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Assessing terrestrial biogeochemical feedbacks in a strategically geoengineered climate

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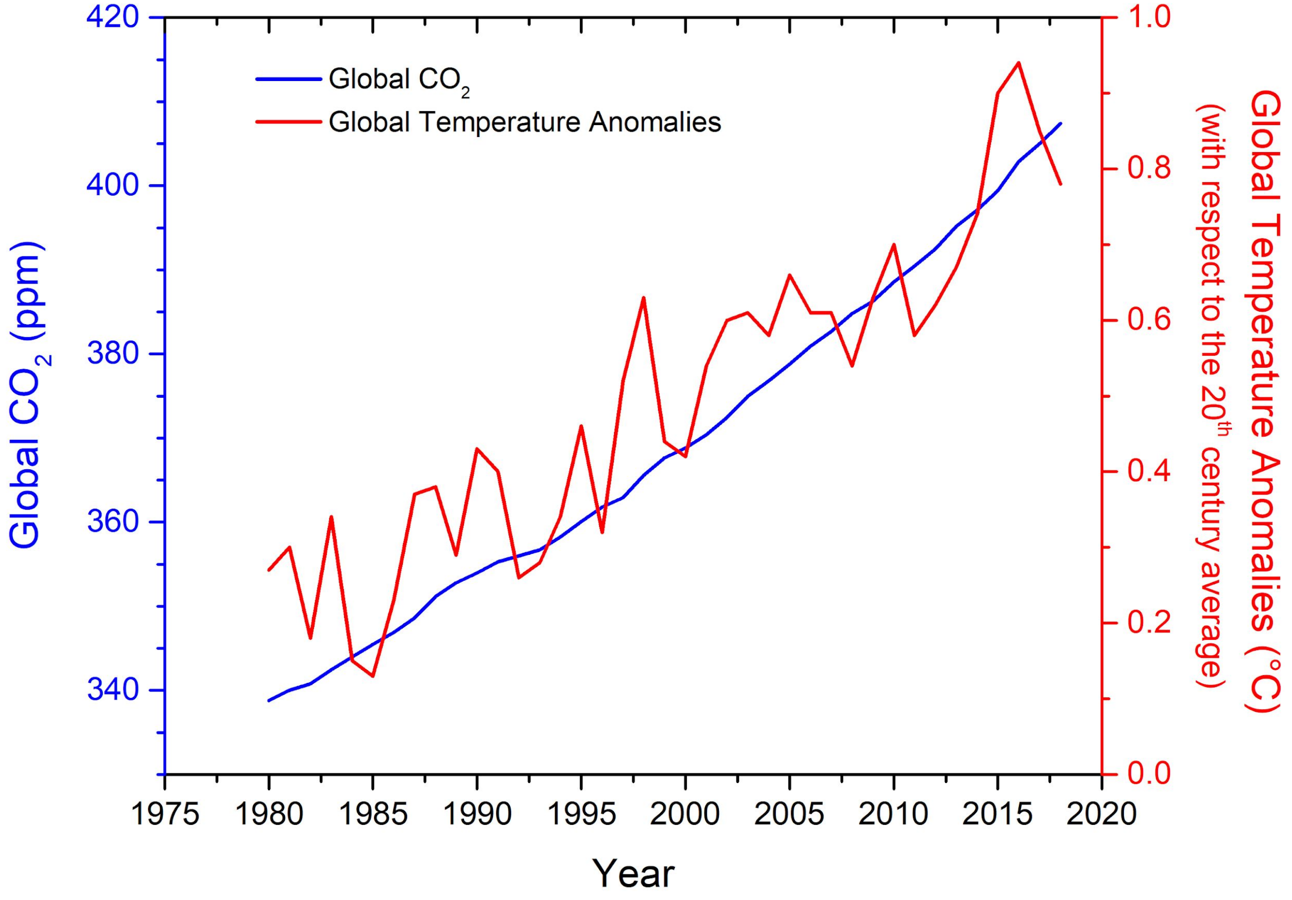
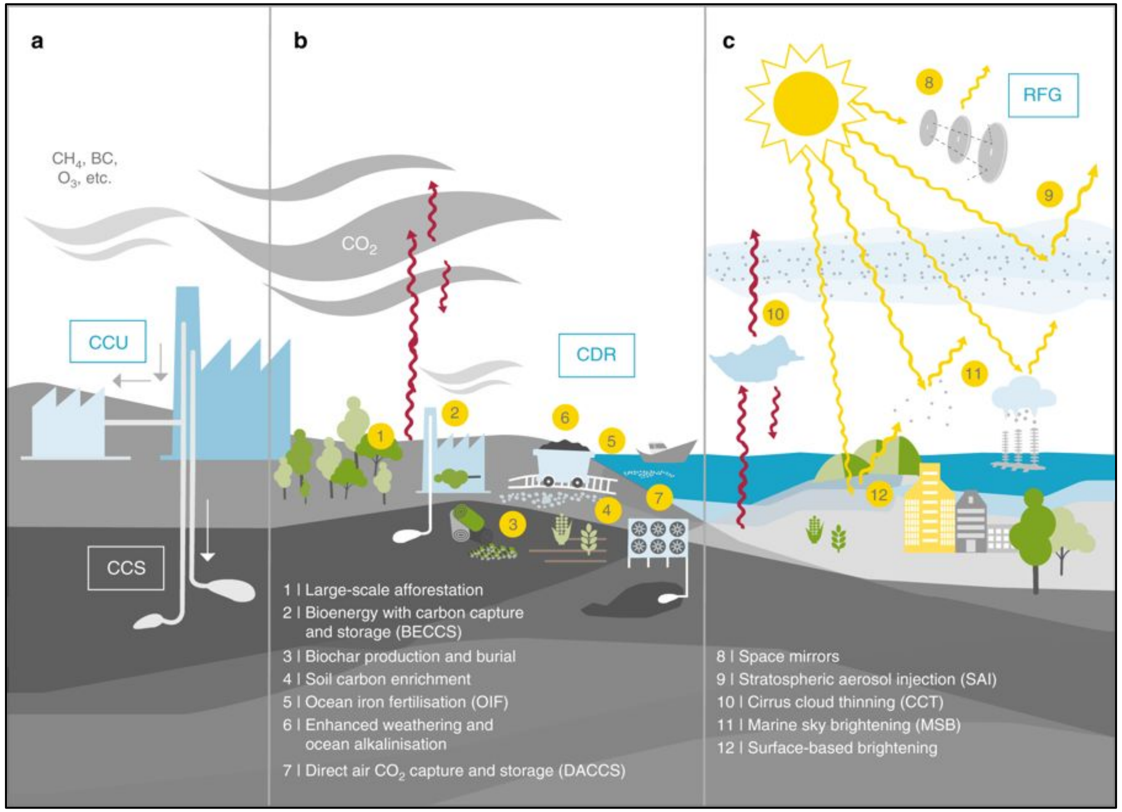
Climate Geoengineering

Global Climate Status



(Data from NOAA ESRL)

