Assessing terrestrial biogeochemical feedbacks in a strategically geoengineered climate

Cheng-En Yang, Forrest M. Hoffman, Simone Tilmes,
Douglas G. MacMartin, Lili Xia, Jadwiga H. Richter,
Ben Kravitz, Michael J. Mills, and Joshua S. Fu

October 25, 2019

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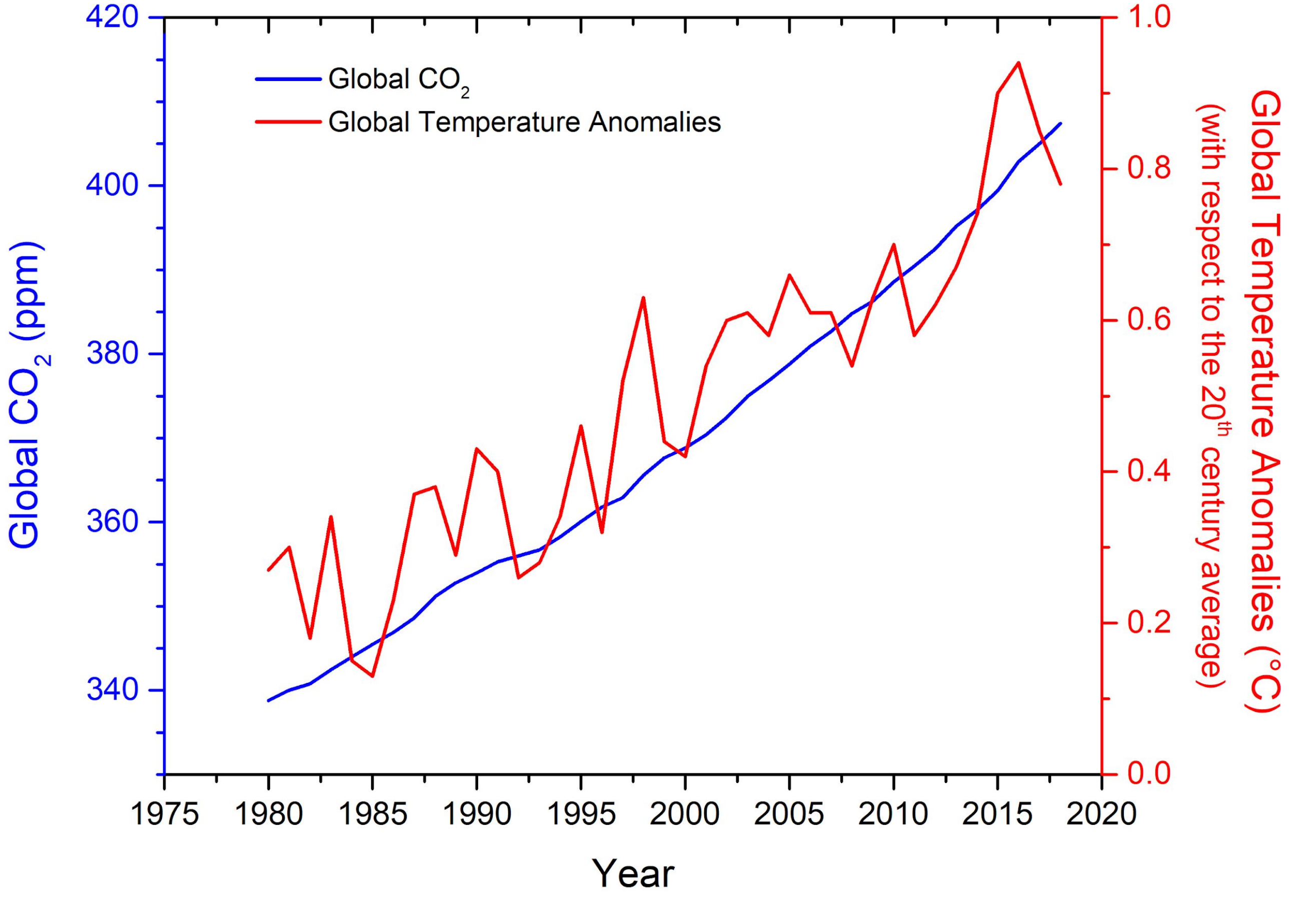
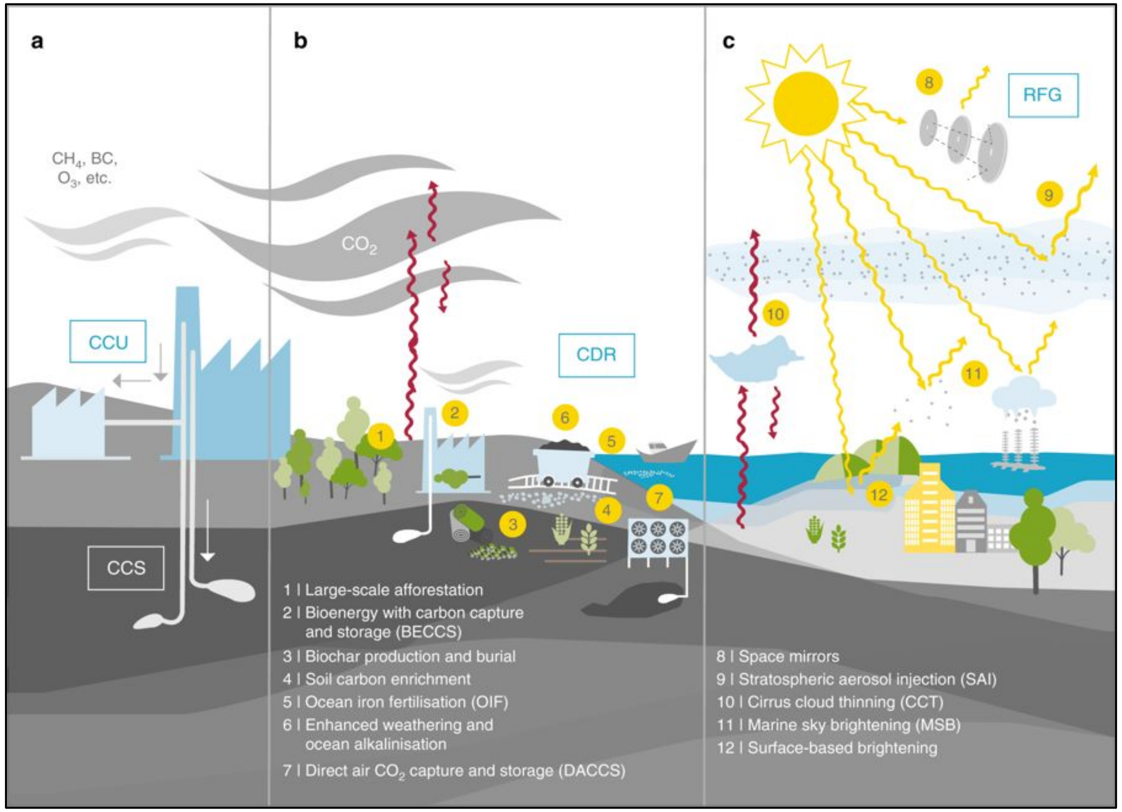
Climate Geoengineering

Global Climate Status



(Data from NOAA ESRL)

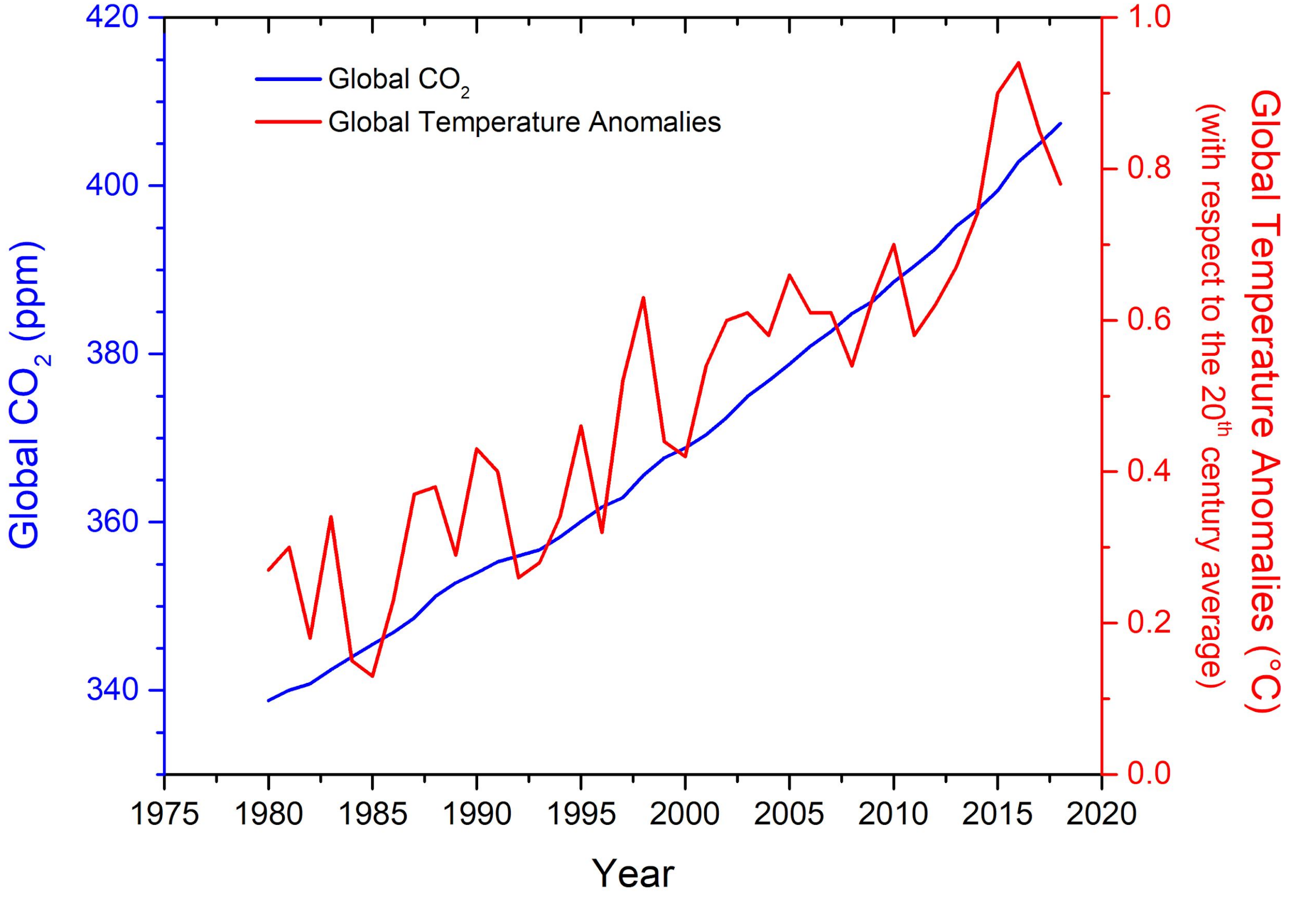
Climate Geoengineering Proposals



(Adopted from Lawrence *et al.*, 2018)

