# Evaluations of Terrestrial Biogeochemical Feedbacks of Stratospheric Geoengineering Strategies

Cheng-En Yang

The University of Tennessee

Oak Ridge National Laboratory

***Collaborators:*** Forrest Hoffman, Simone Tilmes, Jadwiga Richter, Ben Kravitz, Douglas MacMartin, Michael Mills, Joshua S. Fu, Lili Xia, Katie Dagon


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# 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)

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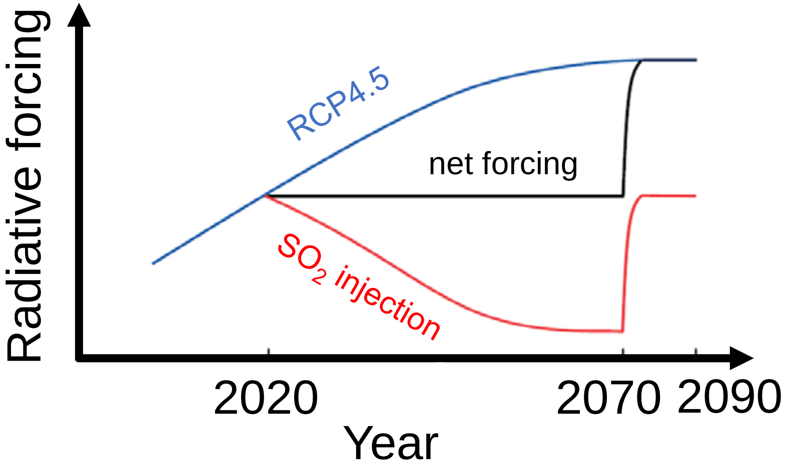
- Strategies to deliberately offset the increasing radiative forcing due to anthropogenic emissions
  - Carbon dioxide removal (CDR)
  - Solar radiation management (SRM) → no $CO_2$ control

# Geoengineering Projects

| Project | Scenario | Synopsis |
| --- | --- | --- |
| Geoengineering Model Intercomparison Project (GeoMIP) | G3 (RCP4.5) |  |



- $SO_2$ injection
  - Single point on the equator at 0° longitude
  - Distributed through the altitude range 16-25 km
  - 2020–2069
  - Abrupt termination at 2070

(Kravitz *et al.*, 2011)

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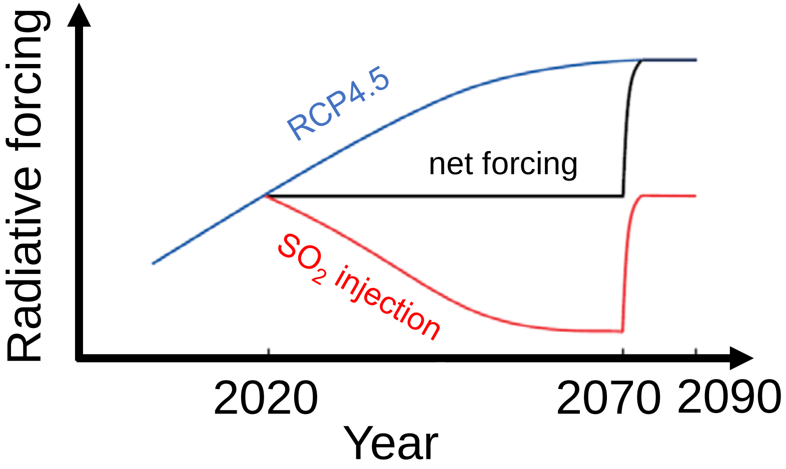
| Geoengineering Model Intercomparison Project (GeoMIP) | G3 (RCP4.5) |  |



- $SO_2$ injection
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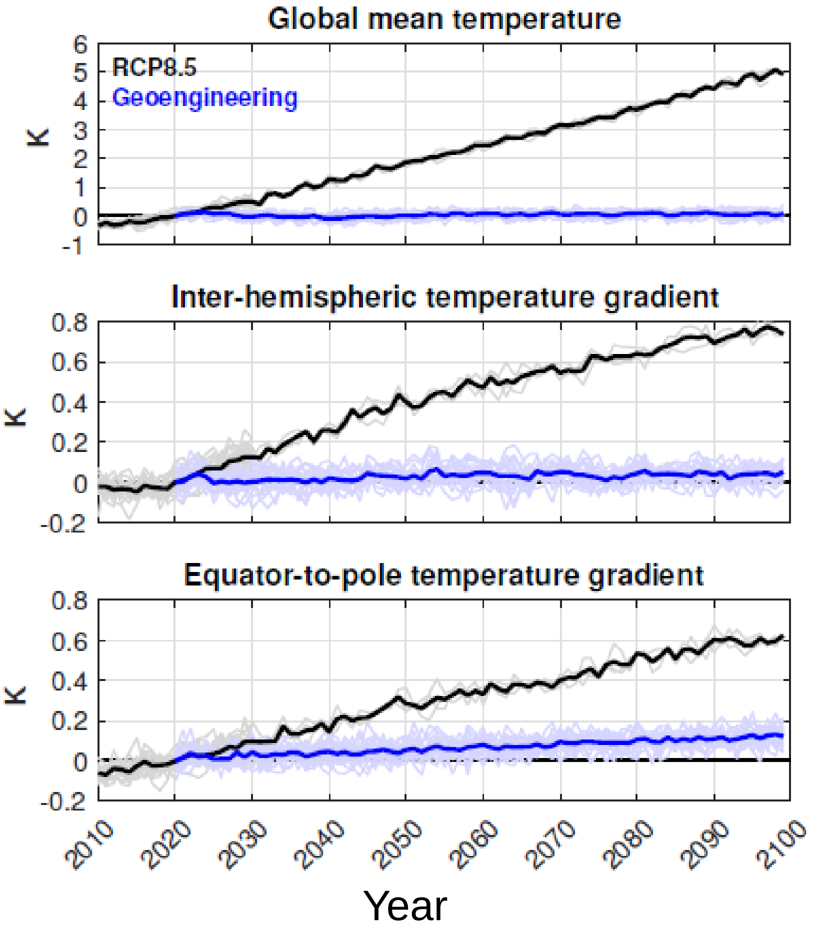
- Uneven cooling between the poles and equator
  - Overcooling of the tropics and undercooling of the poles
  - Shifts in tropical precipitation
  - Continued Arctic summer sea-ice loss

(Kravitz *et al.*, 2011)

# Geoengineering Projects

<table>
<tr><th>Project</th><th>Scenario</th><th>Synopsis</th></tr>
<tr><td>Stratospheric Aerosol Geoengineering Large Ensemble Project<br><br>(GLENS)<br><br>(Available Jan. 2018)</td><td>GLENS<br><br>(RCP8.5)</td><td>
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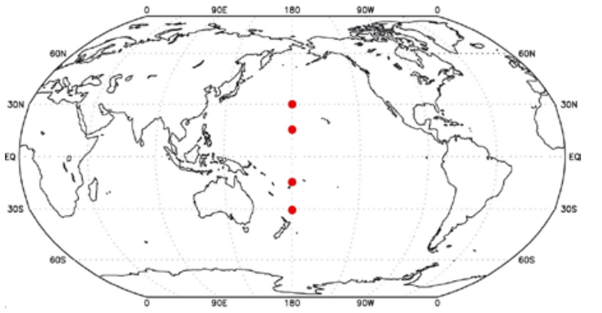
- $SO_2$ injection
  - Optimized, 30°N, 15°N, 15°S, 30°S



(Kravitz *et al.*, 2017)

  - 5 km above tropopause
  - 2020–2069
  - No termination

(Tilmes *et al.*, 2018, accepted)

# Geoengineering Impacts

- Reduced global mean surface temperature warming
- Suppressed precipitation
- Slower hydrological cycle
- Ocean acidification
- Higher photosynthesis rate
- Higher net primary production (NPP)

# Science Questions

- Responses of the terrestrial ecosystem to geoengineering
  - Will land remain a carbon sink?
  - Will every region undergo the same biogeochemistry (BGC) feedbacks?
  - Quantification of the carbon sink strength

