The state of the carbon cycle in CMIP5 models: Processes, feedbacks, and future directions

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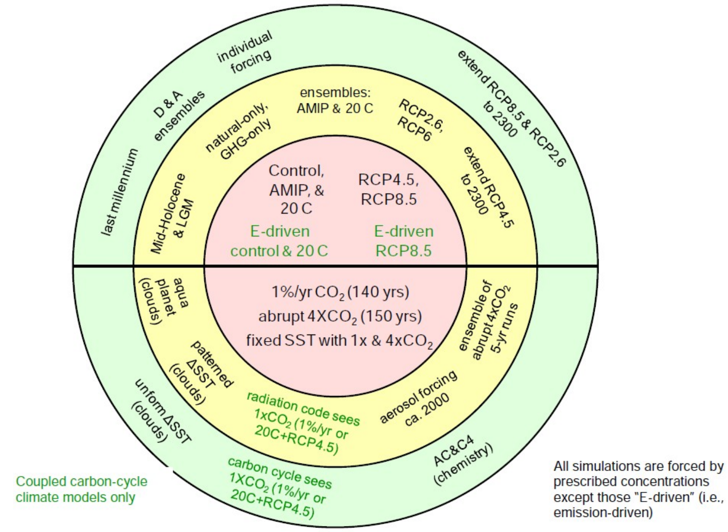
Overview questions

- How well do Earth System Models (ESMs) simulate the observed distribution of anthropogenic carbon in atmosphere, ocean, and land reservoirs?
- How can contemporary observations be used to reduce uncertainties associated with future scenarios?
- What processes control existing model predictions of soil carbon change during the 21st century?

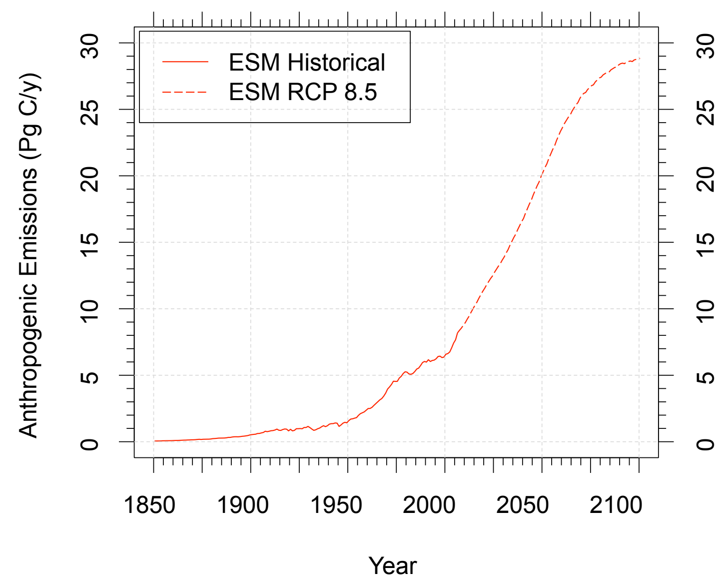
15 fully-prognostic ESMs that performed CMIP5 emissions-forced simulations

Model	Modeling Center
BCC-CSM1.1	Beijing Climate Center, China Meteorological Administration, CHINA
BCC-CSM1.1(m)	Beijing Climate Center, China Meteorological Administration, CHINA
BNU-ESM	Beijing Normal University, CHINA
CanESM2	Canadian Centre for Climate Modelling and Analysis, CANADA
CESM1-BGC	Community Earth System Model Contributors, NSF-DOE-NCAR, USA
FGOALS-s2.0	LASG, Institute of Atmospheric Physics, CAS, CHINA
GFDL-ESM2g	NOAA Geophysical Fluid Dynamics Laboratory, USA
GFDL-ESM2m	NOAA Geophysical Fluid Dynamics Laboratory, USA
HadGEM2-ES	Met Office Hadley Centre, UNITED KINGDOM
INM-CM4	Institute for Numerical Mathematics, RUSSIA
IPSL-CM5A-LR	Institut Pierre-Simon Laplace, FRANCE
MIROC-ESM	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (University of Tokyo), and National Institute for Environmental Studies, JAPAN
MPI-ESM-LR	Max Planck Institute for Meteorology, GERMANY
MRI-ESM1	Meteorological Research Institute, JAPAN
NorESM1-ME	Norwegian Climate Centre, NORWAY

CMIP5 Long-Term Experiments

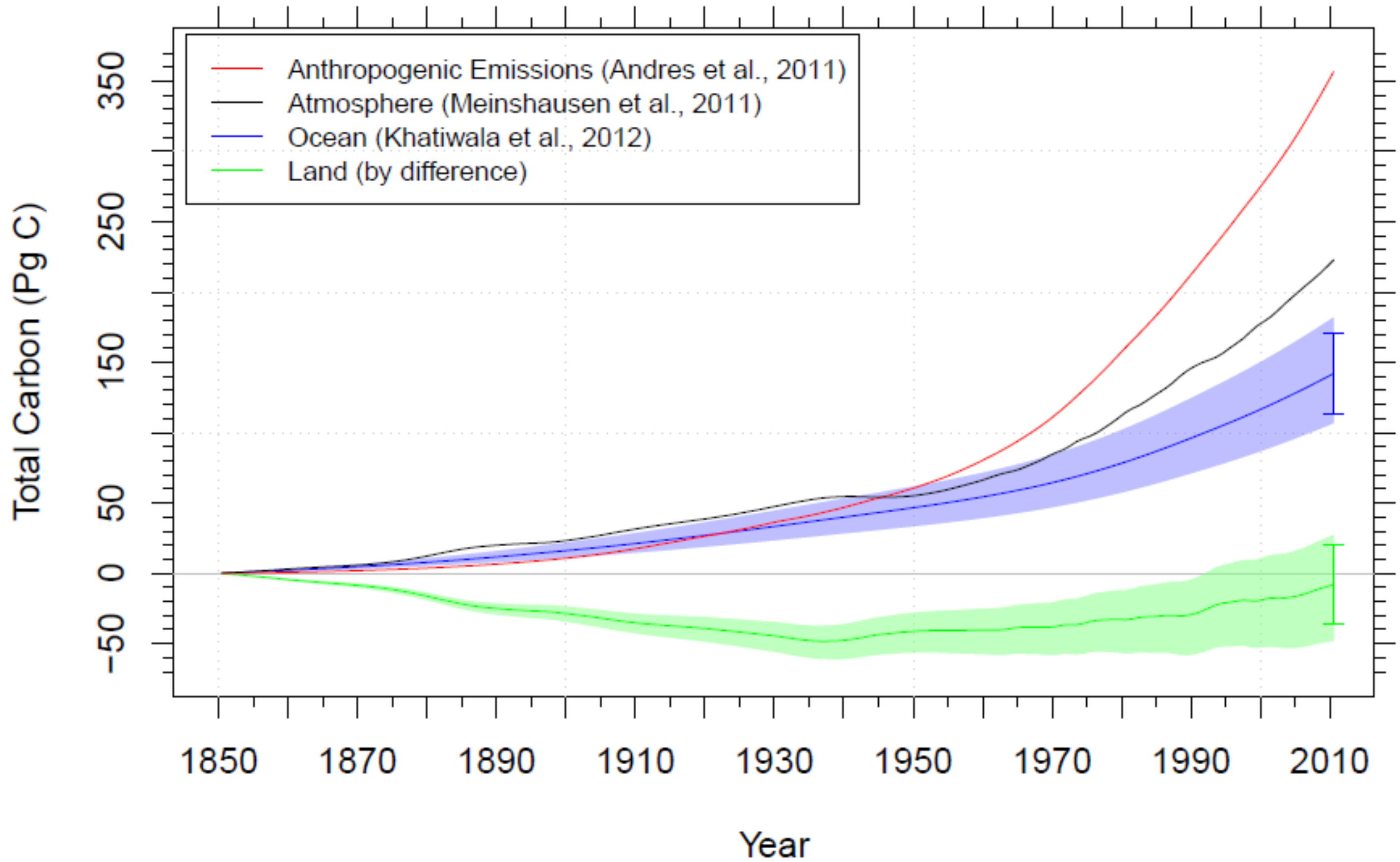


Emissions for Historical + RCP 8.5 Simulations



Hoffman et al. JGR in review

Observed Carbon Accumulation Since 1850



Observational estimates of anthropogenic carbon inventories in atmosphere, ocean, and land reservoirs for 1850–2010. Atmosphere carbon is a fusion of Law Dome ice core CO_2 observations, the Keeling Mauna Loa record, and more recently the NOAA GMD global surface average, integrated for the purpose of forcing IPCC models. Total land flux is computed by mass balance as follows:

$$\Delta C_L = \sum_i F_i - \Delta C_A - \Delta C_O.$$

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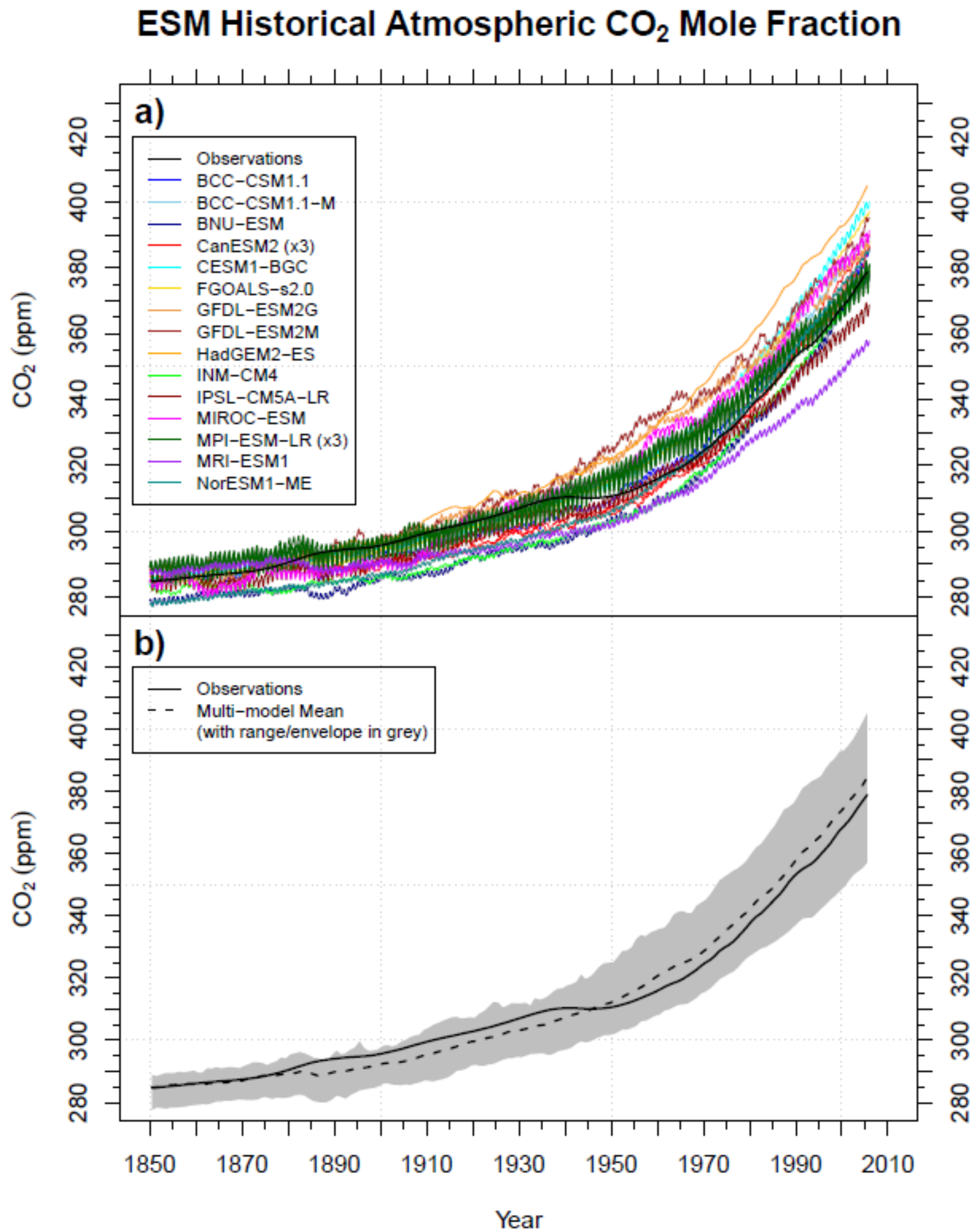
(a) Most ESMs exhibit a high bias in predicted atmospheric CO_2 mole fraction, which ranges from 357–405 ppm at the end of the historical period (1850–2005).

(b) The multi-model mean is biased high from 1946 throughout the 20th century, ending 5.6 ppm above the observed value of 378.8 ppm in 2005.