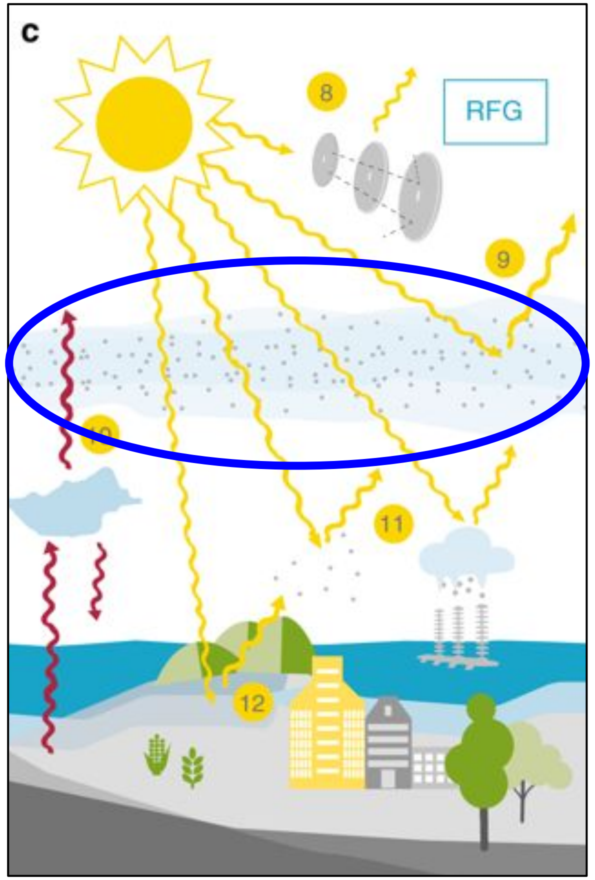
Climate Geoengineering

Global Climate Status



(Data from NOAA ESRL)

Climate Geoengineering Proposals



Adding sunlight reflecting aerosols in lower stratosphere (e.g. SO_2 injection)

(Adopted from Lawrence *et al.*, 2018)

Geoengineering Impacts on Climate

❖ Evaluation of geoengineering in Earth system models (ESMs)

- Suppressed global mean surface temperature warming and precipitation (Tilmes *et al.*, 2013; Kravitz *et al.*, 2013; Irvine *et al.*, 2016)
- Reduced direct radiation but increased diffuse radiation (Robock *et al.*, 2009; Kravitz *et al.*, 2011; Xia *et al.*, 2016)
- Less plant heat stress and higher photosynthesis rate and net primary production (Xia *et al.*, 2016; Kravitz *et al.*, 2013; Cao, 2018)

Little attention has been given to understanding responses of terrestrial (and marine) ecosystems to a geoengineered climate

Science Questions

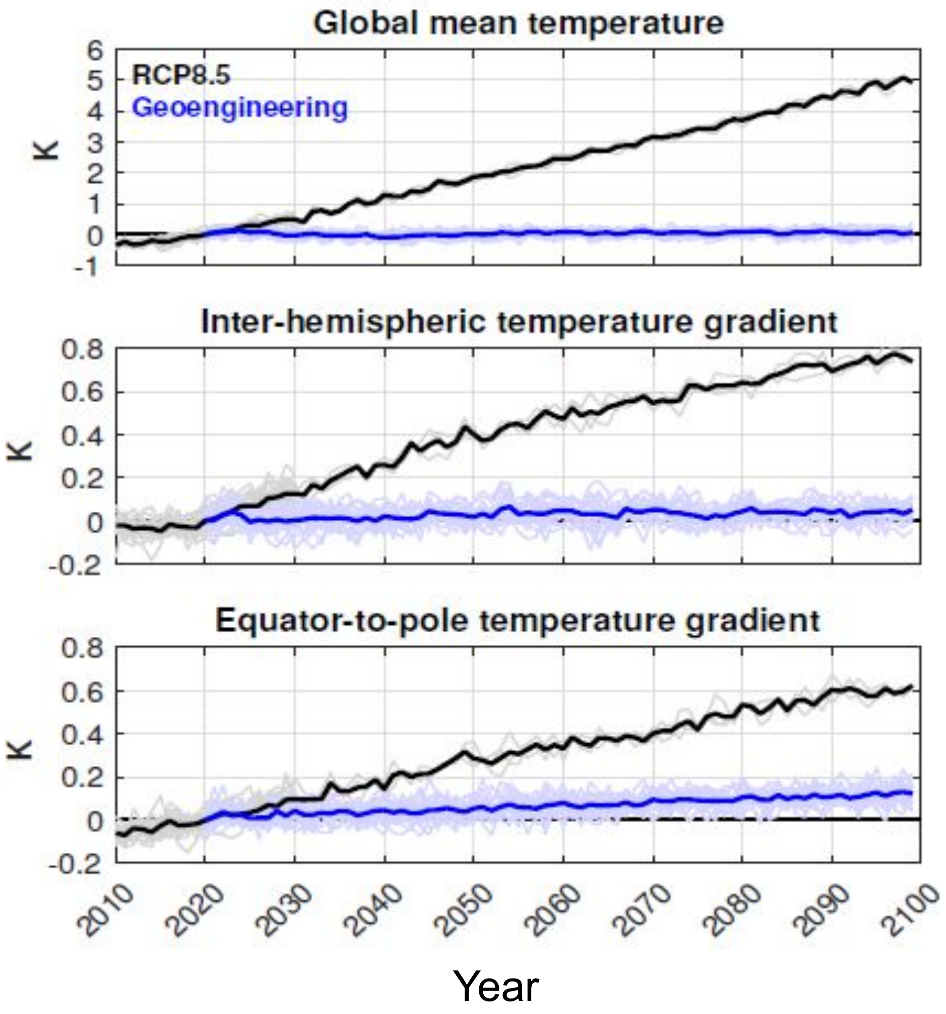
We will investigate responses of terrestrial ecosystems to a geoengineered RCP 8.5 climate through SO_2 injections in the lower stratosphere to address these questions:

- Will terrestrial ecosystems remain a carbon sink?
- How will the land carbon sink change compared with standard RCP 8.5?
- How will those changes affect the global atmospheric CO_2 trajectory?

Modeling Projects for Climate Geoengineering

Project	Geoengineering Model Intercomparison Project **(GeoMIP)** (Kravitz *et al.*, 2011)	Stratospheric Aerosol Geoengineering Large Ensemble Project **(GLENS)** (Tilmes *et al.*, 2018)
Baseline scenarios	RCP4.5 4 × CO_2 +1% CO_2 / yr	RCP8.5
Geoengineering period	2020 – 2069	2020 – 2099
SO_2 injection locations	Single point at the Equator	4 optimized points to avoid uneven cooling between the poles and equator
Ensemble members	1 – 4	20

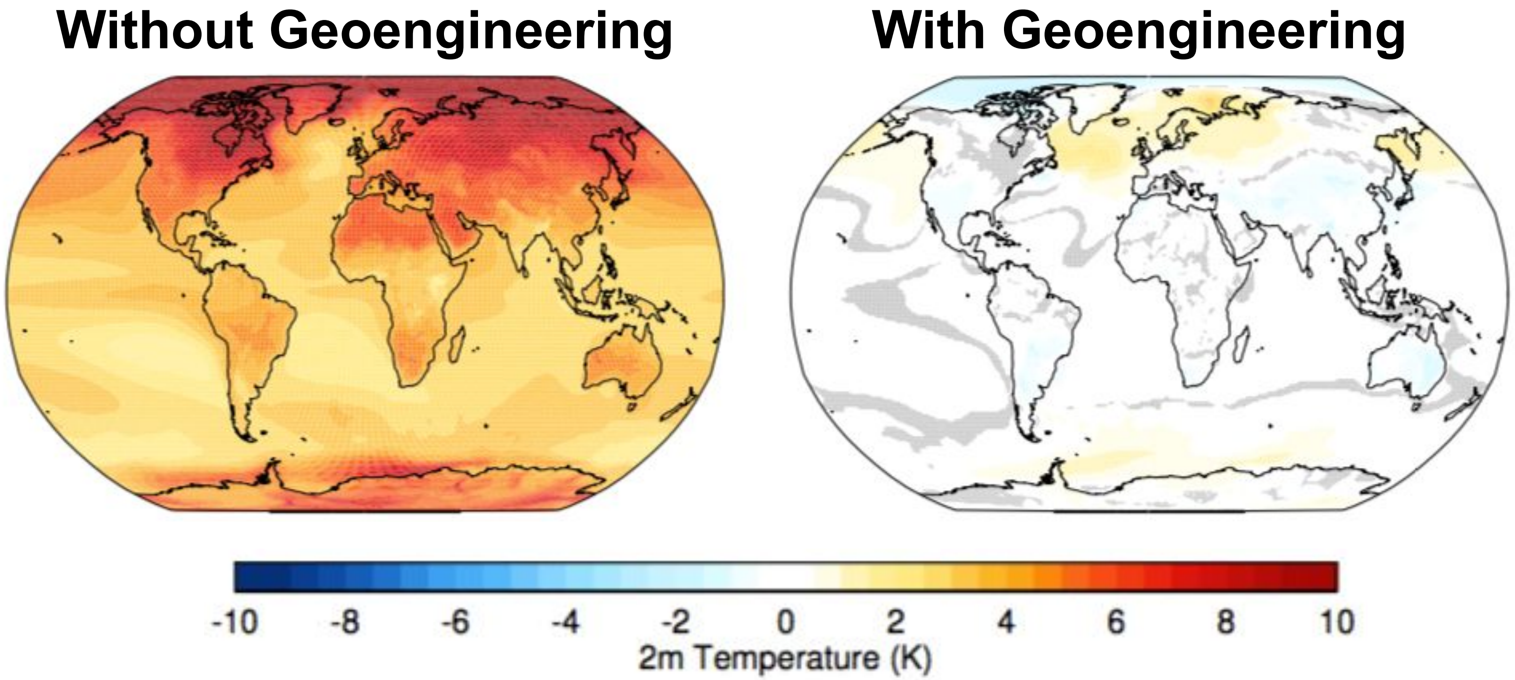
An Overview of GLENS


Global mean temperature

Inter-hemispheric temperature gradient

Equator-to-pole temperature gradient

Surface Temperature Change
(2075–2095 compared to 2010–2030)


