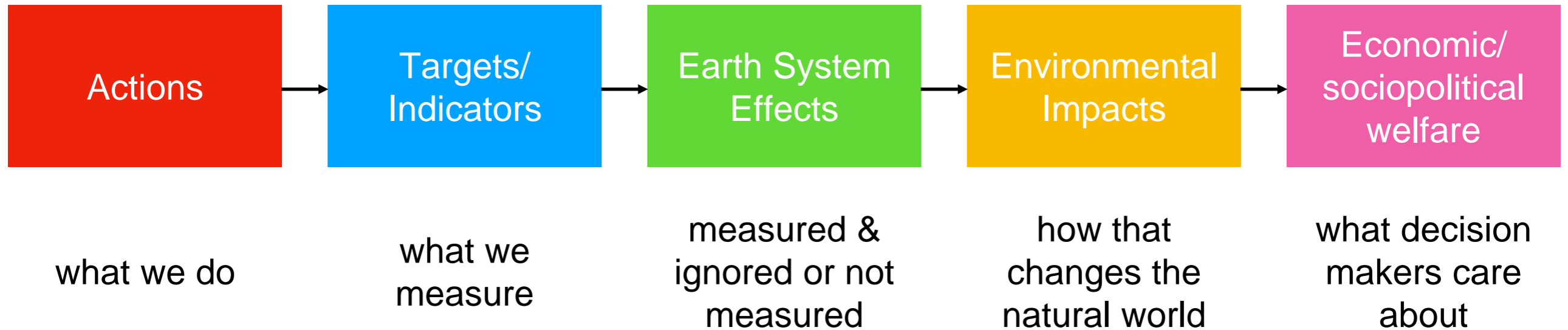


Impossible problems in solar geoengineering impacts assessment?

(prospects for better understanding uncertainty, damage
and how they interact)

Kate Ricke
UC San Diego

Getting to what “we” care about



- emit GHGs
- cut down forests
- block sunlight

- radiation balance
- CO₂ concentrations
- global mean surface temperature
- precipitation

- soil moisture
- permafrost melt
- ocean alkalinity

- coral reef bleaching
- air pollution

- GDP
- lives lost
- refugees trying to get into my country

History (mine) of trying to estimate socioeconomic impacts of solar geoengineering

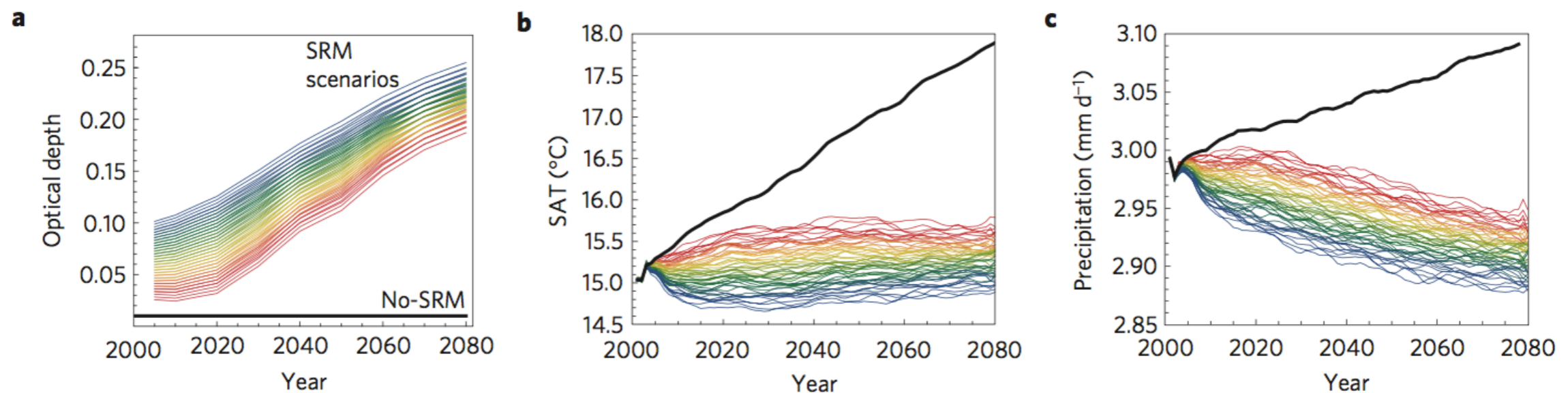
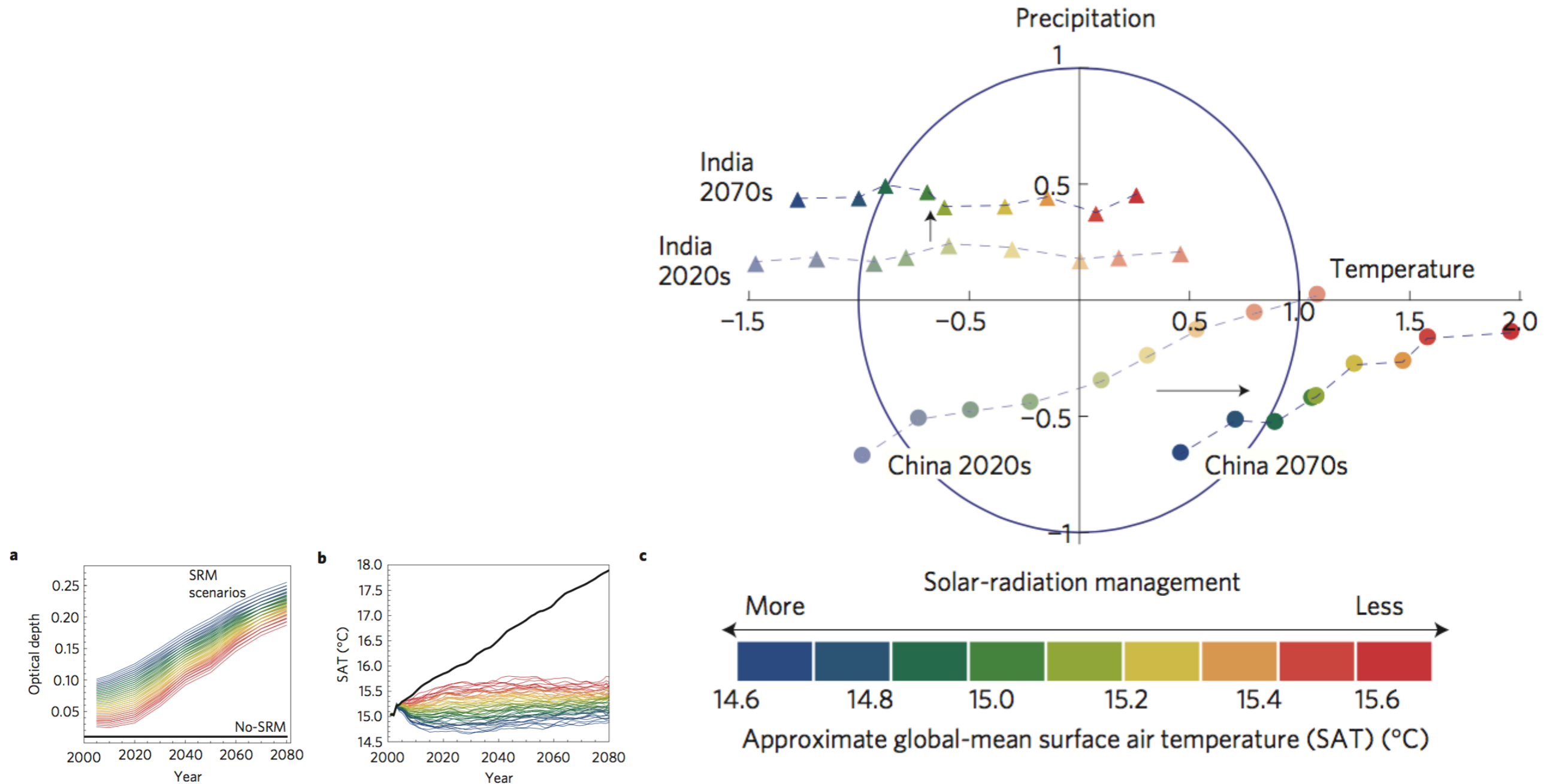