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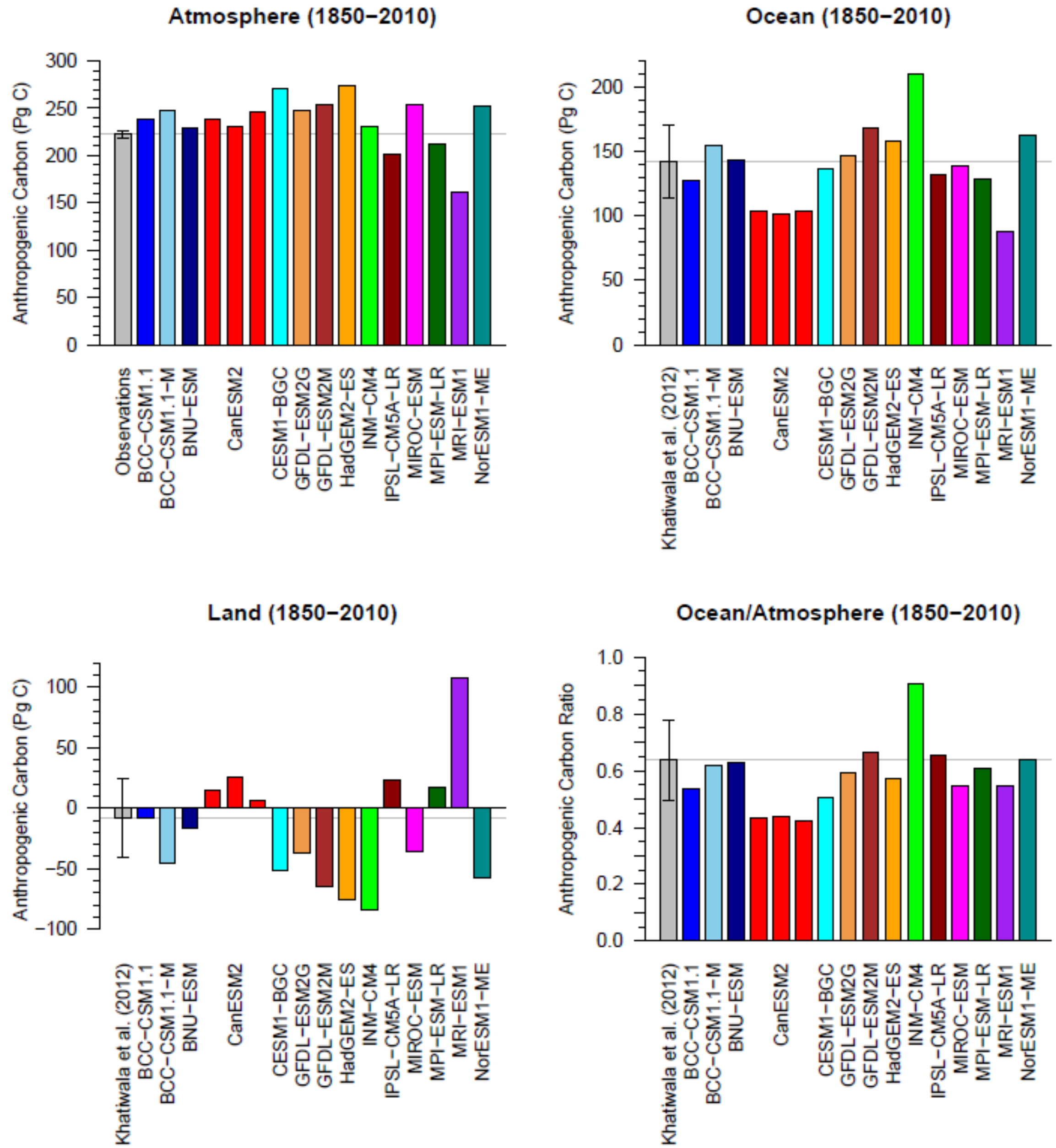
Model inventory comparison with Khatiwala et al. (2012)

Once normalized by their atmospheric carbon inventories, most ESMs exhibit a low bias in anthropogenic ocean carbon accumulation through 2010.

The same pattern holds for the Sabine et al. (2004) inventory derived using the ΔC^* separation technique.



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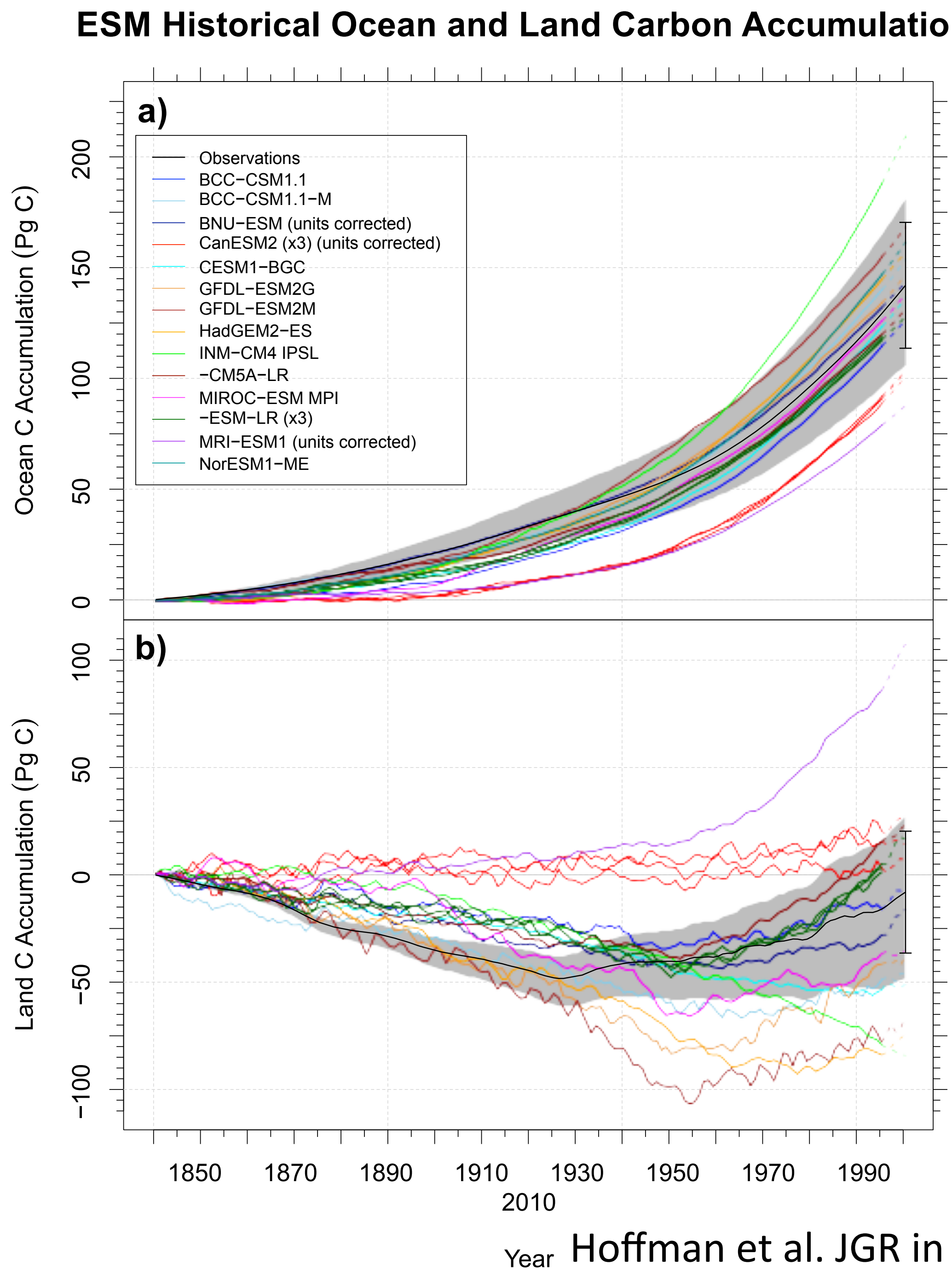
(a) Ocean inventory estimates have a fairly persistent ordering during the second half of the 20th century.

(b) ESMs have a wide range of land carbon accumulation responses to increasing CO_2 and land use change, ranging from a net source of 84 PgC to a sink of 107 PgC in 2010.



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Question 1

How well do Earth System Models (ESMs) simulate the observed distribution of anthropogenic carbon in atmosphere, ocean, and land reservoirs?

- Most ESMs exhibit a high bias in predicted atmospheric CO_2 mole fraction, ranging from 357–405 ppm in 2005
- The multi-model mean atmospheric CO_2 mole fraction is biased high from 1946 onward, ending 5.6 ppm above observations in 2005
- Once normalized by atmospheric carbon accumulation, most ESMs exhibit a low bias in ocean accumulation in 2010
- ESMs predict a wide range of land carbon accumulation in response to increasing CO_2, land use change and other forcing agents, ranging from −84 to 107 Pg C in 2010

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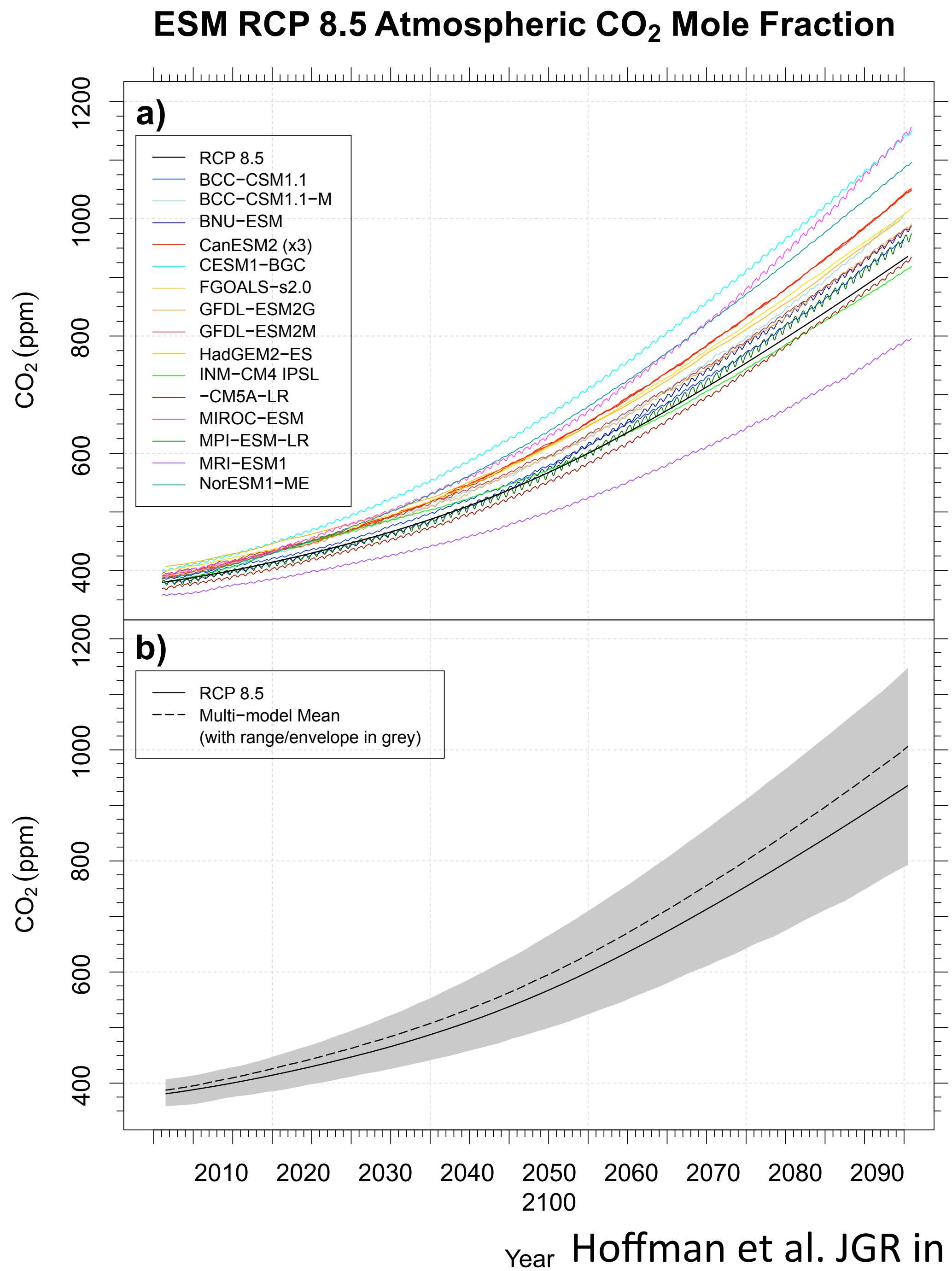
Question 2

Can we use contemporary atmospheric CO_2 observations to constrain future CO_2 projections?



