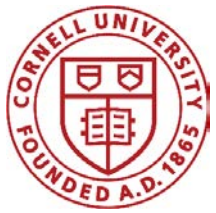


# Geoengineering is a Design Problem

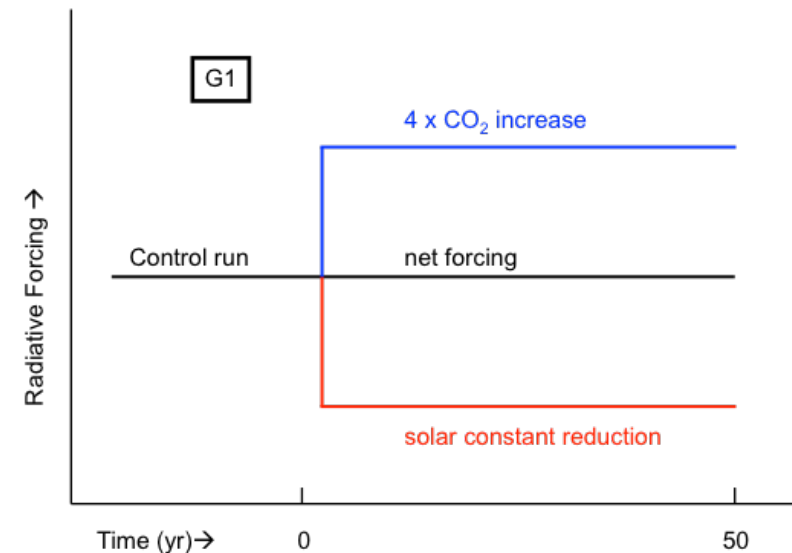
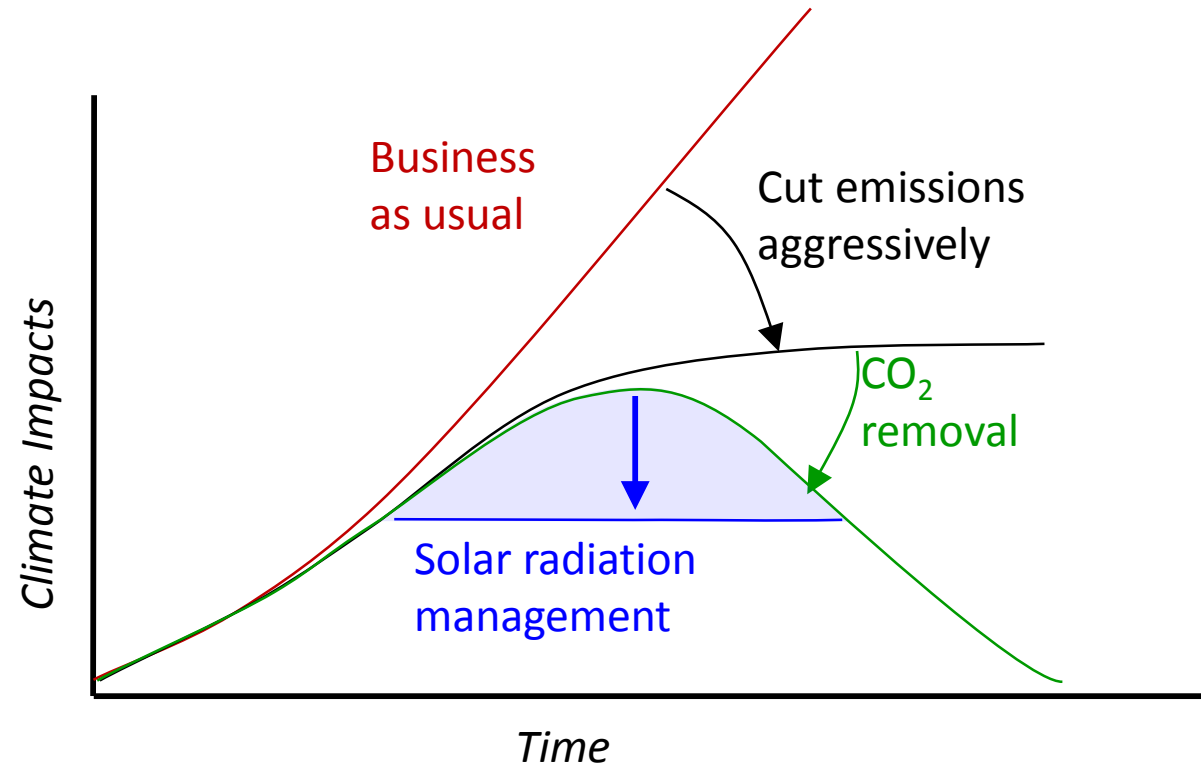
Douglas MacMartin (Cornell)

