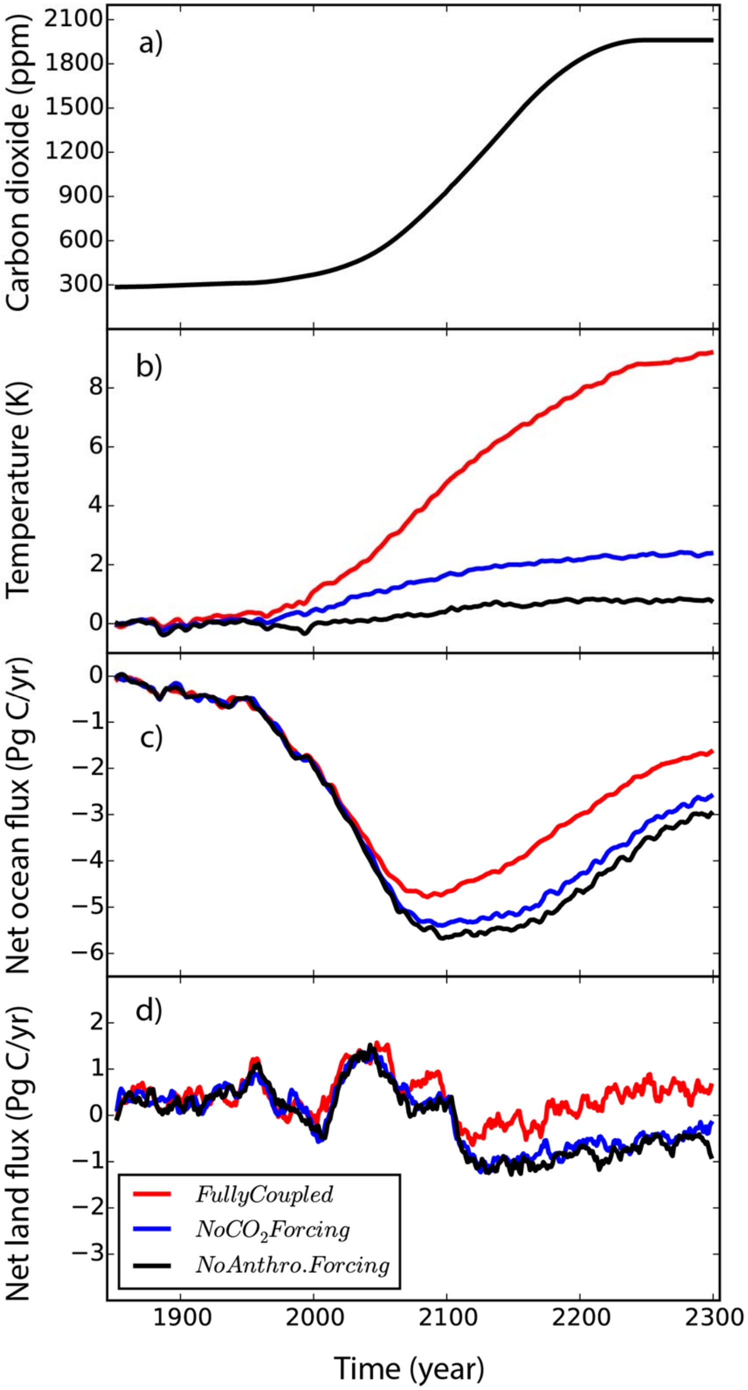

Annual Mean for GPP (gC/m2/day): FLUXNET-MTE, 1982-2005


Annual Mean for GPP (gC/m2/day): CESM1-BGC, 1982-2005

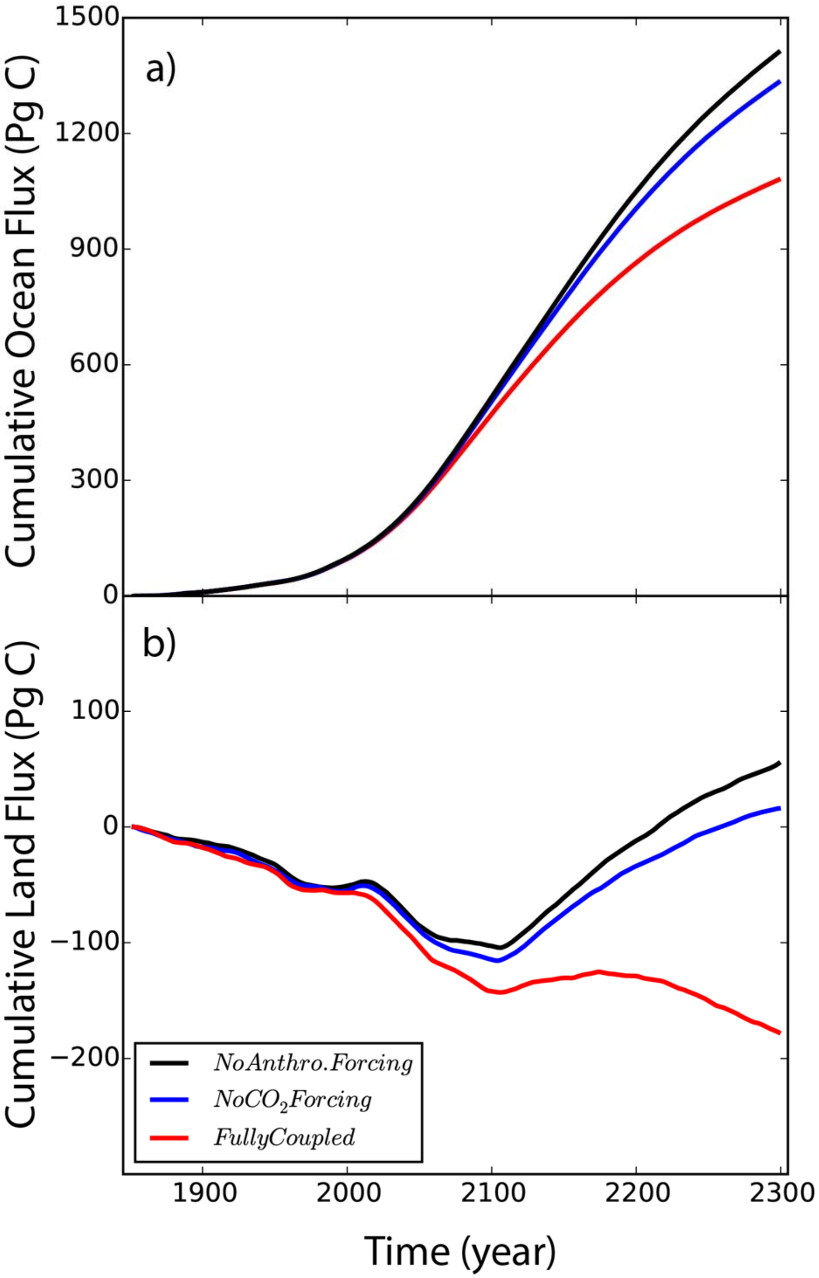

Annual Mean for GPP (gC/m2/day): cesm1_2bgc, 1982-2005

Process and number of variables	CESM 1	CESM 1.2
Carbon cycle and ecosystems (9)	**0.54**	**0.61**
Hydrological cycle (3)	**0.66**	**0.77**
Radiation and energy (7)	**0.80**	**0.80**
Forcing variables (4)	**0.83**	**0.84**
Variable to variable relationships (10)	**0.67**	**0.71**
Overall score:	**0.65**	**0.69**

Mu et al., Lawrence et al. in prep.