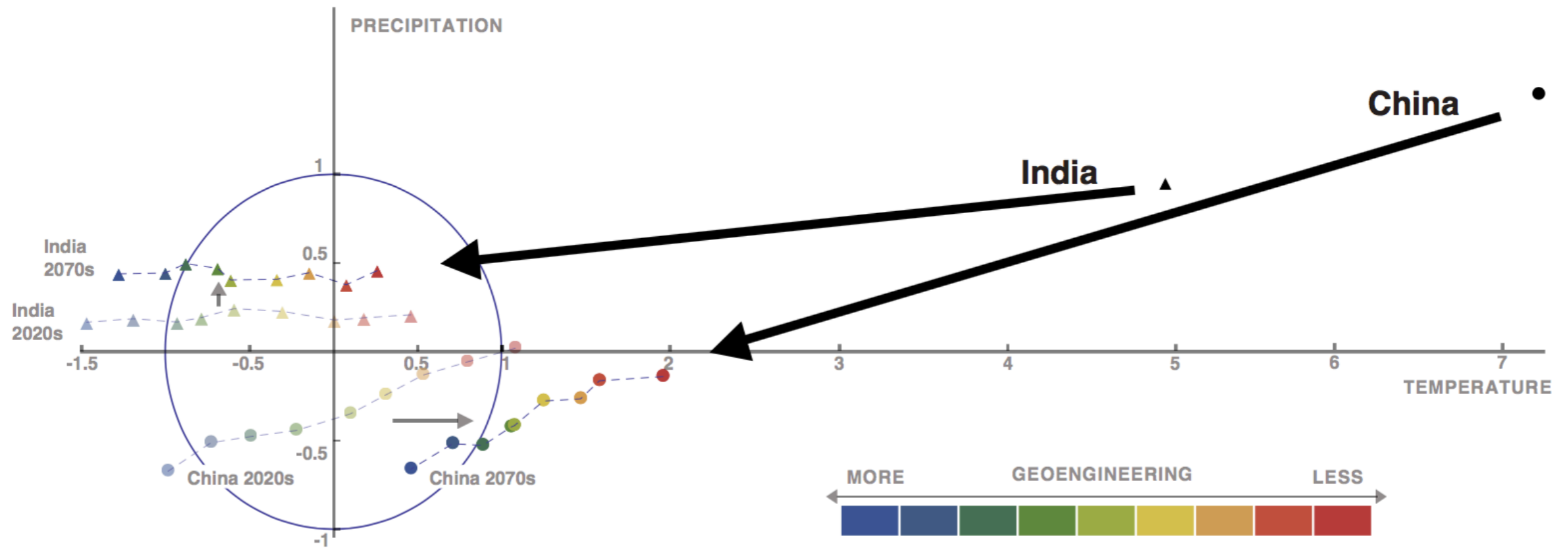
Figure 1 | Time series of global optical depth, temperature and precipitation of the 54 scenarios examined. a-c, SRM and no-SRM scenarios (a), five-year average global-mean near-surface (1.5 m) air temperature (b) and five-year average global-mean precipitation rate (c), all displayed over the length of the 80-model-year simulations.

History (mine) of trying to estimate socioeconomic impacts of solar geoengineering