Based on collaboration with Ben Kravitz, Simone Tilmes, Jadwiga Richter,  
Mike Mills, and many others



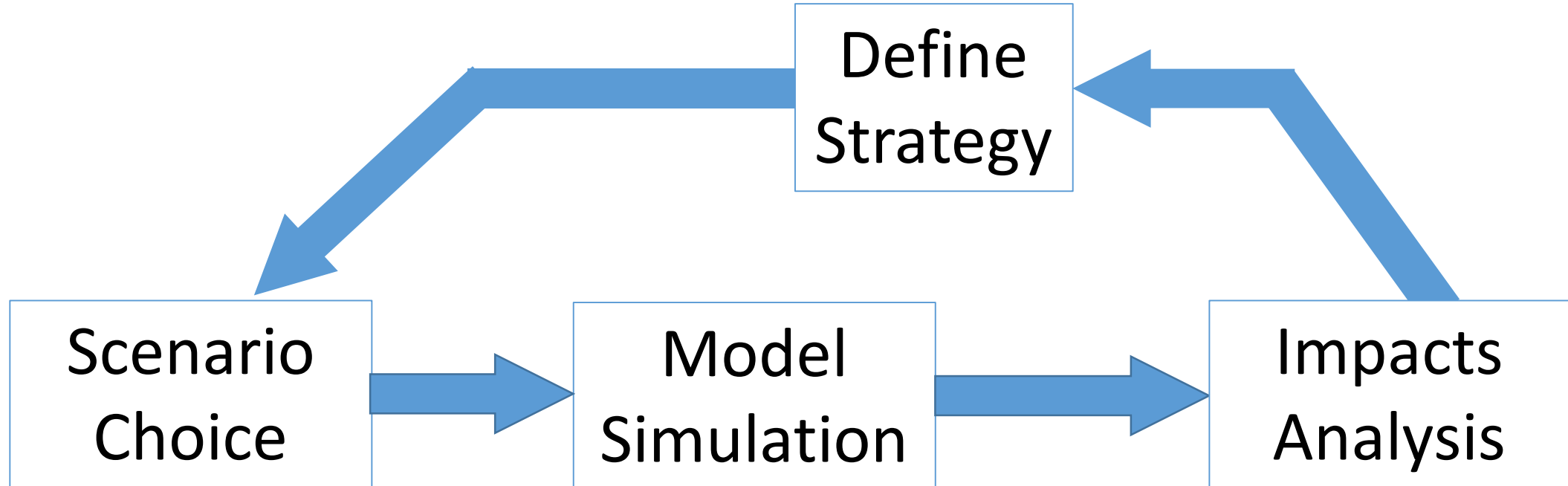
# Motivation

- Solar Geoengineering in *addition to* mitigation,
  - might reduce risks
  - more research needed to understand impacts
- Mitigation is necessary but not sufficient
  - Meeting 1.5°C without solar geoengineering is unrealistic
- Impacts of *limited* solar geoengineering in comparison to not using geoengineering?