Randerson et al. (2015) GBC



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

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

Randerson et al. (2015) GBC

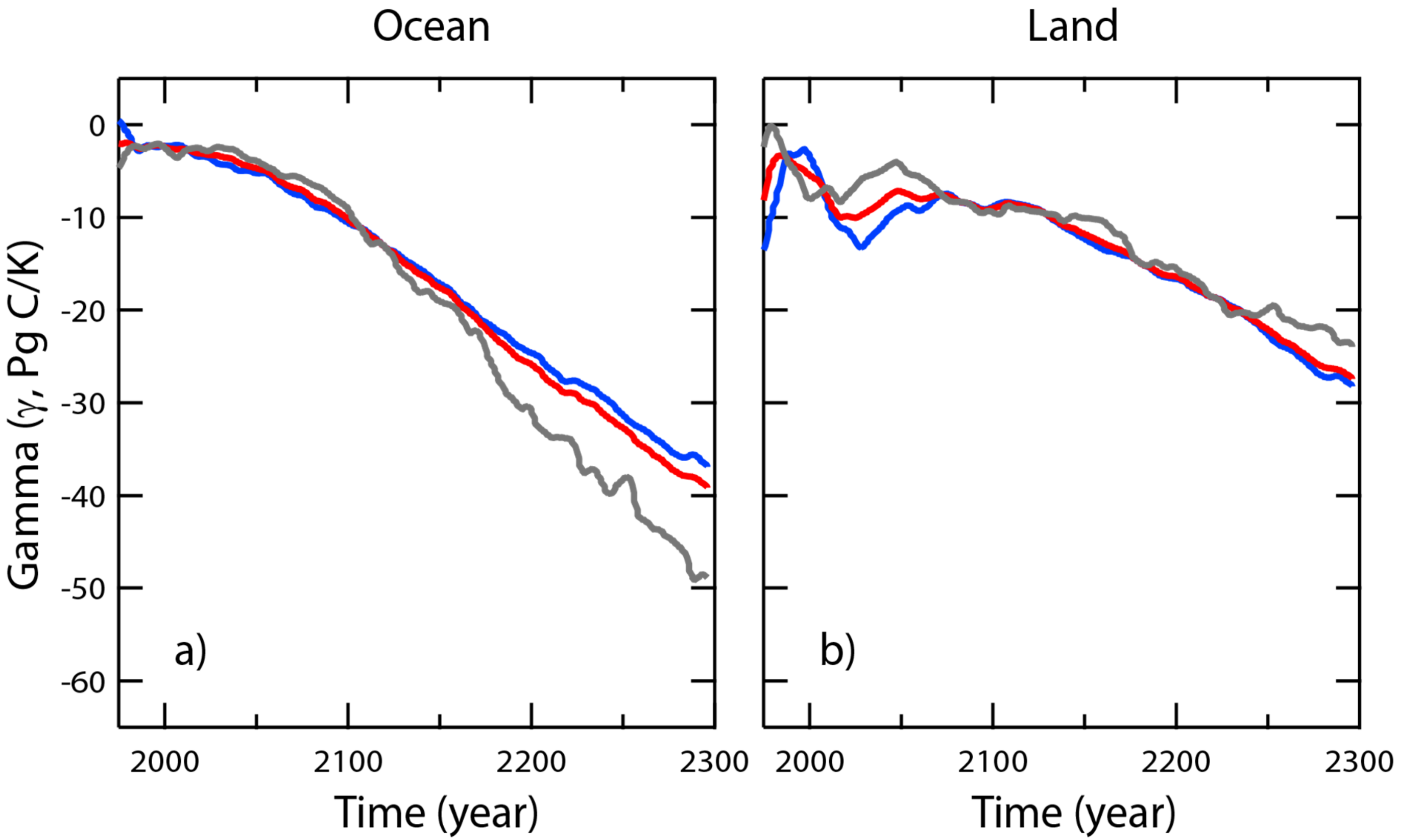
Climate-carbon feedback parameters

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

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

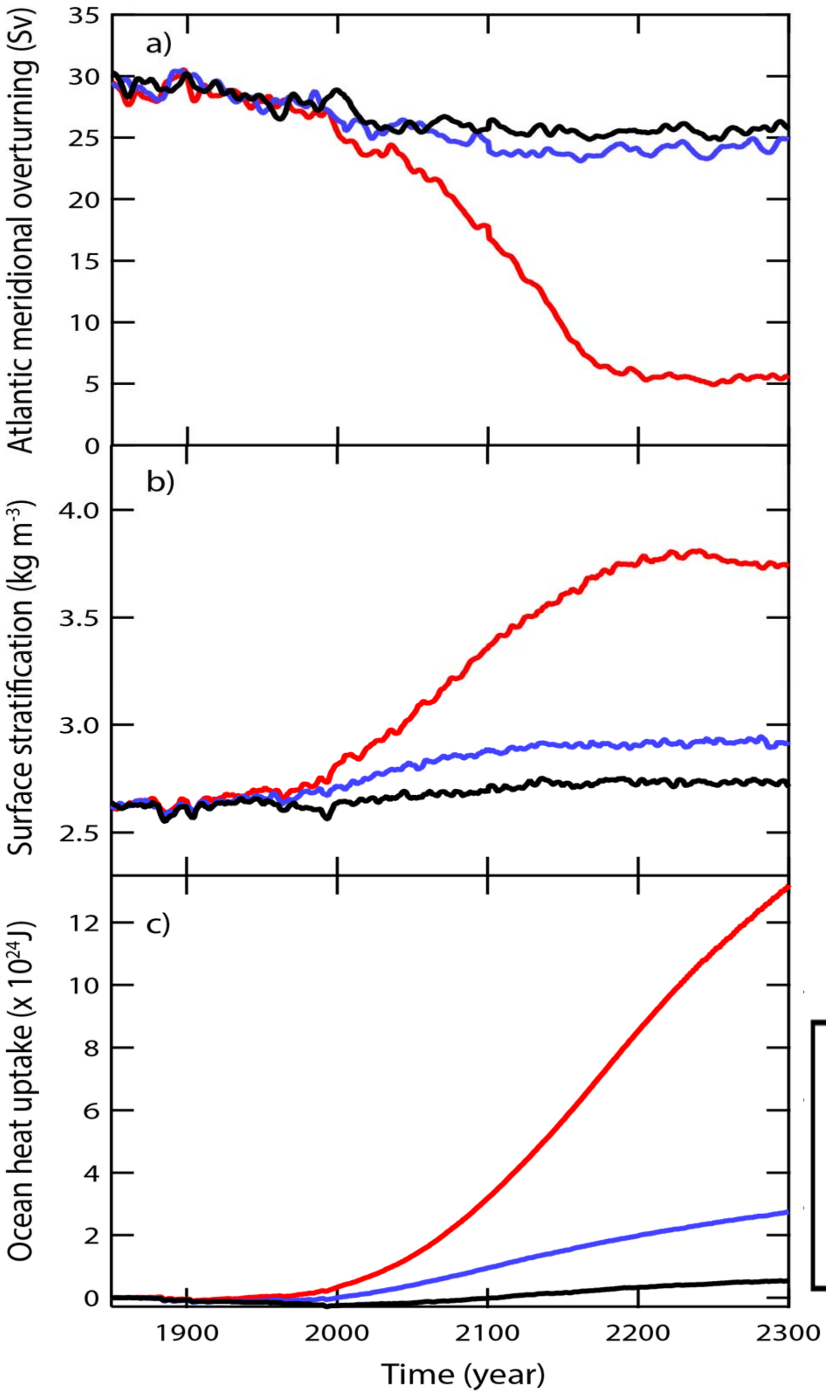
Randerson et al. (2015) GBC

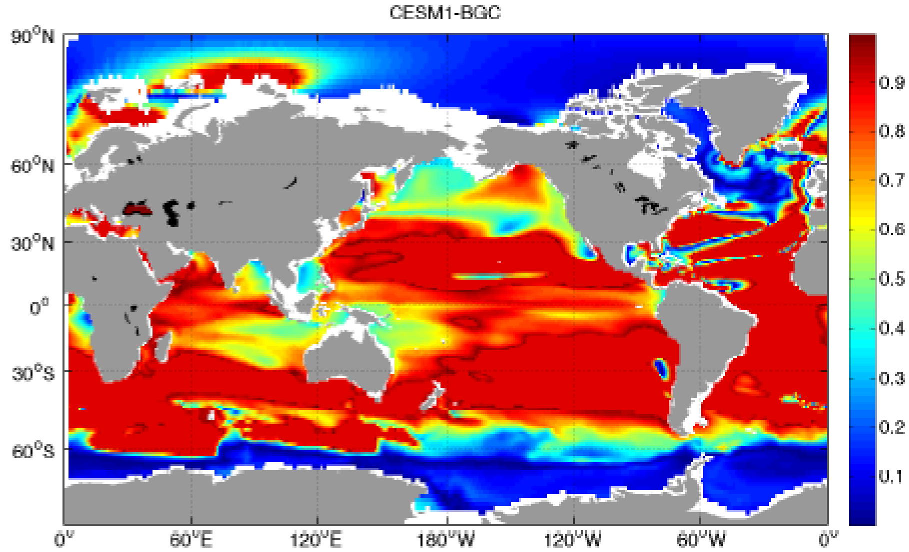
Ocean contributions to the climate-carbon feedback overtake land after 2100