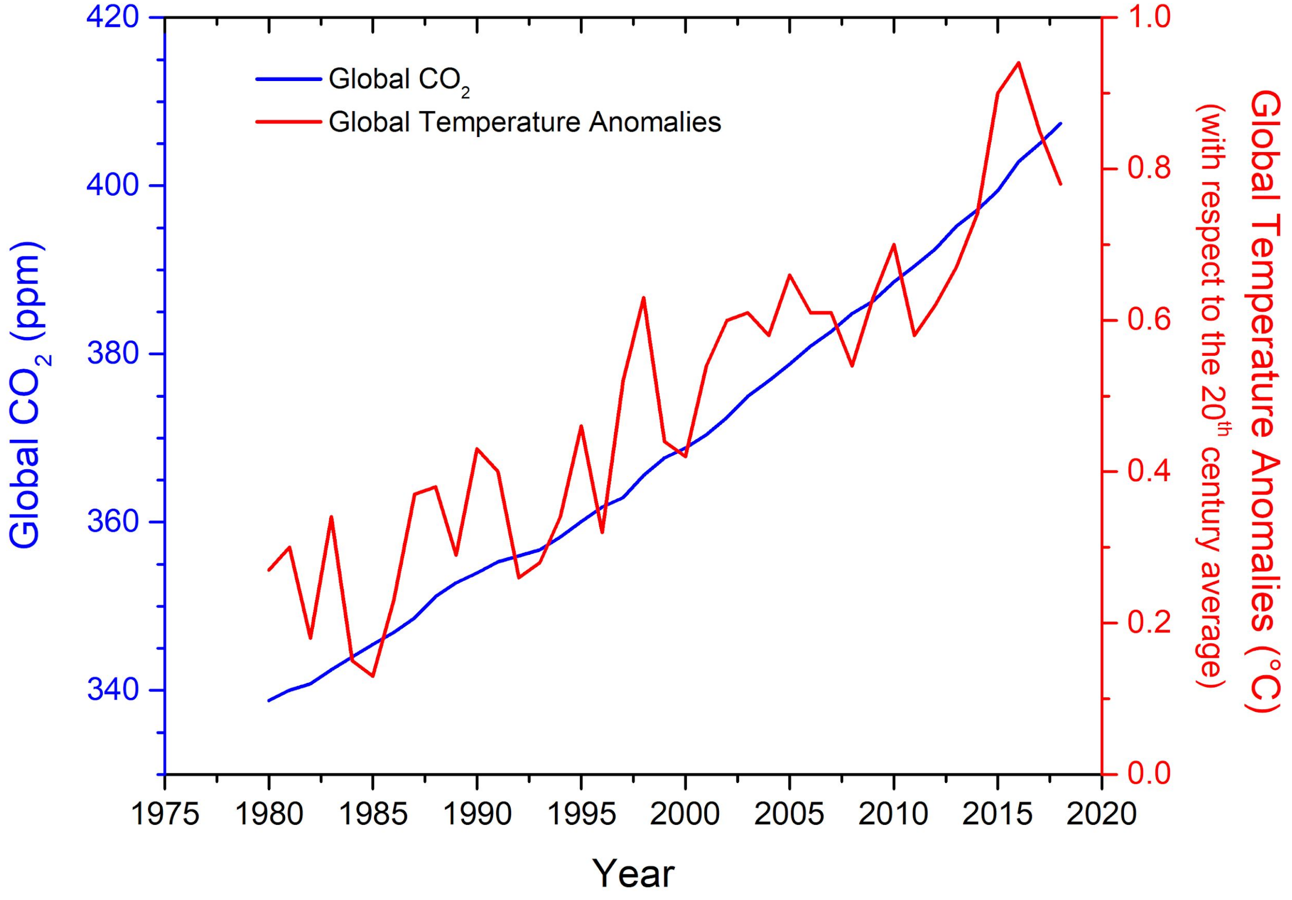
Climate Geoengineering Proposals



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

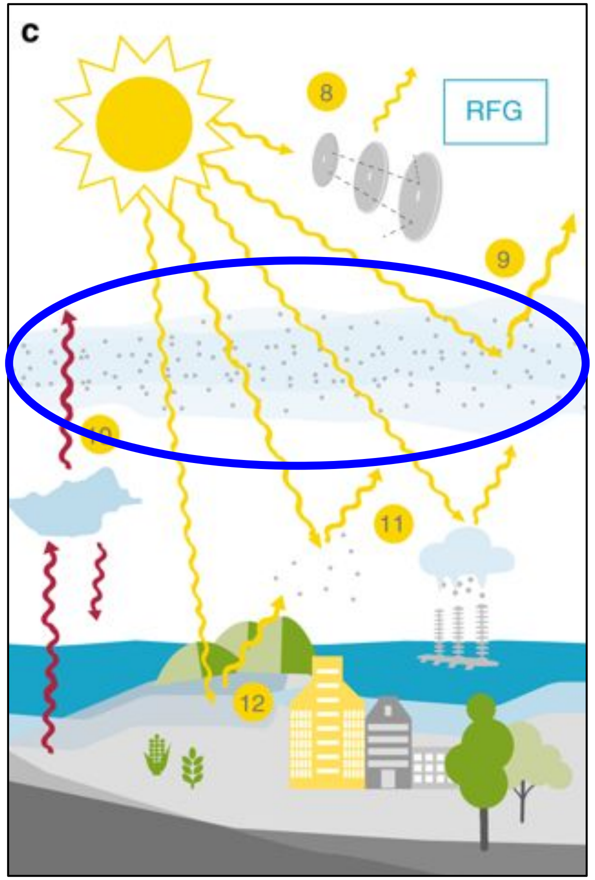
Climate Geoengineering

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)

Concepts of Climate Geoengineering

- "… artificially enhancing earth's albedo and thereby cooling climate by adding sunlight reflecting aerosol in the stratosphere … additionally counteract the climate forcing of growing CO_2 emissions."– *P. J. Crutzen (2006)*

- Strategies to deliberately offset the increasing radiative forcing due to anthropogenic emissions
  - Carbon dioxide removal (CDR)
  - Solar radiation management (SRM) → no CO_2 control