Without Geoengineering

With Geoengineering

(Tilmes *et al.*, 2018)

Analytical Method

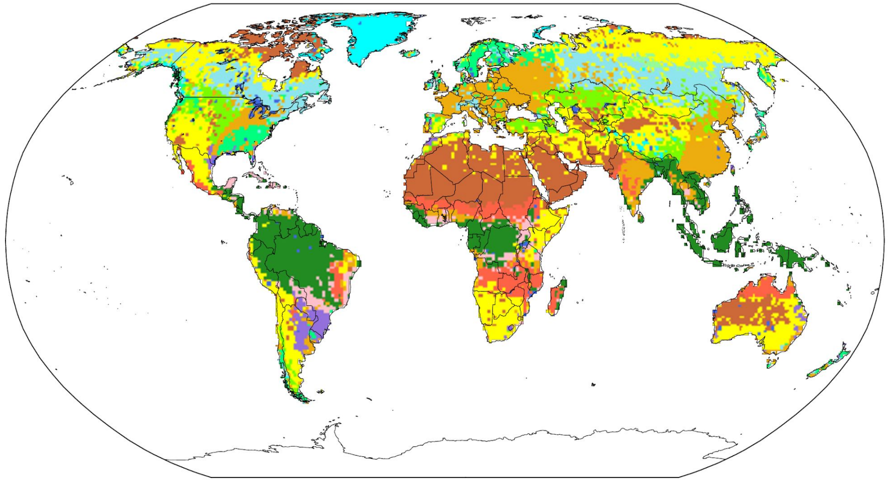
- Dataset: 3 of 20 ensemble members from GLENS

Scenarios	Baseline (***BASE***)	RCP8.5 (***RCP85***)	Geoengineering (***GEOENG***)
Duration	2010 – 2019	2020 – 2097	2020 – 2097
Time slices	—	2020 – 2039 (short-term) 2050 – 2069 (mid-term) 2078 – 2097 (long-term)	

- Regions: global and 13 IGBP ecoregions

Global Ecoregions and Terrestrial Carbon Cycle

❖ International Geosphere-Biosphere Programme (IGBP) ecoregions

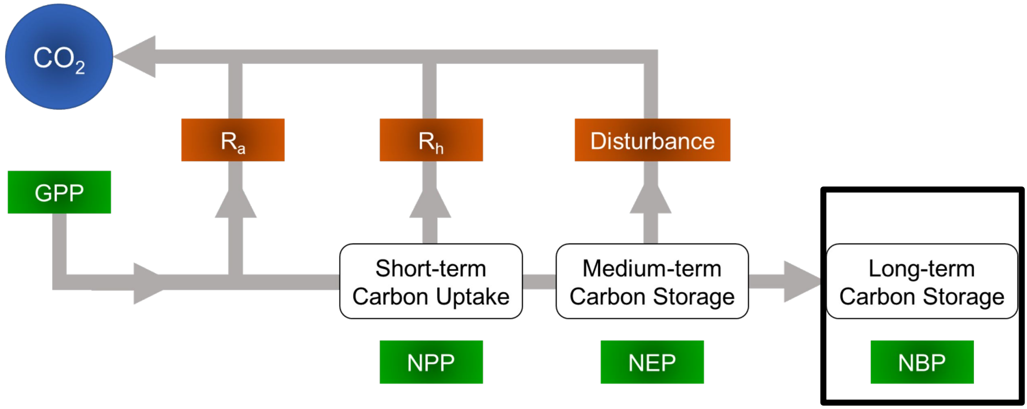


1	Water Bodies
2	Evergreen Needleleaf Forest
3	Evergreen Broadleaf Forest
4	Deciduous Needleleaf Forest
5	Mixed Forest
6	Open Shrublands
7	Woody Savannas
8	Savannas
9	Grasslands
10	Croplands
11	Cropland/Natural Vegetation Mosaic
12	Permanent Snow and Ice
13	Barren/Sparsely Vegetated

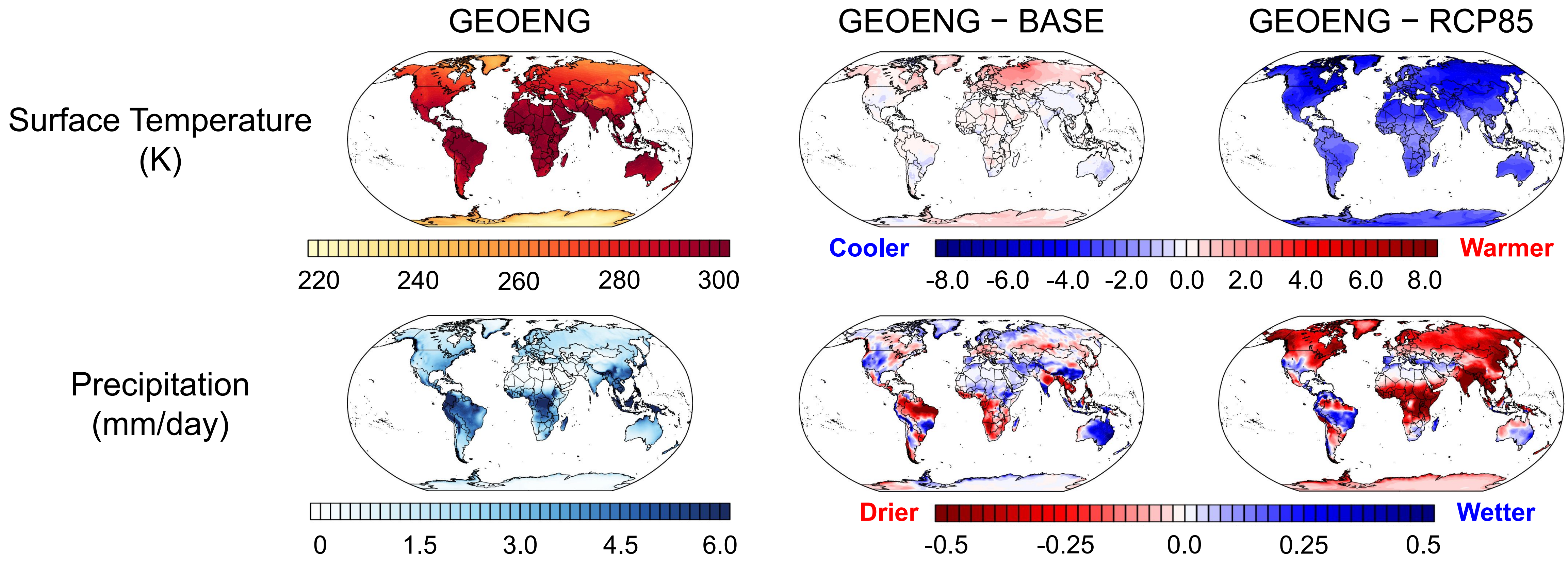
❖ Global terrestrial carbon variables

- GPP: gross primary production
- NPP: net primary production
- NEP: net ecosystem production
- NBP: net biome production

- R_a: autotrophic respiration
- R_h: heterotrophic respiration
- Disturbance (e.g. harvest, forest clearance, and fire)