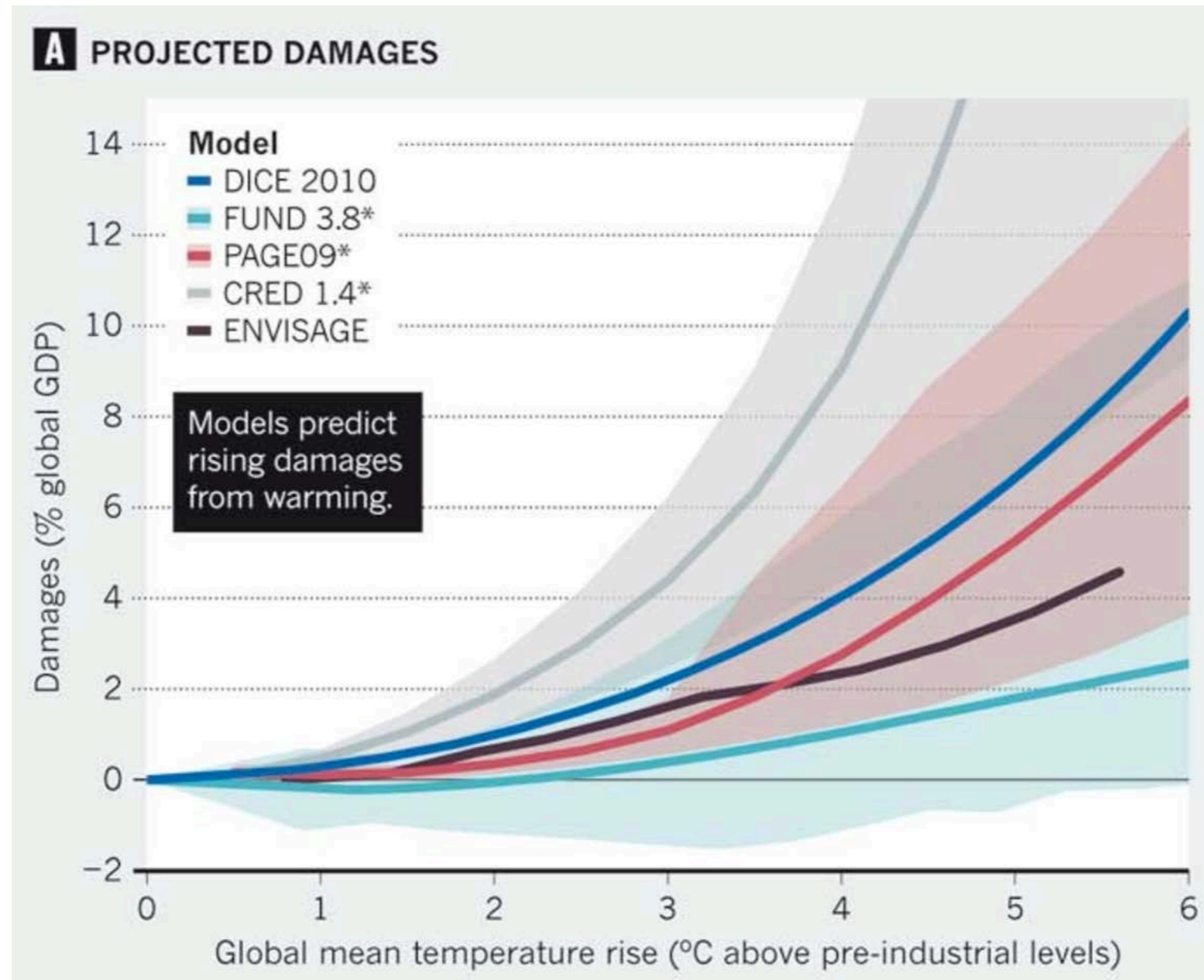


Ricke, Allen & Morgan (2010)

What does it mean for impacts?



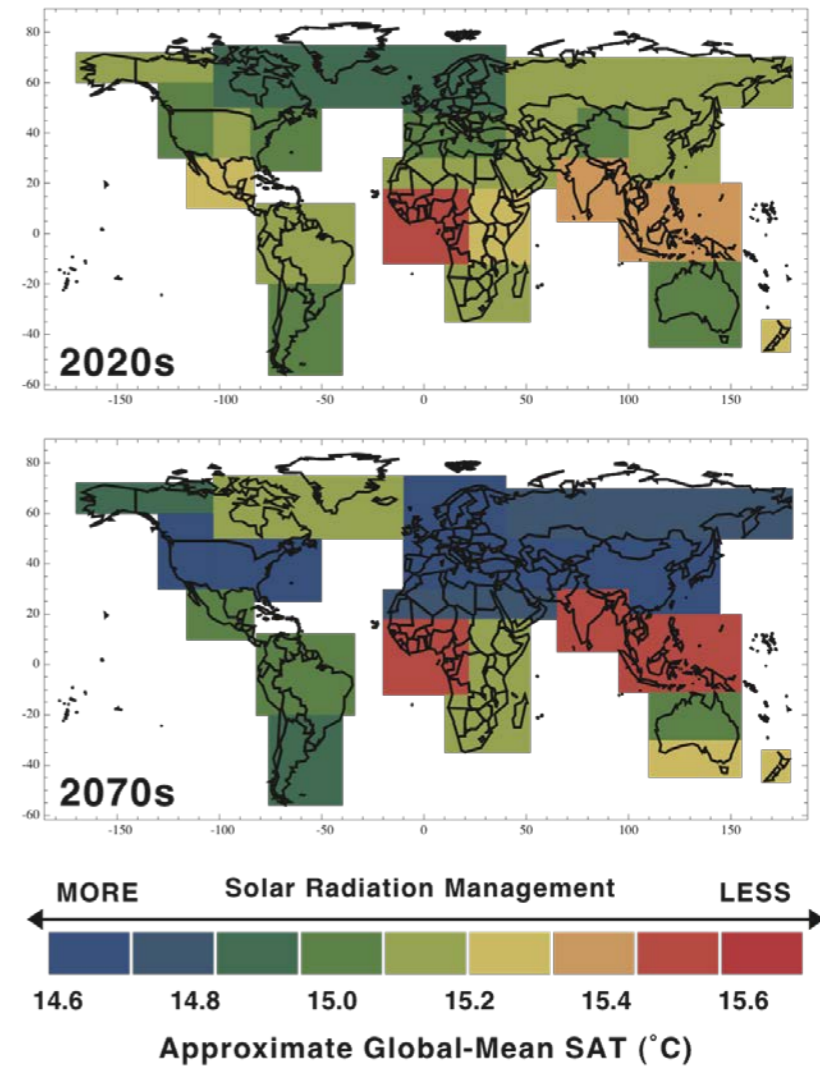
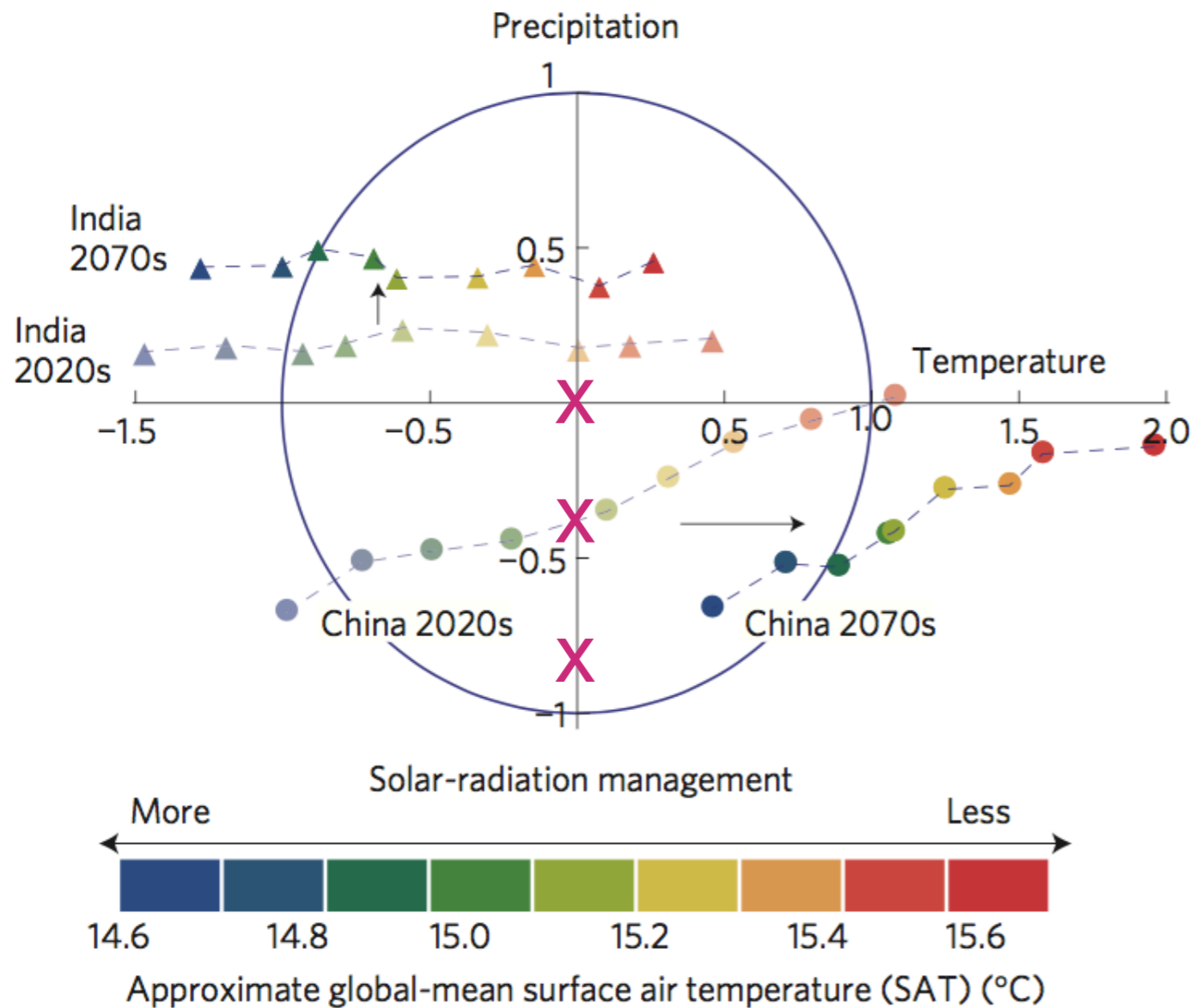
Temperature-based damage functions