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

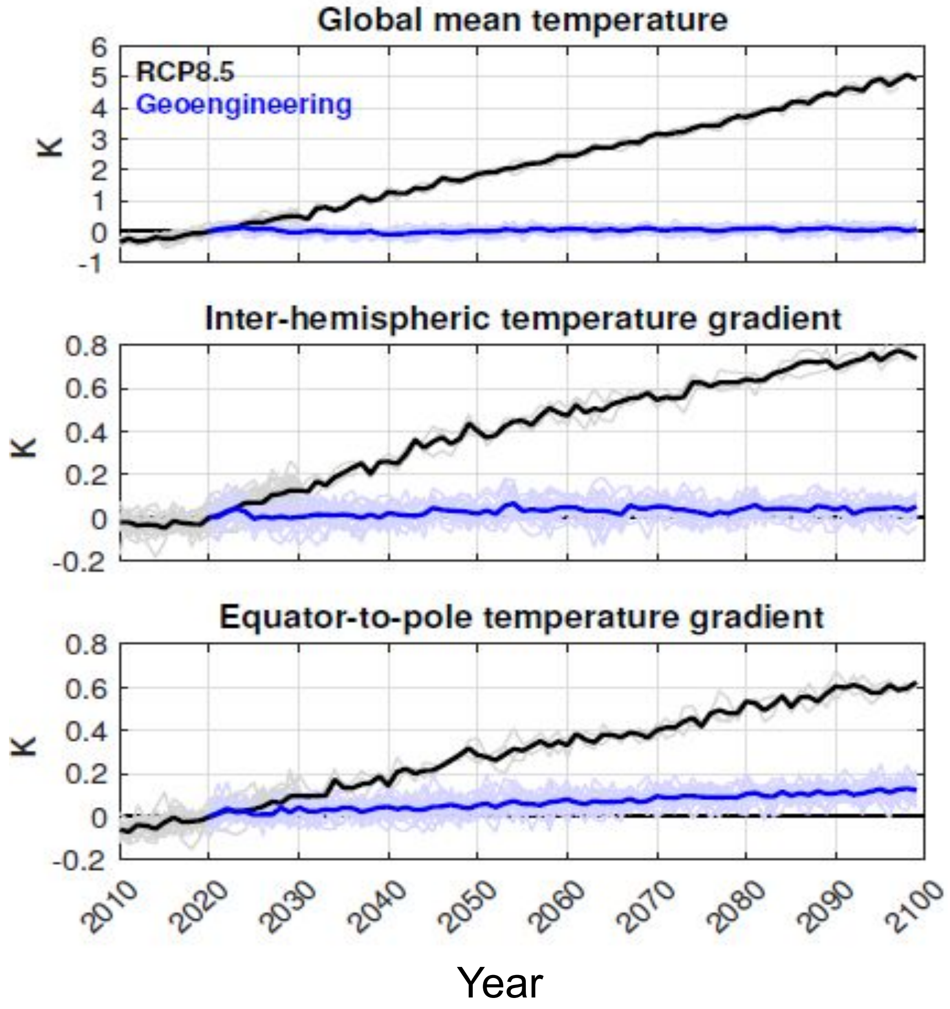
We will investigate responses of terrestrial ecosystems to a geoengineered RCP 8.5 climate through SO_2 injections in the lower stratosphere to address these questions:

- 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?

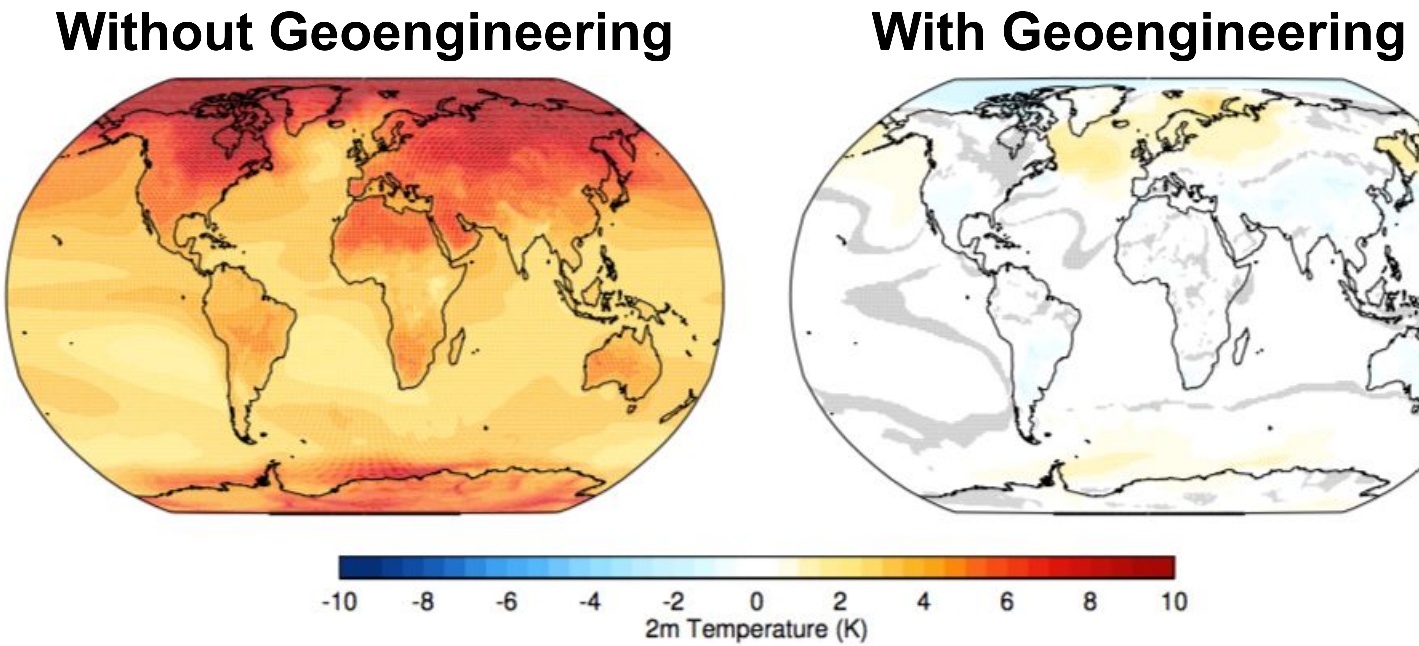
Modeling Projects for Climate Geoengineering

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



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



(Tilmes *et al.*, 2018)

How about the terrestrial biogeochemical feedbacks?

Analytical Method

❖ Dataset: 3 of 20 ensemble members from GLENS

❖ Scenarios

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)	

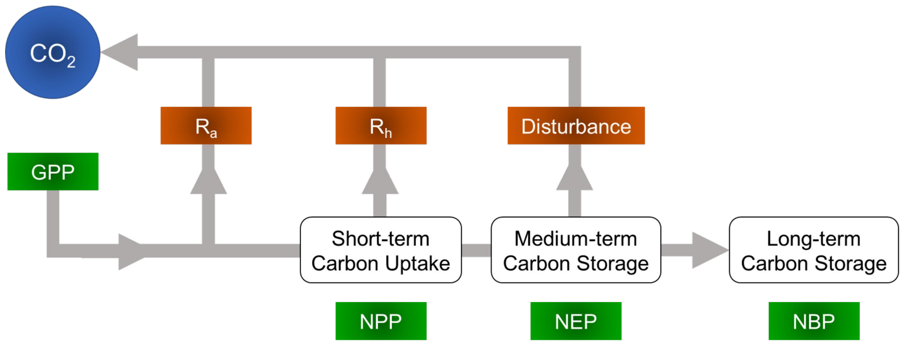
❖ Regions: global and 13 IGBP ecoregions