Changes in Temperature and Precipitation

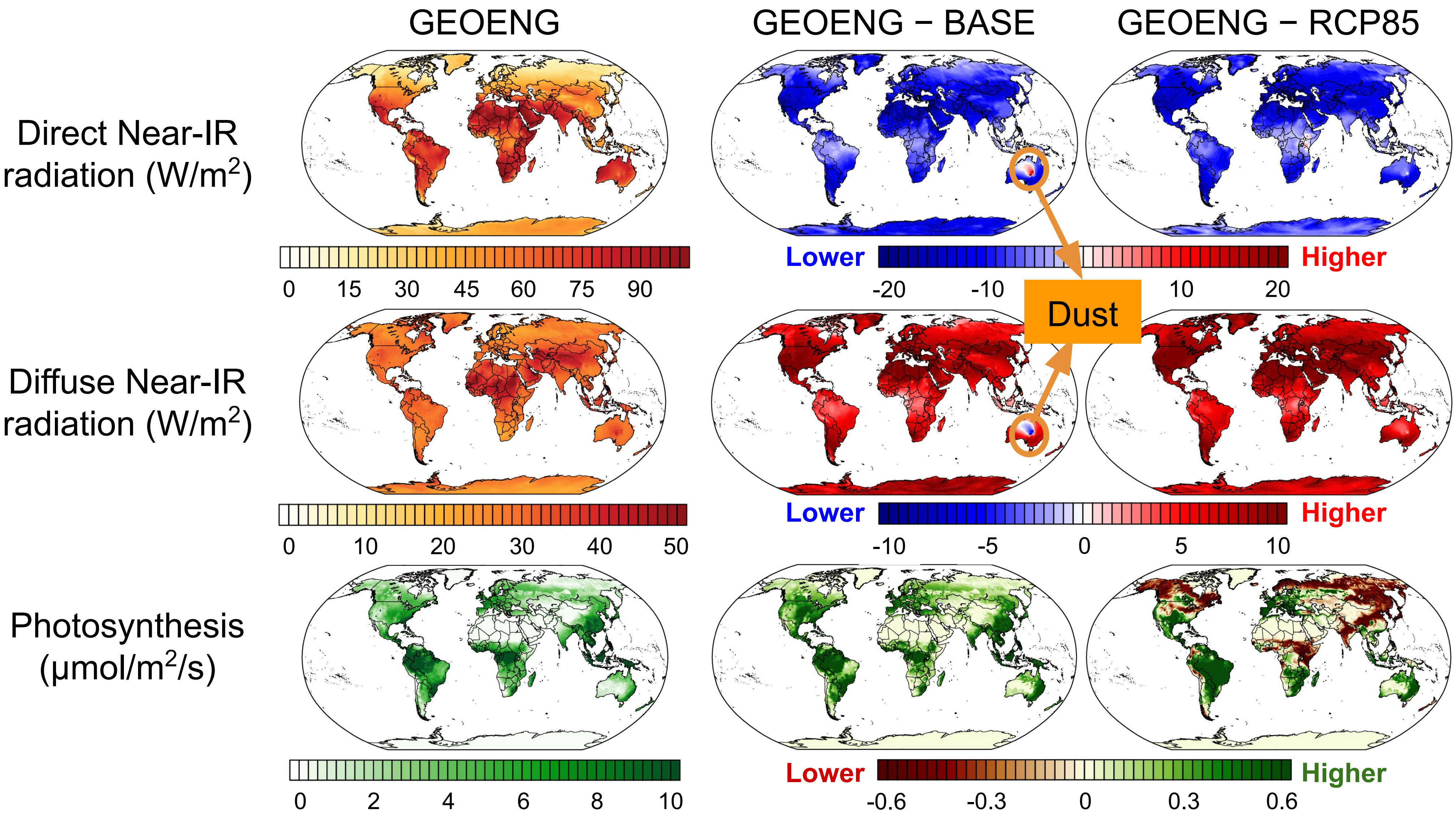


- Global mean temperature maintained at 2020 levels in GEOENG
- Lower precipitation in GEOENG than RCP85
  - Cooler temperatures
  - Aerosol-cloud interactions
- Climate effects in GLENS are well described by other researchers

(Averaging period: BASE=2010−2019, RCP85=2020−2097, GEOENG=2020−2097)

(Yang *et al.*, submitted)

Changes in Radiation and Photosynthesis

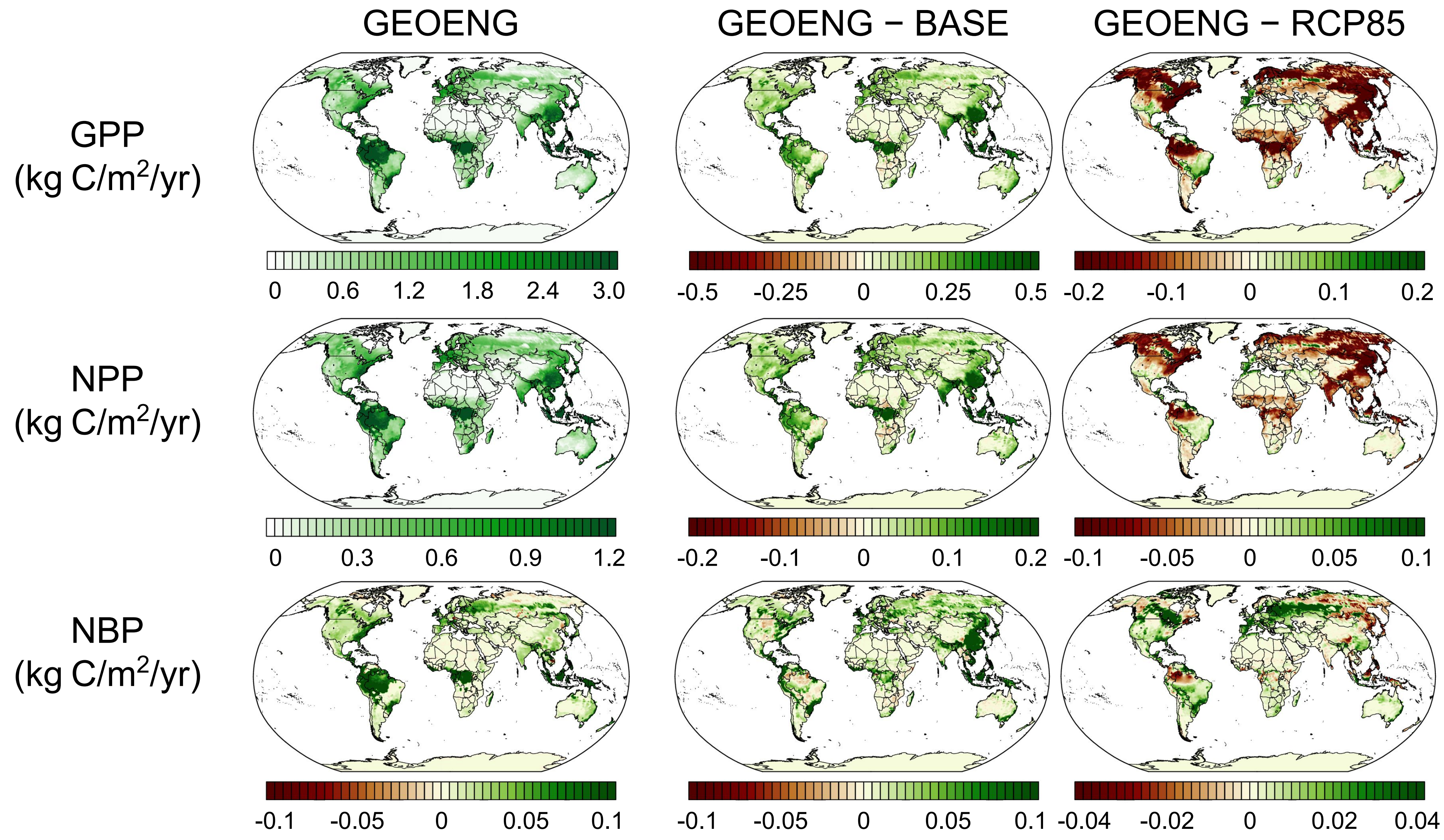


(Averaging period: BASE=2010−2019, RCP85=2020−2097, GEOENG=2020−2097)

- Aerosols reduce direct downward radiation but increase diffuse radiation
- Regions with both enhanced precipitation and diffuse radiation undergo higher photosynthesis
- In RCP 8.5, higher photosynthesis rates at high latitudes result from permafrost thawing

(Yang *et al.*, submitted)

Changes in Terrestrial Carbon Uptake



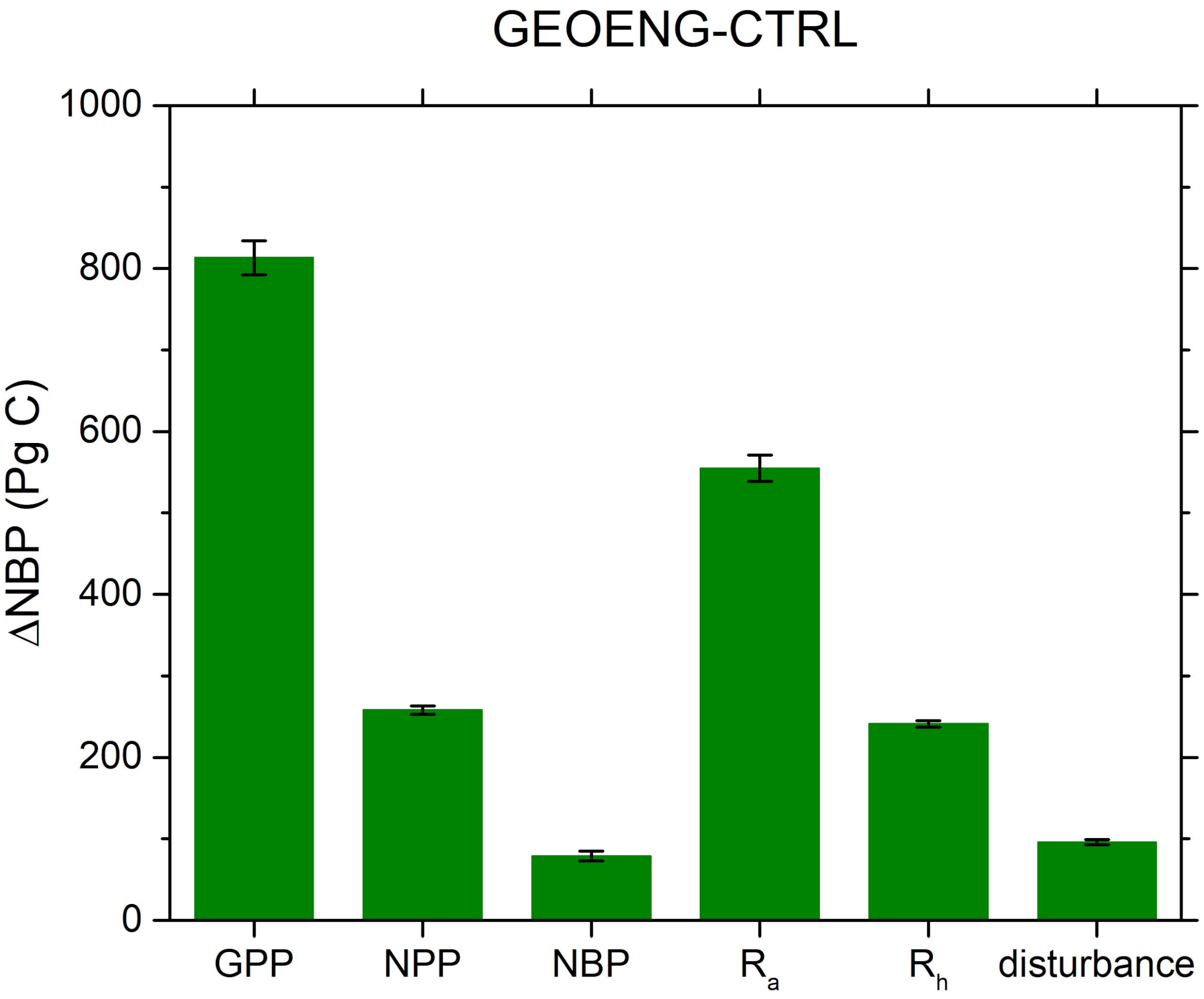
(Averaging period: BASE=2010−2019, RCP85=2020−2097, GEOENG=2020−2097)

Lower **Higher**

- Enhanced GPP, NPP, and NBP in GEOENG compared to BASE due to increased diffuse radiation and rising atmospheric CO_2
- Rising temperatures and precipitation reductions in some regions constrain productivity increases in RCP85, especially north of Amazon and India/China