“The bottom line here is that the damage functions used in most IAMs are completely made up, with no theoretical or empirical foundation”

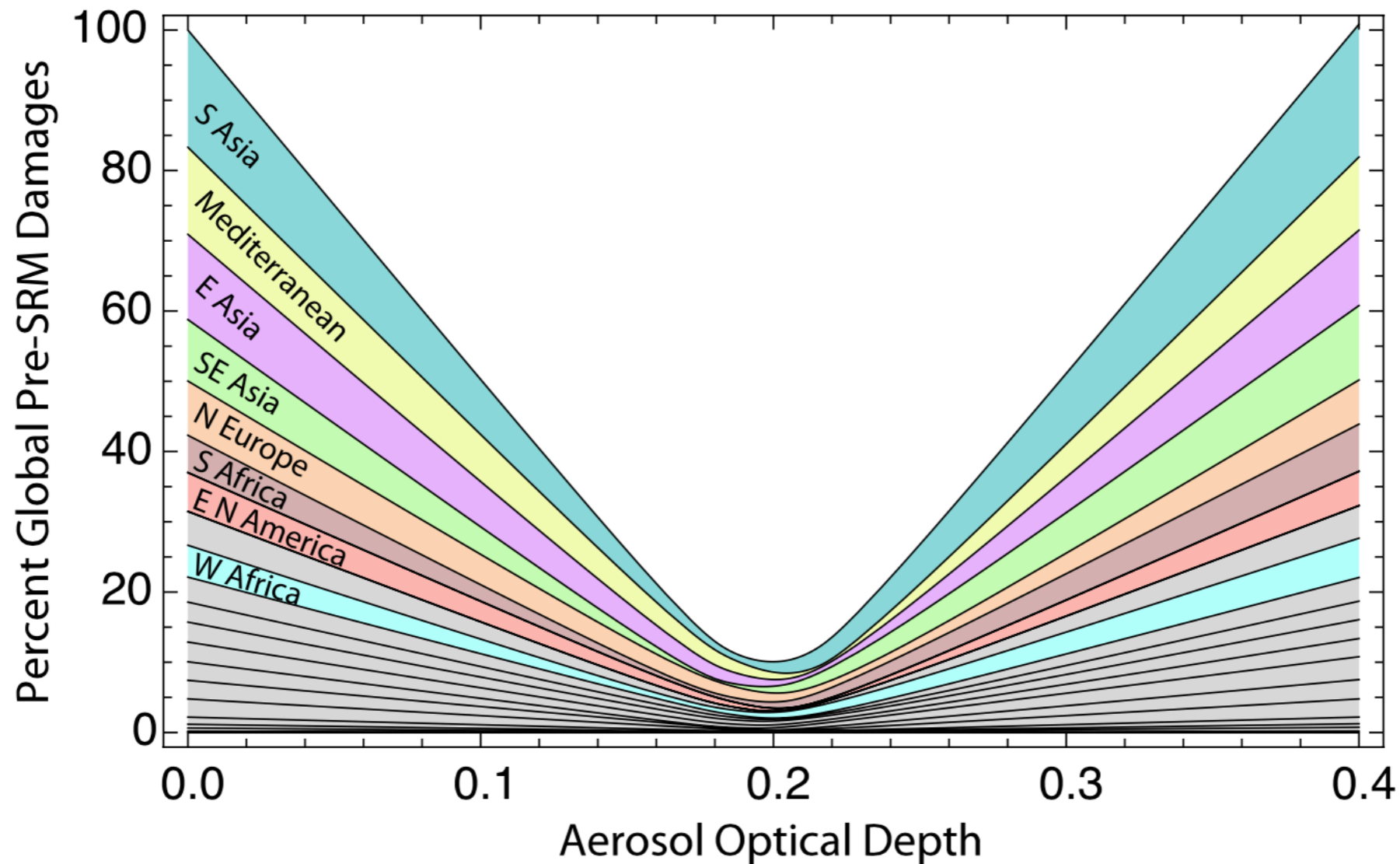
- Pindyck (2013)

Many different futures and we can't tell their implications for damage apart



Ricke, Allen & Morgan (2010)