Global Ecoregions and Terrestrial Carbon Cycle

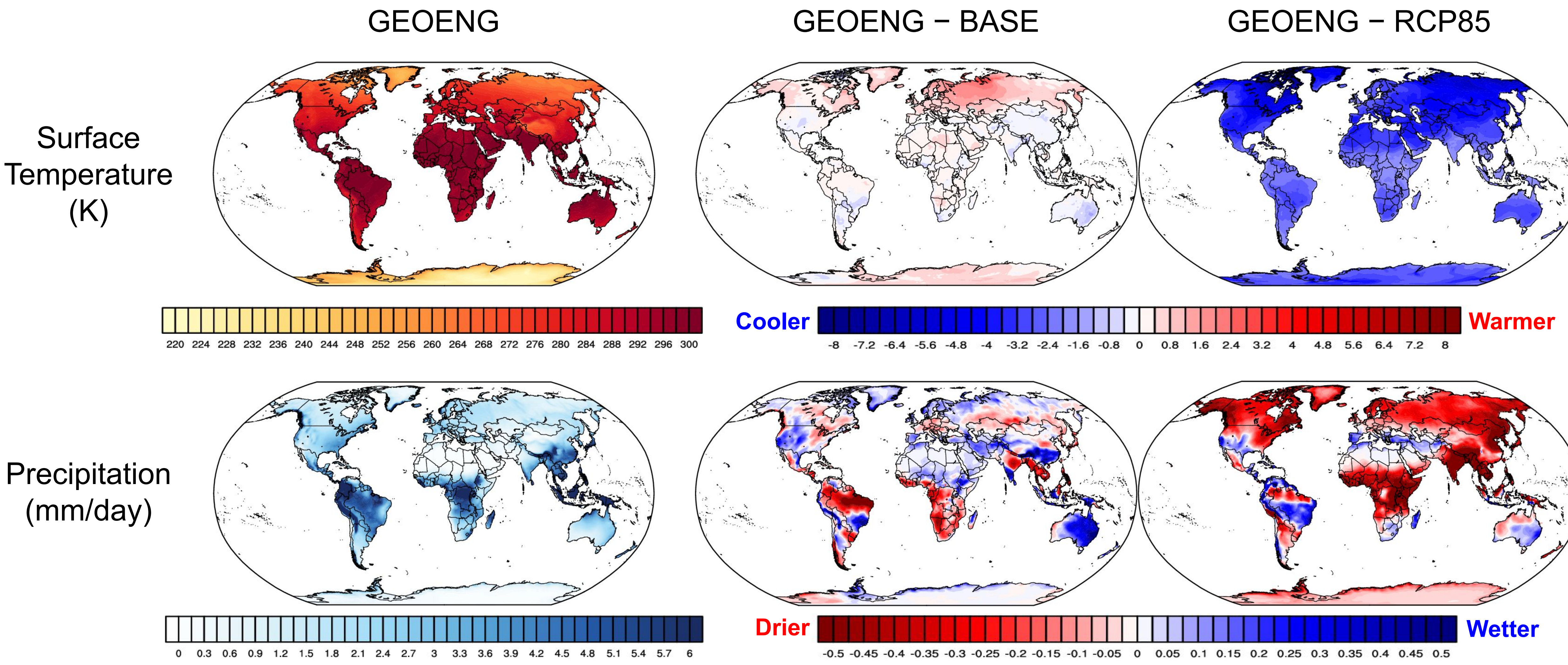
❖ International Geosphere-Biosphere Programme (IGBP) ecoregions

❖ 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)