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

Randerson et al. (2015) GBC

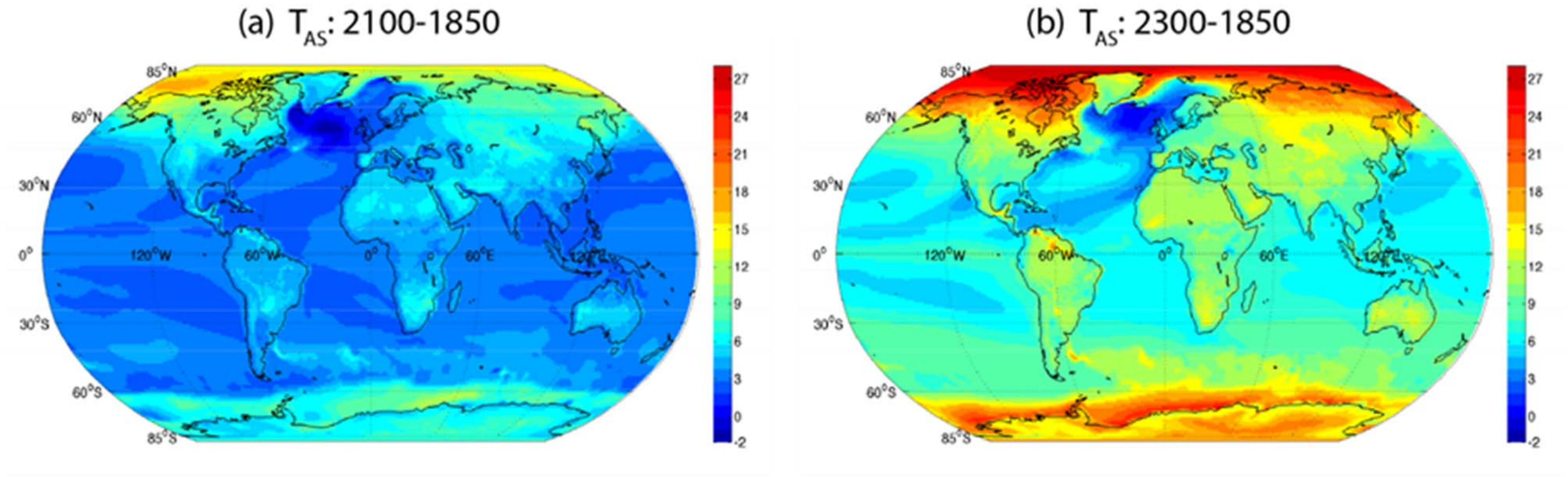




CESM1(BGC) temperature and salinity drivers of stratification at 2100

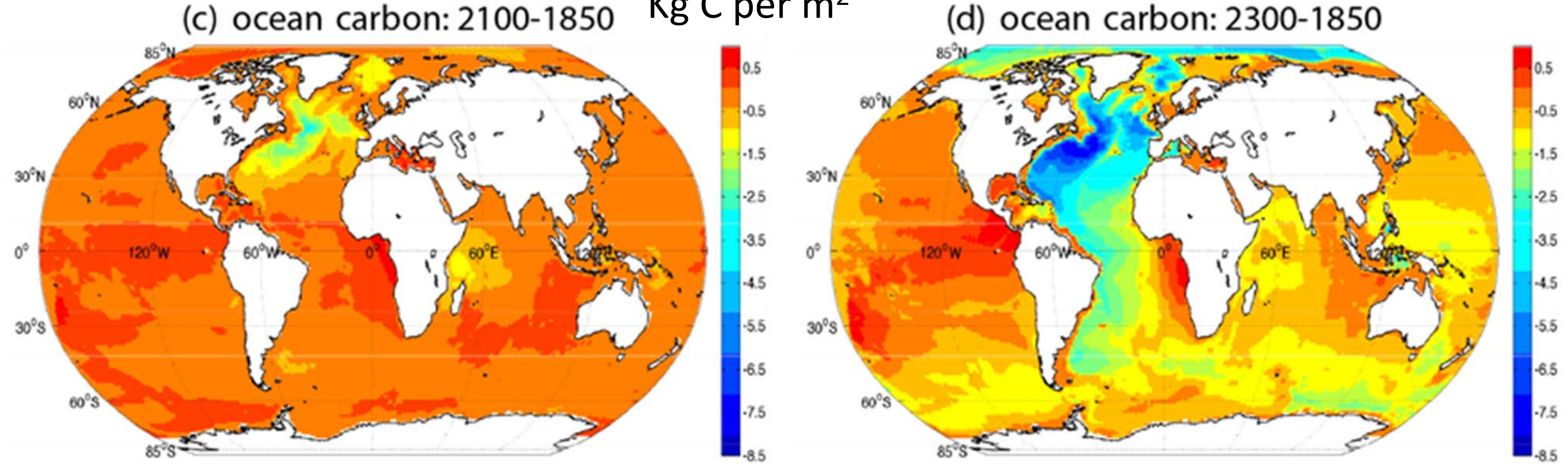
Randerson et al. (2015) GBC, Fu et al. (2015) BGD