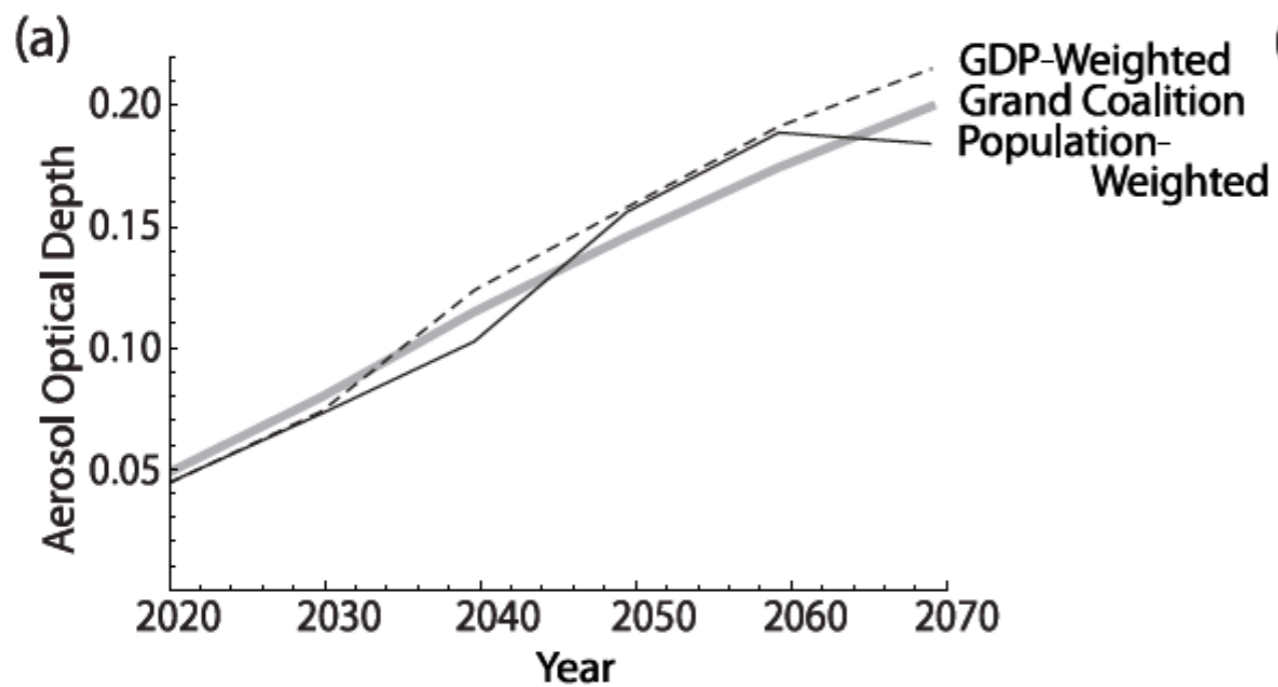
Making up our very own damage function



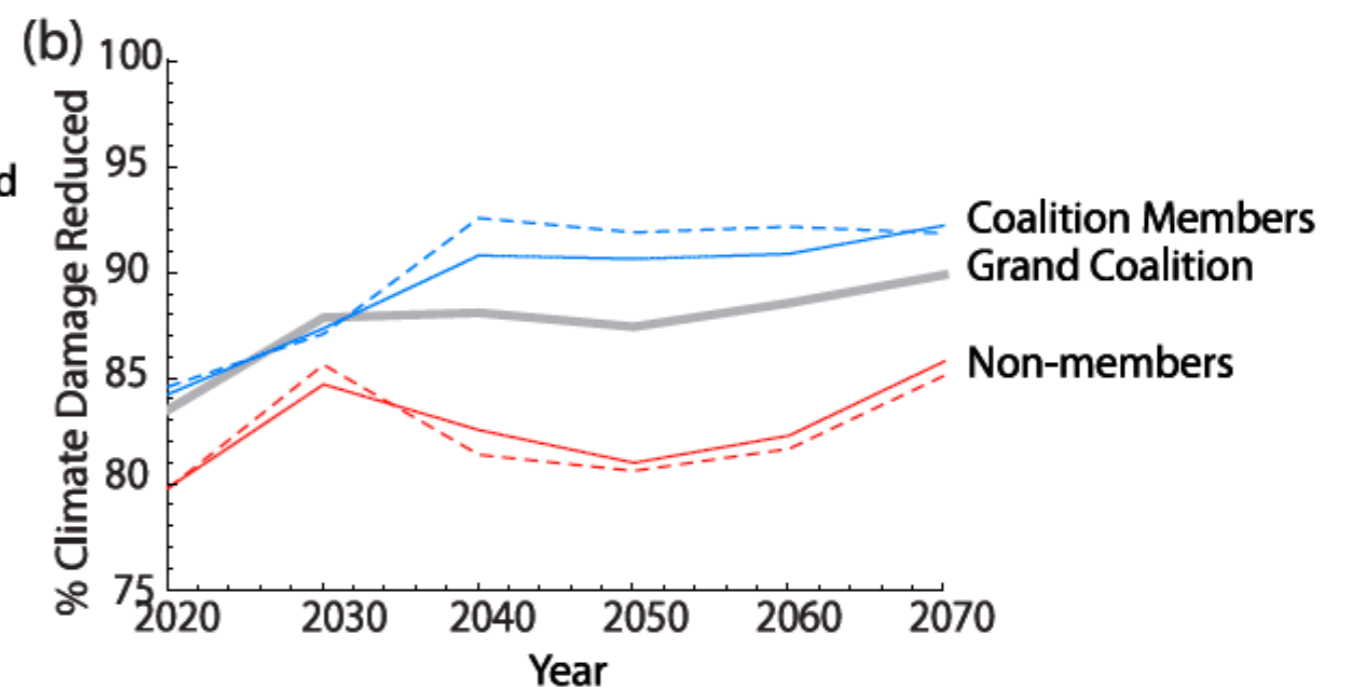
Ricke, Moreno-Cruz & Caldeira (2013)

Making up our very own damage function

Amount of SG



Damage reduction



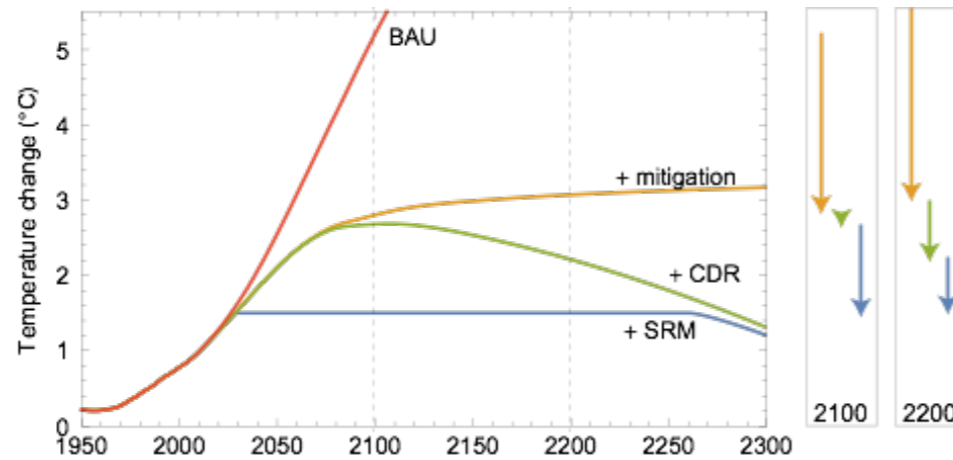
Ricke, Moreno-Cruz & Caldeira (2013)

Why this problem is so hard

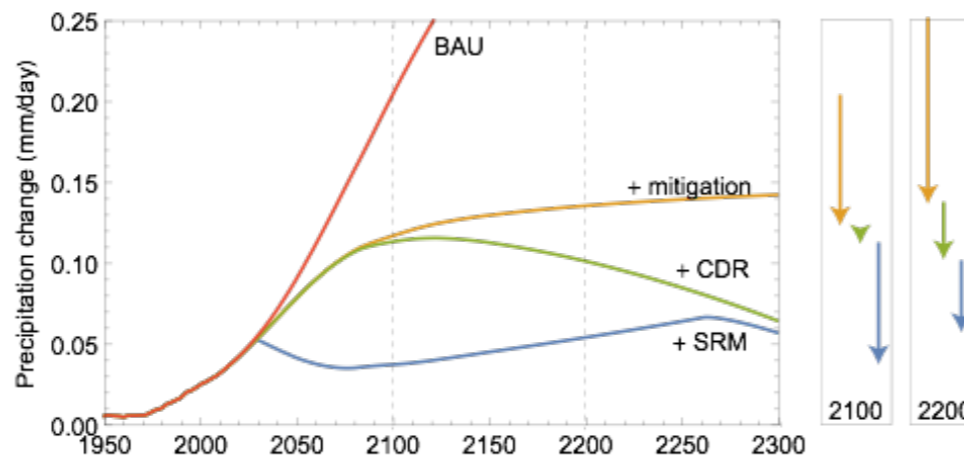
1. Conventional correlates become decoupled
2. Nonlinearity keeps increasing with socioeconomic relevance
3. Lack of “laws of economics” makes mechanistic models untenable
4. Attempt to control for the most important factors driving socioeconomic change (fixed effects) may be scooping up things that are very much climatologically relevant