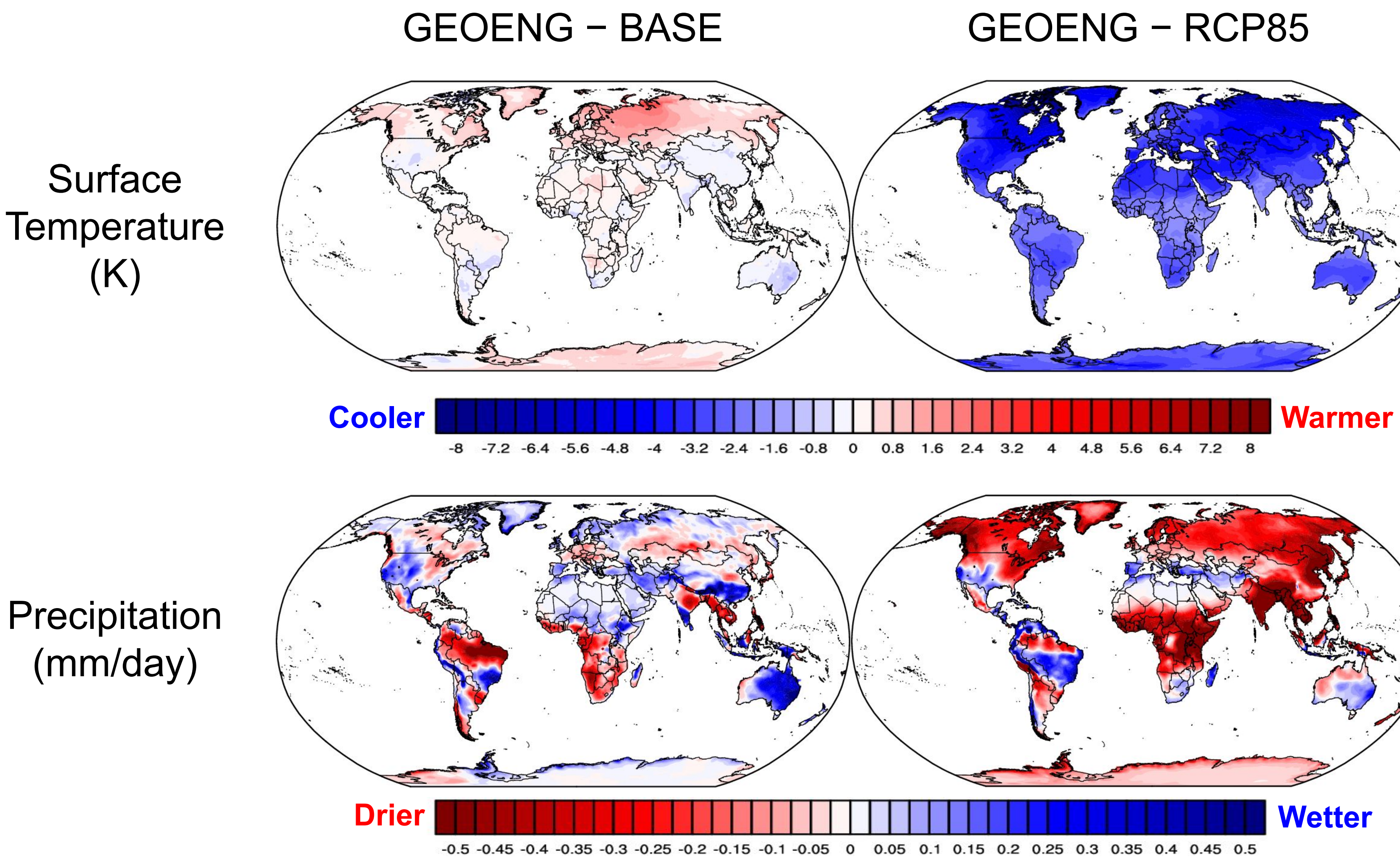


Changes in Temperature and Precipitation



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

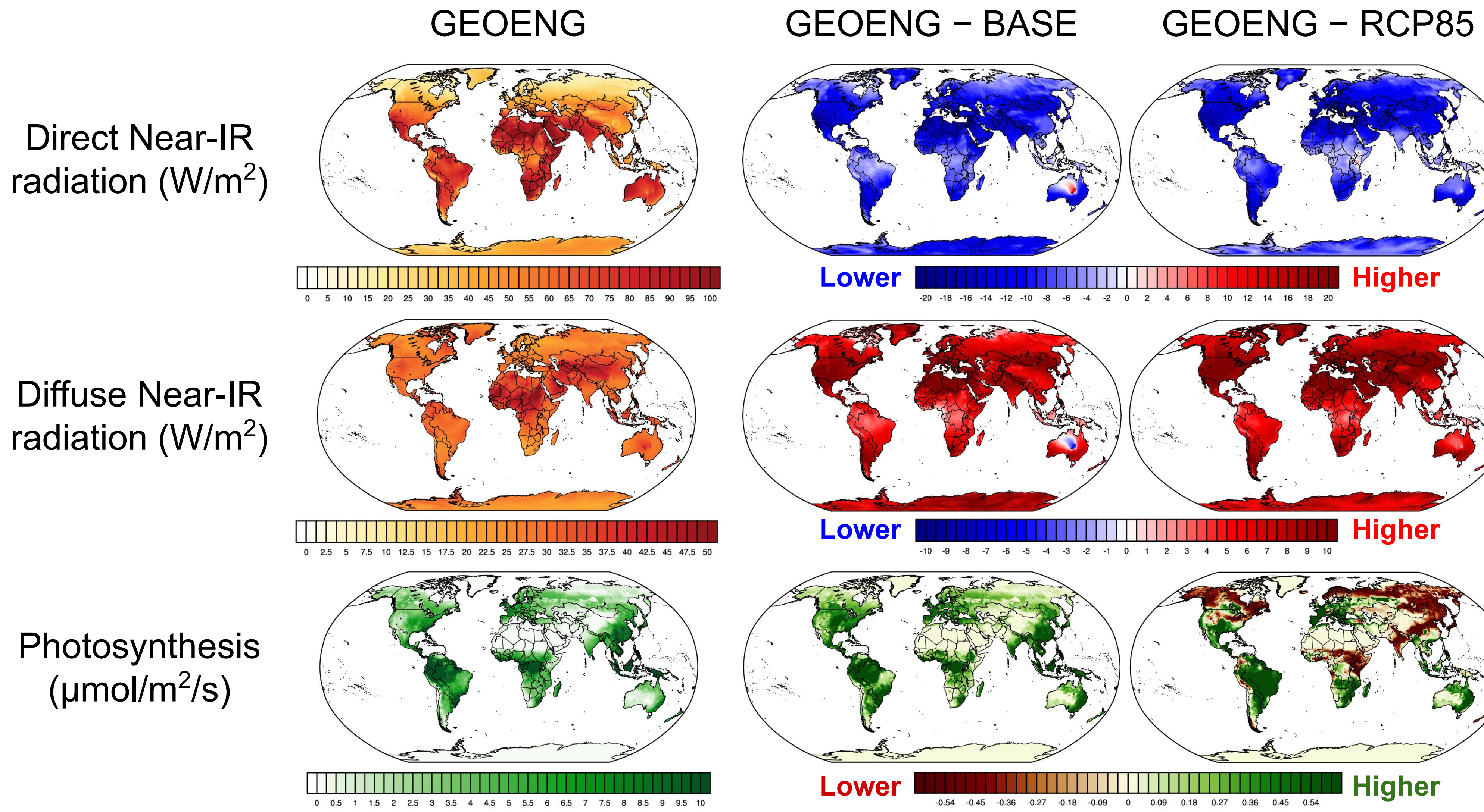
Changes in Temperature and Precipitation



- Global mean temperature is 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)