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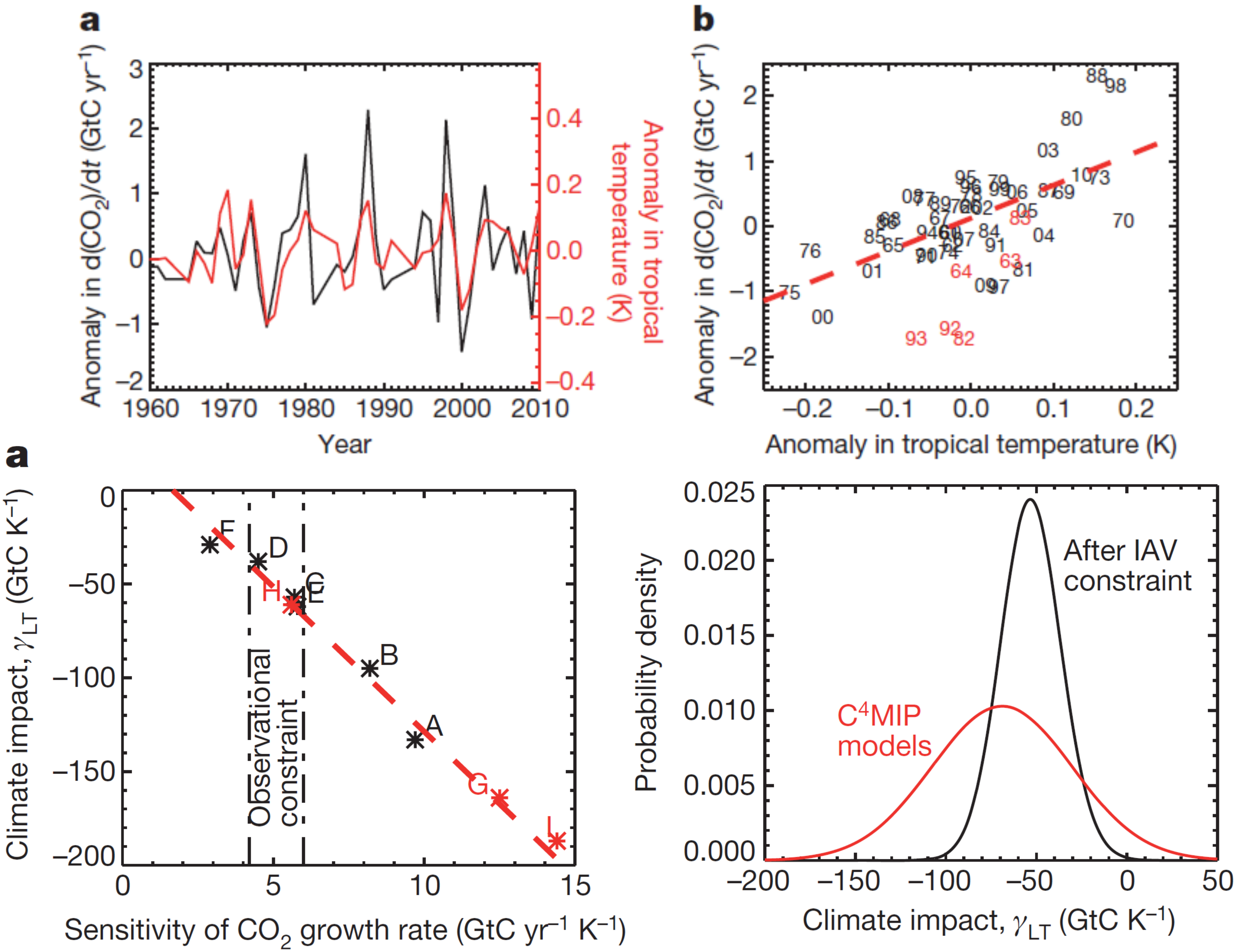
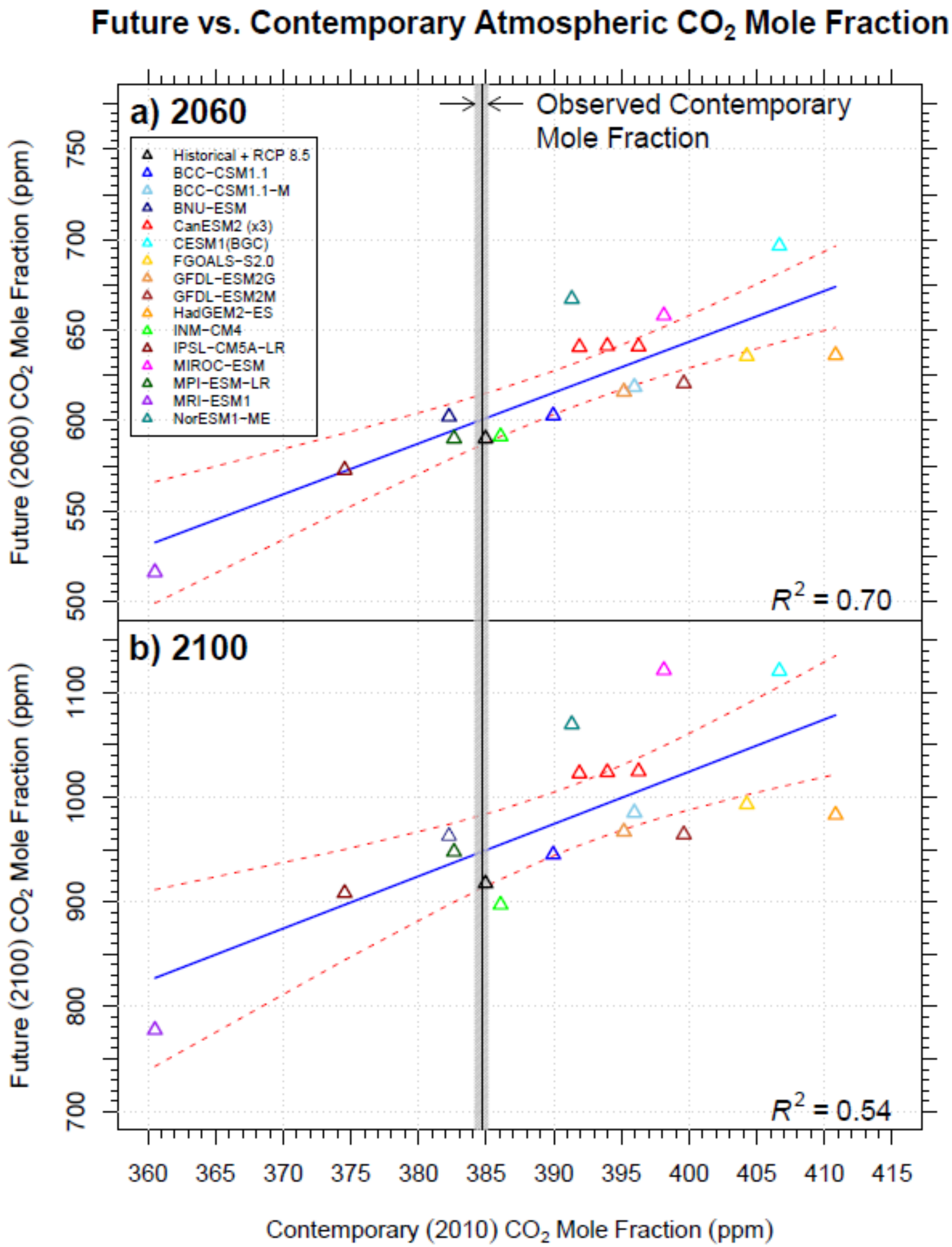


Cox et al. 2013

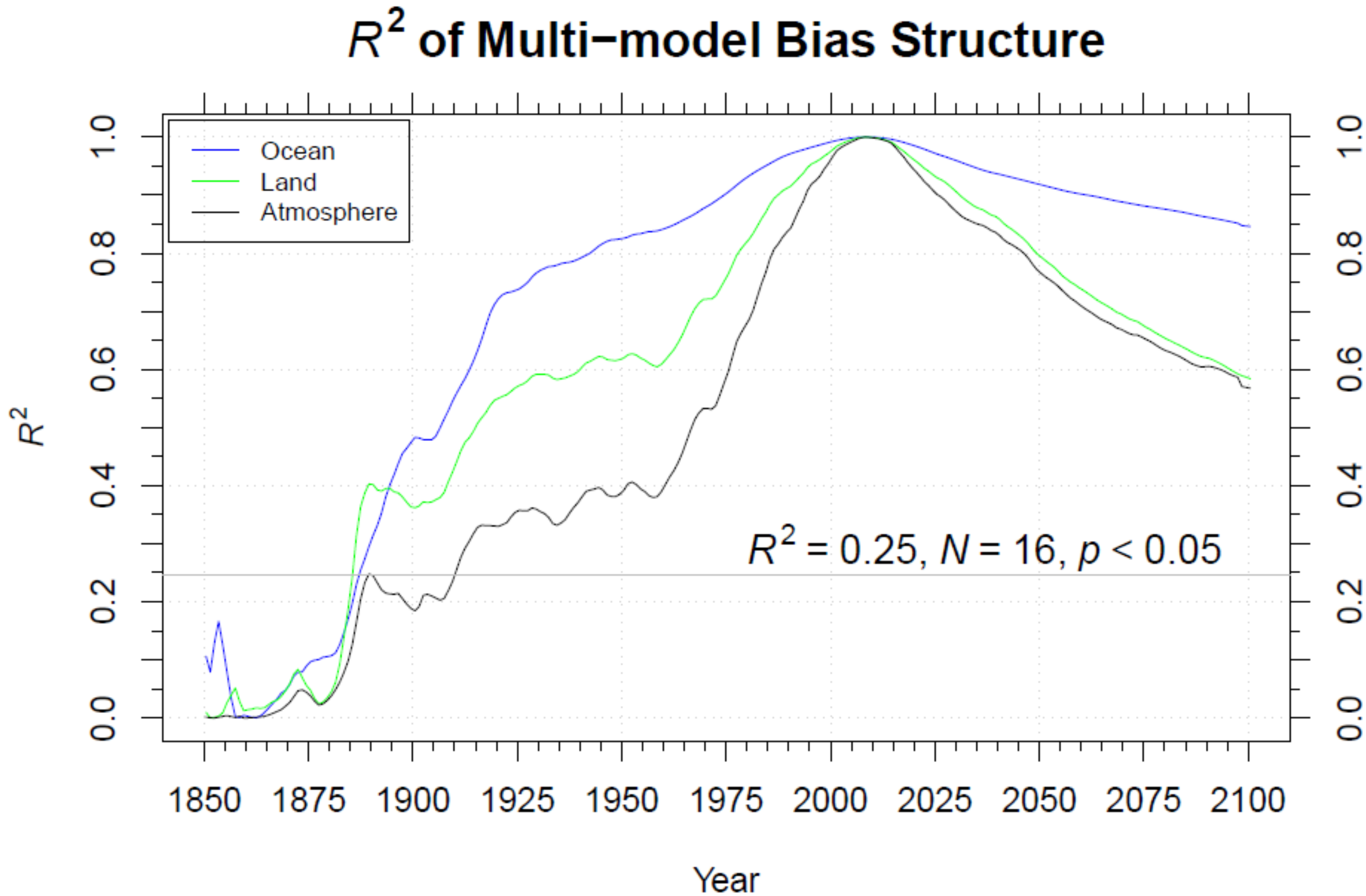
We developed a new emergent constraint from carbon inventories.

A relationship exists between contemporary and future atmospheric CO_2 levels over decadal time scales because carbon model biases persist over decadal time scales.

Observed contemporary atmospheric CO_2 mole fraction is represented by the vertical line at 384.6 ± 0.5 ppm.

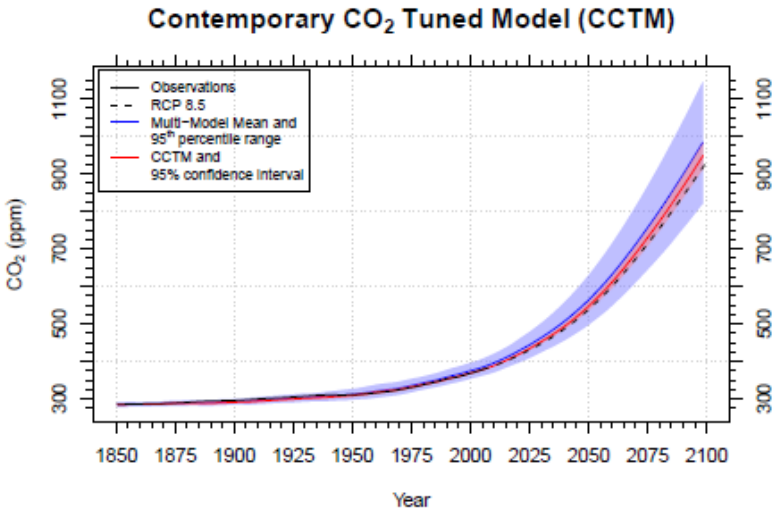


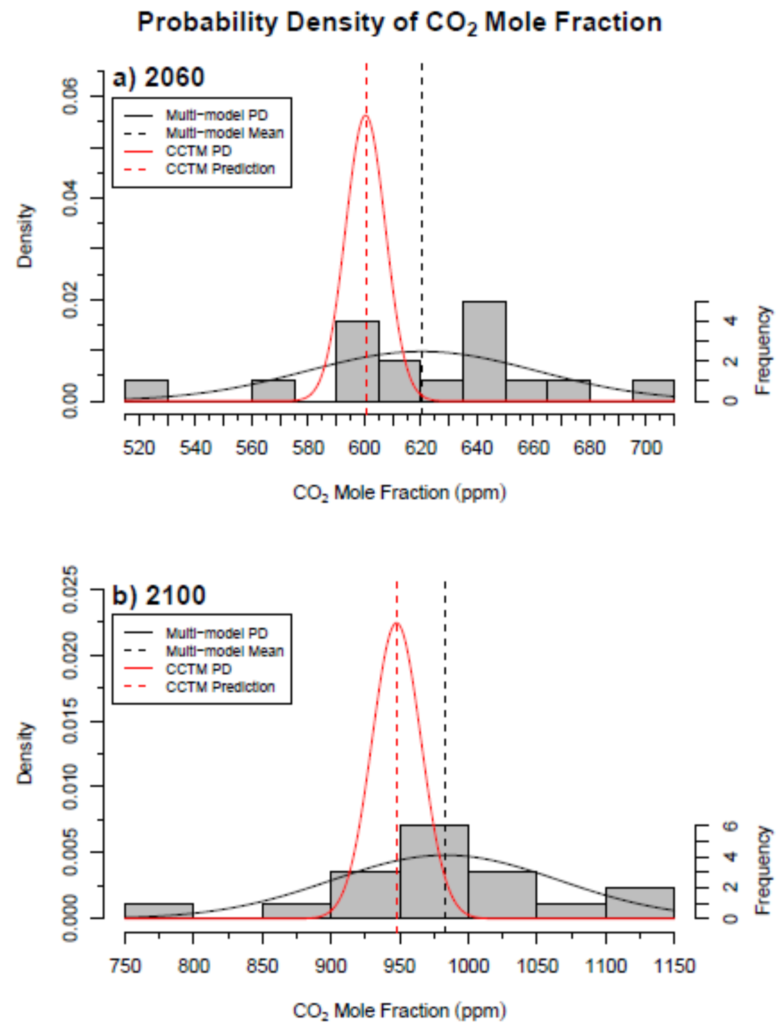
Hoffman et al. JGR in review



The coefficients of determination (R^2) of the multi-model bias structure relative to the set of CMIP5 model atmospheric CO_2, and ocean and land carbon predictions for 2010 are statistically significant for 1910–2100.

Hoffman et al. JGR in review





We used this regression to create a contemporary CO_2 tuned model (CCTM) estimate of the atmospheric CO_2 trajectory for the 21st century.

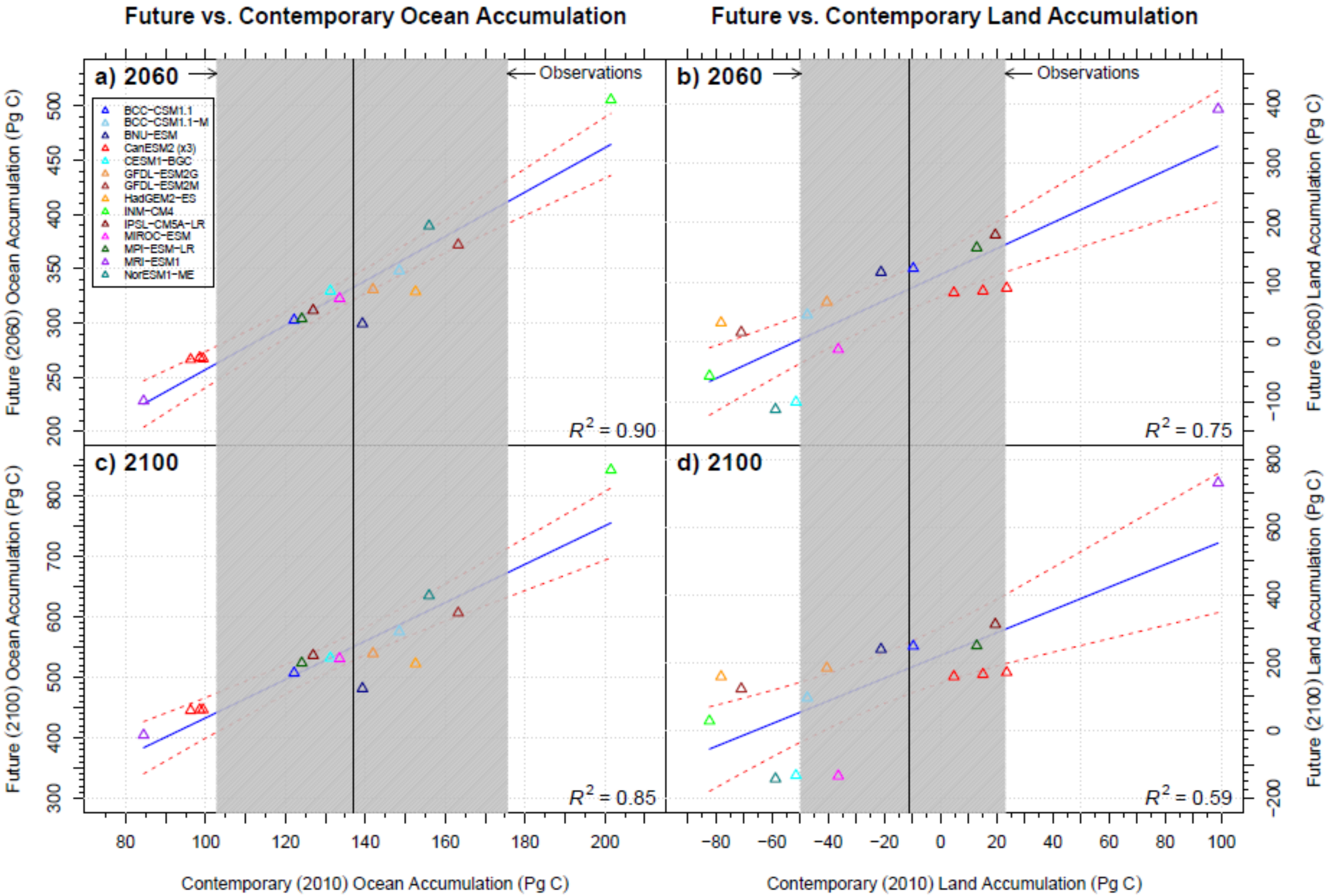
The width of the probability density is much smaller for the CCTM, by almost a factor of 6 at 2060 and almost a factor of 5 at 2100, indicating a significant reduction in the range of uncertainty for the CCTM prediction.