# My talk in one slide





# Impacts depend on implementation

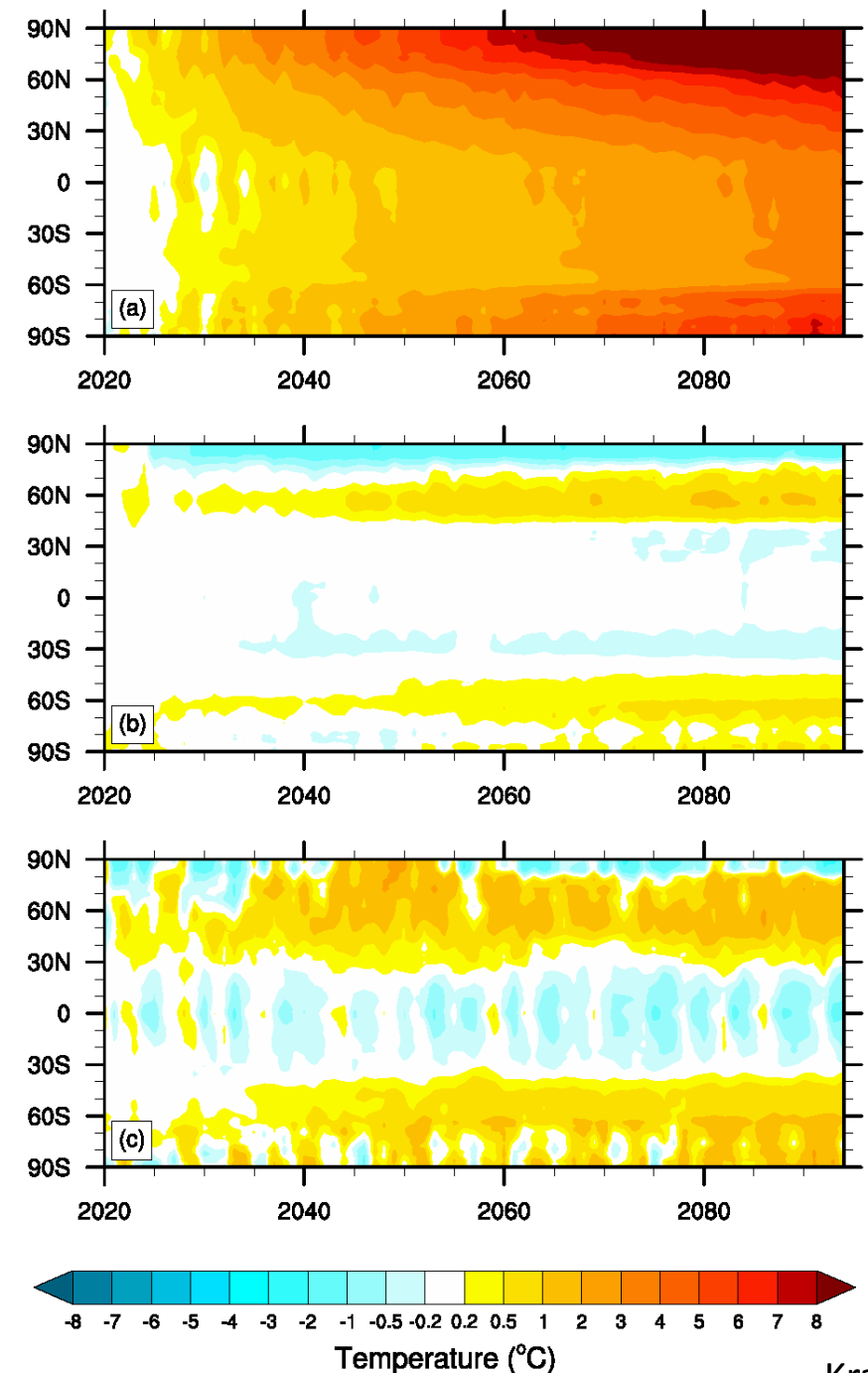
- How much?
  - E.g.,  $3^{\circ}\text{C} \rightarrow 1.5^{\circ}\text{C}$  is different from  $3^{\circ}\text{C} \rightarrow 0^{\circ}\text{C}$
- What latitude to inject stratospheric aerosols (or precursors)?
  - Most simulations conducted with equatorial or tropical injection
  - Choose injection amount in each hemisphere to maintain ITCZ
  - Injecting at higher latitudes preferentially increases aerosol loading at higher latitudes
- Season of injection?
- Altitude?
- Composition?
  - Sulfate heats lower stratosphere (changing dynamics) and impacts ozone chemistry
  - Other materials would have different effects...

} Manage  
temperature  
gradients



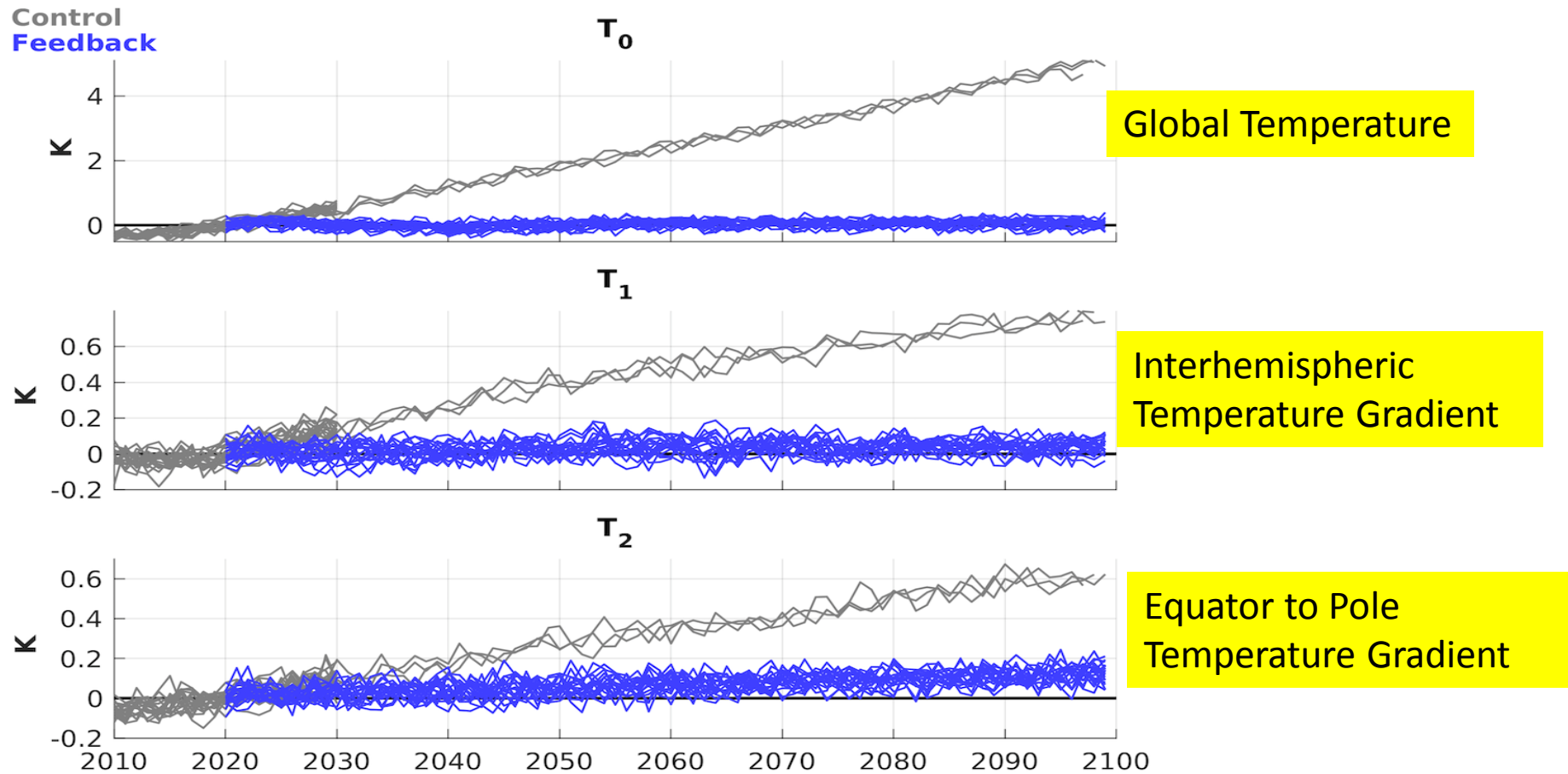
# Simulations with stratospheric aerosols