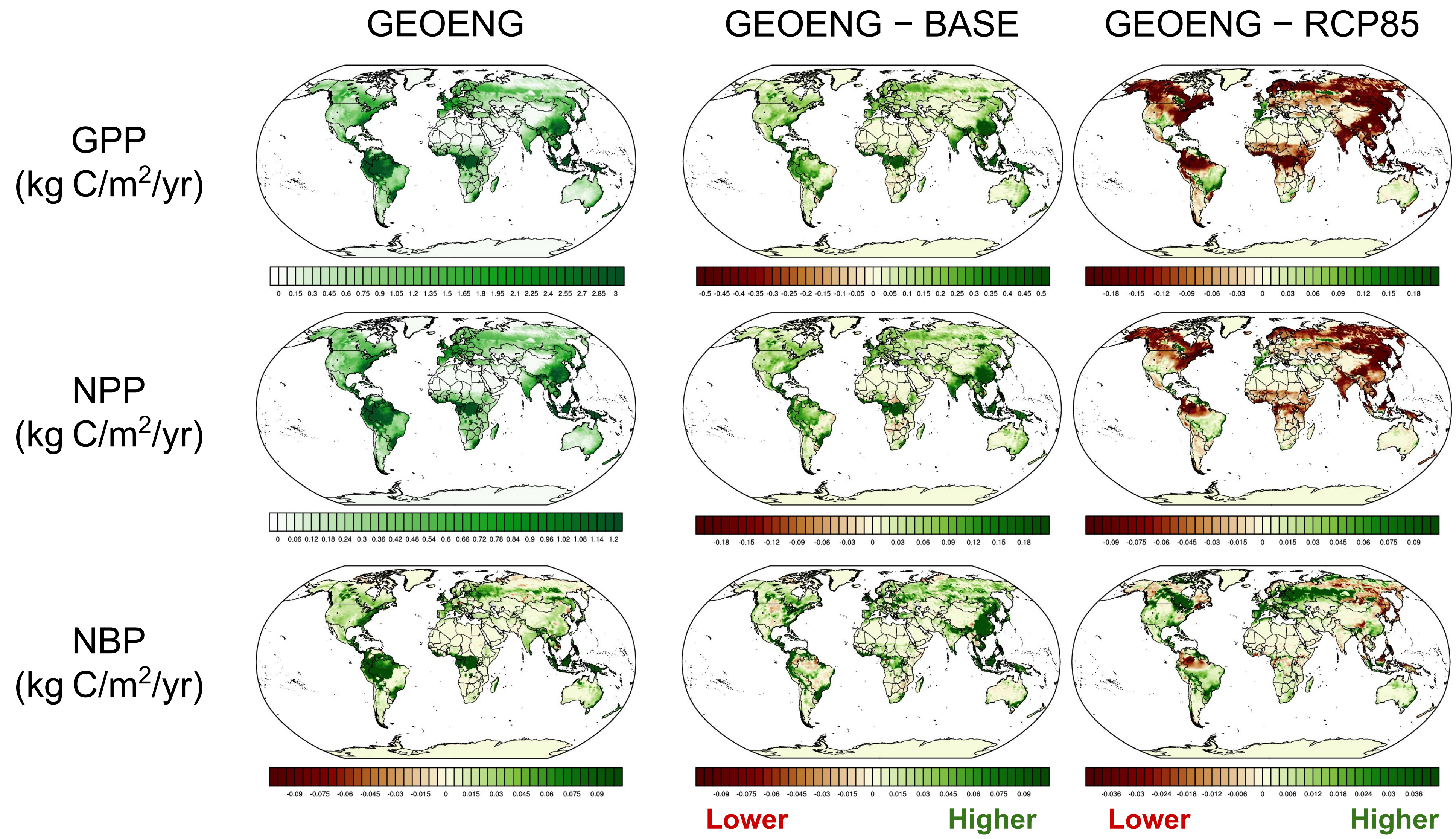
Changes in Radiation and Photosynthesis



- 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

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

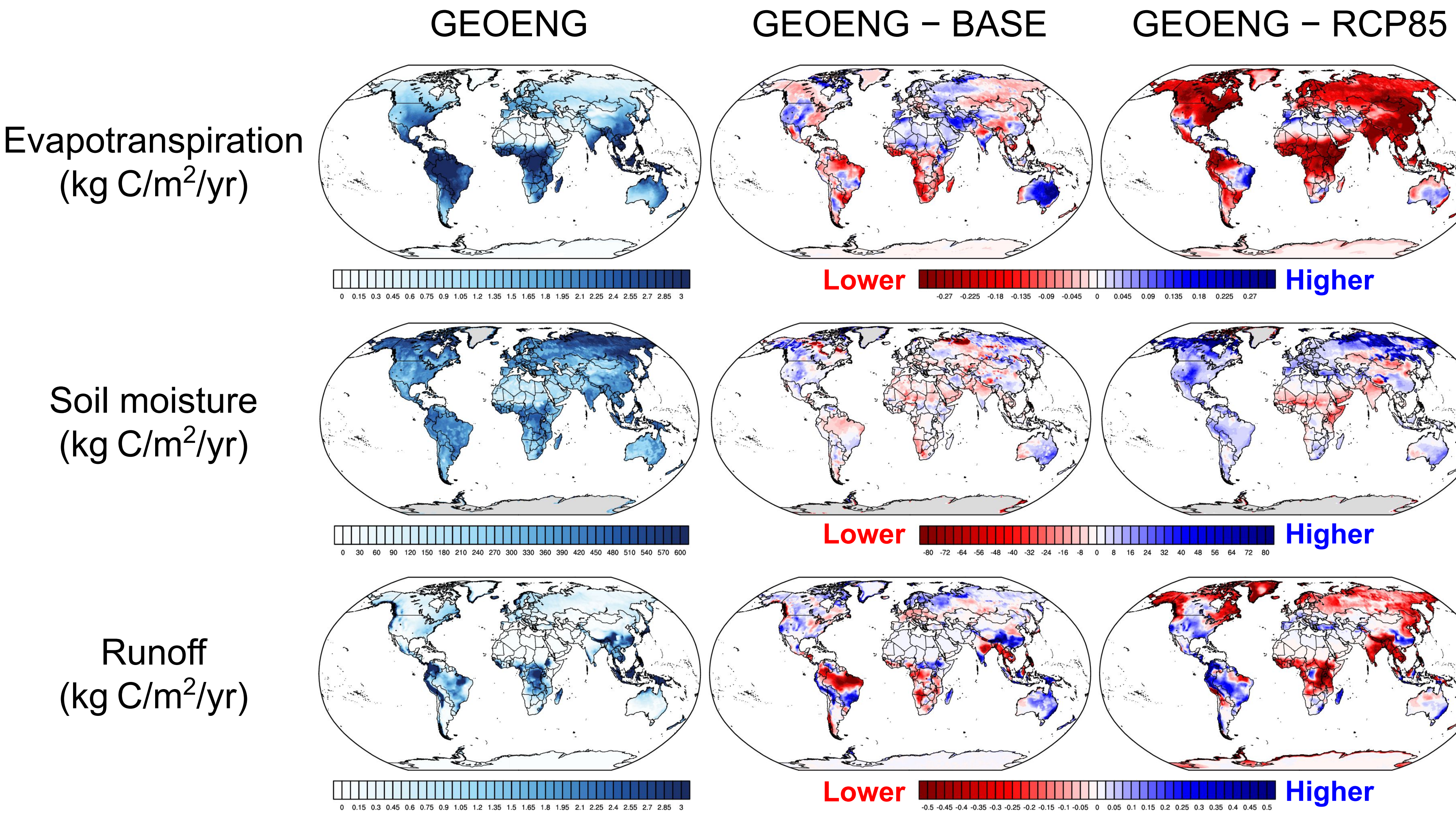
Changes in Terrestrial Carbon Uptake



- 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

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

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)

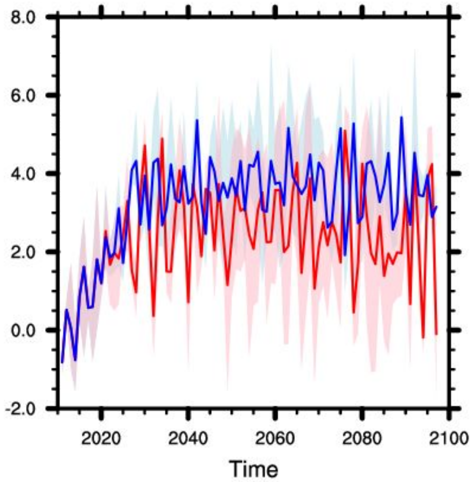
Carbon Sink Strength

NBP
(Pg C/yr)

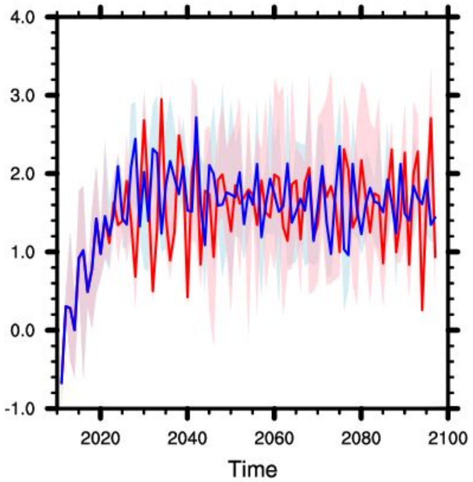
— RCP85
— GEOENG

(Yang *et al.*, in prep.)