Best estimate tuned using Mauna Loa CO2 data:

At 2060: 600 ±14 ppm, 21 ppm below the multi-model mean

At 2100: 947 ± 35 ppm, 32 ppm below the multi-model mean

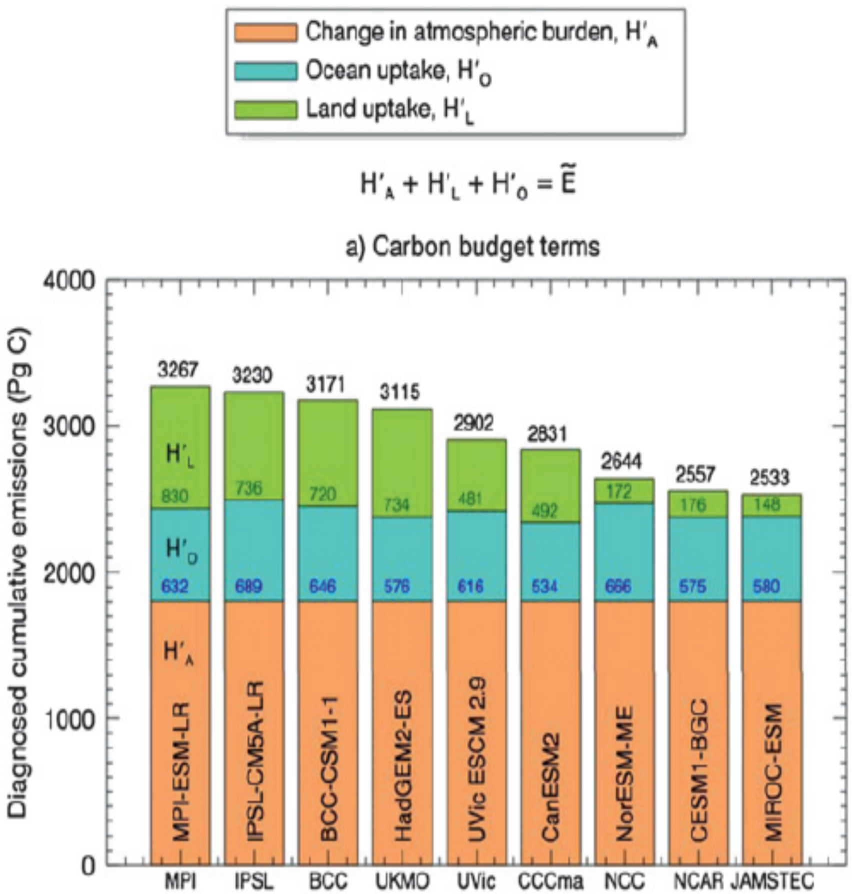
Hoffman et al. JGR in review



We also developed a multi-model constraint on the evolution of ocean and land anthropogenic inventories. Since observational uncertainties are higher for ocean and land, uncertainties in future estimates cannot be reduced as much as for atmospheric CO_2.

Future constraints conclusions

- A considerable amount of the model-to-model variability of CO_2 in the 21st century can be traced to biases that exist at the end of the observational record.
- Bias persistence was highest for the ocean, followed by land, and then by the atmosphere.
- Carbon cycle biases are likely primarily linked with concentration–carbon feedback processes:
  - ocean – Southern Ocean overturning, vertical mixing processes
  - land – CO_2 fertilization, allocation to woody pools, nutrient limitation
- Future fossil fuel emissions targets designed to stabilize CO_2 levels would be too low if estimated from the multi-model mean of ESMs.
  - ESMs overestimate contemporary CO_2 with observed emissions.
- Models could be improved through extensive comparison with observations and community model benchmarking.



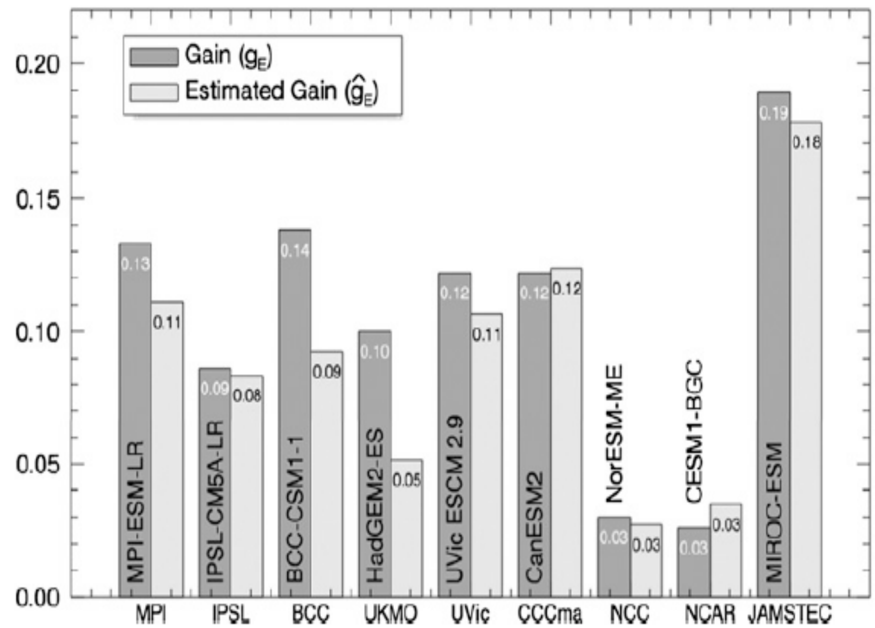
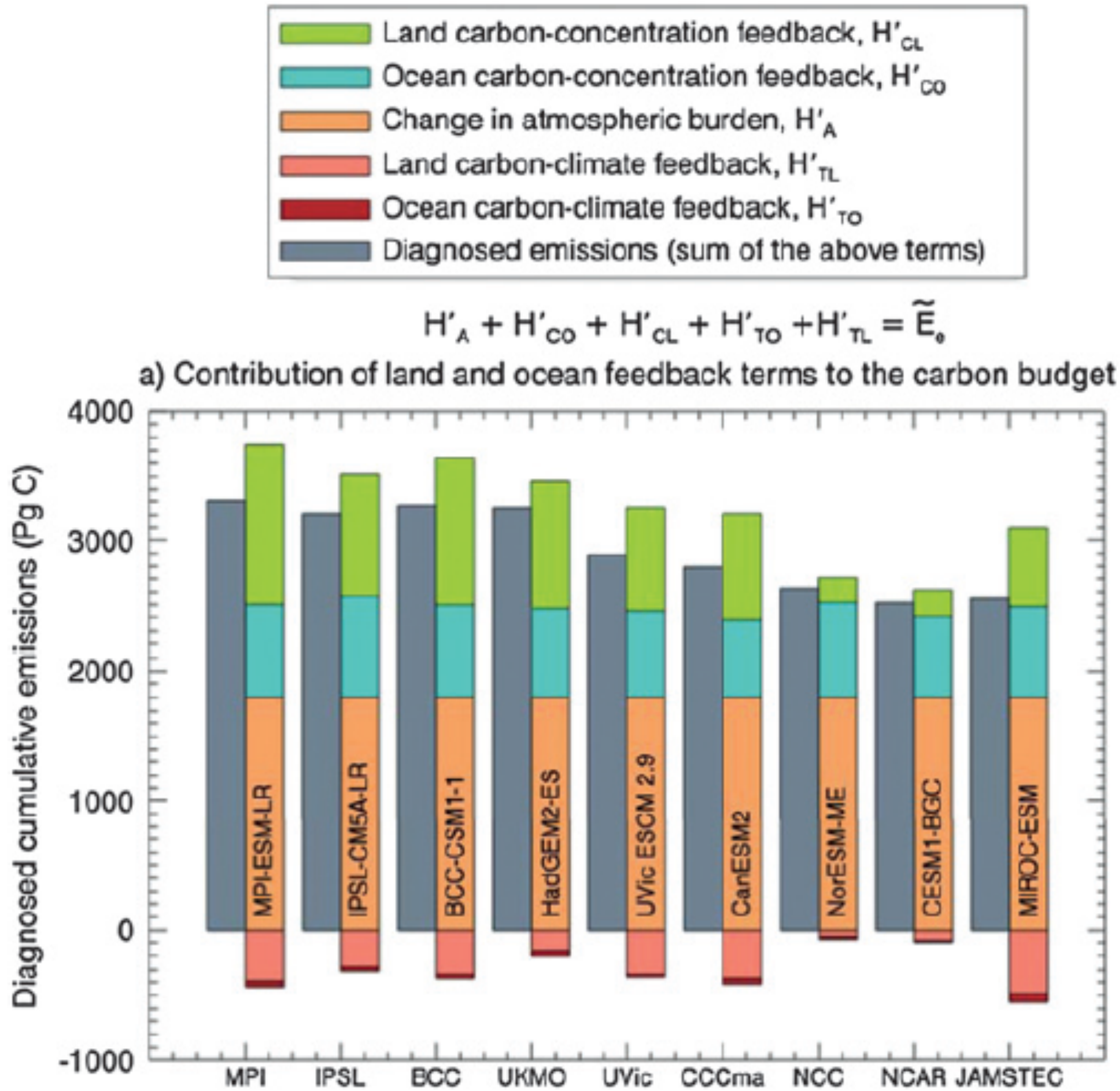


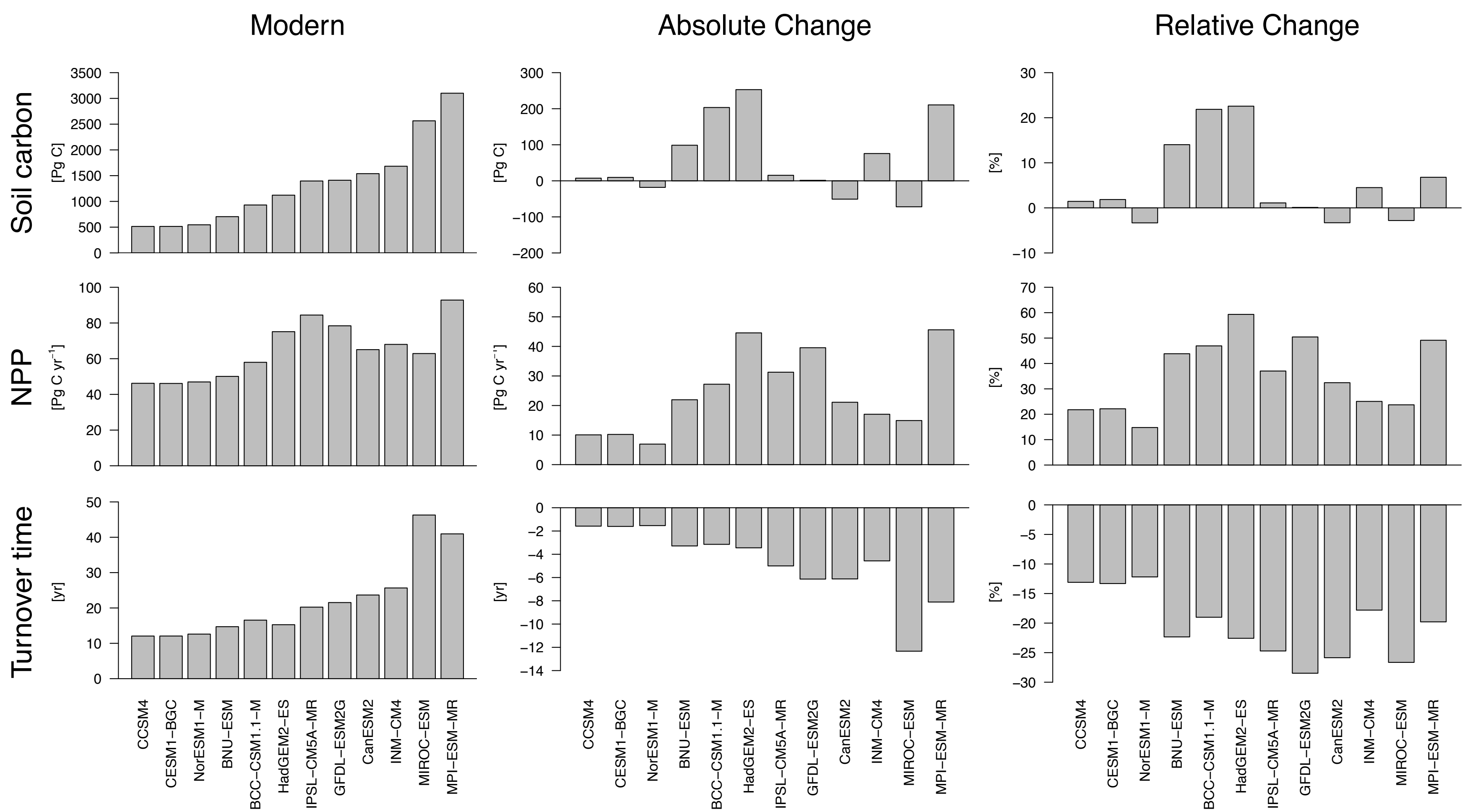
FIG. 9. Gain g_E [Eq. (13)] and its estimated value based on feedback parameters $\hat{g}_E$ [Eq. (15)] for the nine participating models.