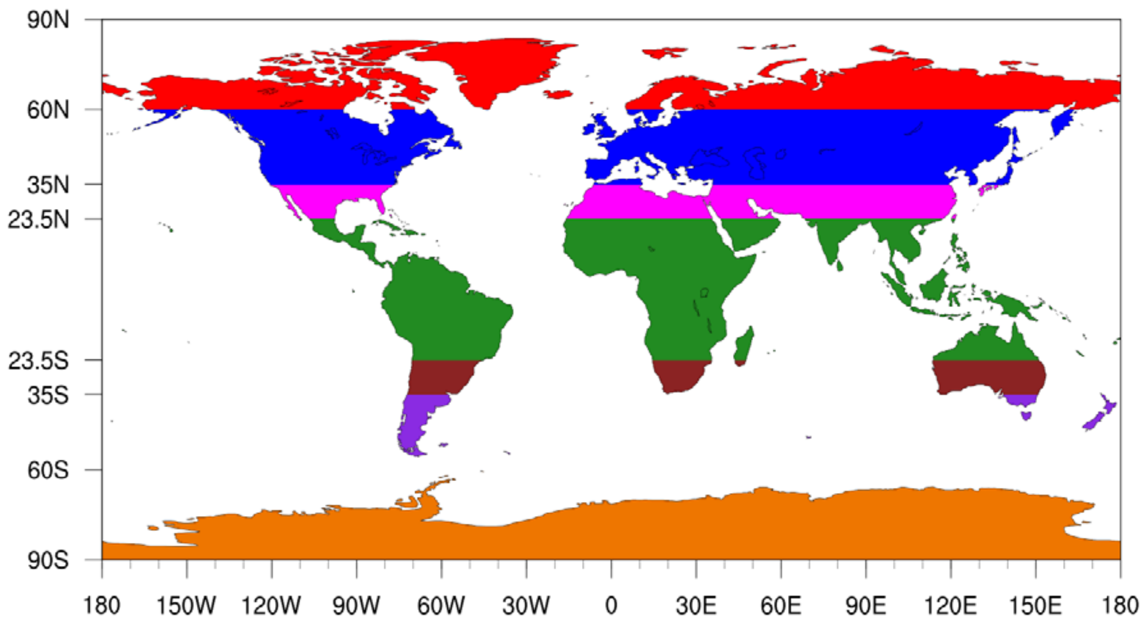
# Analytical Methods

| Data | Model | RCP | Geoengineering | Note |
|---|---|---|---|---|
| GeoMIP G3 | HadGEM2-ES | 4.5 | 2020–2069 | 2070–2089 post-geoengineering |
| GLENS | CESM1-WACCM | 8.5 | 2020–2099 | 3 of 20 ensemble members |

## Regions

Global (GLB)

- NH polar (NHP)
- NH midlatitude (NHM)
- NH subtropics (NHS)
- Tropics (TRP)
- SH subtropics (SHS)
- SH midlatitude (SHM)
- SH polar (SHP)