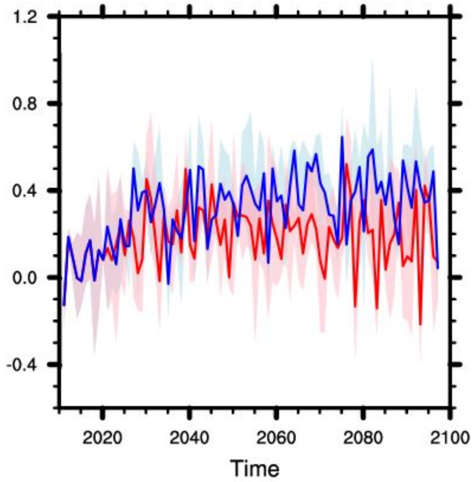
Global



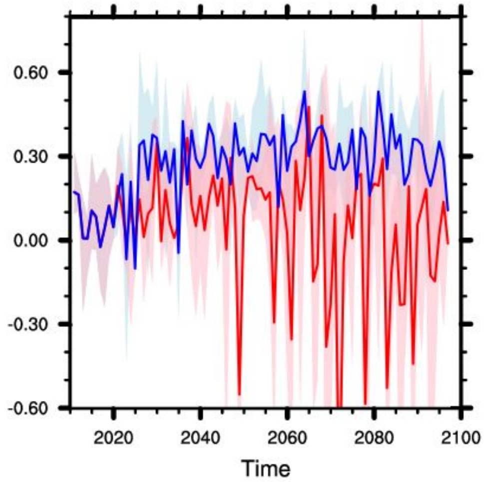
Evergreen broadleaf forest



Open shrublands



Mixed forest



Time period	**Cumulated Terrestrial Biogeochemical Feedbacks (unit: Pg C)**											
	RCP85	GEOENG	Δ	RCP85	GEOENG	Δ	RCP85	GEOENG	Δ	RCP85	GEOENG	Δ
All time	198	277	79	125	130	5	16	27	11	4	23	19
2020 – 2039	50	62	12	31	35	4	4	5	1	2	5	3
2050 – 2069	56	77	21	33	33	0	5	8	3	2	7	5
2078 – 2097	43	73	30	32	33	1	3	8	5	−1	6	7

Carbon Sink Strength

Time period	Cumulated Terrestrial Biogeochemical Feedbacks (unit: Pg C)											
	Global			Evergreen broadleaf forest			Open shrublands			Mixed forest		
	RCP85	GEOENG	Δ	RCP85	GEOENG	Δ	RCP85	GEOENG	Δ	RCP85	GEOENG	Δ
All time	198	277	79	125	130	5	16	27	11	4	23	19
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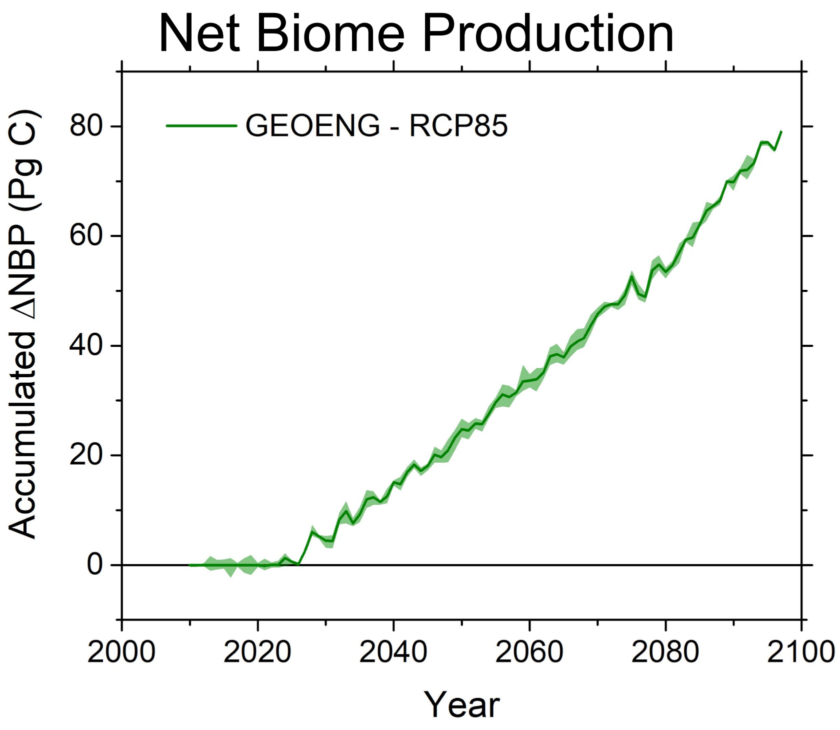
2078 – 2097	43	73	30	32	33	1	3	8	5	−1	6	7

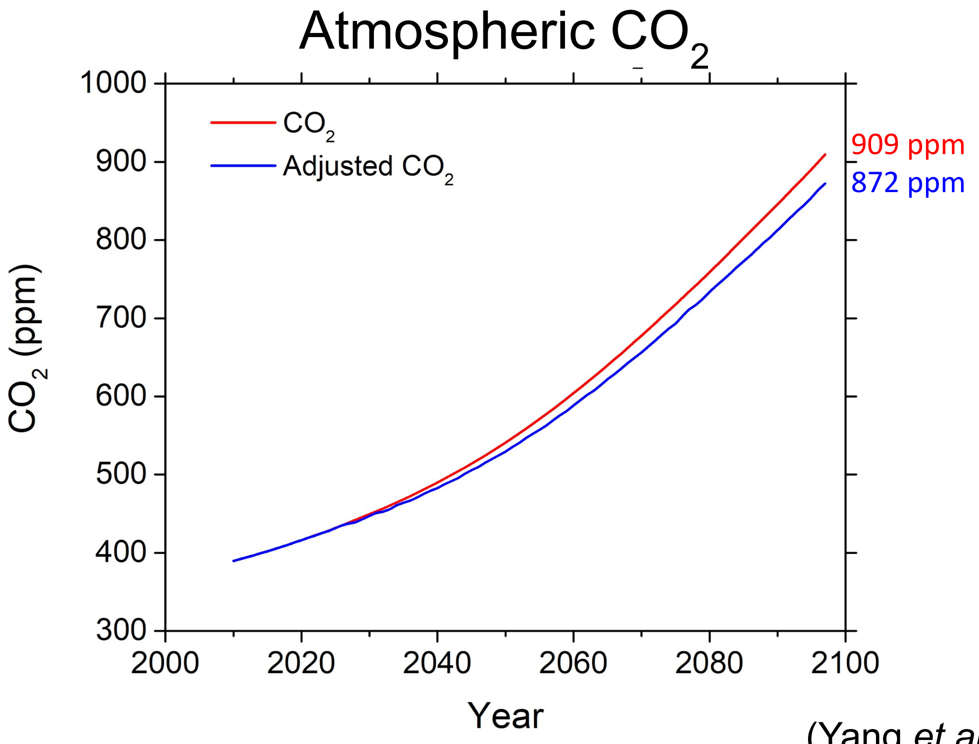
- More carbon stored in terrestrial ecosystems in GEOENG over time
- The largest carbon sink pool is Evergreen broadleaf forests
- The most sensitive ecoregions to climate geoengineering are mixed forests and croplands

(Yang *et al.*, in prep.)