Arora et al. (2013)

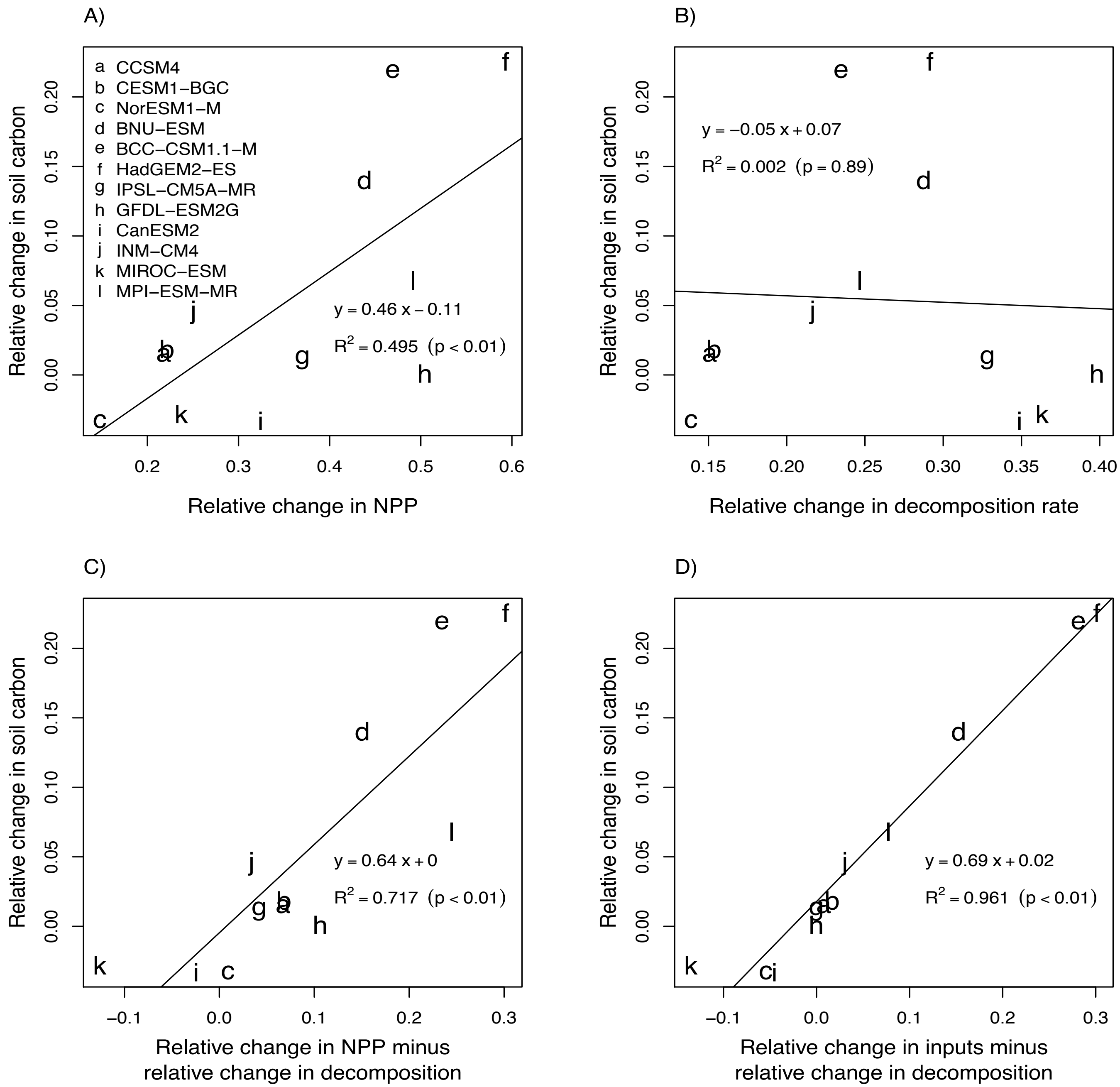


Arora et al. (2013)

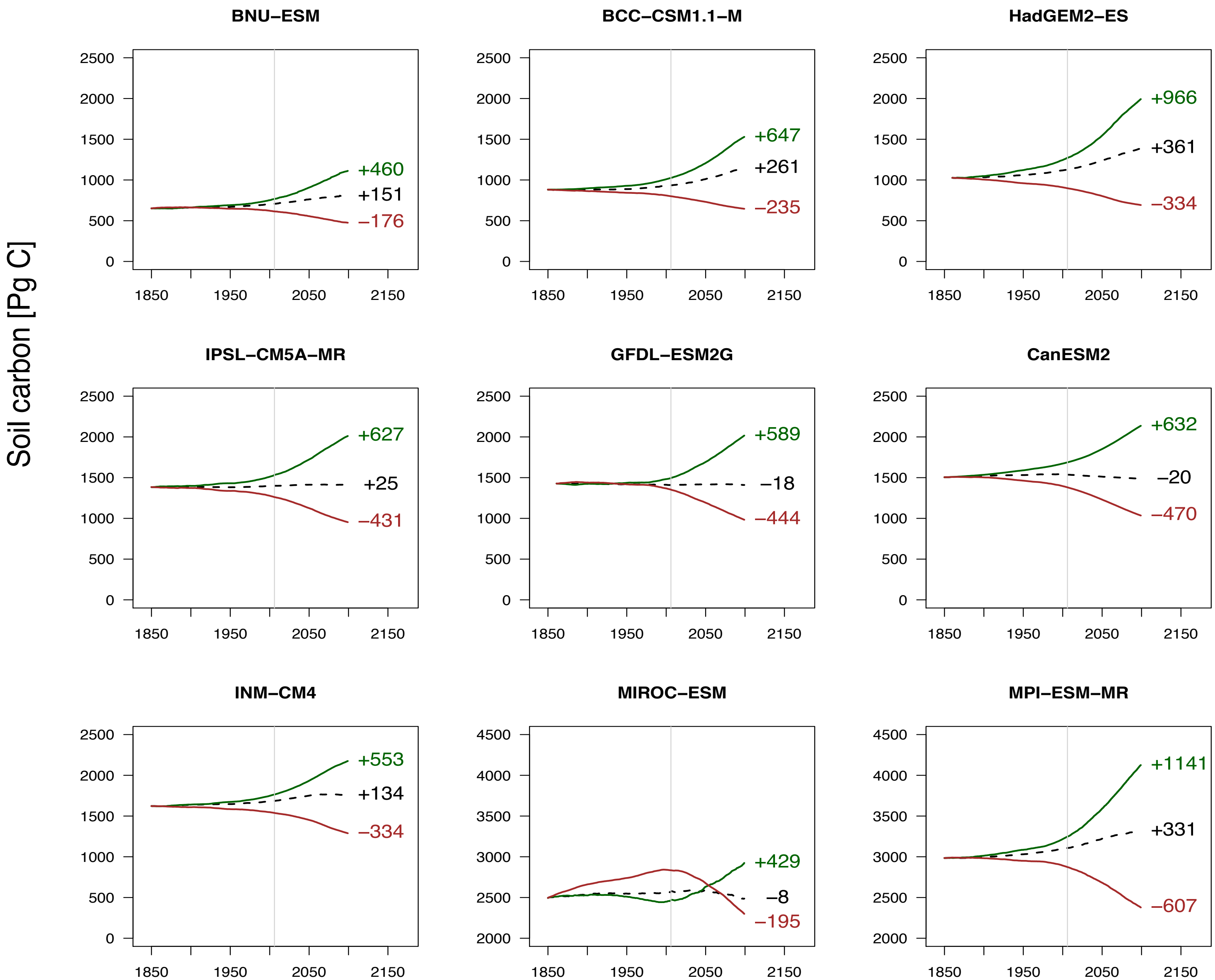
Model estimates of soil carbon change during the 21st Century from RCP 8.5 (2100 - 2006)



Todd Brown et al.



Todd Brown et al.



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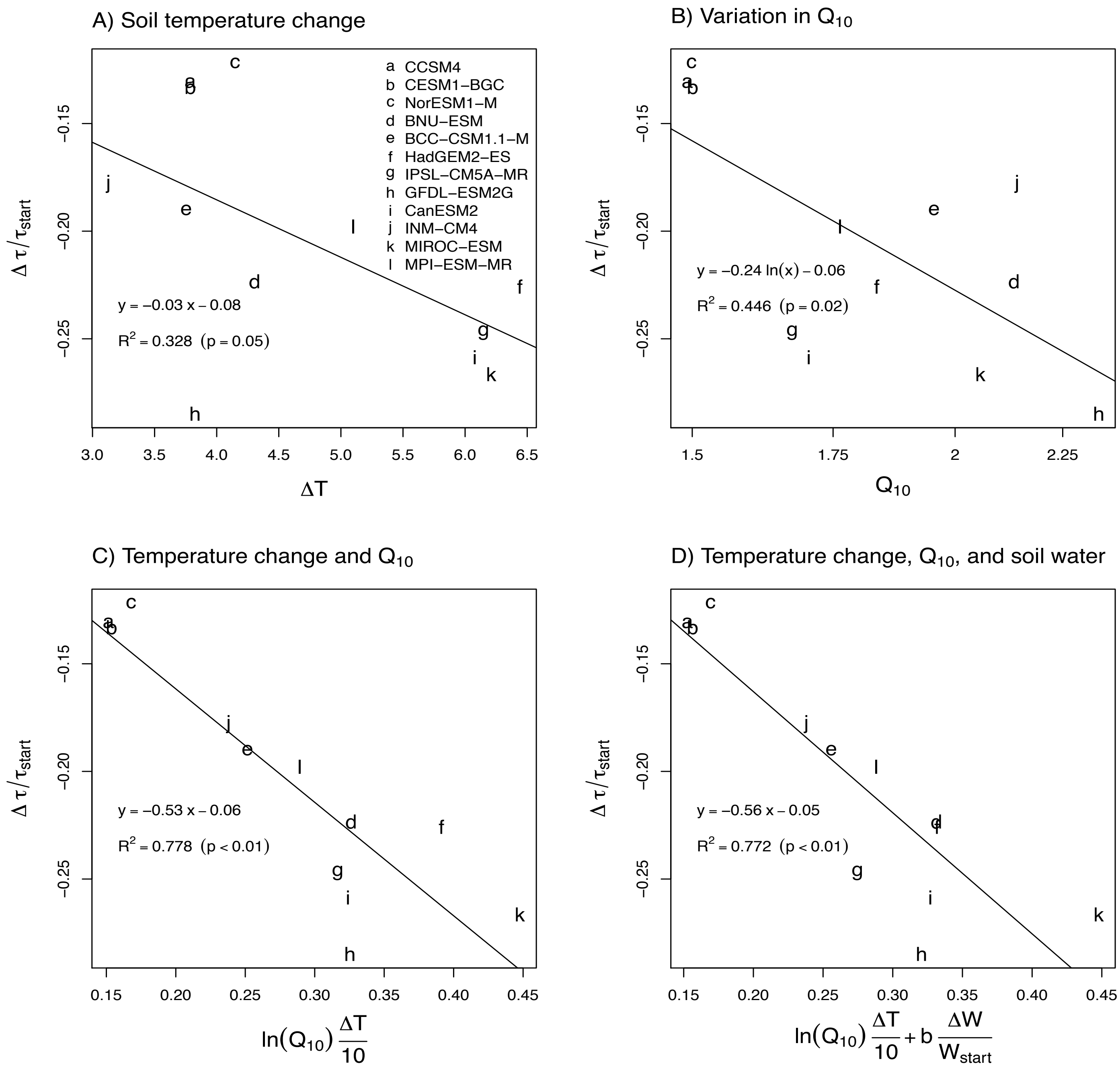


Todd Brown et al.

Conclusions for the representation of carbon cycle processes in CMIP5 ESMs

- Carbon-concentration feedbacks more important than climate-carbon feedbacks in contributing to ESM variability in atm. CO_2 predictions to 2100

- Emerging constraints can constrain the temperature sensitivity of carbon losses from the terrestrial biosphere and the combined representation of ocean and land C cycle processes

- Highly linear relationship between GPP increases, NPP increases, soil temperature changes, and soil carbon responses in the model

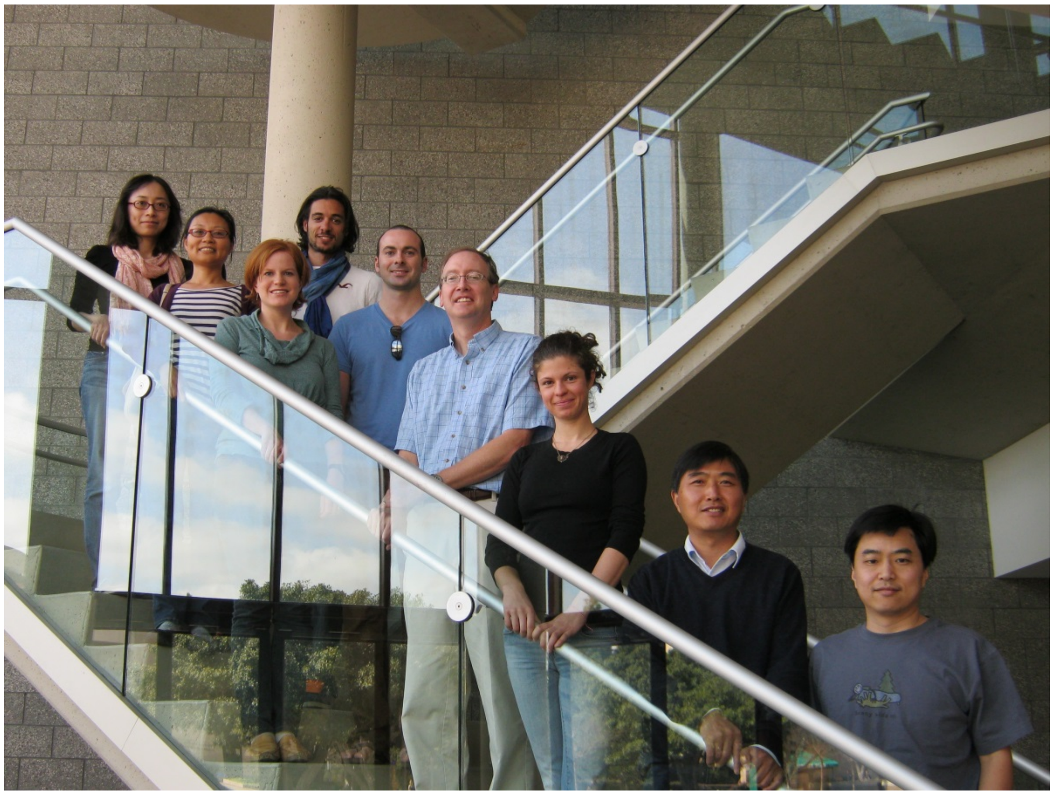
Future short-term directions (for CMIP6)