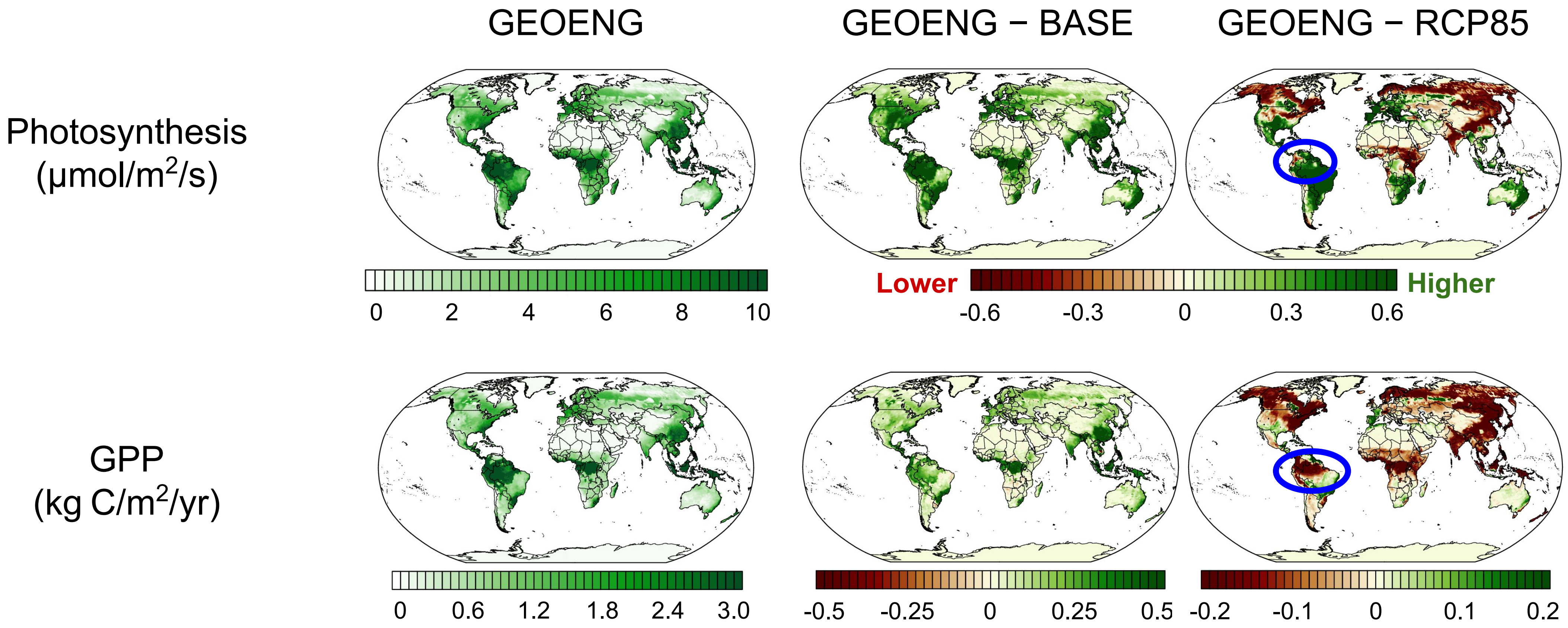
(Yang *et al.*, submitted)

Changes in Terrestrial Carbon Uptake



- Lower ecosystem respiration and diminished disturbance effects under geoengineering

Photosynthesis and Gross Primary Production

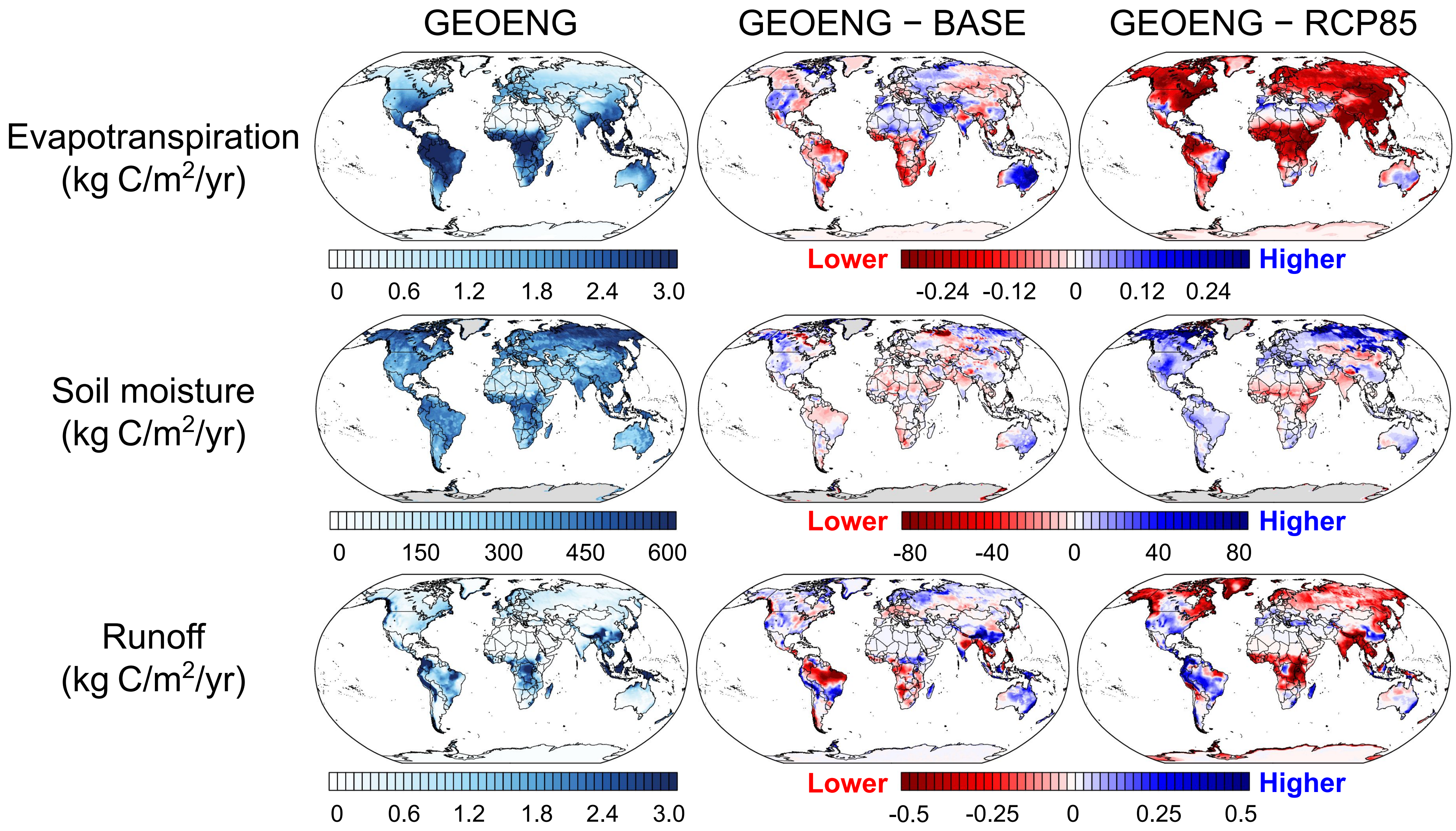


Down-regulated photosynthesis due to ***nitrogen limitation***.

(Averaging period: BASE=2010−2019, RCP85=2020−2097, GEOENG=2020−2097)

(Yang *et al.*, submitted)

Changes in Water Cycle



- Lower temperatures result in lower ET while increasing precipitation can enhance ET
- Soil moisture is related to precipitation as well as temperature changes
- Runoff ∝ precip − ET

(Averaging period: BASE=2010−2019, RCP85=2020−2097, GEOENG=2020−2097)

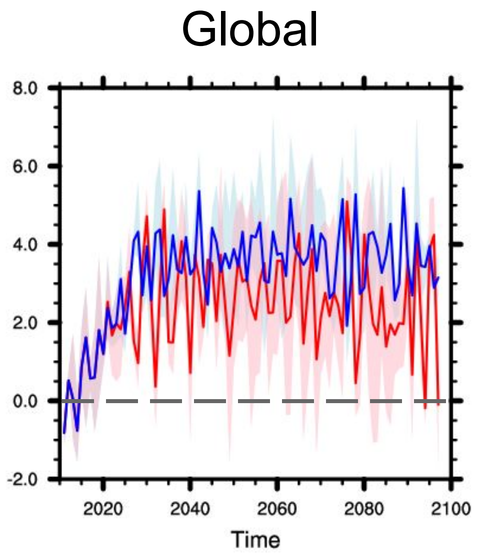
(Yang *et al.*, submitted)

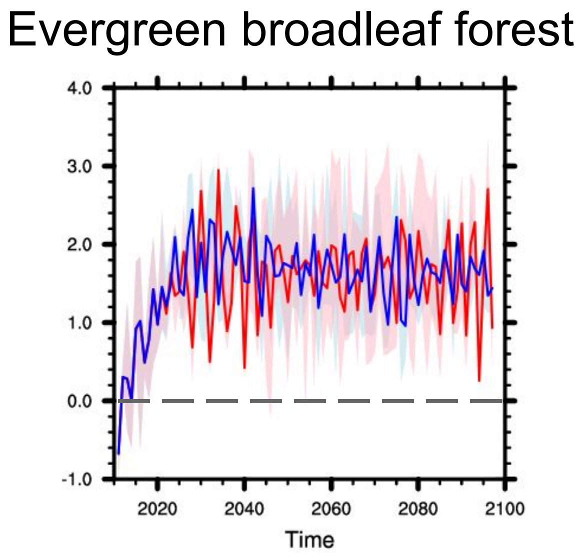
Carbon Sink Strength

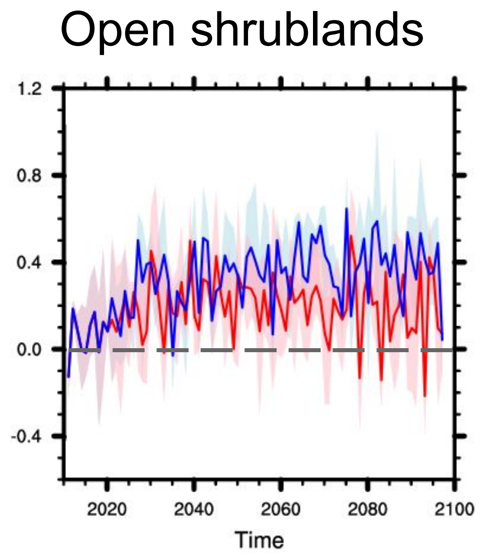
NBP (Pg C/yr)