The decoupling problem

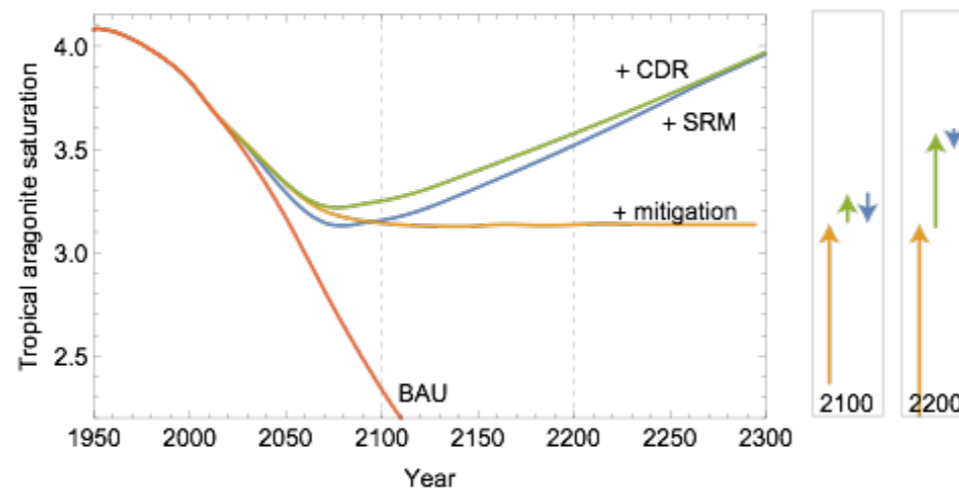
warming



hydrology



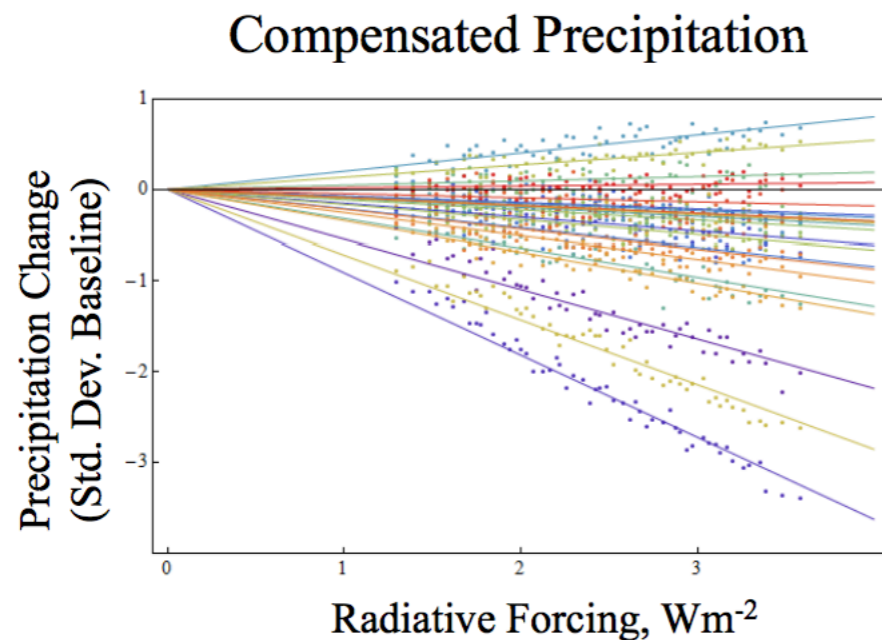
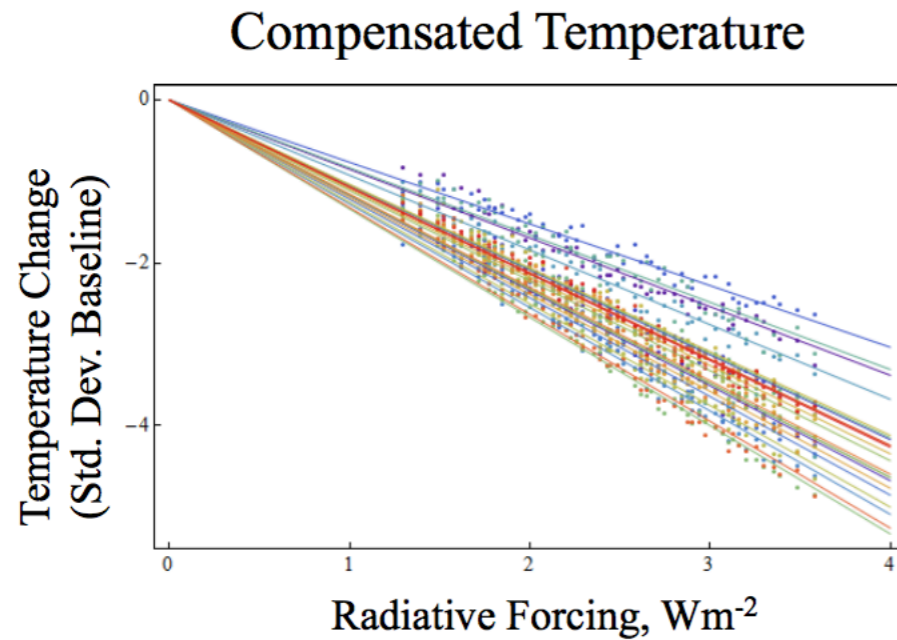
ocean acidification



Restoration of temperature precipitation and ocean chemistry is not proportional.