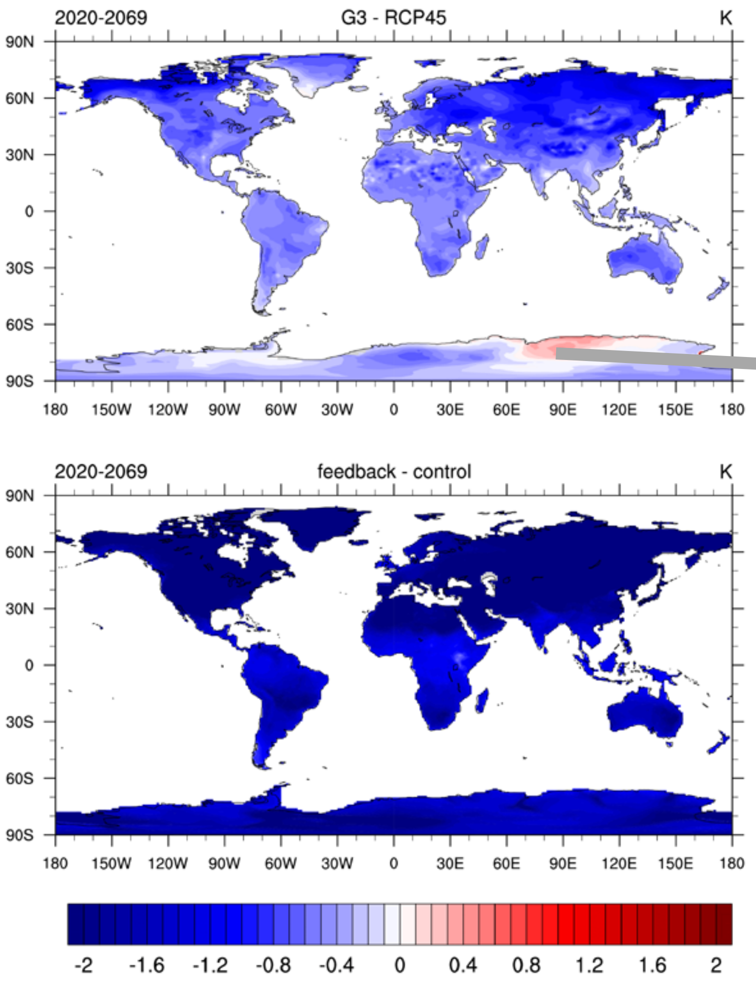


# 50–year Mean Annual Changes over Land

Surface Temperature

GeoMIP
G3 – RCP45

GLENS
Feedback – RCP85



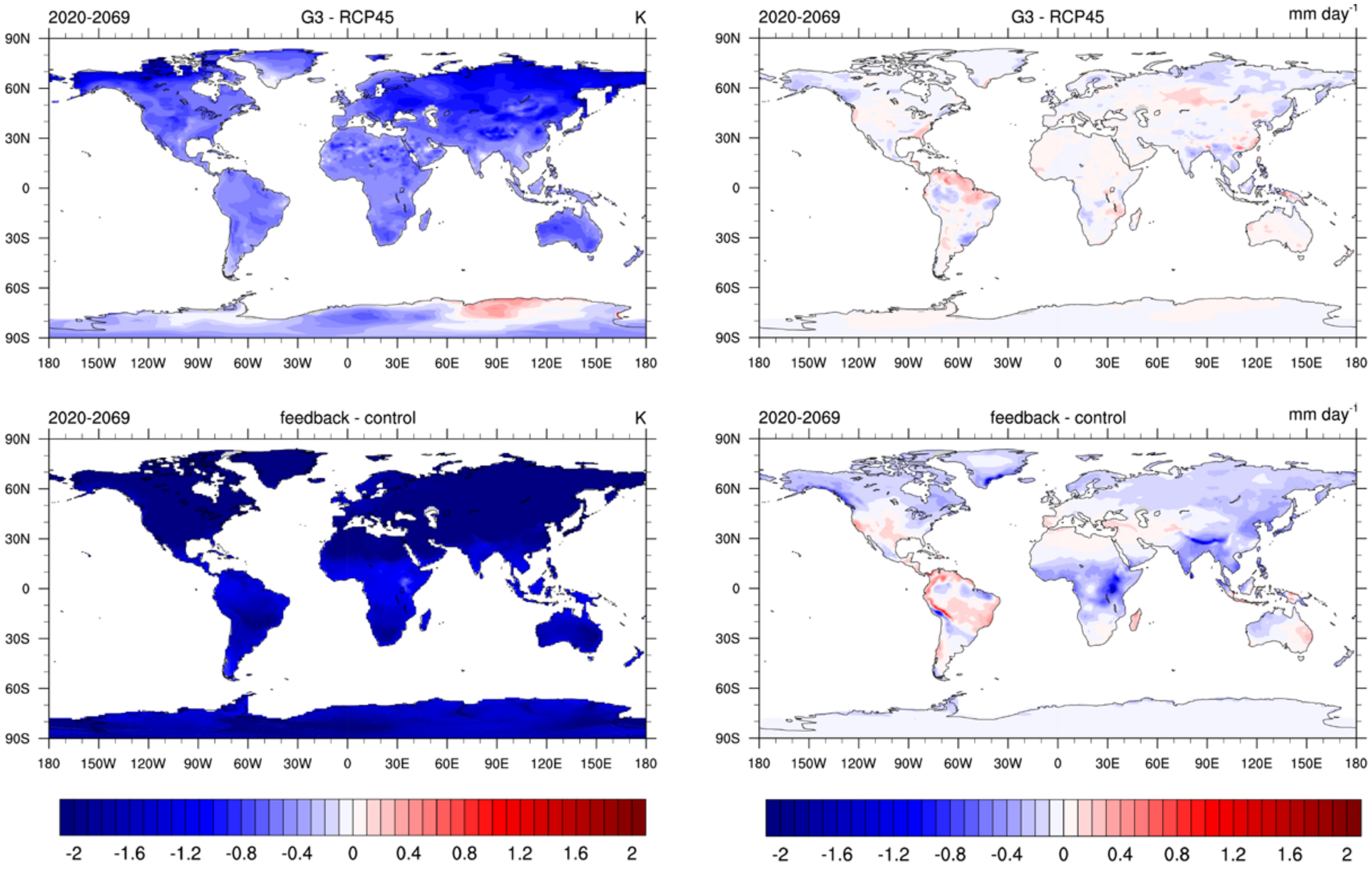

Ice melting due to uneven cooling

# 50–year Mean Annual Changes over Land

Surface Temperature | Precipitation

GeoMIP
G3 – RCP45

GLENS
Feedback – RCP85




- ❖ Reduced precipitation
  - Cooler temperature
  - Aerosol indirect effect
- ❖ Increasing precipitation in South America due to reduced dryness (cooler temperature)

# 50–year Mean Annual Changes over Land

Surface Temperature | Precipitation | Surface Shortwave Radiation

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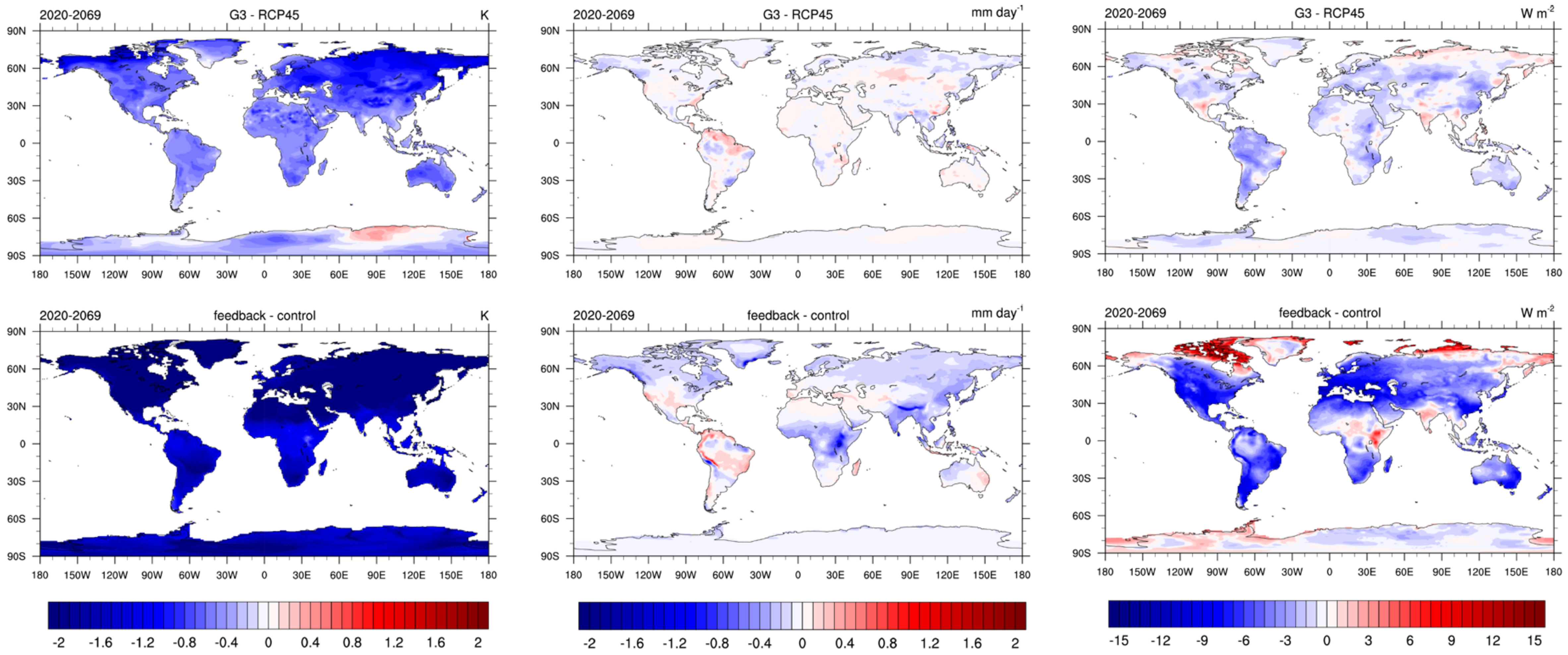

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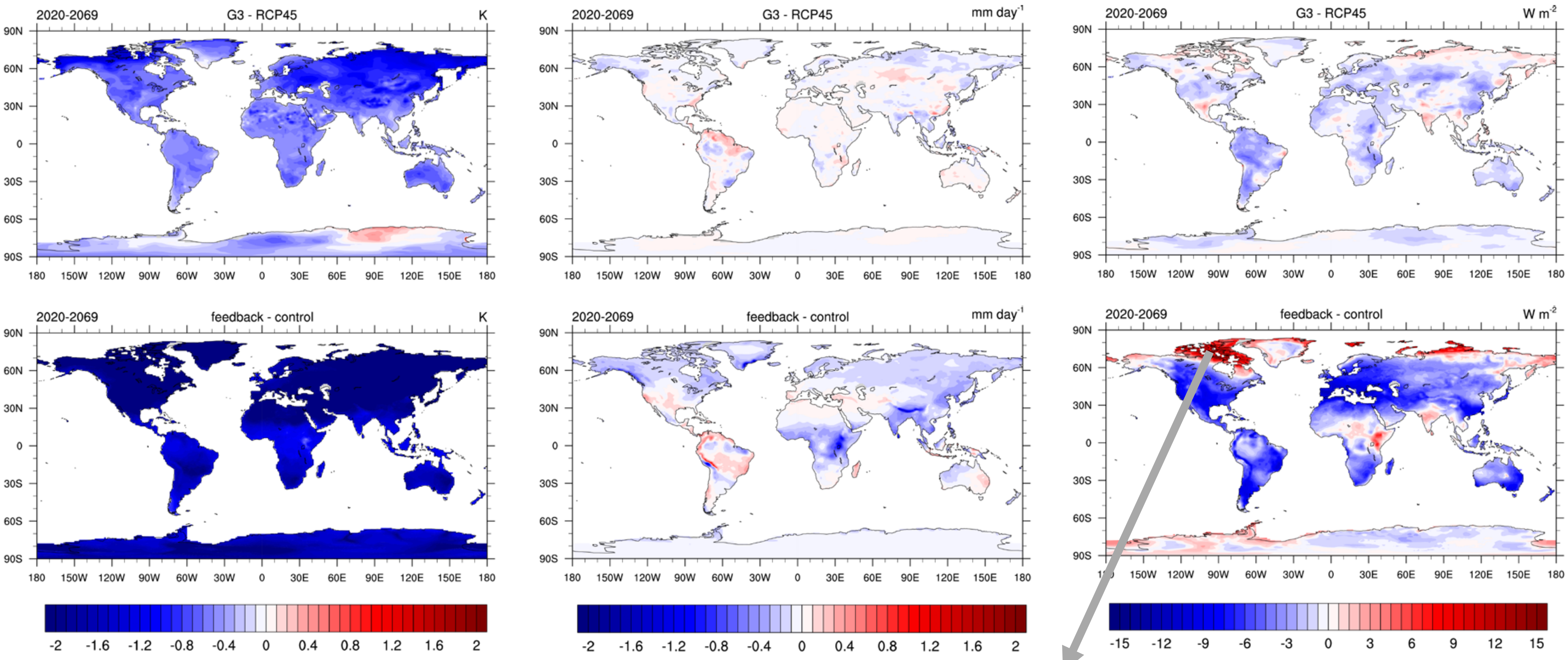