Accounting for Terrestrial Ecosystem Feedbacks

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



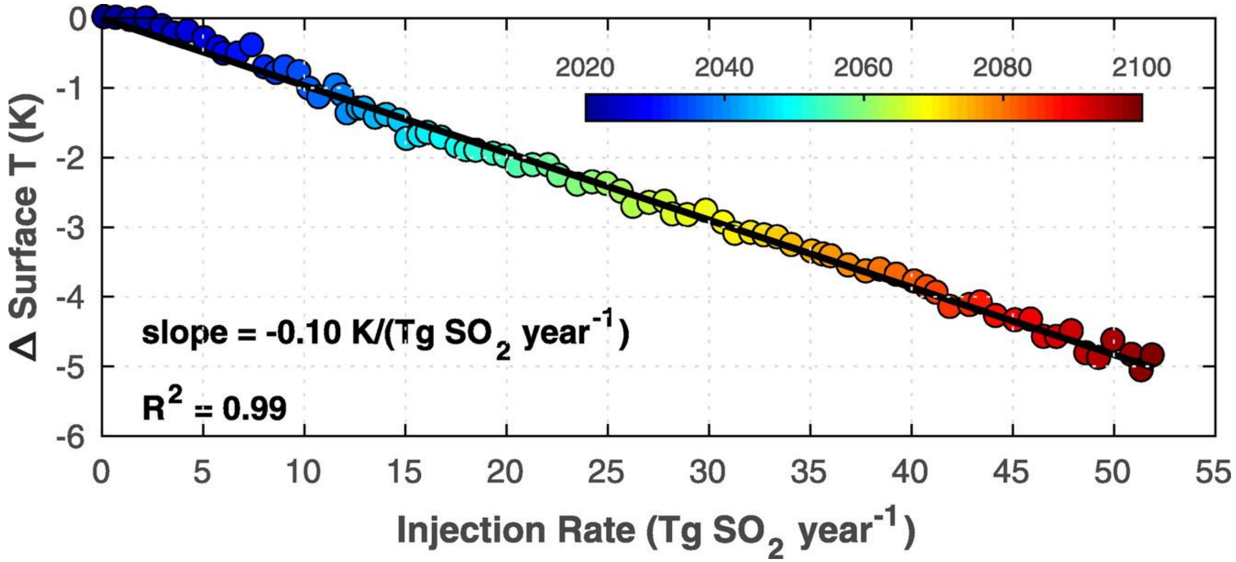


(Yang *et al.*, in prep.)

- 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 7% at 2097 due to the terrestrial carbon feedback because of increased vegetation productivity ($\Delta[CO_2]_{atm}$ = 37 ppm)

Next Steps

- Thus, sulfate aerosol injection could be similarly reduced to maintain the 2020 global temperature target
- We can estimate the global adjusted radiative forcing and temperature change due to the increased land sink
- Then we can estimate a lower sulfate injection rate when accounting for terrestrial feedbacks



(Tilmes *et al.*, 2018)

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

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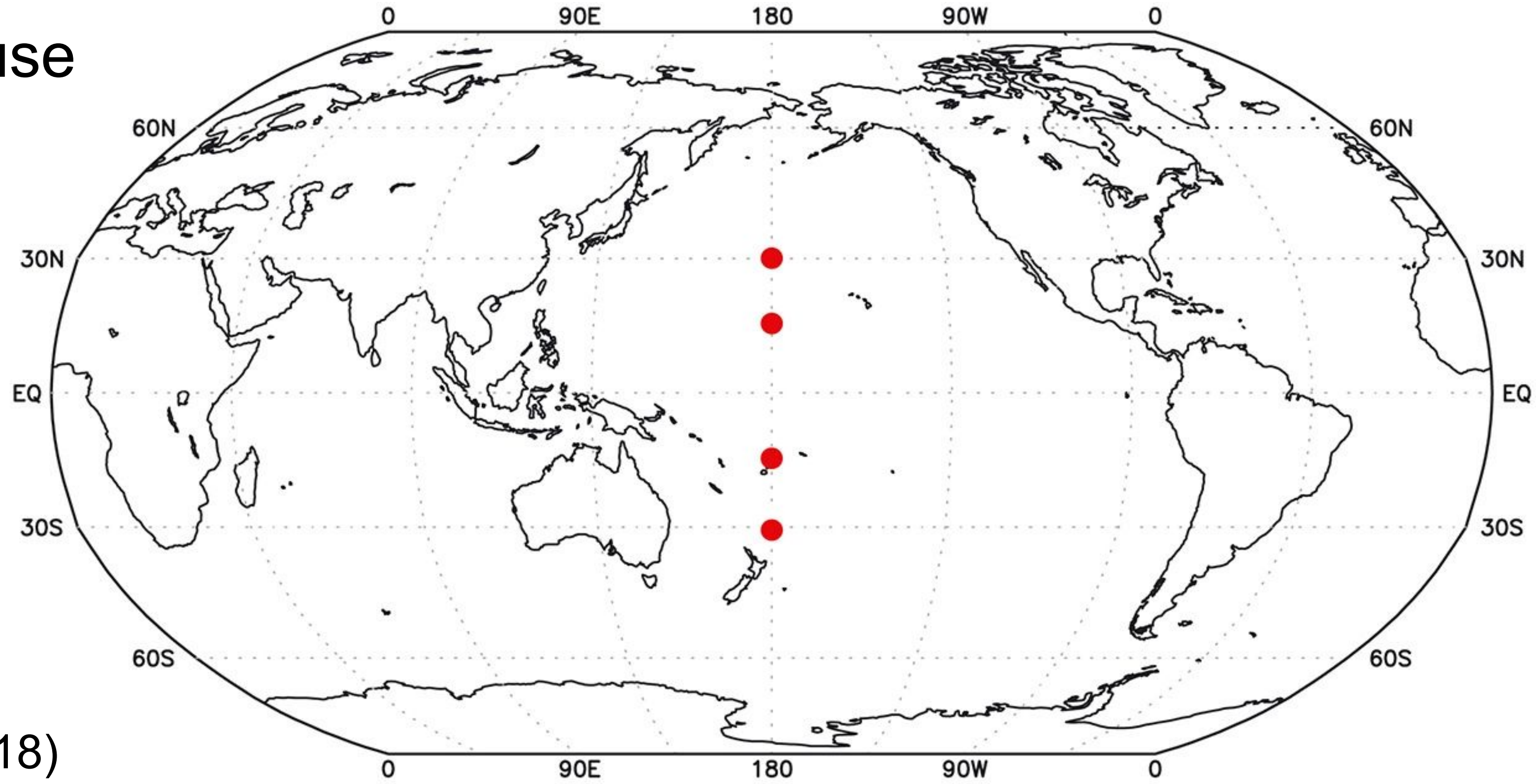
Optimized SO_2 Injection Locations

- SO_2 injection points
  - Optimized, 30°N, 15°N, 15°S, 30°S
  - 5 km above tropopause



(*Kravitz et al.*, 2018)