- Zonal mean temperature with
  - No geoengineering
  - Equatorial  $\text{SO}_2$  injection to maintain global mean temperature (bottom)
  - $\text{SO}_2$  injection at 30S, 15S, 15N, 30N, maintaining
    - Global mean temperature
    - Interhemispheric gradient
    - Equator to pole gradient





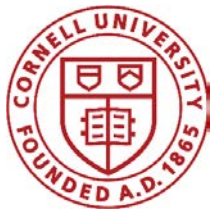
# Large Ensemble Geoengineering Simulations



20-Member Ensemble, RCP8.5 pathway

20 Control simulations 2010-2030 (references period), 3 going up to 2099

20 Geoengineering simulations 2020-2099

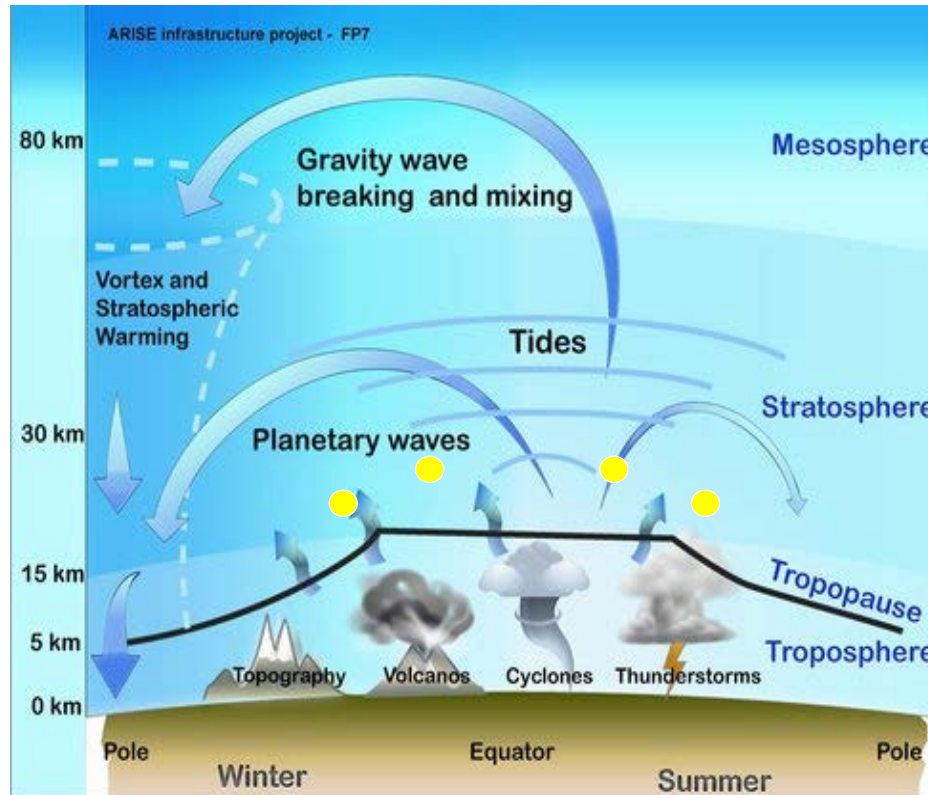


# The future...

- What are the robust projected impacts?
- Which of those are unavoidable?
- Which might be influenced by a different deployment strategy?
- What are the inherent trade-offs?
- What can geoengineering do, and what can it not do?