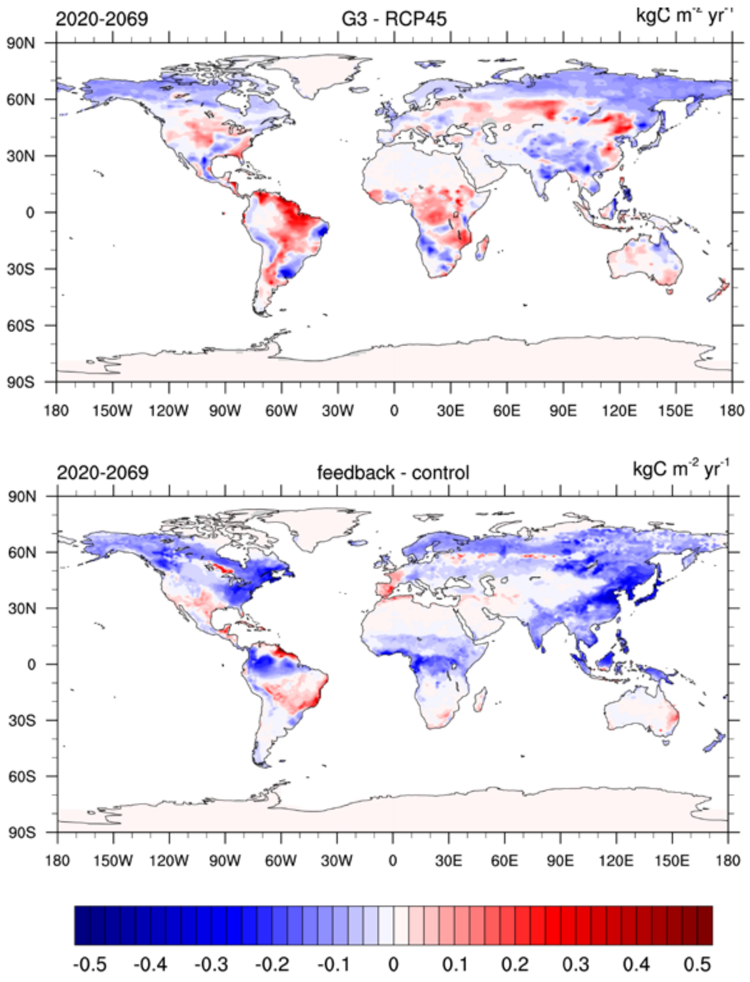

Reduced cloudiness at high latitudes

# 50–year Mean Annual Changes over Land

Gross Primary Production (GPP)

GeoMIP
G3 – RCP45

GLENS
Feedback – RCP85




❖ Higher GPP in the Tropics

- Increased diffuse light

❖ Lower GPP in high latitudes

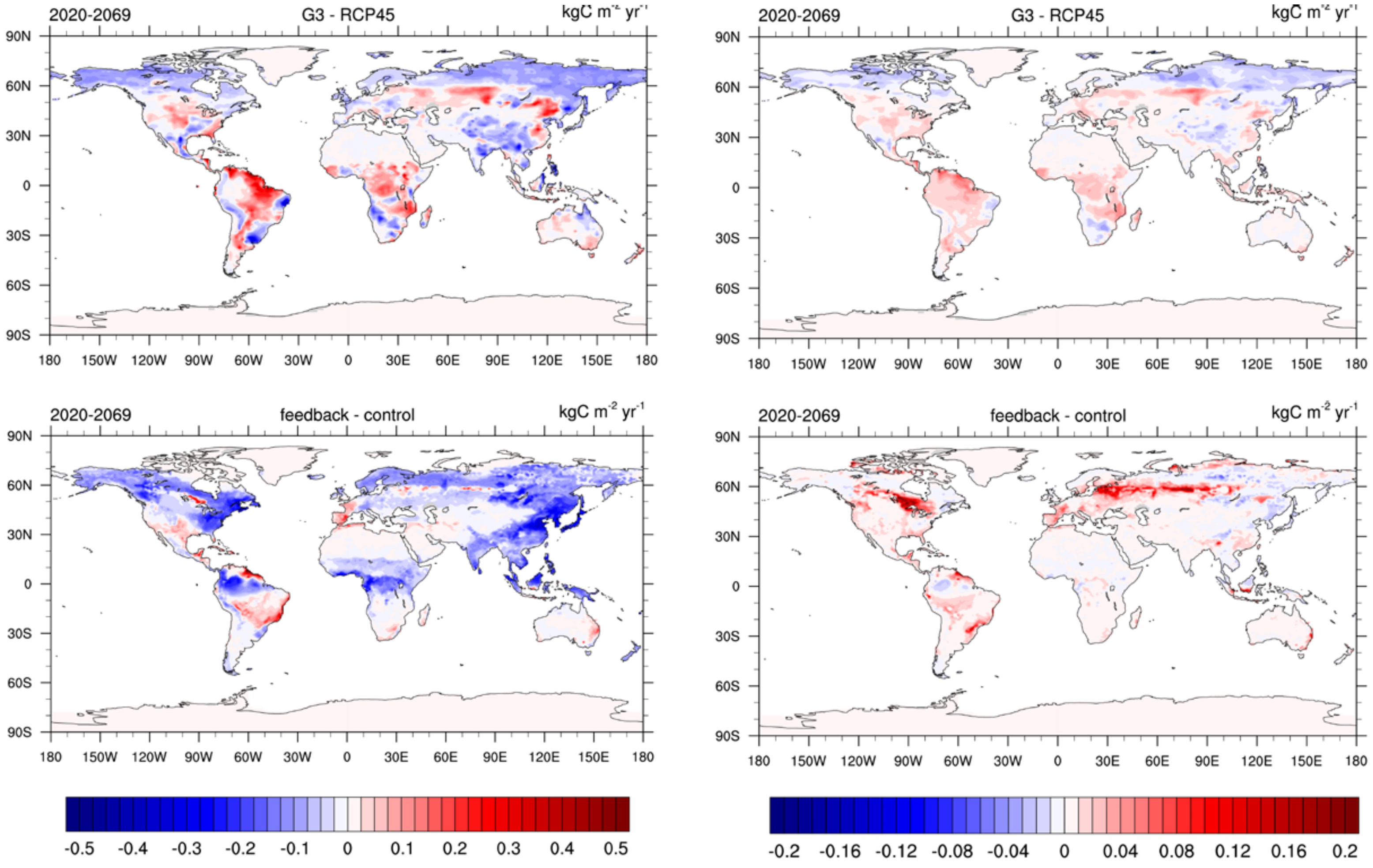
- Reduced SW
- Cooler surface temperature

# 50–year Mean Annual Changes over Land

Gross Primary Production (GPP) | Net Biome Production (NBP)

GeoMIP G3 – RCP45

GLENS Feedback – RCP85




- ❖ Significant increase at 60°N
  - Land use change?
  - Reduced heterotrophic respiration?
- ❖ Reduced carbon sink in G3