Shutdown in Atlantic Meridional Overturning Reduces Carbon Uptake in CESM


(a) T_{AS}: 2100-1850

(b) T_{AS}: 2300-1850

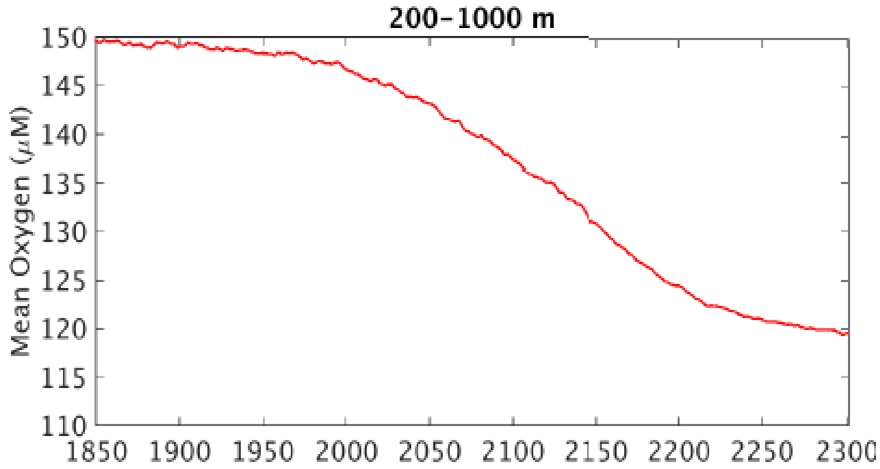
Kg C per m^2


(c) ocean carbon: 2100-1850

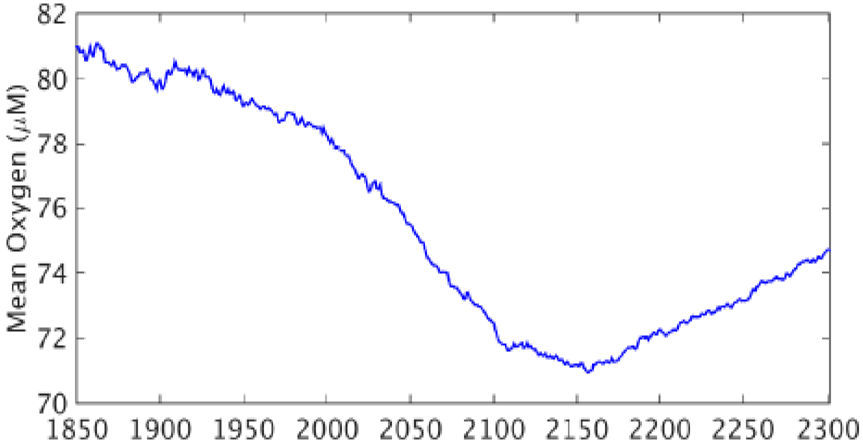
(d) ocean carbon: 2300-1850

Randerson et al. (2015) GBC

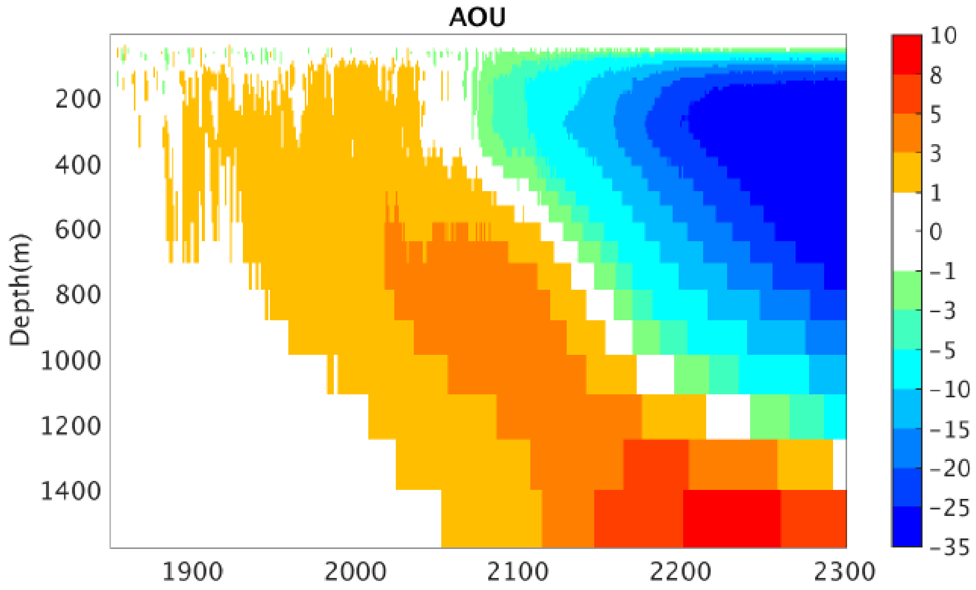
Tropical ocean anoxia reverses after 2100



(a) Global Mean O_2



(b) Mean O_2 in 30S-30N



(b) AOU changes relative to 1850-60

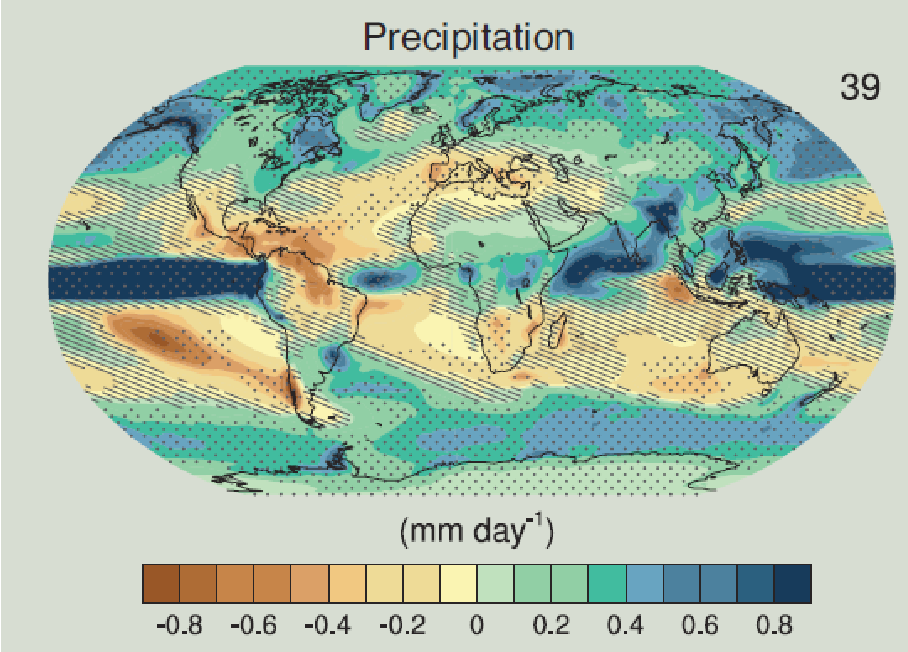
Fu, Moore, Lindsay, Randerson, in prep.

Vulnerability of Central America and northern South America to changing drought

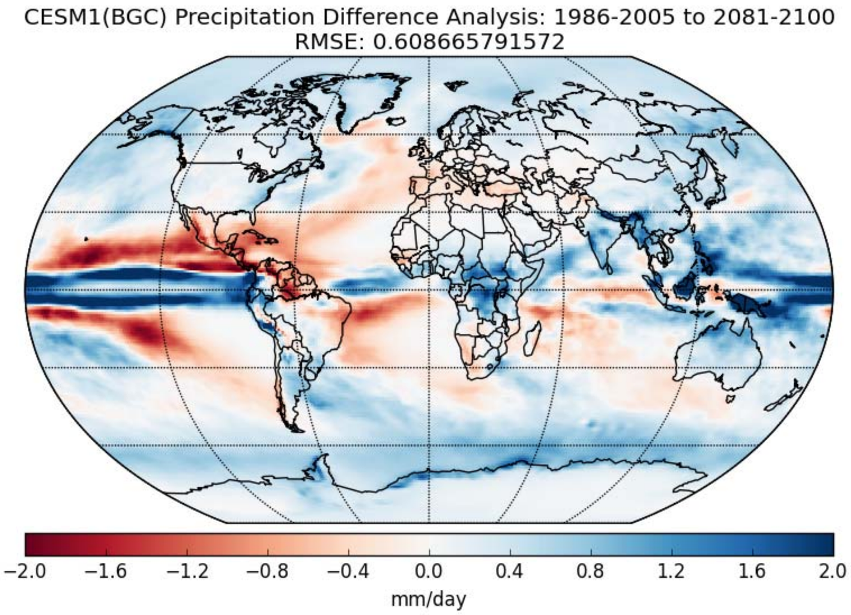
Precipitation changes for Representative Concentration Pathway 8.5

(2081-2100) – (1986-2005)

CMIP5 multi-model mean, IPCC AR1 TS



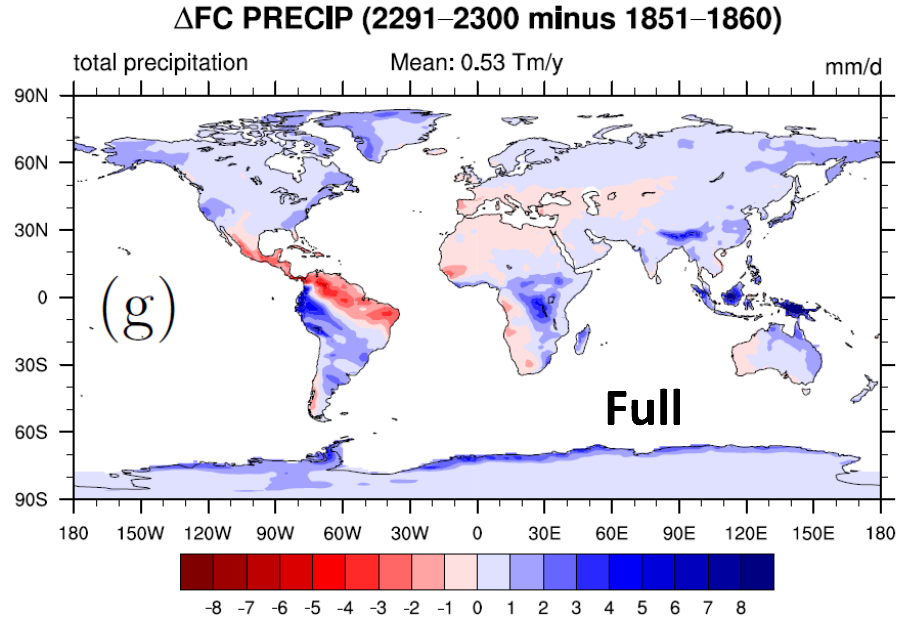
CESM1(BGC)