# NCAR Whole Atmosphere Community Climate Model



CESM(WACCM):

- 0.9 x 1.25° horizontal resolution
- 140 km top of model
- 70 vertical layers
- Interactive Quasi-Biannual Oscillation (QBO)
- Modal aerosol model
- Prognostic volcanoes and aerosol microphysics
- Full stratospheric chemistry
- Coupling to ocean, ice, land

System Identification:

Single Injection Matrix (42 experiments) for SO<sub>2</sub> injections:

Identify correlation between injection locations and temperature response

Best combination: 30N/30S, 15N/15S; 5 km above the tropopause

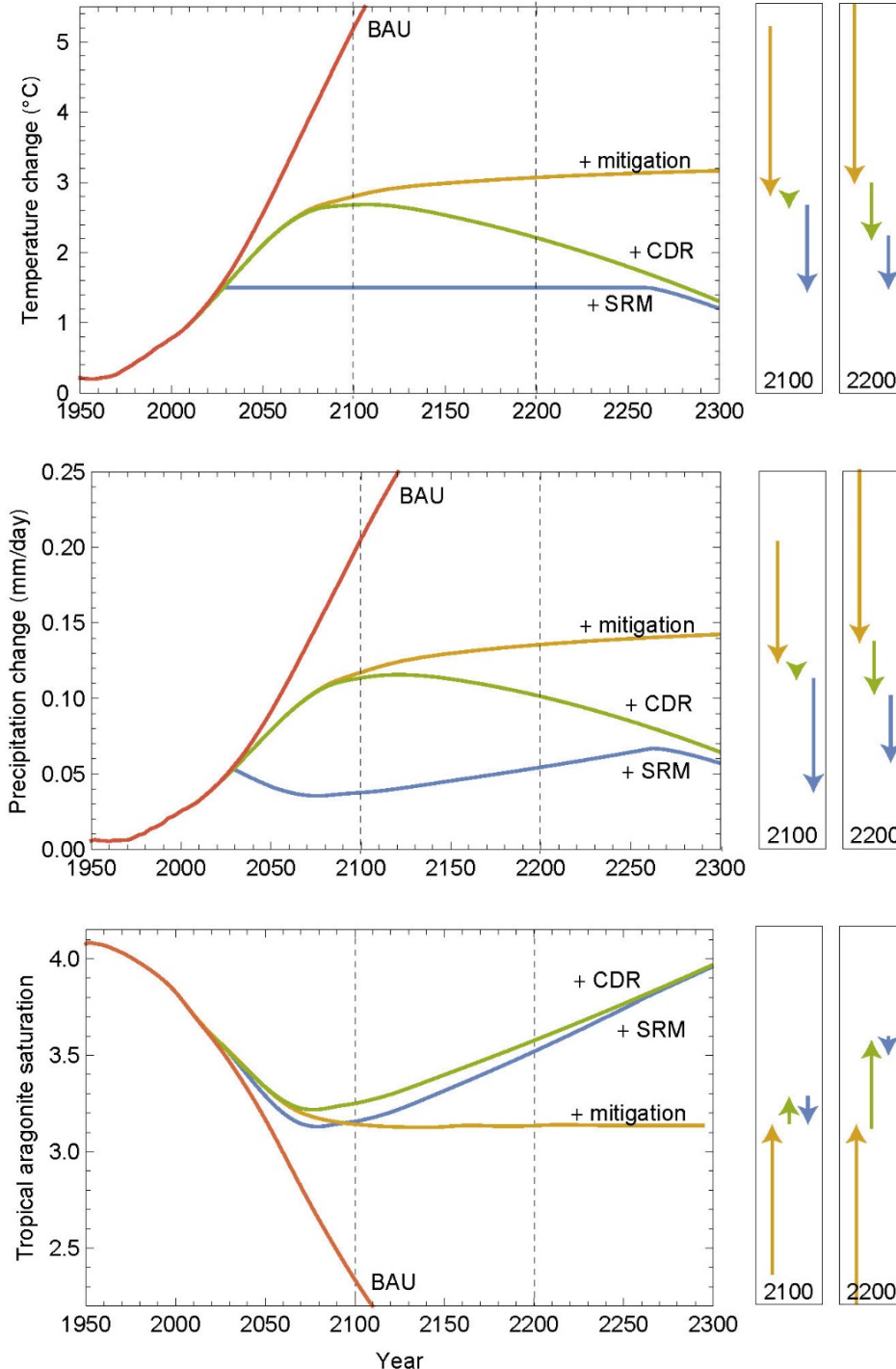
*Mills et al., 2017, Tilmes et al., 2017, MacMartin et al, 2017, Richter et al, 2017*