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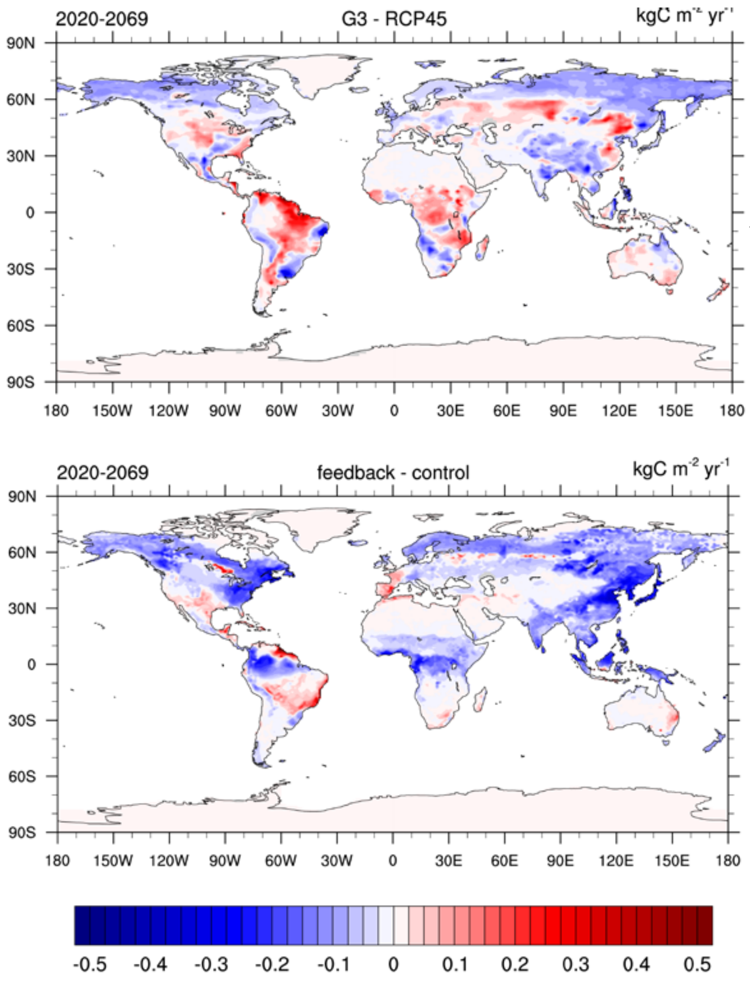
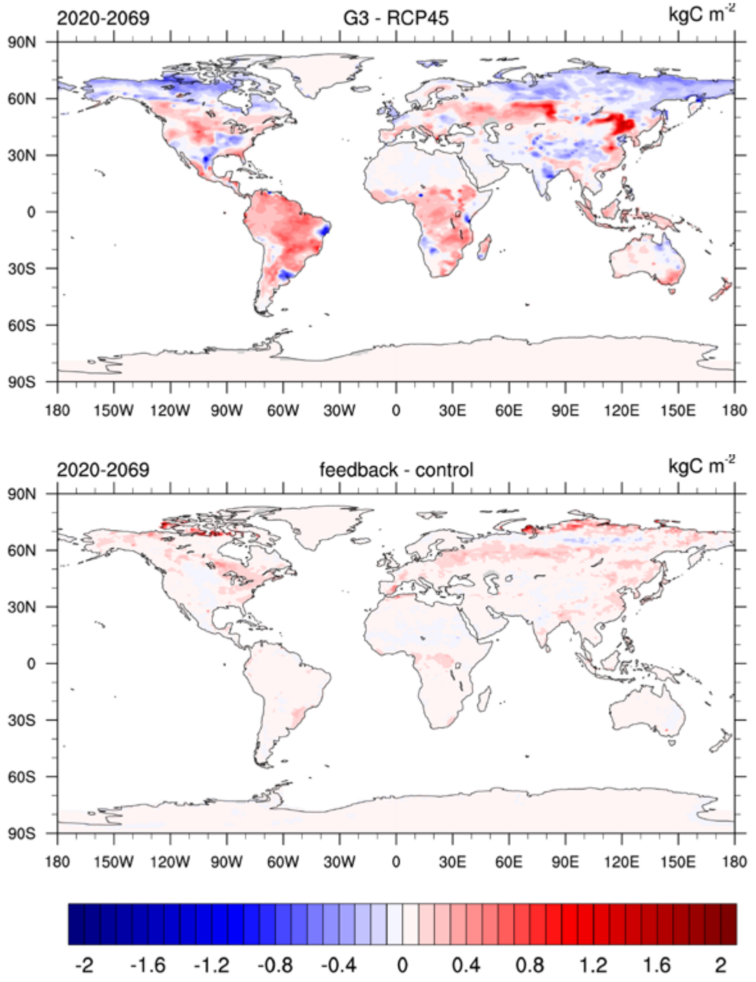


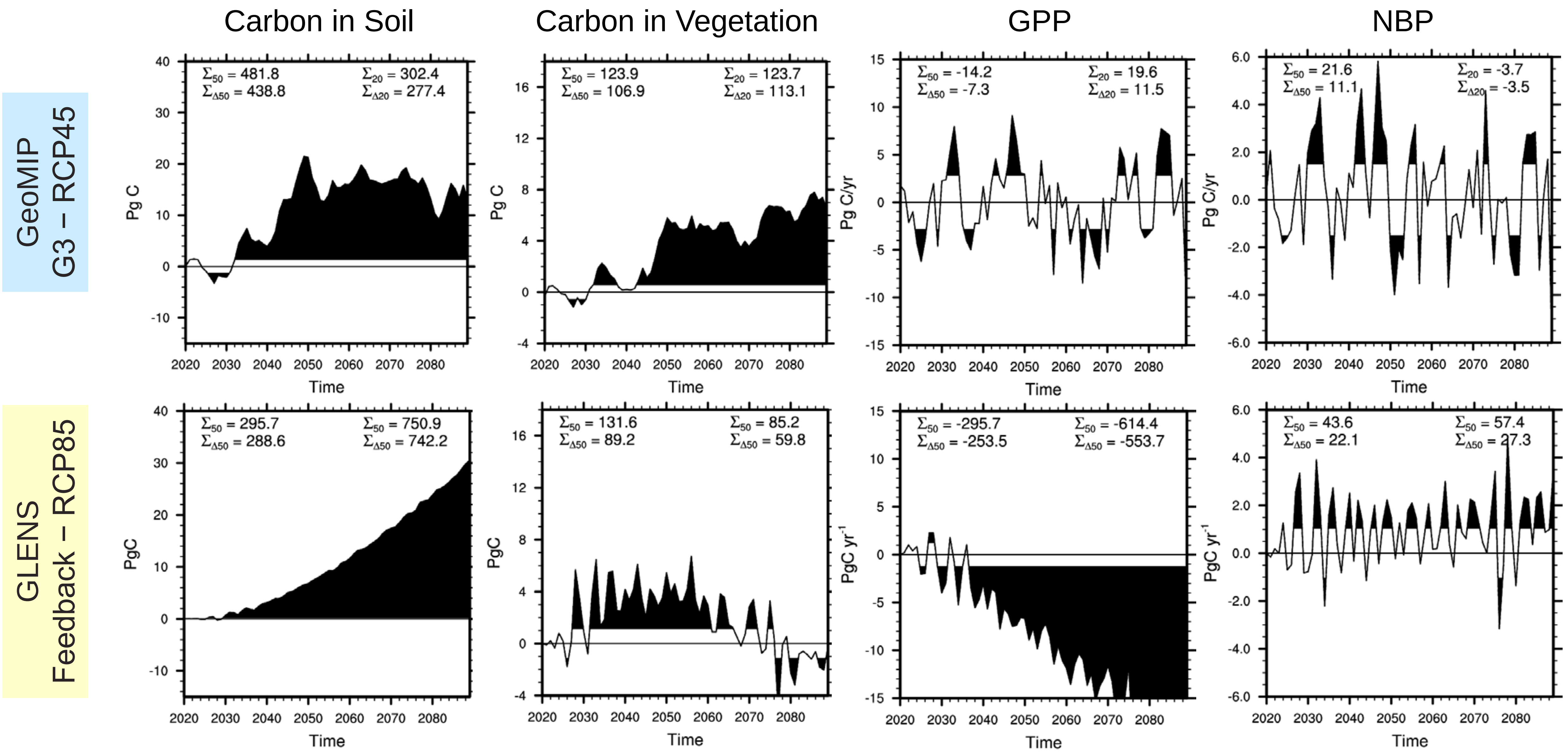

❖ Carbon in soil

- Similar spatial pattern as GPP in G3 (higher production)
- More litter in GLENS as a result of reduced production → reduced carbon in vegetation expected