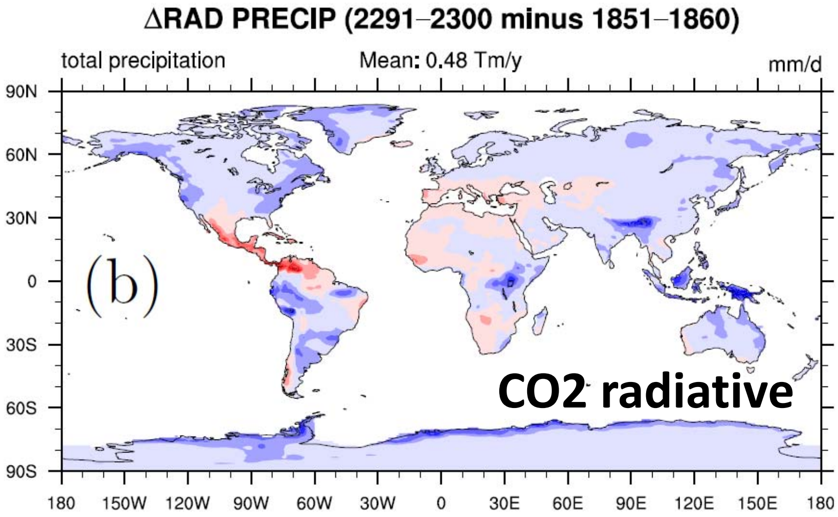
mm/day

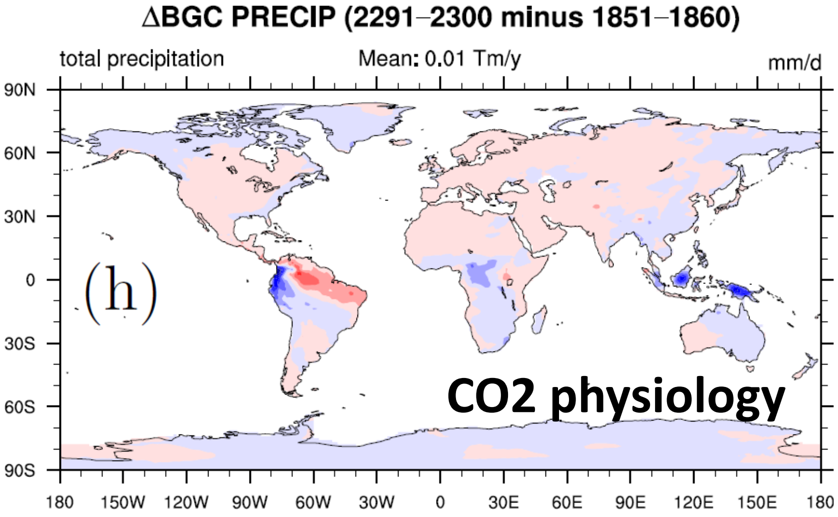
Hydrological cycle changes are not uniform across tropical land, with most models drying more in South America than in Africa or Asia

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

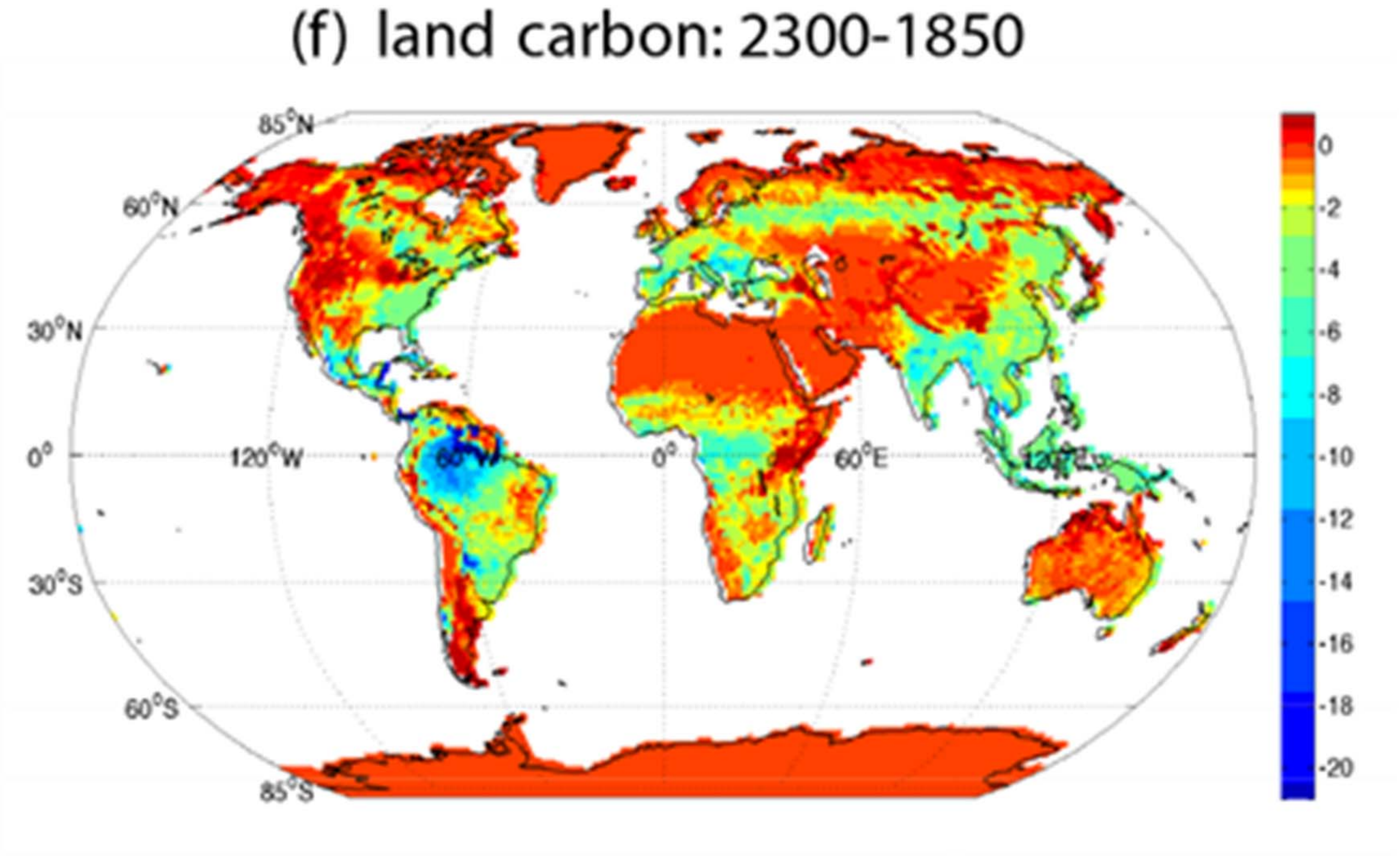


Hoffman (2015)
Ph.D. thesis, ms.
in prep.