🟥 RCP85

🟦 GEOENG

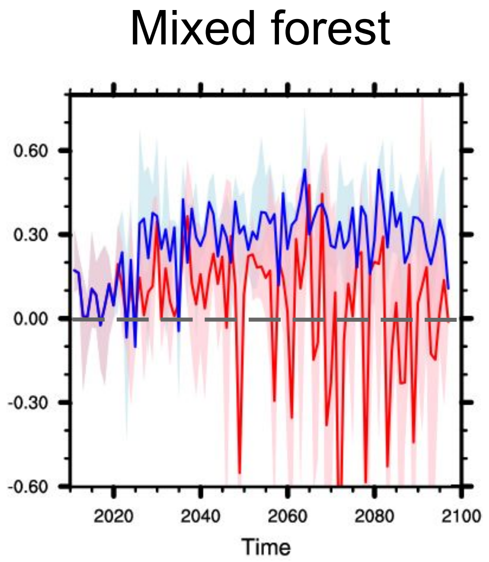

Global

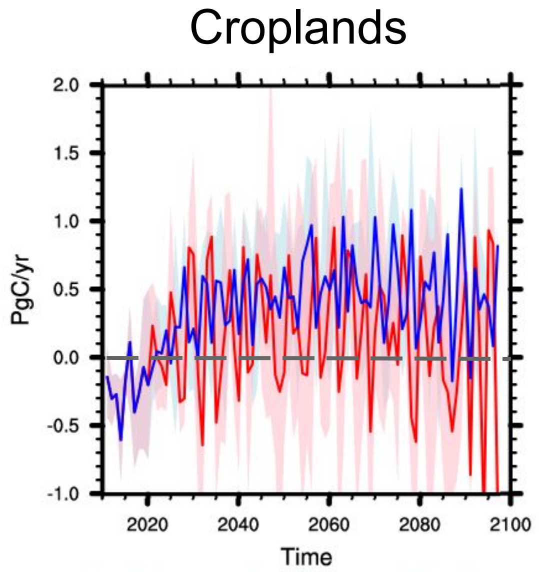

Evergreen broadleaf forest


Open shrublands

NBP > 0 ⇒ Storing carbon from the atmosphere

NBP < 0 ⇒ Releasing carbon to the atmosphere


Mixed forest


Croplands

(Yang *et al.*, submitted)

Carbon Sink Strength

RCP85	GEOENG	Δ

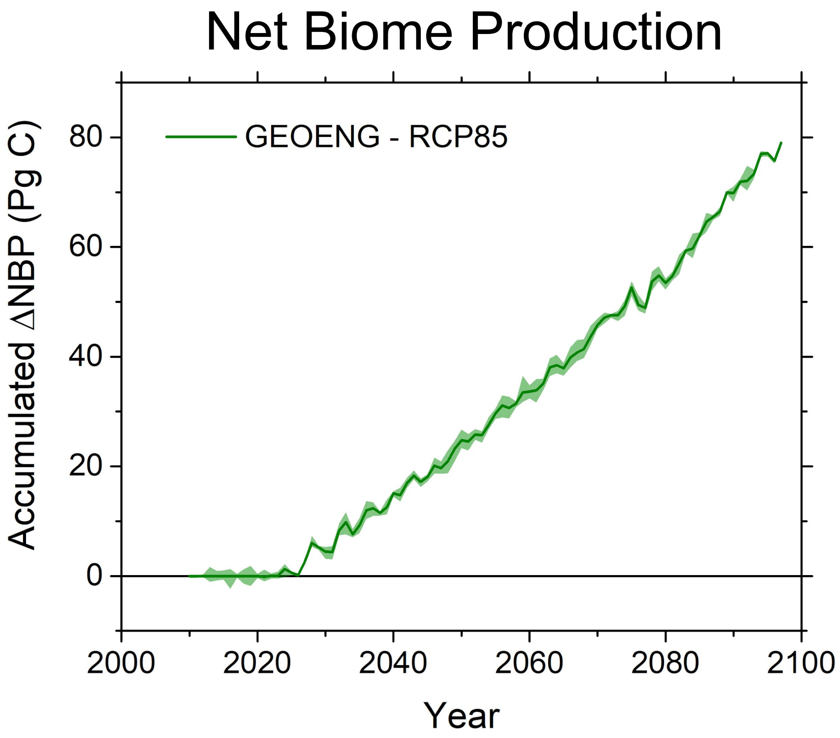
Time period	Cumulated Terrestrial Biogeochemical Feedbacks (unit: Pg C)														
	Global			Evergreen broadleaf forest			Open shrublands			Mixed forest			Croplands		
All time	198	277	79	125	130	5	16	27	11	4	23	19	2	2	0
2020 – 2039	50	62	12	31	35	4	4	5	1	2	5	3	-9	-9	1
2050 – 2069	56	77	21	33	33	0	5	8	3	2	7	5	4	10	6
2078 – 2097	43	73	30	32	33	1	3	8	5	−1	6	7	3	10	7

- More carbon stored in terrestrial ecosystems in GEOENG over time
- The largest carbon sink pool is Evergreen broadleaf forests
- The most sensitive ecoregions to climate geoengineering are mixed forests and croplands

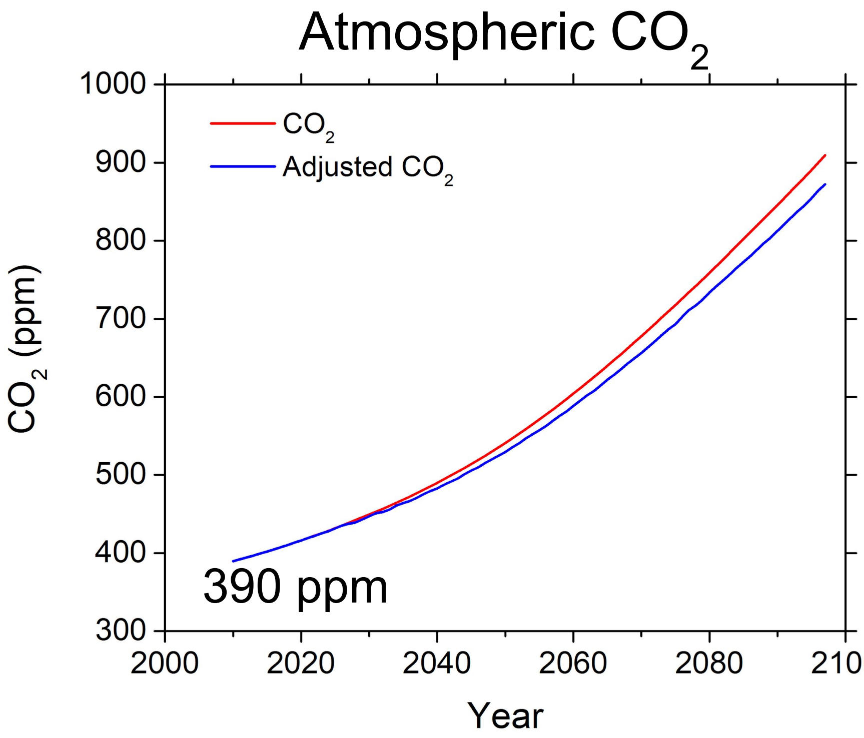
(Yang *et al.*, submitted)

Accounting for Terrestrial Ecosystem Feedbacks

We can adjust the global CO_2 trajectory to account for terrestrial ecosystem feedbacks



79 Pg C



909 ppm

872 ppm

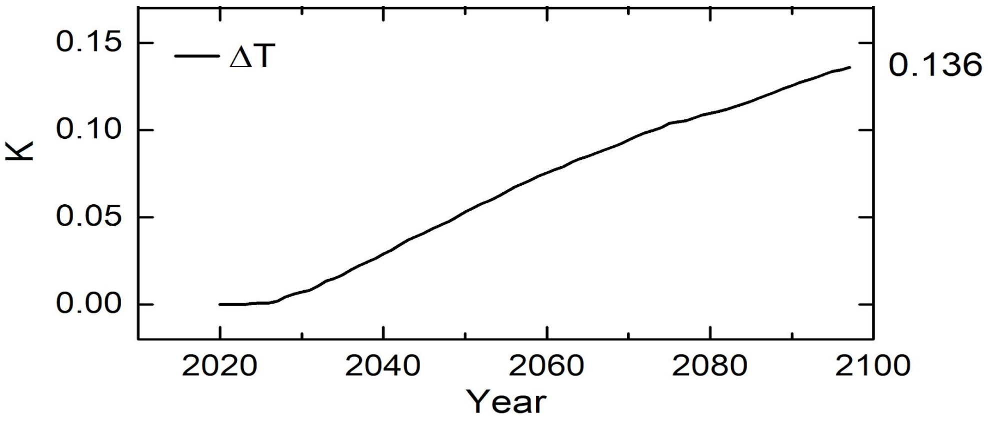
- Increased vegetation productivity under geoengineering resulted in an additional 79 Pg C sink by the end of the 21st century in comparison with RCP 8.5
- Increase in atmospheric CO_2 should have been reduced by 4% at 2097 due to the terrestrial carbon feedback because of increased vegetation productivity ($\Delta[CO_2]_{atm}$ = 37 ppm)

(Yang *et al.*, submitted)