Carbon in Soil



# GLB Terrestrial Ecosystem Responses



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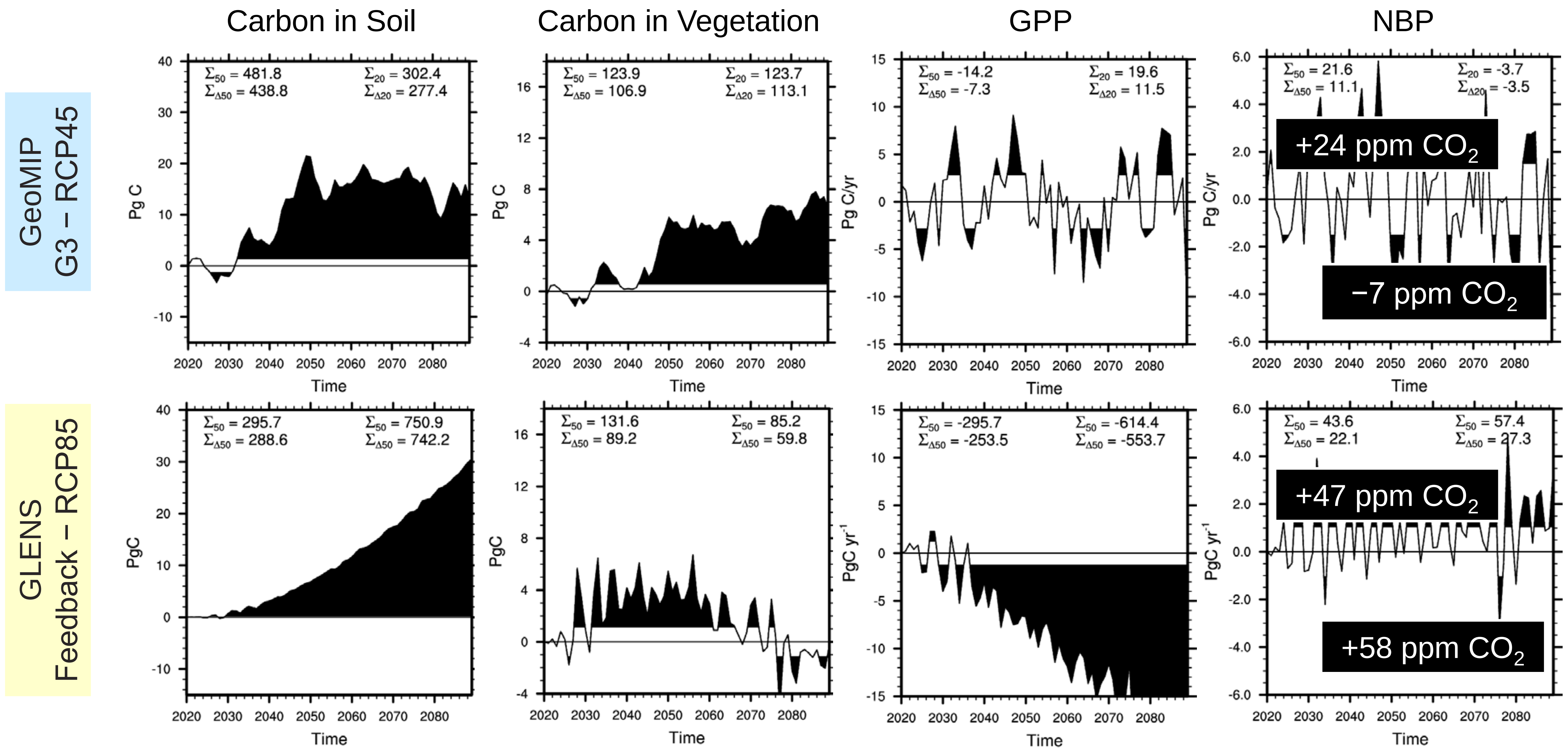
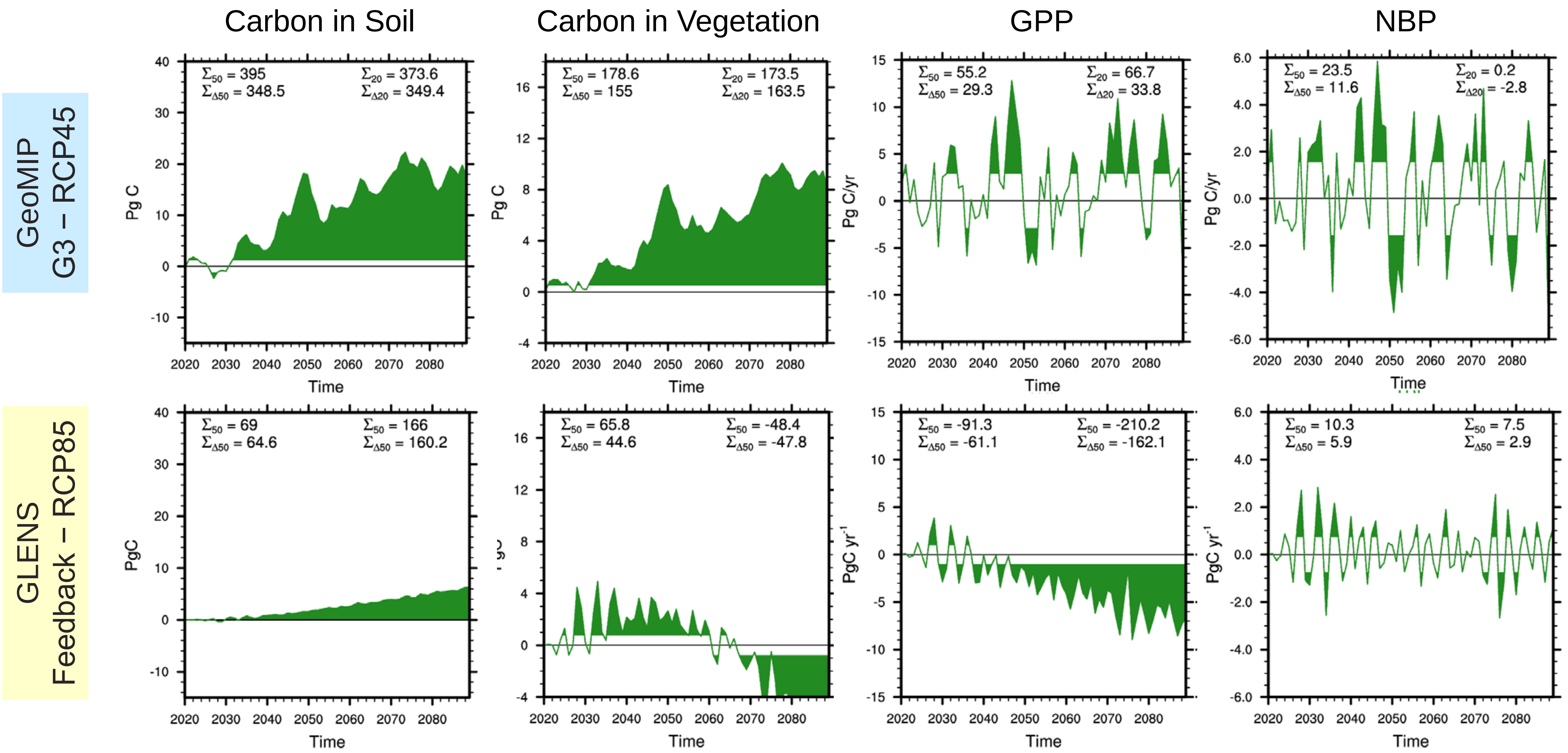