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

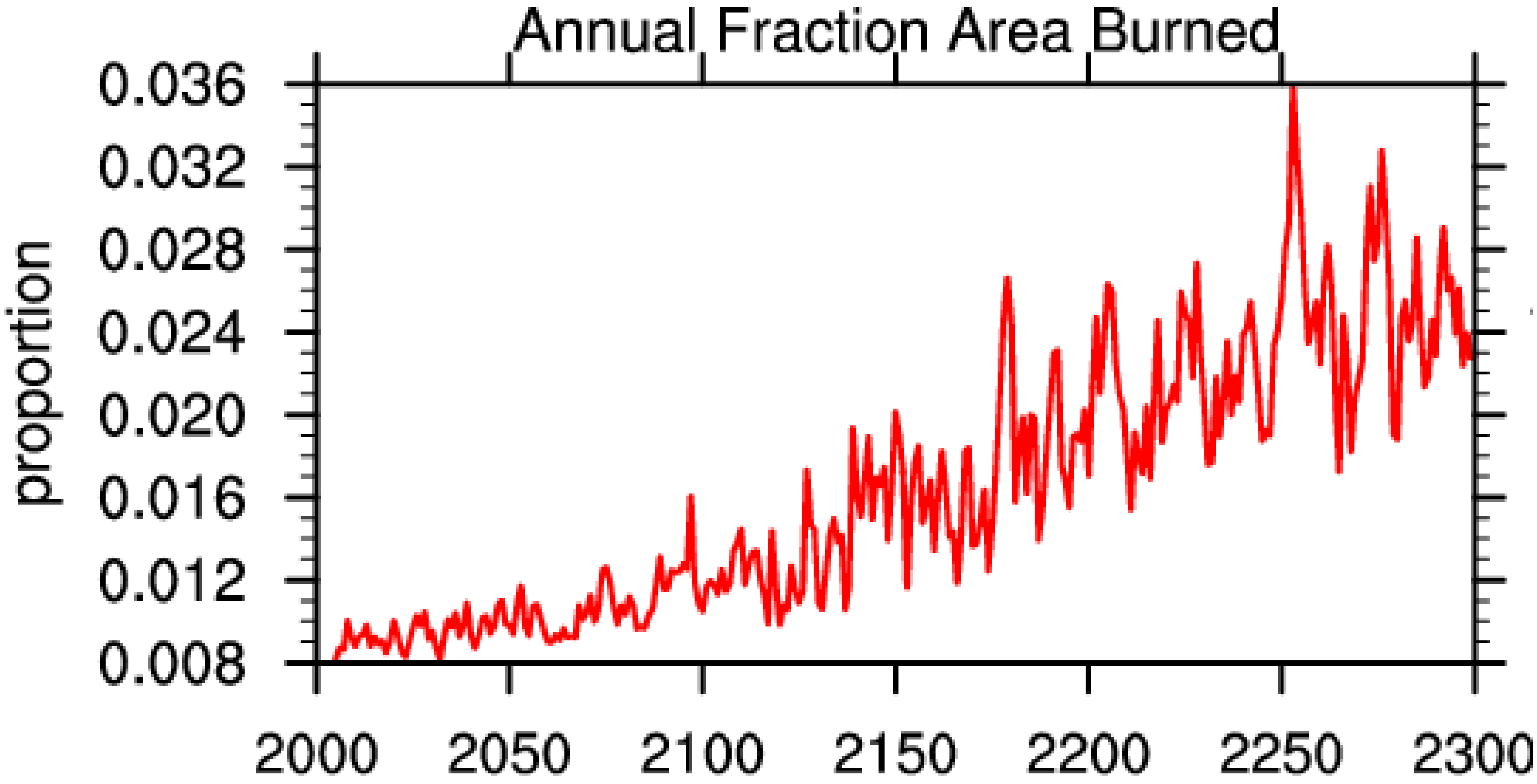


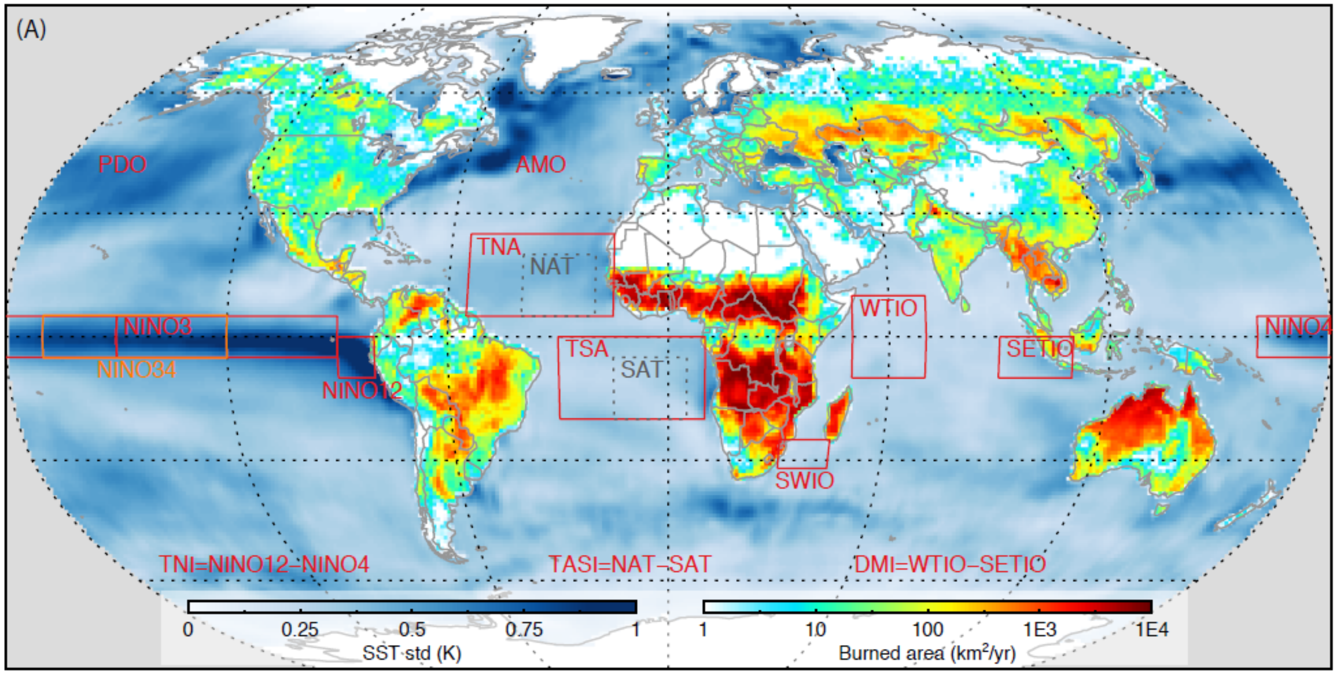
(f) land carbon: 2300-1850

Kg C per m^2

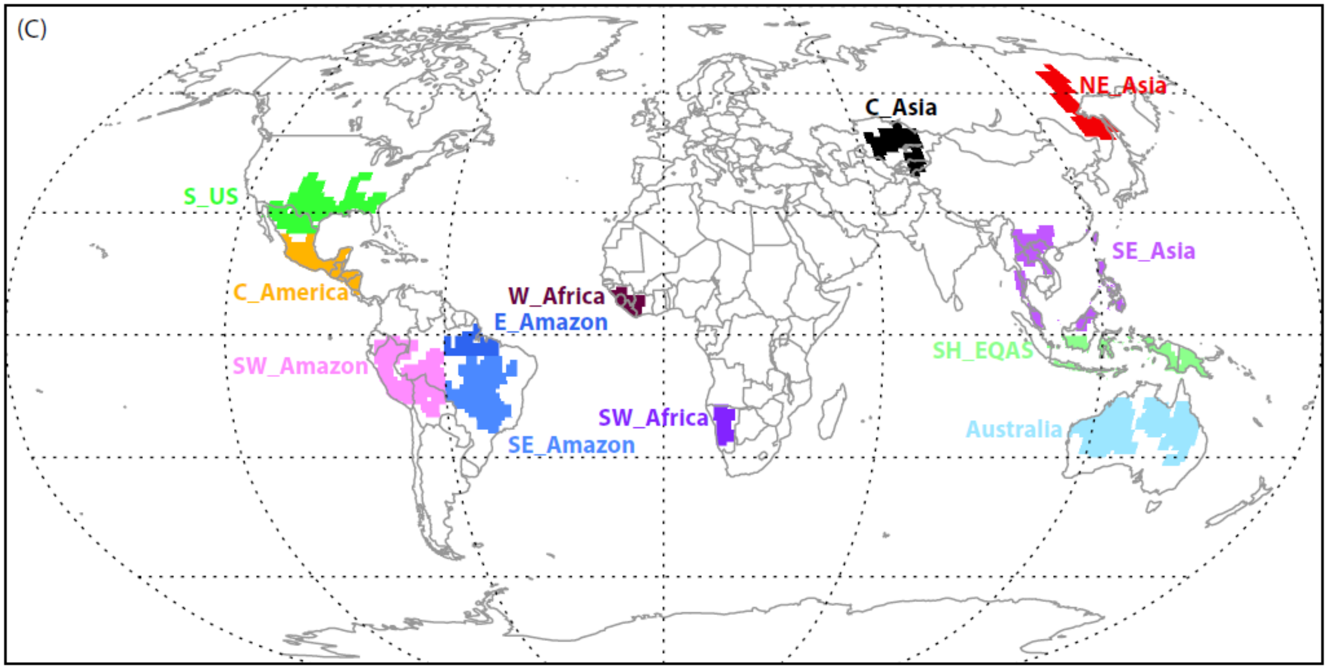
Randerson et al. (2015) GBC

Amazon broadleaf forest burned area from the fully coupled simulation



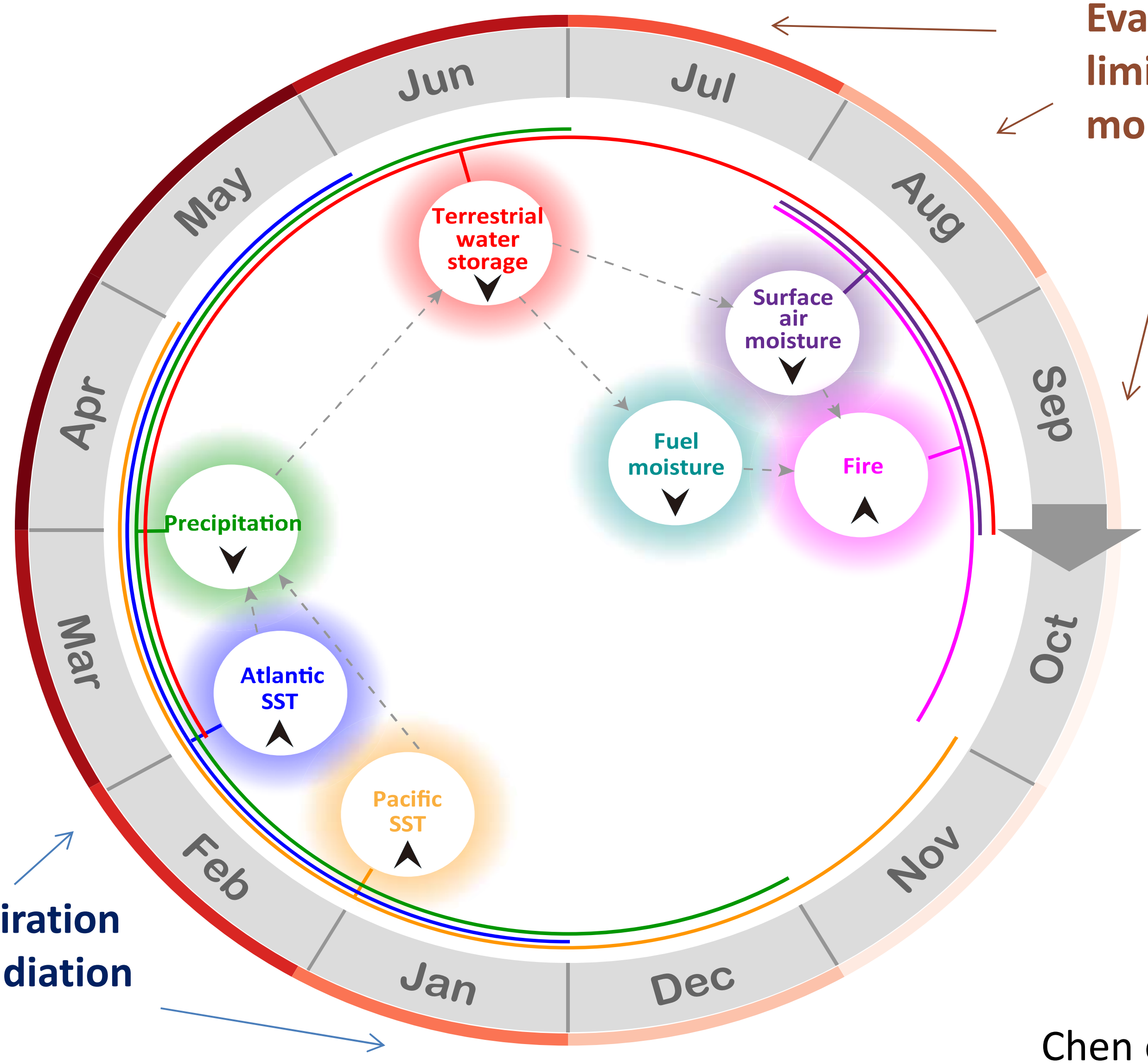


Toward the development of a global early warning system for fires