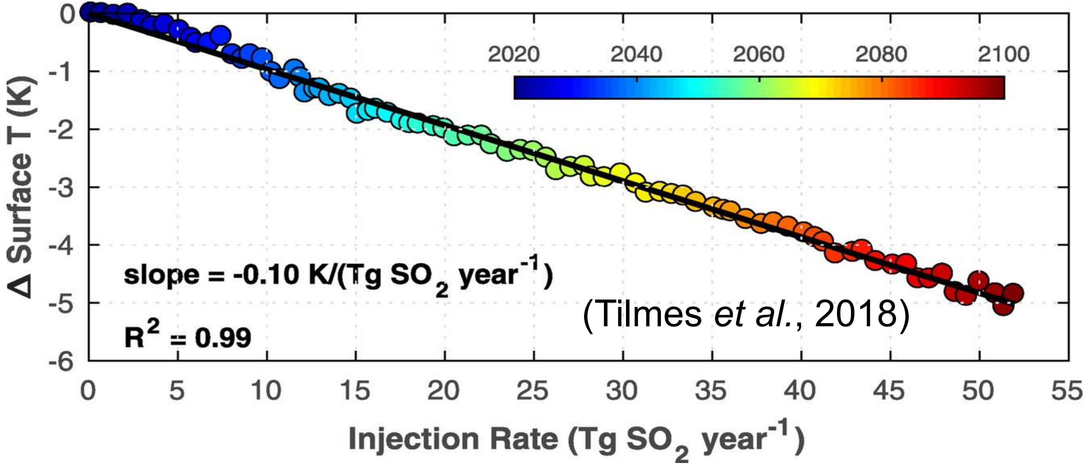
Reduced SO_2 Injection Effort

Global adjusted radiative forcing and temperature change due to the increased land sink ➡ lower SO_2 injection rates to maintain the 2020 global temperature target

Temperature changes due to feedbacks

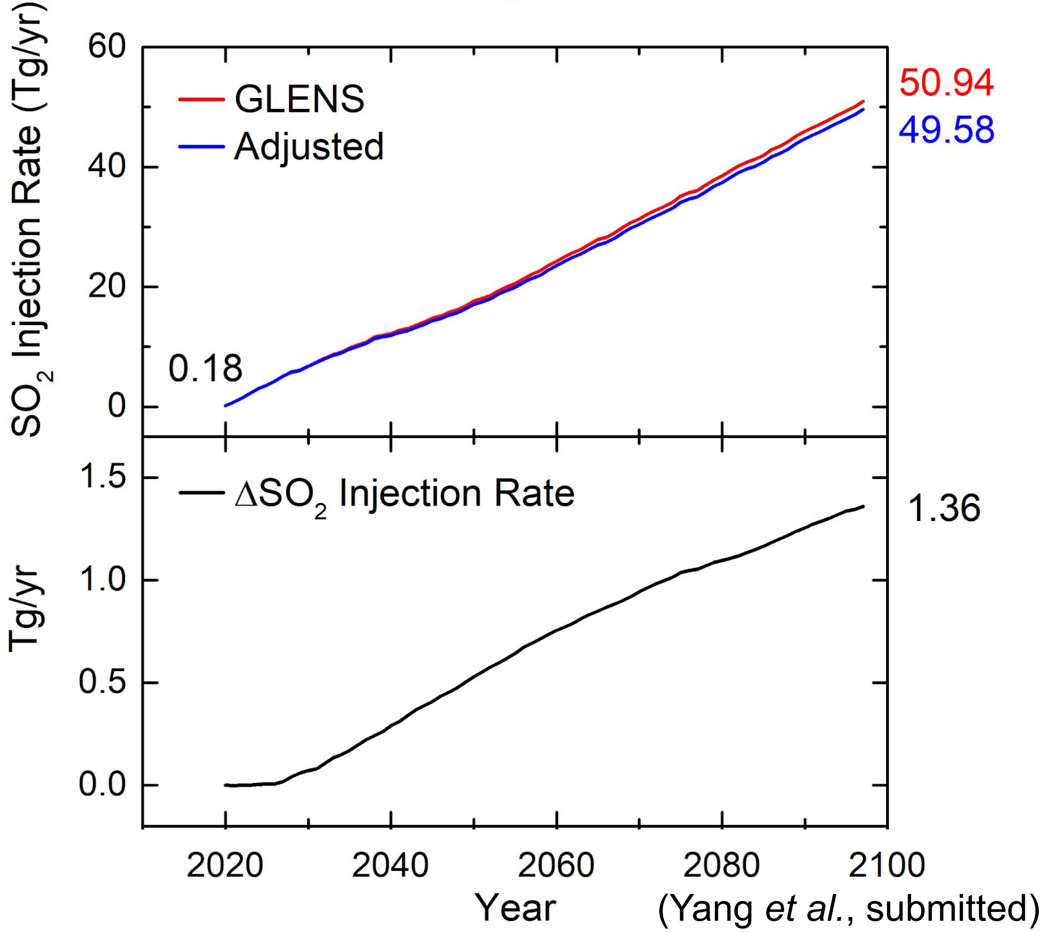


SO_2 injection rate vs surface temperature changes



(Tilmes *et al.*, 2018)

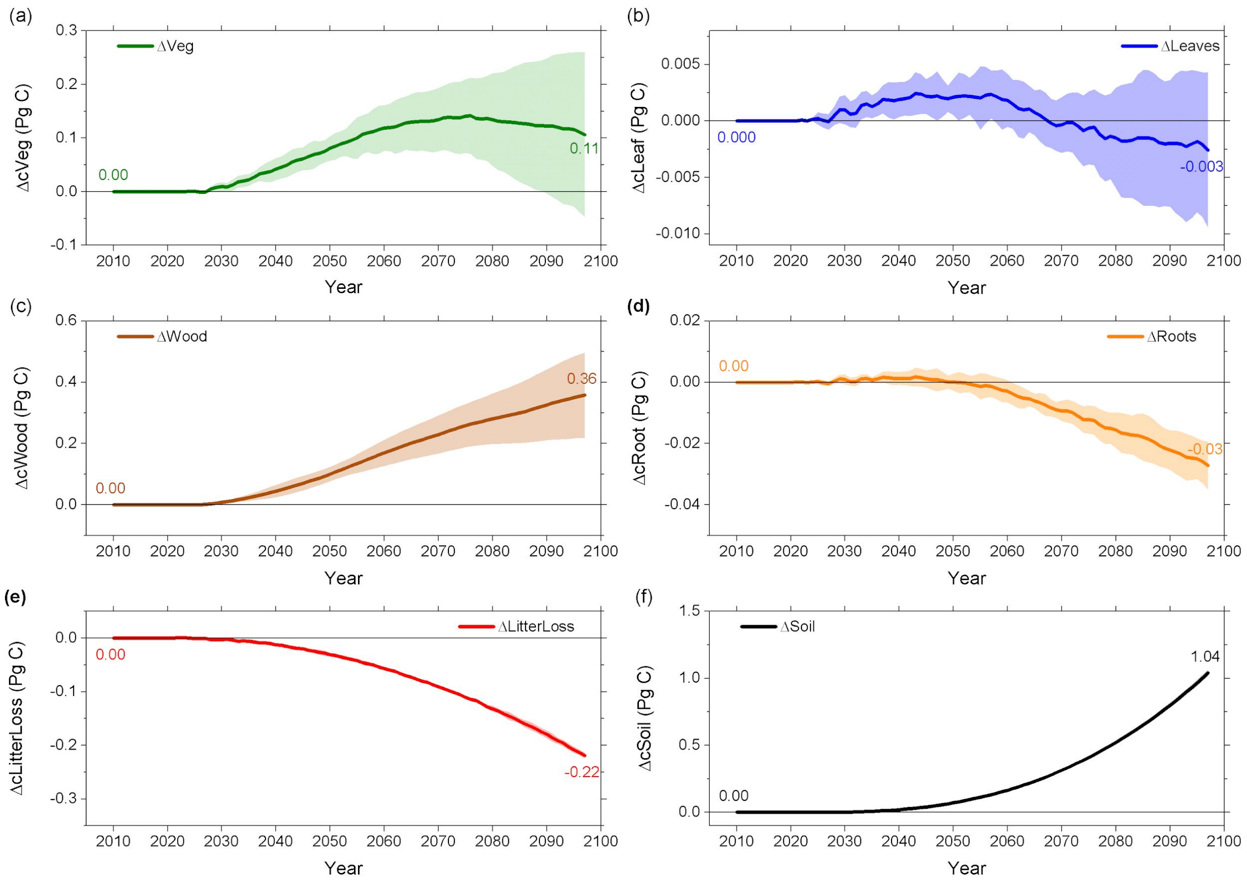
Terrestrial Ecosystem Feedbacks



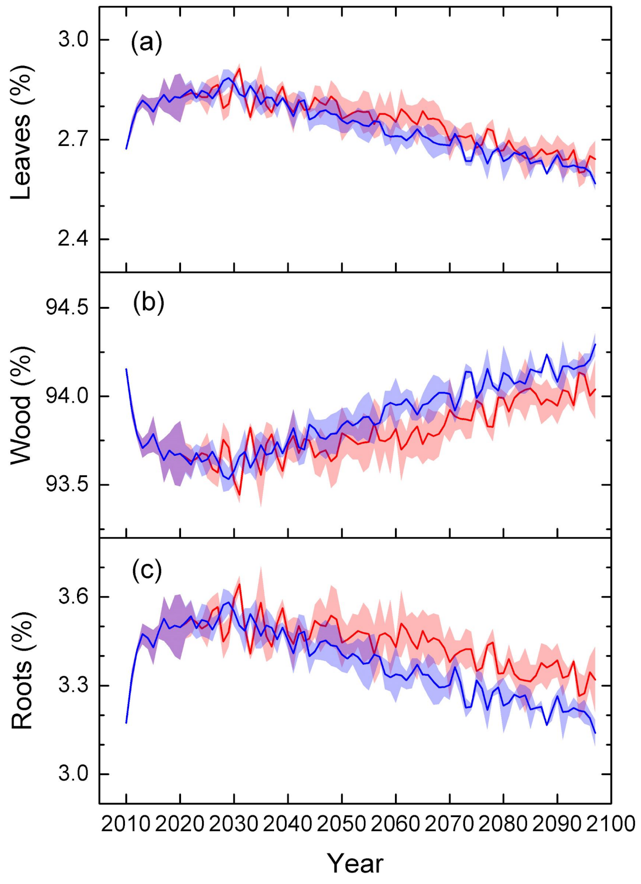
(Yang *et al.*, submitted)

Changes in Biomass and Carbon Allocation

Biomass (Pg C)



Carbon Allocation (%)