# TRP Terrestrial Ecosystem Responses



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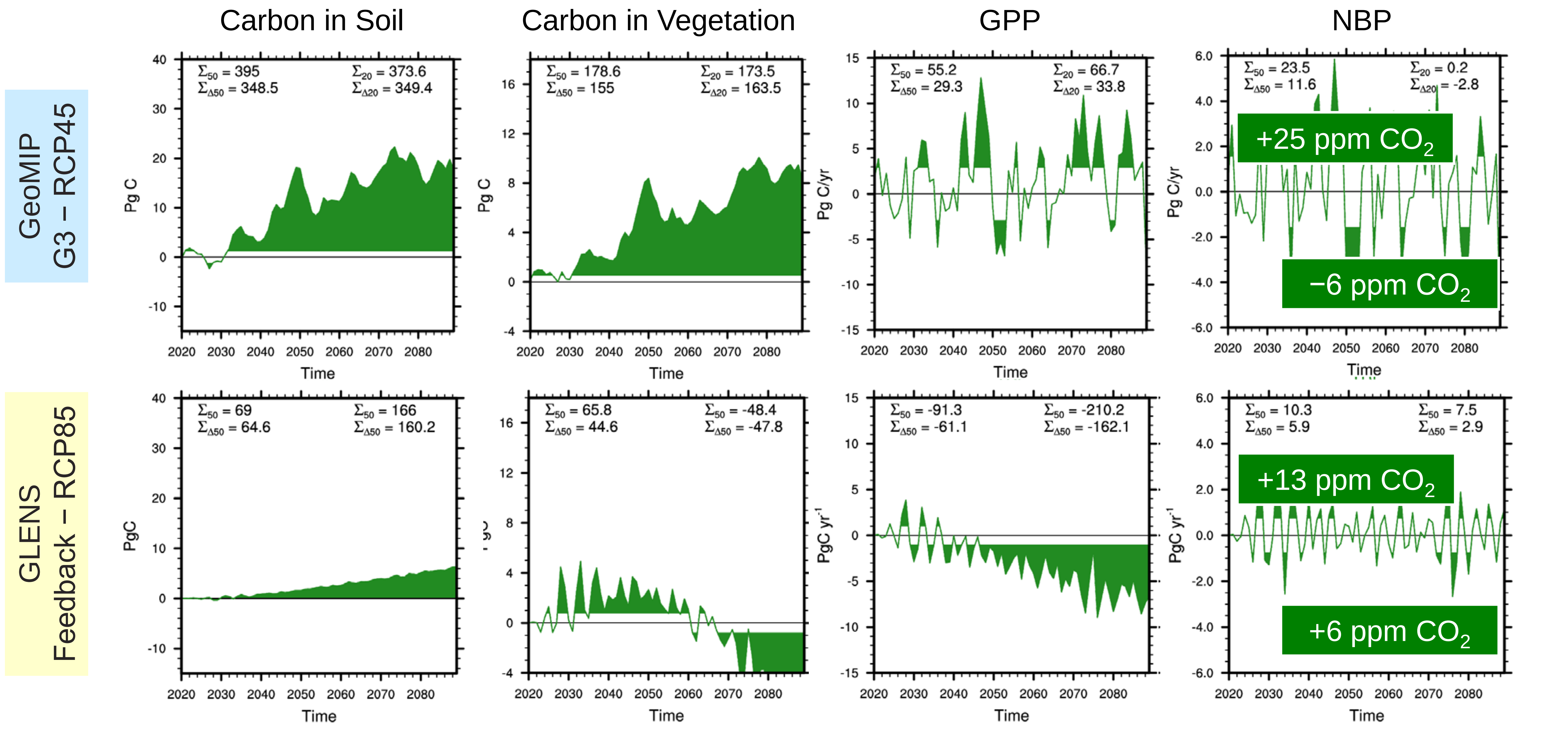
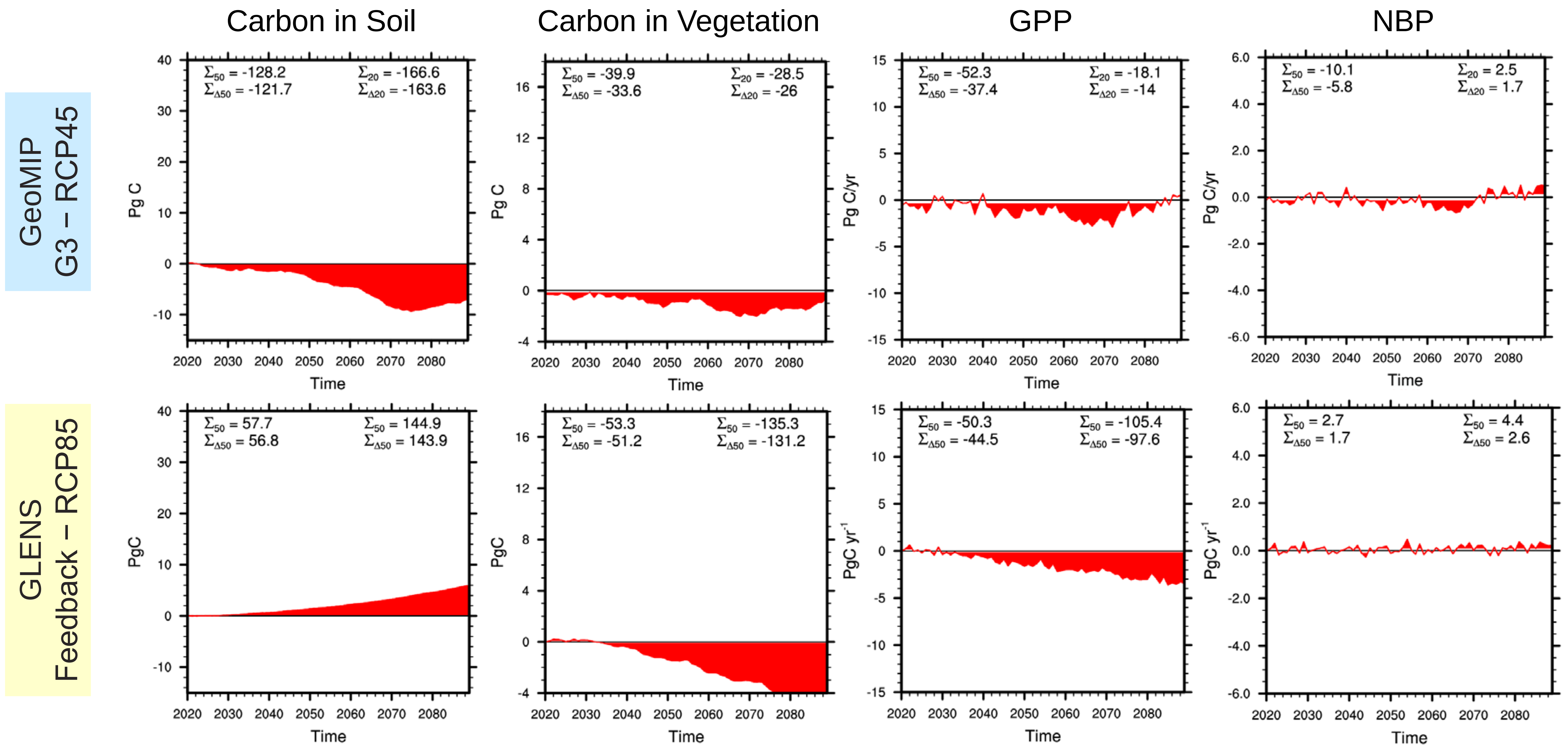