Chen, Randerson, et al. In prep.

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

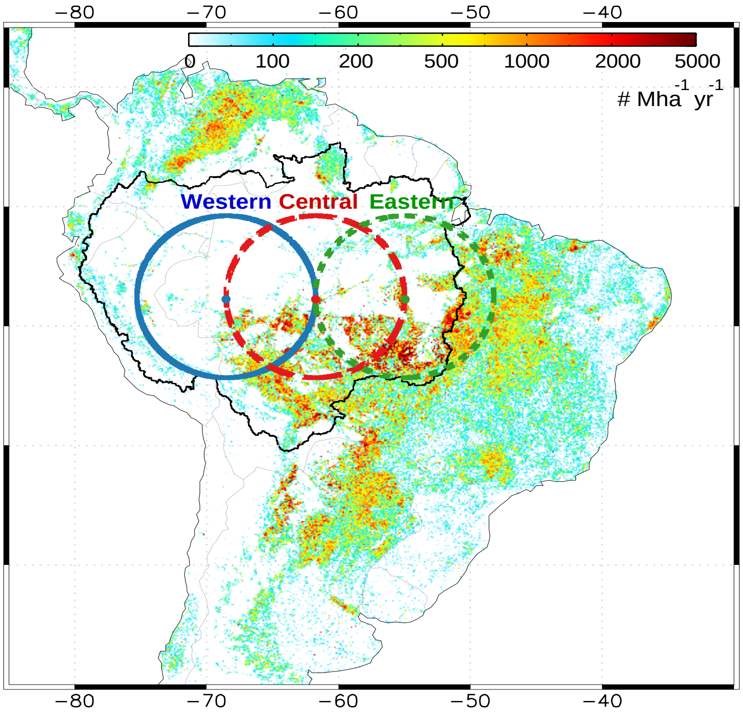


Evapotranspiration limited soil moisture reserves

Evapotranspiration limited by radiation

Chen et al. (2013) JGR-B

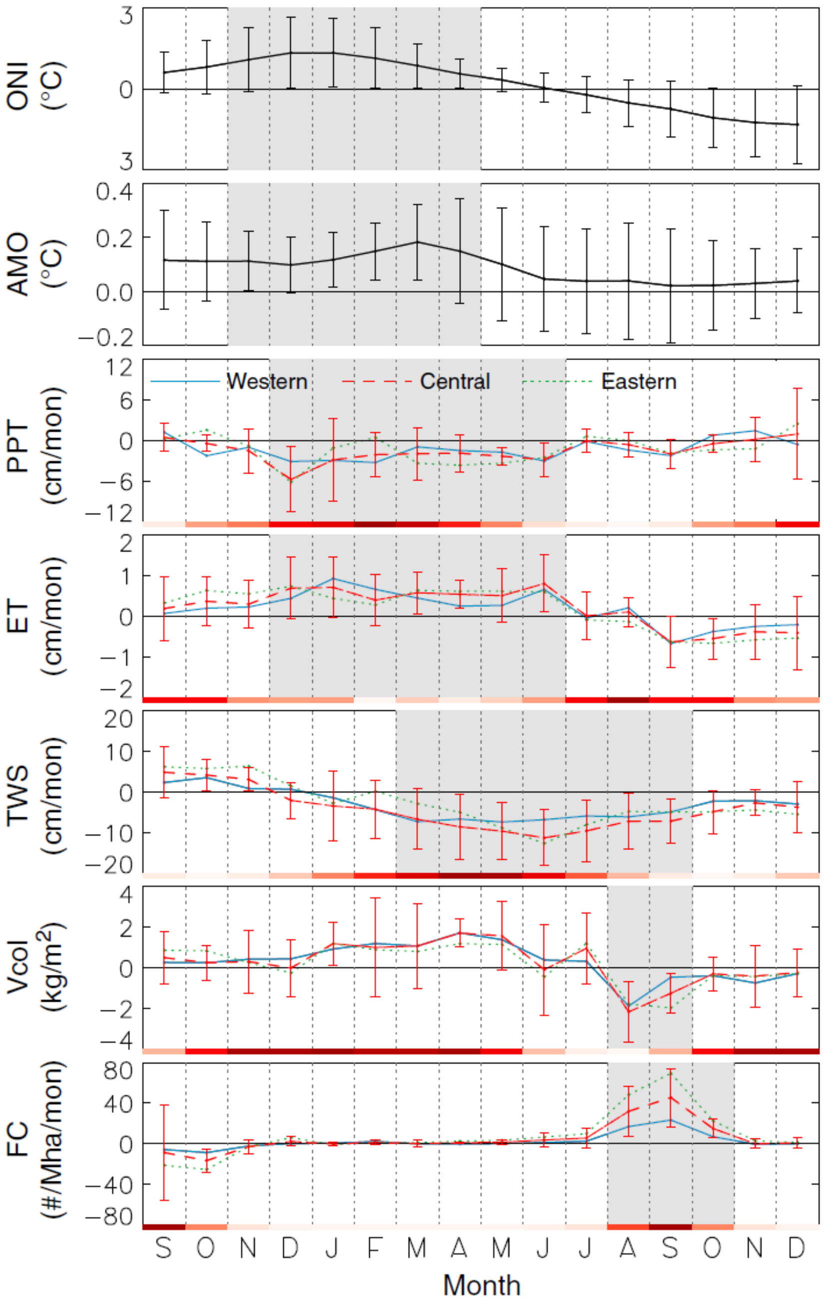
Test of the forest – soil moisture capacitor hypothesis for fire season predictions using satellite observations