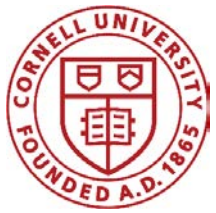




# Emulated Response\*

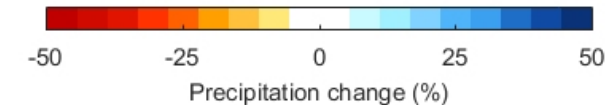
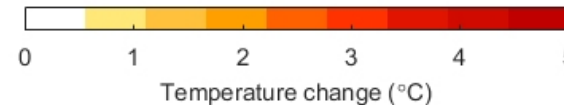
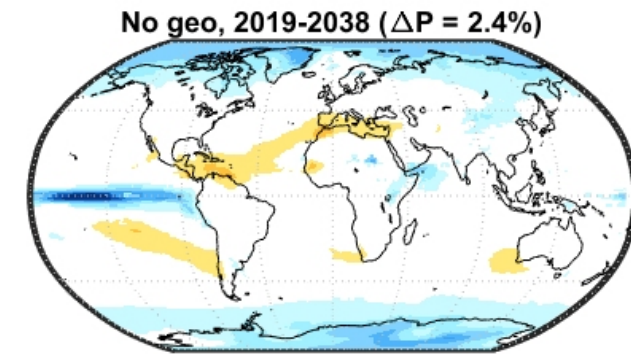
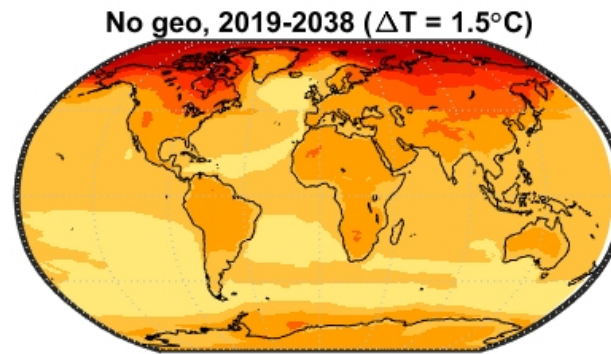
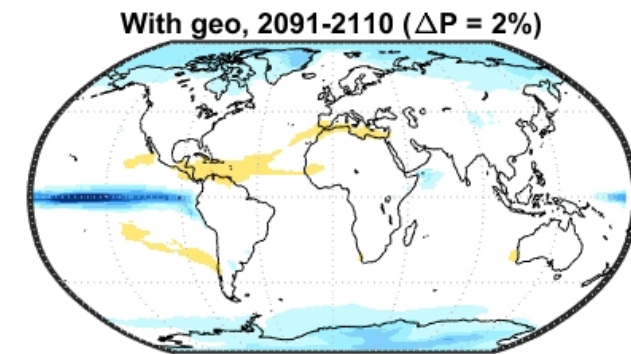
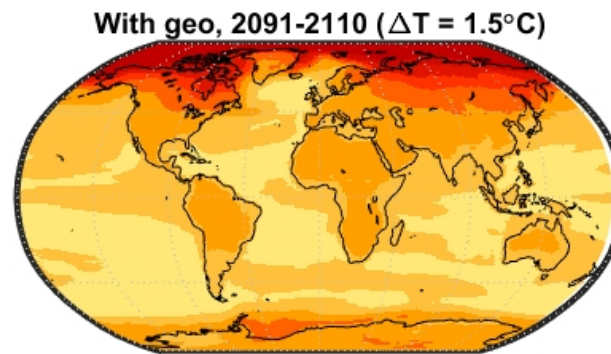
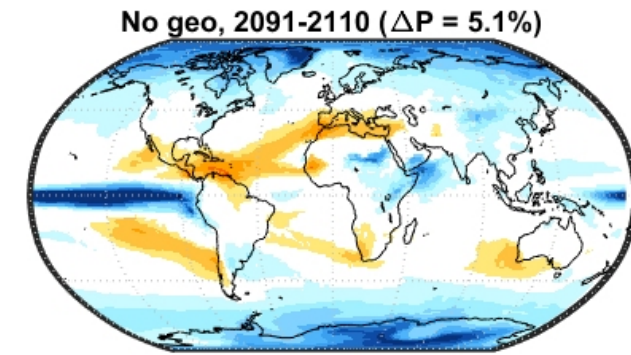
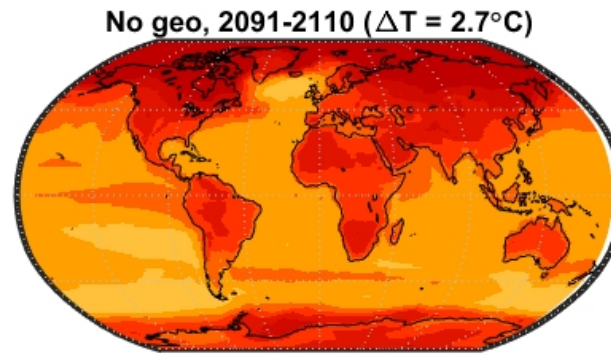
- If solar engineering maintains temperature,
- Global mean precipitation is proportionally closer to preindustrial
  - If SRM compensates 100% of temperature (as in G1), will over-compensate precip.
- Some variables (e.g. tropical aragonite saturation) are relatively unchanged with SRM
  - This ignores carbon cycle feedbacks (reducing temperature enhances sinks)