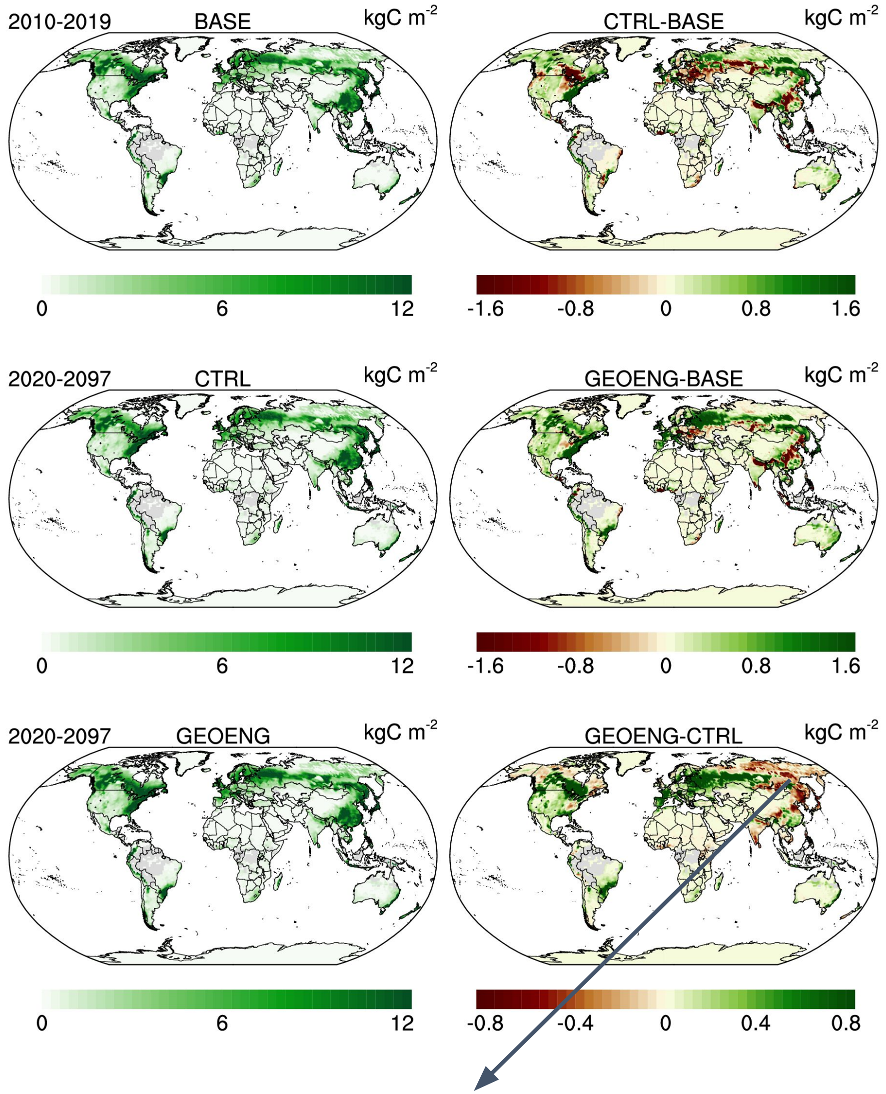


- More biomass in vegetation and soil
- Reduced biomass in leaves and fine roots but increased biomass in wood

- Slightly more carbon allocated in wood

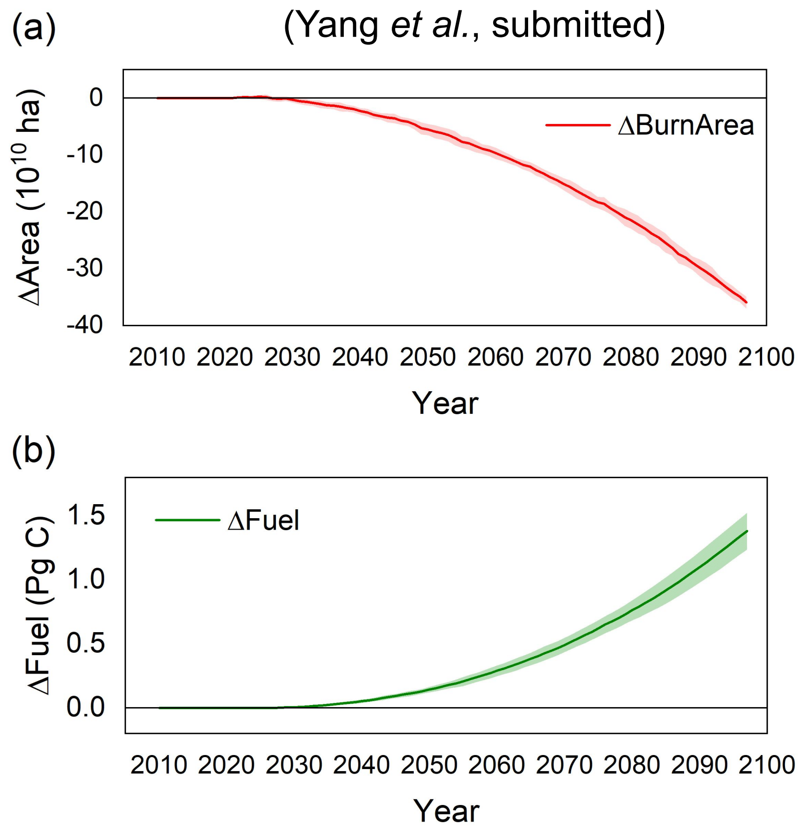
(Yang *et al.*, submitted)

Changes in Burned Area and Fuel Loads



Lower surface temperature and precipitation

(Yang *et al.*, submitted)



- Reduced burned area due to lower temperature
- Increasing fuel loads as a result of smaller fire impacts

Summary

Responses of terrestrial ecosystems to a geoengineered RCP 8.5 climate through SO_2 injections in the lower stratosphere

- Will the terrestrial ecosystems remain a carbon sink?
  Yes, globally terrestrial ecosystems will remain a carbon sink under the geoengineered climate.

- How will the land carbon sink change compared with standard RCP 8.5?
  At the end of 21st century, terrestrial ecosystems reduce ~79 Pg C under the RCP 8.5 scenario with aerosol geoengineering.

- How will those changes affect the global atmospheric CO_2 trajectory?
  At the end of 21st century, the terrestrial carbon feedback reduces the atmospheric CO_2 mole fraction by 7% under geoengineering.

Continued Geoengineering Research

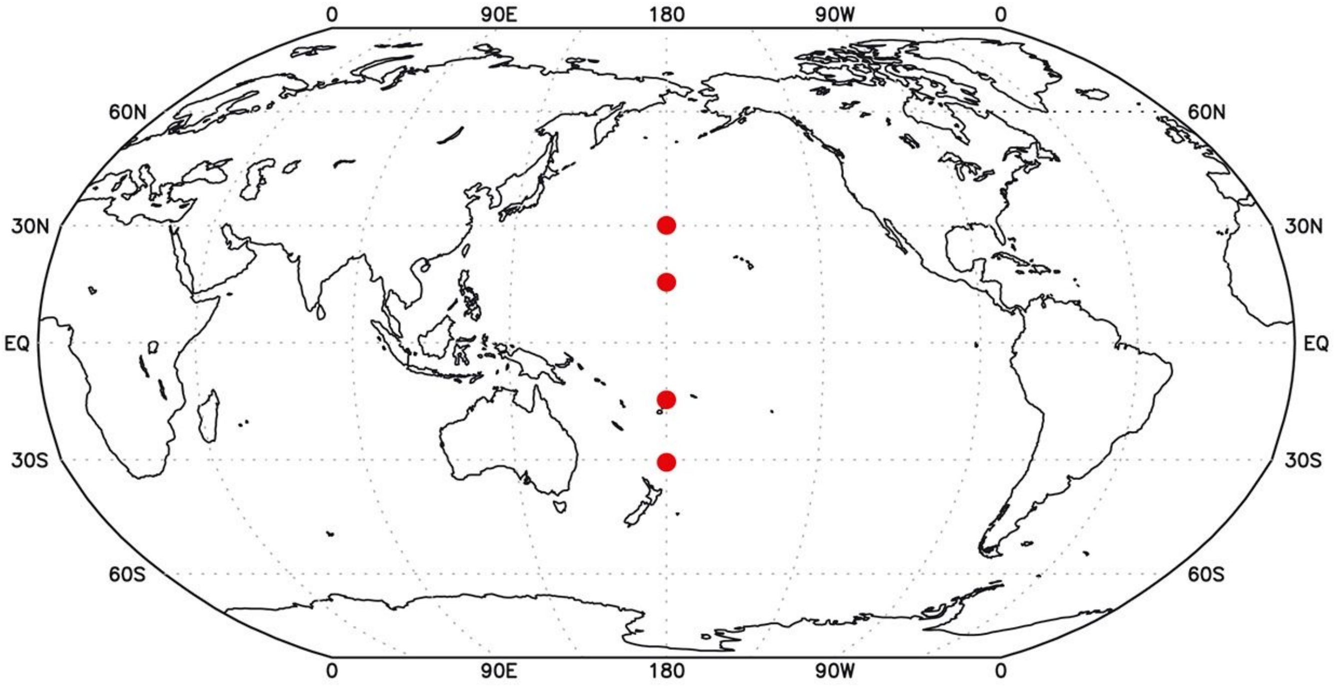
- Additional simulation experiments, many of which are proposed for GeoMIP in CMIP6, are needed:
  - Emissions-driven (instead of concentration-forced) ESM simulations would integrate all carbon fluxes and prognostically determine the atmospheric CO_2 trajectory
  - ESM simulations with coupled ocean biogeochemistry would account for marine feedbacks that are likely to be most strongly affected by increased ocean acidification

Acknowledgements

This research was supported by the Reducing Uncertainties in Biogeochemical Interactions through Synthesis and Computation (RUBISCO) Scientific Focus Area (SFA), which is sponsored by the Regional and Global Model Analysis (RGMA) Program in the Climate and Environmental Sciences Division (CESD) of the Biological and Environmental Research (BER) Program in the U.S. Department of Energy Office of Science. This research used resources of the Oak Ridge Leadership Computing Facility (OLCF) at Oak Ridge National Laboratory (ORNL), which is managed by UT-Battelle, LLC, for the U.S. Department of Energy under Contract No. DE-AC05-00OR22725.

Optimized SO_2 Injection Locations

- SO_2 injection locations
  - 30°N, 15°N, 15°S, 30°S, arbitrarily at 180°E
    - 15°N and 15°S at 25 km
    - 30°N and 30°S at 22.8 km



(*Kravitz et al.*, 2017)