MacMartin, Ricke & Keith (2018)

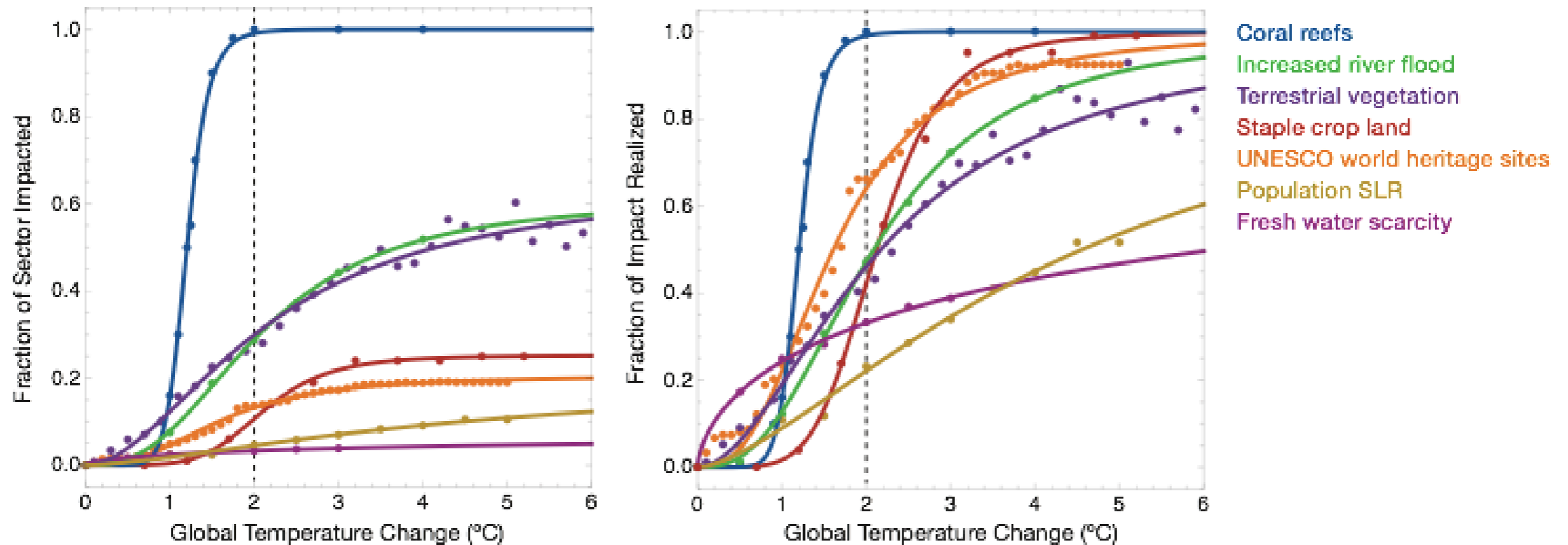
Problem: Nonlinearity increasing with socioeconomic relevance



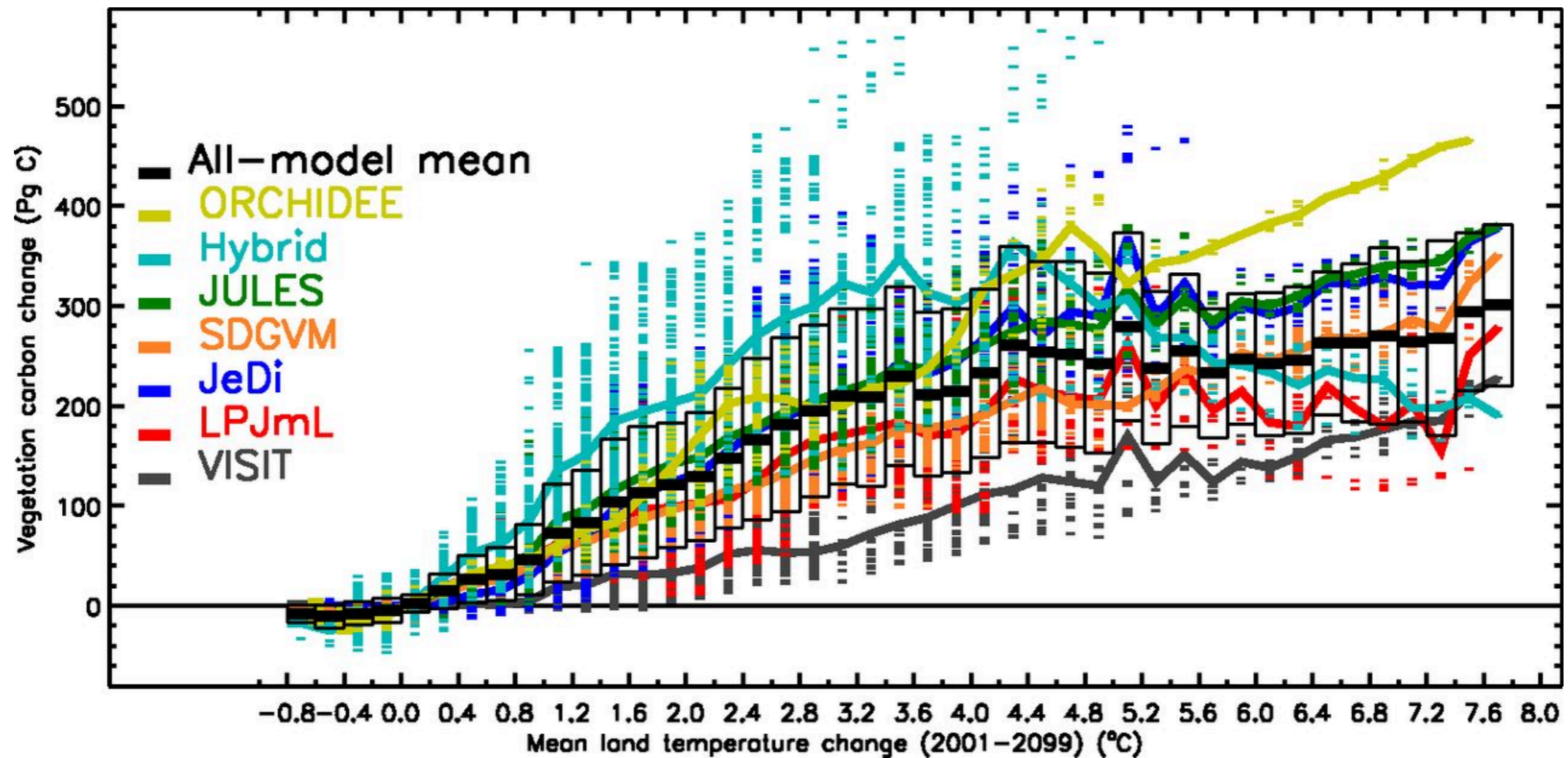
There are many nice linearities in our indicators

Moreno-Cruz, Ricke & Keith (2011)