# NHP Terrestrial Ecosystem Responses



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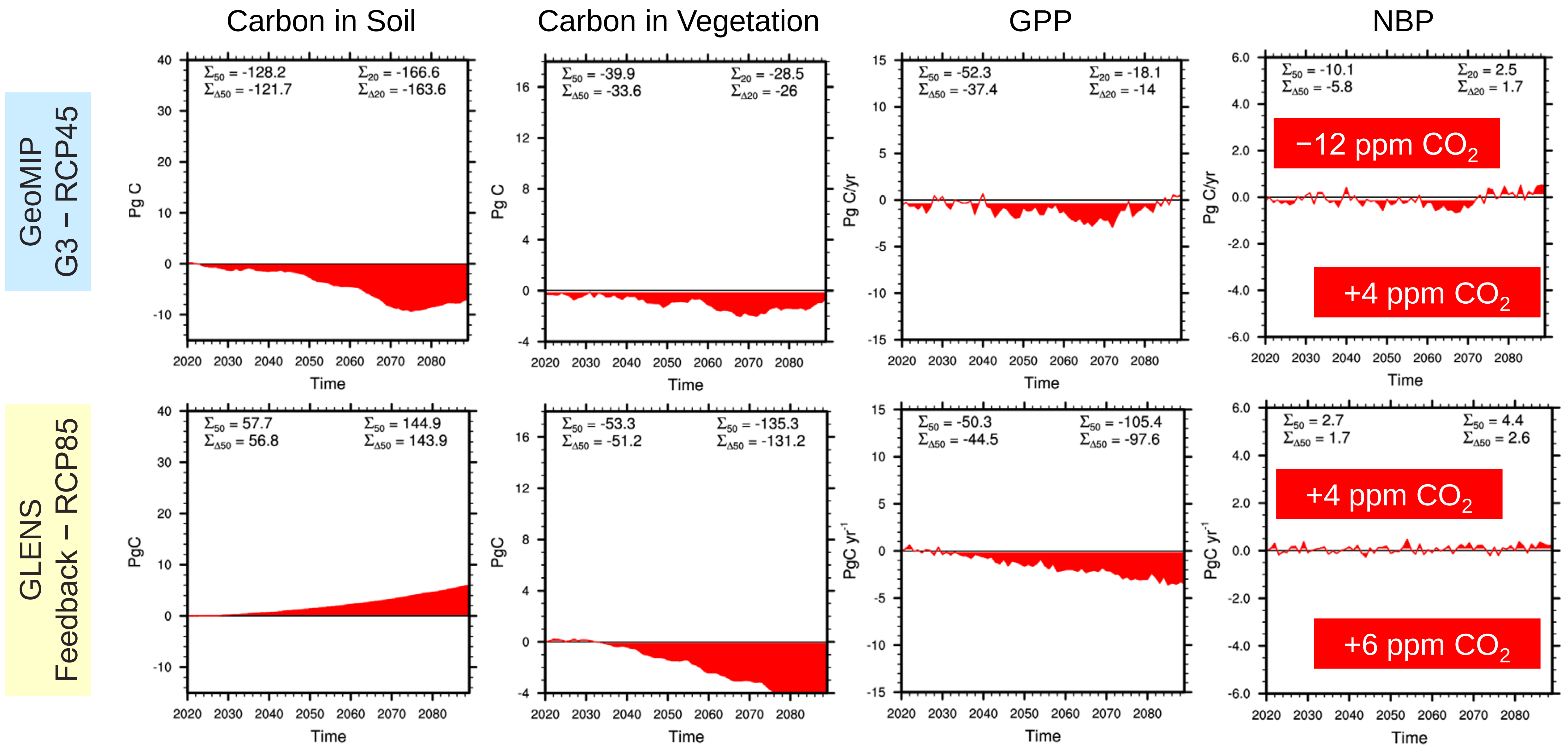


# Summary

- Responses of the terrestrial ecosystem to geoengineering
  - Remaining a ***carbon sink***
    - G3: +24 ppm $CO_2$ equivalent
    - GLENS: +47 ppm $CO_2$ equivalent
  - Fast BGC feedbacks return to RCP 4.5 conditions after sudden termination of geoengineering (G3)
  - Different RCP scenarios and aerosol injection strategies lead to different feedbacks
    - G3: ***weakened carbon sink strength*** in most regions except NHP
    - GLENS: ***enhanced carbon sink strength*** in most regions except TRP and SHM

# Summary

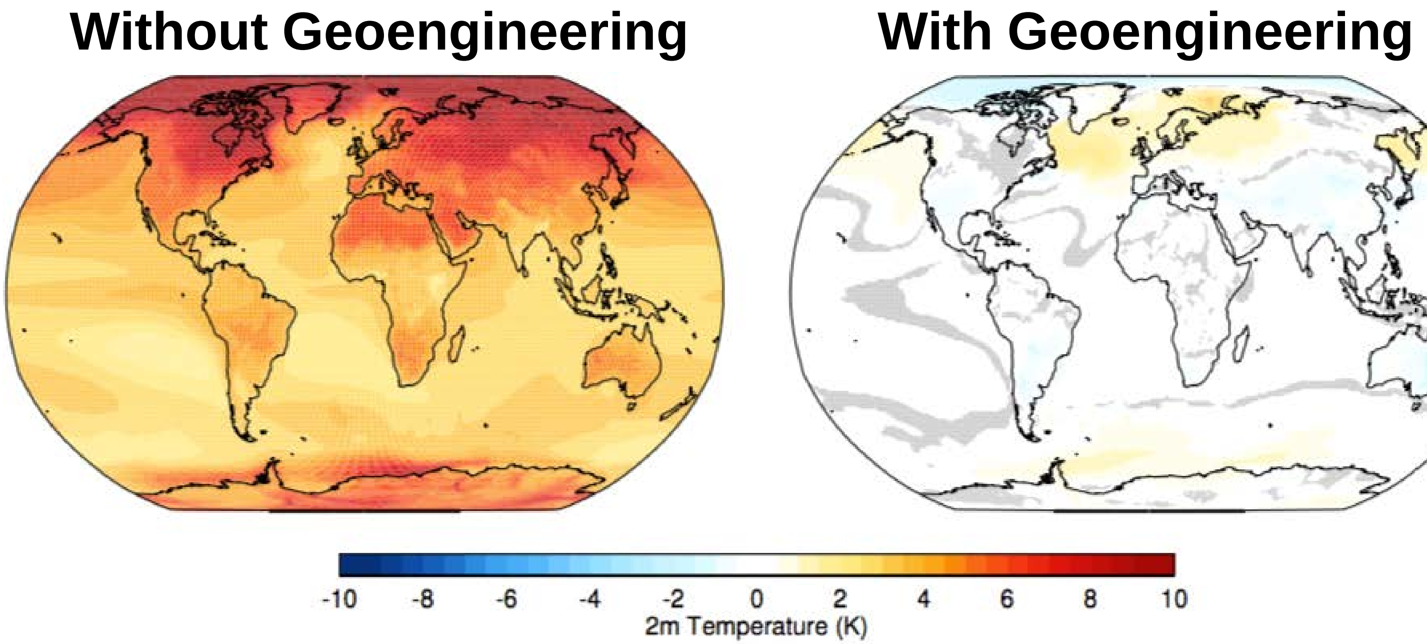
- ❖ Climate forcing – $CO_2$ concentration
  - Same $CO_2$ fertilization effect on BGC feedbacks between RCP8.5 and Feedback runs

    ➡ Simulations driven by $CO_2$ emissions

- ❖ Less aerosol injection is required when accounting for BGC feedbacks
- ❖ More analysis required for GLENS runs
- ❖ Ocean BGC feedbacks are not yet considered
- ❖ Future comparison of GeoMIP for CMIP6 models

# Geoengineering Large Ensemble (GLENS) Project

Surface Temperature Change
in 2075-2095 compared to 2010-2030




**Looking for community engagement to evaluate impacts & understand processes**

Core Team: Simone Tilmes (NCAR), Yaga Richter (NCAR), Ben Kravitz (PNNL)
Doug MacMartin (Cornell University), Michael Mills (NCAR)

NCAR

**http://www.cesm.ucar.edu/experiments/cesm1.2/GLE/**

NSF

# Acknowledgements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Caltech

# Thank You

# Question?