# Spatial response

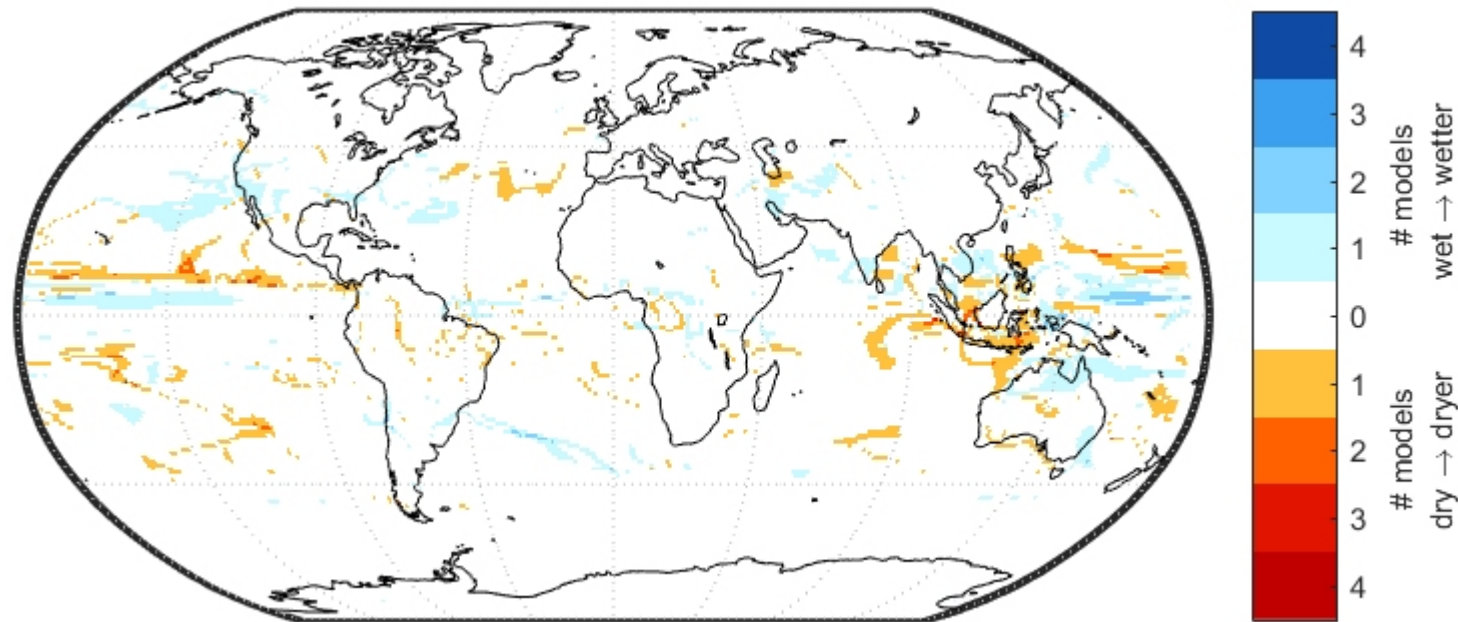
- Median over 12 models
- Response projected onto 4 EOFs