- Reduce biases in the representation of 20th century atmospheric CO_2 time series through improved representation of stocks and surface fluxes

- Improve the representation of:
  - Vegetation dynamics
  - Permafrost carbon
  - Anoxia controls on soil carbon and NPP
  - Disturbance processes
  - Damping of NPP increases for soil carbon storage:
    - Enhanced vegetation mortality
    - Soil carbon priming and stabilization

Acknowledgements

Lab Group:



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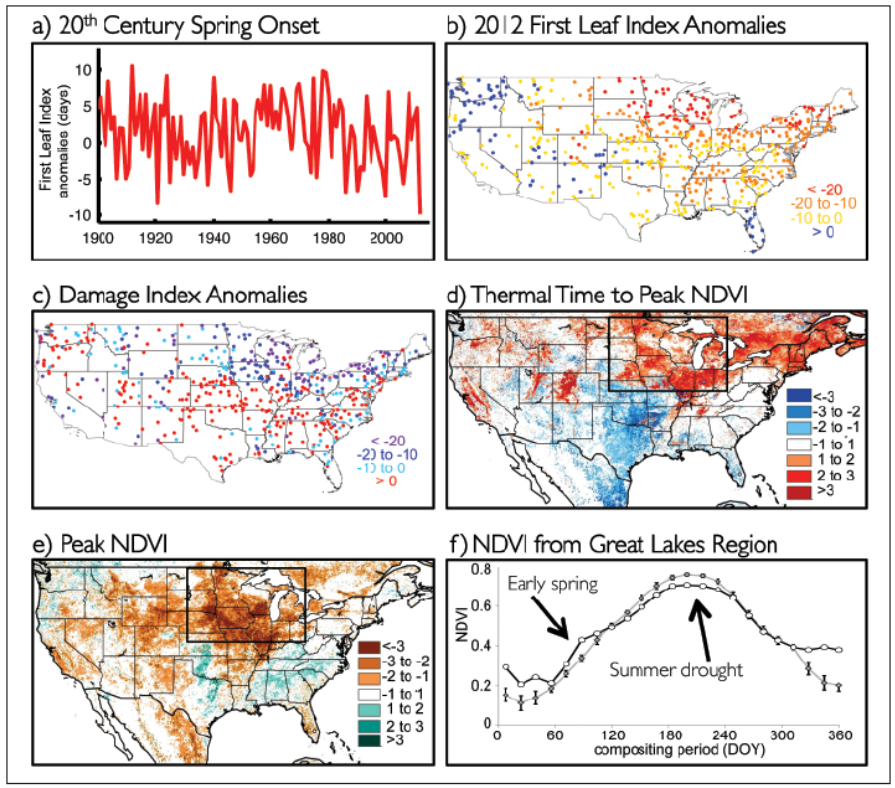
The False Spring of 2012, Earliest in North American Record

PAGES 181–182

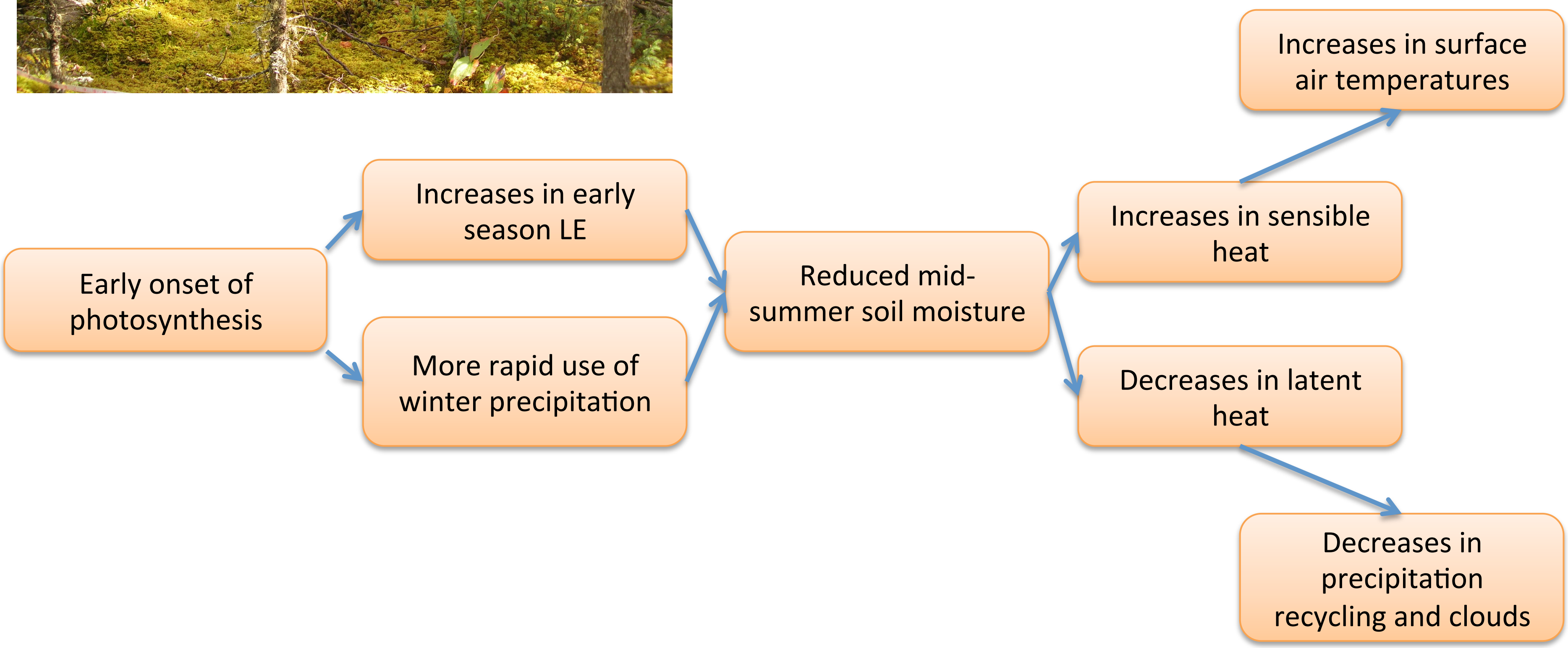


Phenology—the study of recurring plant and animal life cycle stages, especially their timing and relationships with weather and climate—is becoming an essential tool for documenting, communicating, and anticipating the consequences of climate variability and change. For example, March 2012 broke numerous records for warm temperatures and early flowering in the United States [*Karl et al.*, 2012; *Elwood et al.*, 2013]. Many regions experienced a "false spring," a period of weather in late winter or early spring sufficiently mild and long to bring vegetation out of dormancy prematurely, rendering it vulnerable to late frost and drought.

As global climate warms, increasingly warmer springs may combine with the random climatological occurrence of advective freezes, which result from cold air moving from one region to another, to dramatically increase the future risk of false springs, with profound ecological and economic consequences [e.g., *Gu et al.*, 2008; *Marino et al.*, 2011; *Augspurger*, 2013]. For example, in the false spring of 2012, an event embedded in long-term trends toward earlier spring [e.g., *Schwartz et al.*, 2006], the frost damage to fruit trees totaled half a billion dollars in Michigan alone, prompting the federal government to declare the state a

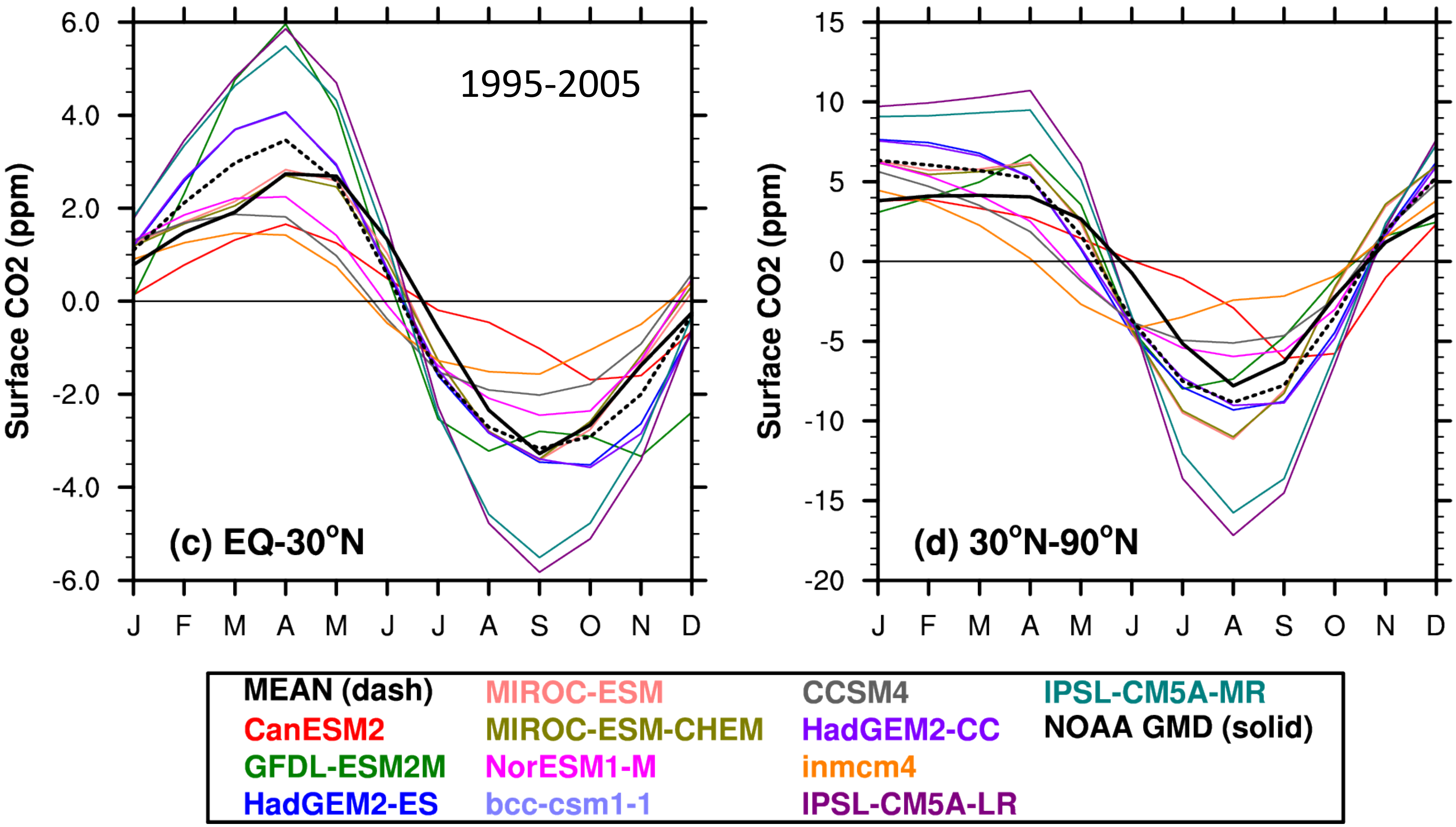
Ault et al.

How much of mid-summer climate variability can be explained by spring onset of photosynthesis?

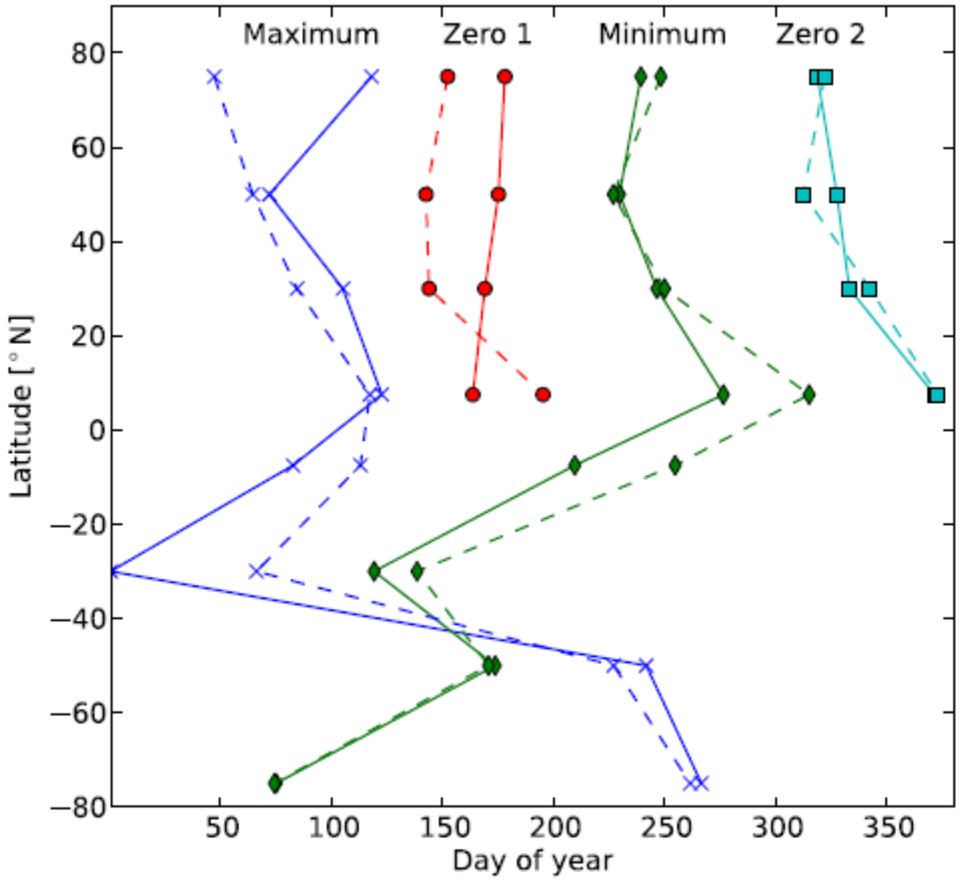


Atmospheric CO_2 is drawn down too early in spring in most CMIP5 Earth system models