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



TRMM

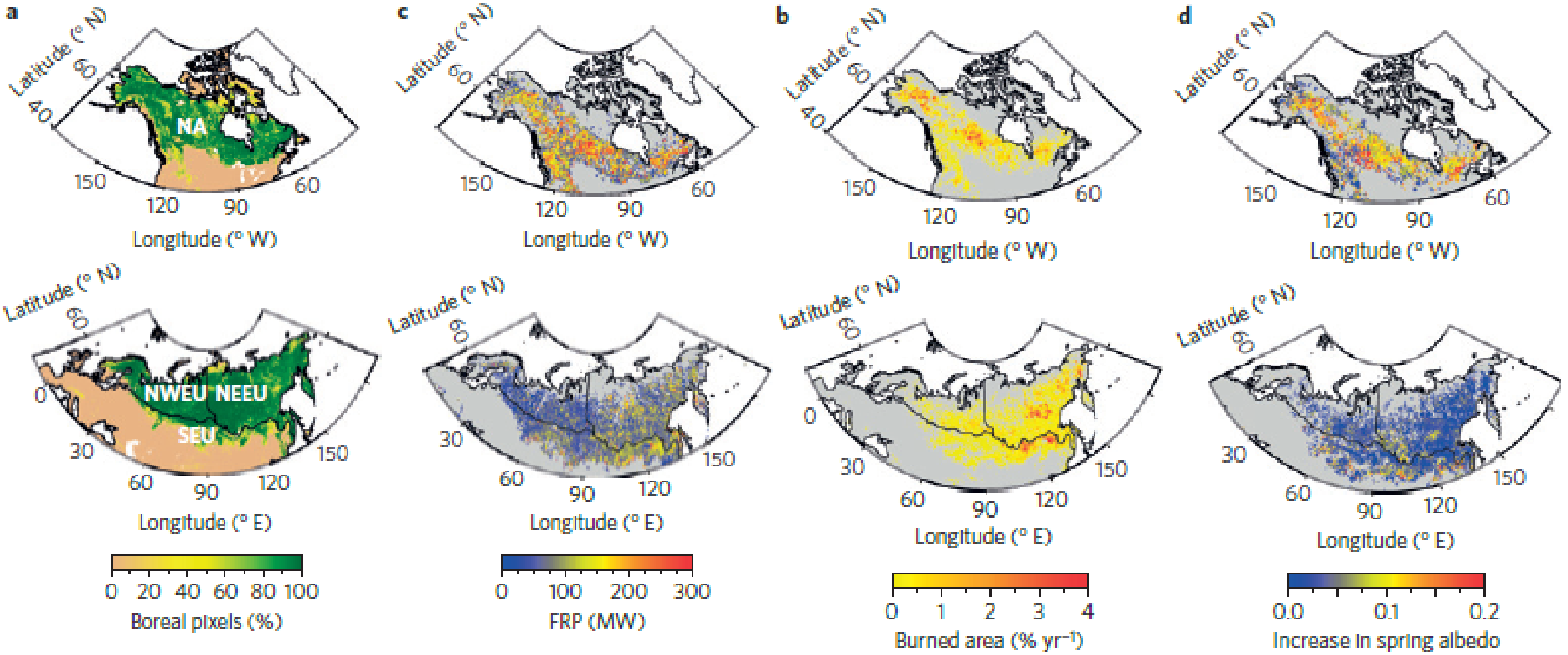
MODIS

GRACE

AIRS

MODIS

Capturing fire-mediated feedbacks in ESMs may require representing species-level effects



The presence of a single species in North America (black spruce) may cause fires to burn hotter and have greater long-term climate cooling effects

Rogers, Soja, Goulden, and Randerson. 2015. Influence of tree species on continental differences in boreal fires and climate feedbacks. Nature Geosciences. DOI: 10.1038/NGEO2352.

Conclusions

- Our understanding of Earth system dynamics, including processes that may contribute to ecosystem collapse, is woefully incomplete beyond 2100

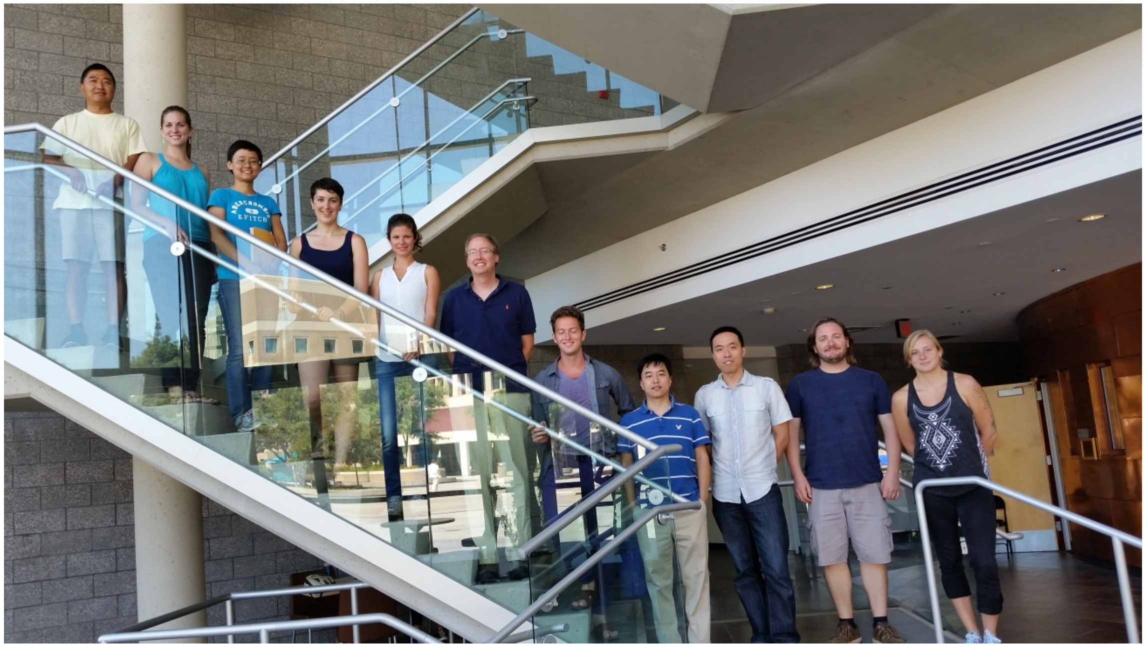
- Ocean contribution to the climate-carbon feedback increases considerably over time for a “business as usual” scenario, and exceeds contributions from land after 2100
  - Land feedback likely reduced from land use change
  - Ocean feedback strength closely related to ocean heat content and AMOC shutdown

- Forcing from non-CO_2 agents for the RCP8.5 scenario is almost enough to surpass the 2 °C dangerous interference limit

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

- A better understanding and representation of fire processes in ESMs is essential for accurately predicting carbon cycle dynamics in drought-prone areas

James Randerson
Department of Earth System Science, UC Irvine
jranders@uci.edu
http://sites.uci.edu/randersonlab/



Funding support from DOE Office of Science Biological and Environmental Research to the Biogeochemical Cycles Feedbacks Project, the National Science Foundation, NASA, and the Gordon and Betty Moore Foundation