# Does SRM make climate worse?

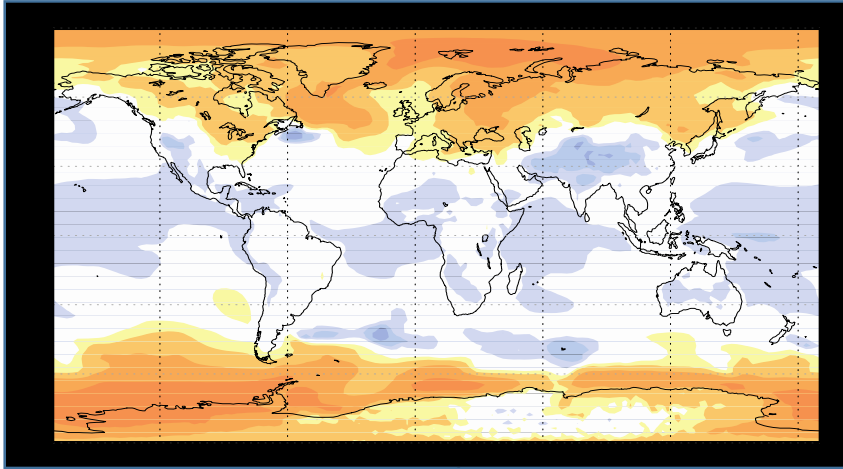
- One metric someone might care about:
  - Places where CO<sub>2</sub> makes climate wetter, and SRM makes wetter still, or
  - Where CO<sub>2</sub> decreases precipitation, and SRM decreases it further
  - And where the change is statistically significant over 20 years



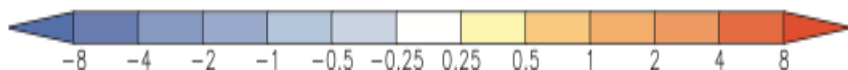
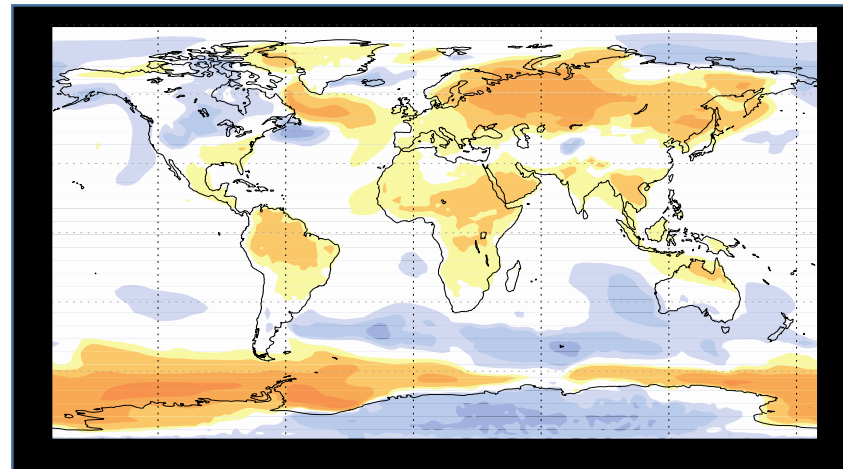


# New Strategies to Reduce Side Effects and Risks

Global dimming



Strategic geoengineering



## New Approach:

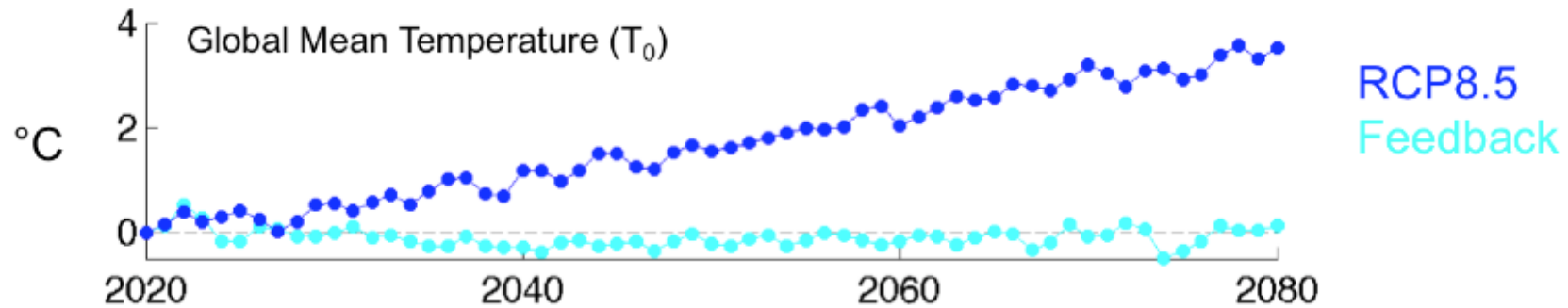
1. Set climate goals to reduce side effects
2. Design experiment, e.g. choose multiple injection locations
3. Run feedback control to manage variability and uncertainty
4. Examine side effects, set new goals
5. Independent verification using a different model





# Feedback-Controlled Simulation with CESM(WACCM)

Goal: keep climate at 2020 conditions using stratospheric SO<sub>2</sub> injections



- Use feedback algorithm to identify amount and location of annual injection of SO<sub>2</sub>
- Prior knowledge of emissions scenario or climate sensitivity not required