- GEOS-Chem with CMIP5 net biosphere production (NBP) and prescribed ocean and fossil fuel fluxes, sampled at NOAA GMD stations and compared with observations (1995-2005)



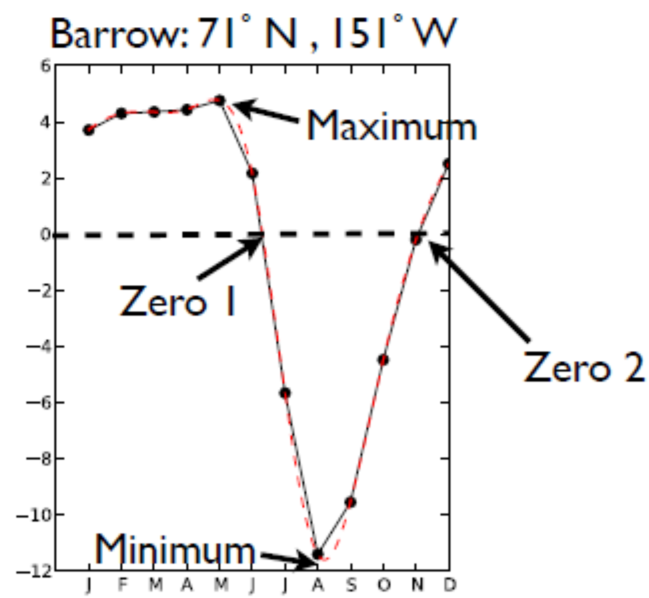
Diagnostics of the phase of the annual cycle of atm. CO_2



NOAA GMD Observations

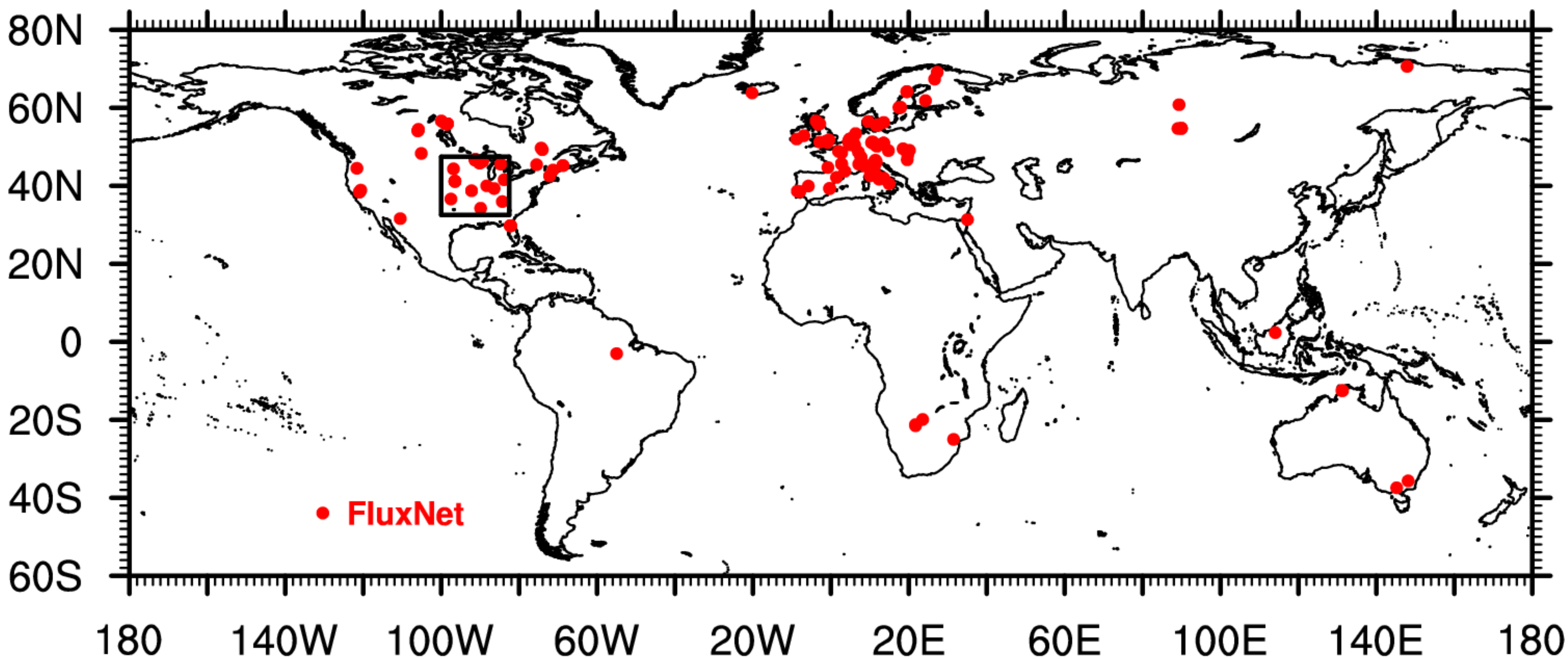
CESM

The onset of the growing season occurs too early in CESM.



Keppel-Aleks et al. (J. of Climate, 2013)

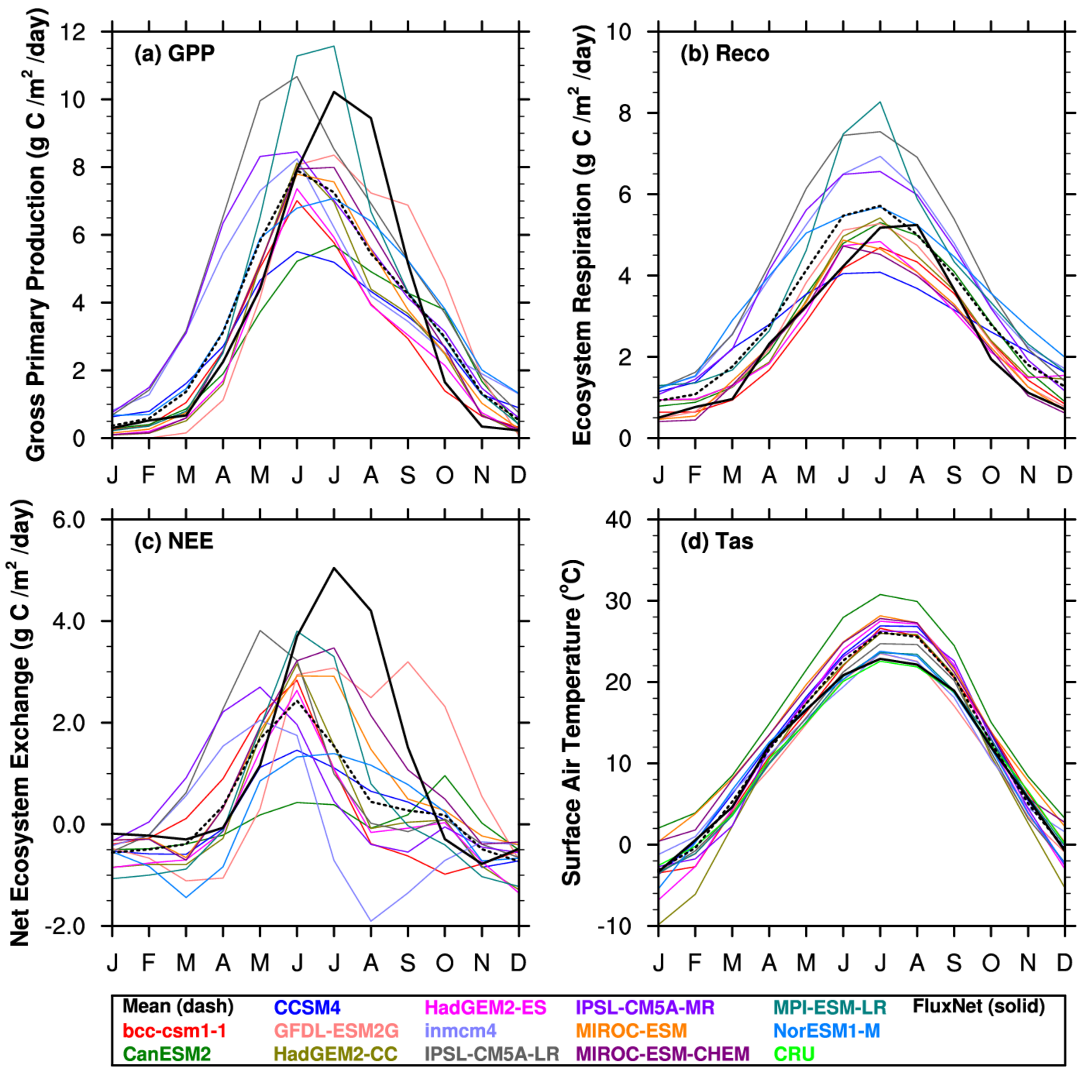
What are the causes of the early season uptake bias?
Eddy covariance observations from FLUXNET provide constraints



GPP appears to be the primary culprit for the early NEE uptake and CO_2 drawdown

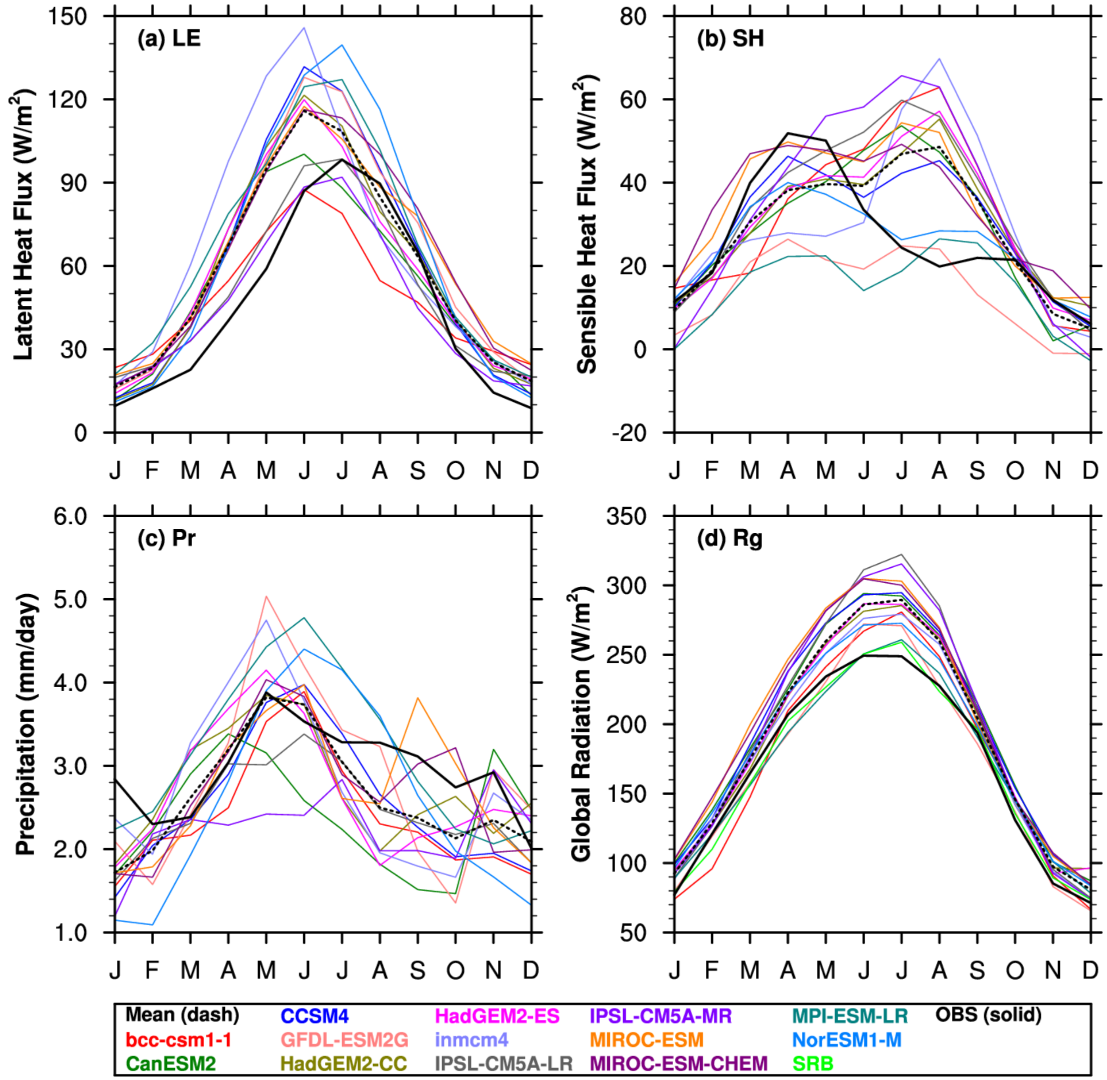
- Fluxnet sites in North America between 35N and 45N

Model grid cells extracted and sampled at all measurement sites during the times obs. were available



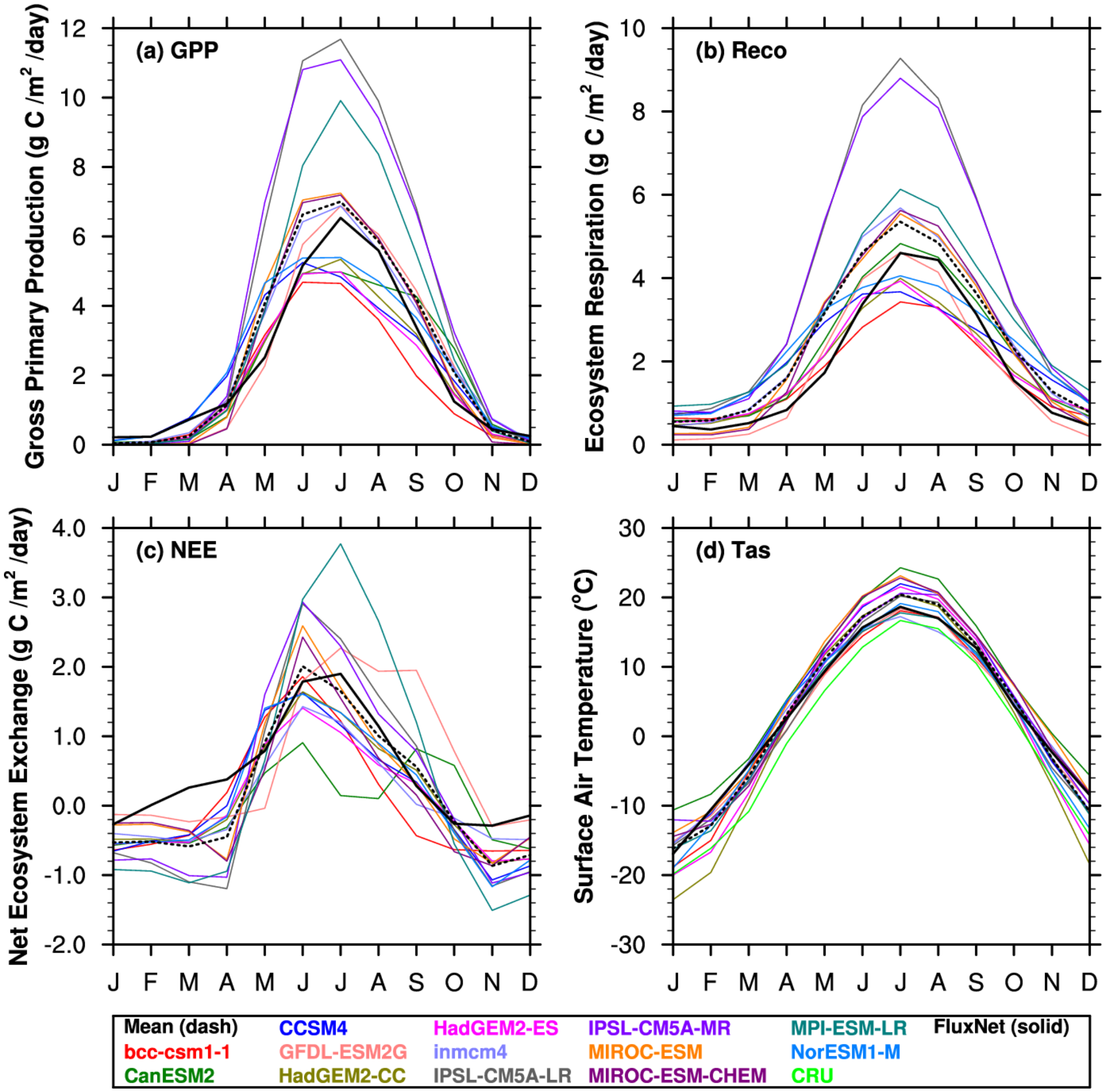
Early onset of photosynthesis may have consequences for the seasonal dynamics of surface energy exchange

- Fluxnet sites in North America between 35N and 45N

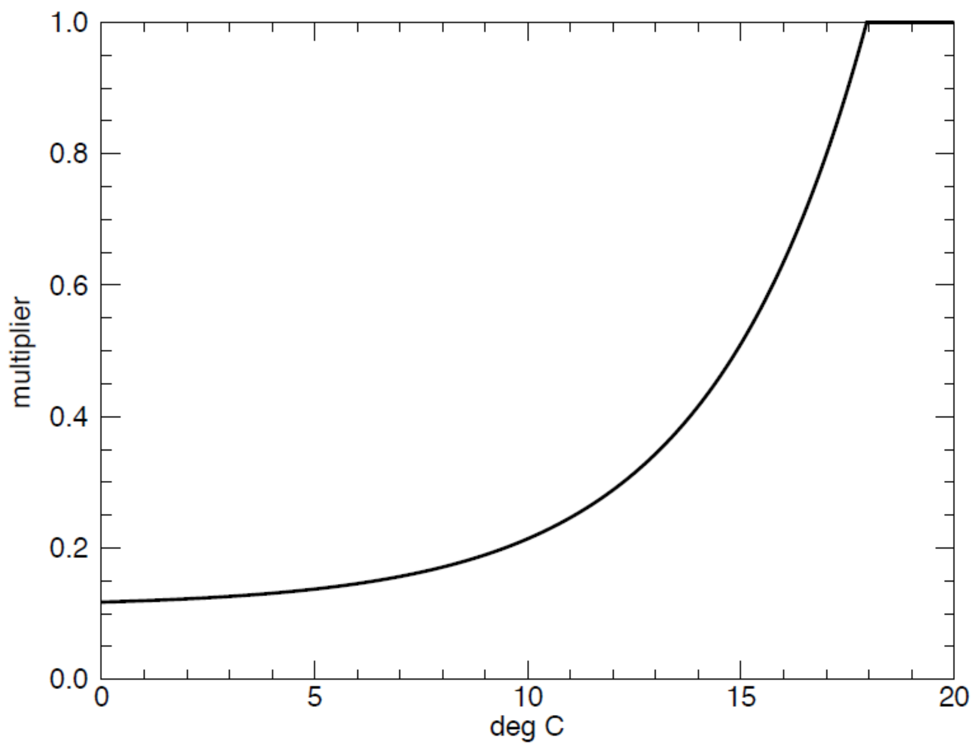


Strength of the early season uptake bias varies by region

- Fluxnet sites in North America between 45N and 60N

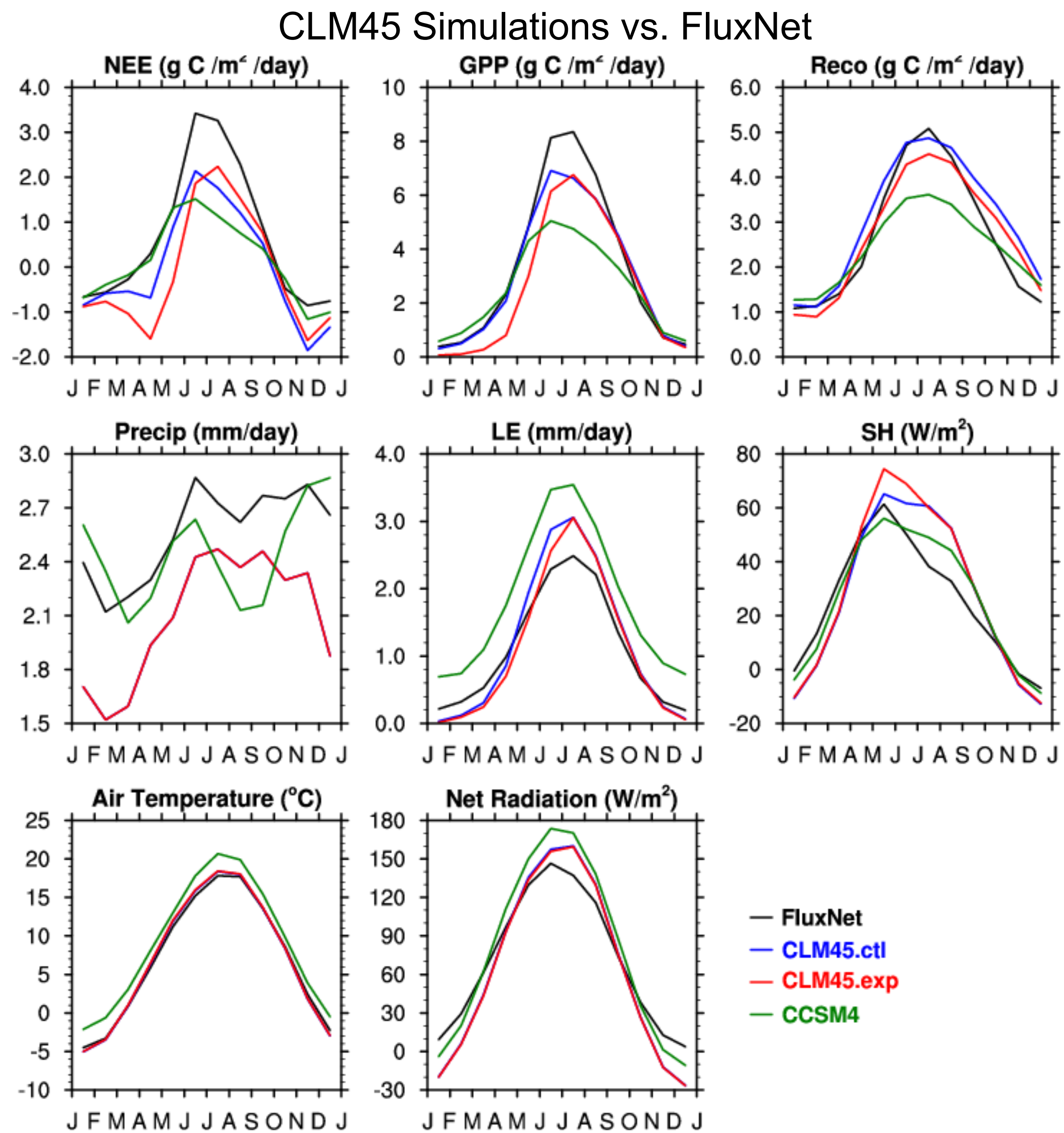


Modify CLM4.5 to simulate delayed recovery from cold-hardening and false-spring avoidance

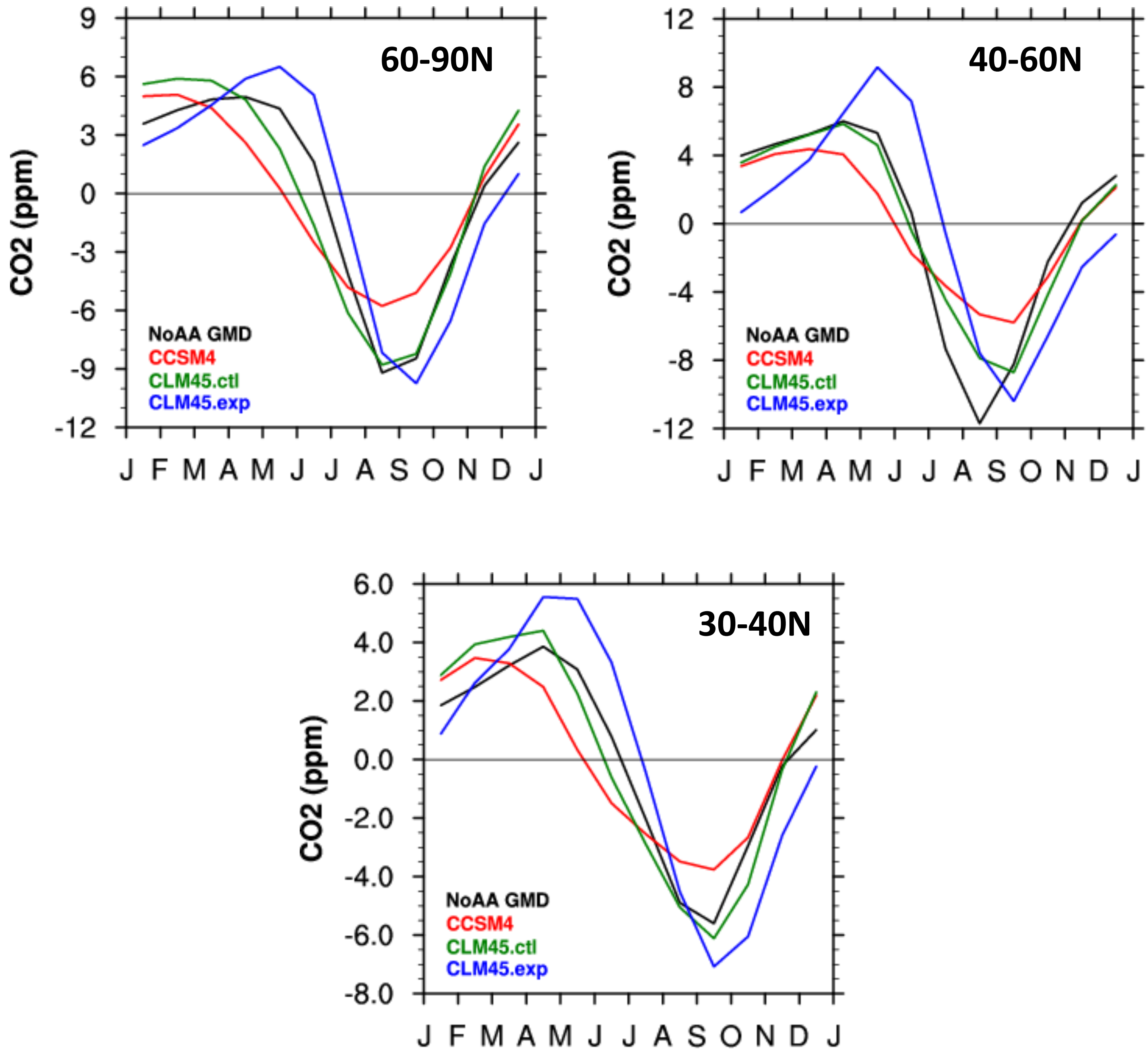


Clm tag: clm4_0_60
Vcmax modified during January to June by applying the above scalar using 10 day mean 2m air temperature

40-60N



CLM45 Simulations vs. FluxNet
NEE (g C /m² /day)
GPP (g C /m² /day)
Reco (g C /m² /day)
Precip (mm/day)
LE (mm/day)
SH (W/m²)
Air Temperature (°C)
Net Radiation (W/m²)
J F M A M J J A S O N D J
FluxNet
CLM45.ctl
CLM45.exp
CCSM4


60-90N
40-60N
30-40N
CO2 (ppm)
NoAA GMD
CCSM4
CLM45.ctl
CLM45.exp
J F M A M J J A S O N D J
9
6
3
0
-3
-6
-9
-12
8
4
-4
-8
6.0
4.0
2.0
0.0
-2.0
-4.0
-6.0
-8.0

Next Steps and Conclusions

- Evaluate CLM4.5 GPP onset experiments in CAM5 with a slab ocean to look at mid-summer climate responses
- - examine canopy evaporative fraction
- - soil temperatures and controls on spring ET

- Early season onset bias will have important consequences for the representation of mid-summer drought stress in evergreen conifer ecosystems (Monson et al. 2005) and for fire behavior (Westerling et al. 2006) in ESMs

- The timing of photosynthesis initiation in spring may influence regional climate in mid-summer, with early onset of GPP causing higher air temperatures and reduced precipitation recycling

- Cold hardening and temperature acclimation algorithms need to be integrated with existing photosynthesis and stomatal conductance models
  - Unpackaging membrane and protein systems increases vulnerability to late spring frost events
  - Need to combine with improvements in phenology (Richardson et al., 2012)

- Next steps: we need to improve our understanding of how the existing photosynthesis timing biases influence the representation of climate-induced drought stress during the 21st century