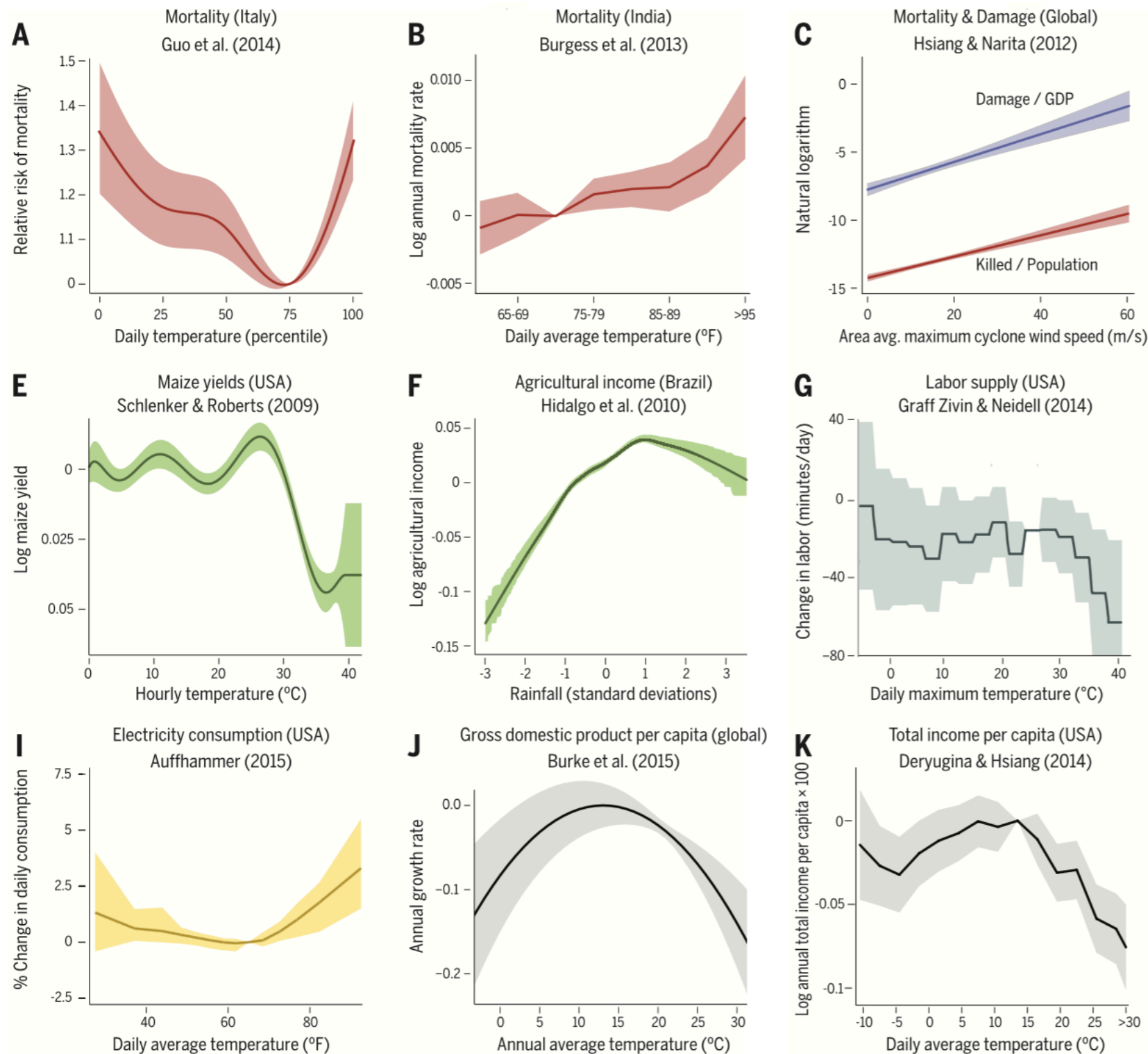
Non-linearities in impacts (perhaps surmountable)



Mechanistic effects/impacts model results



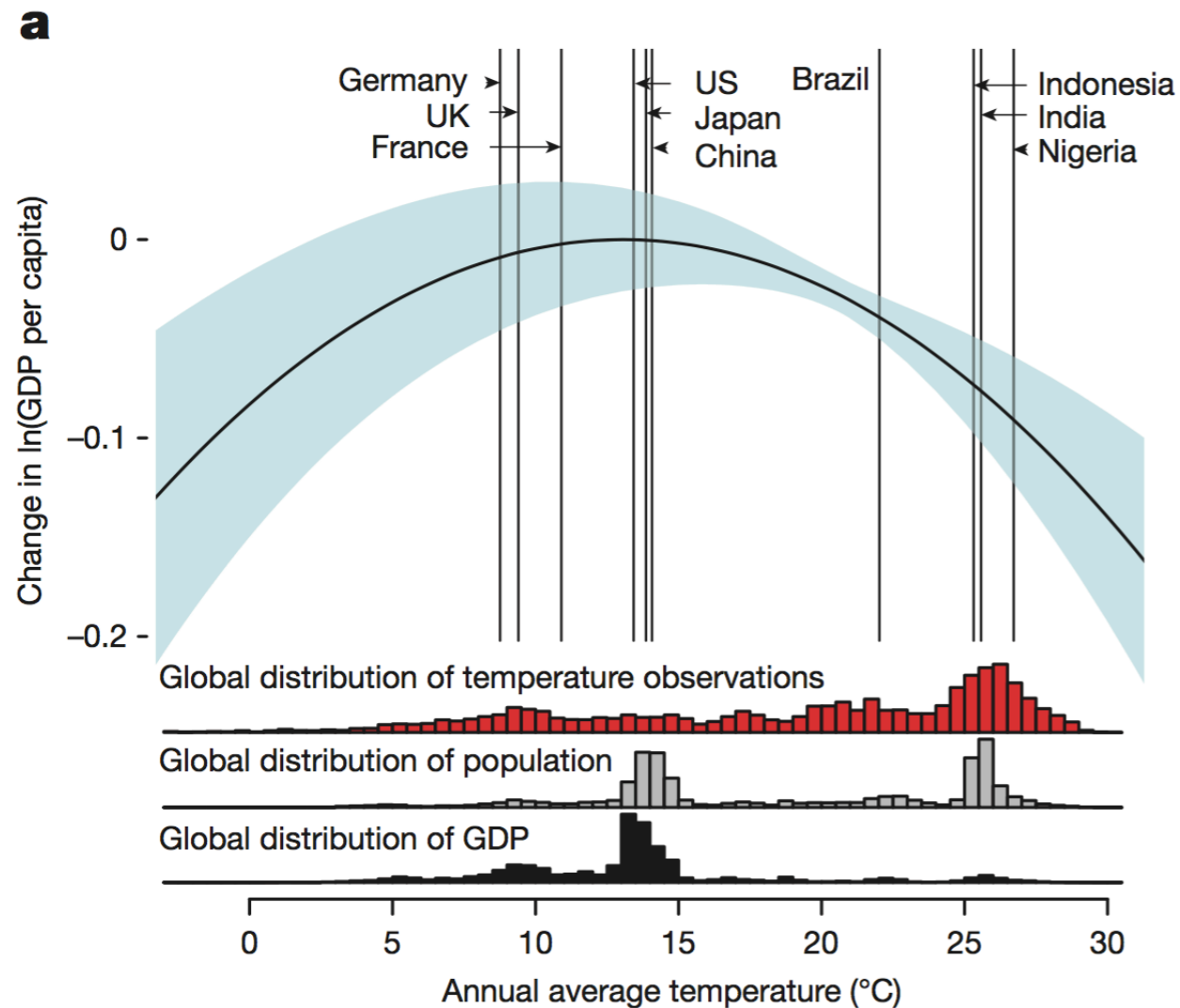
State-of-the-art socioeconomic impacts assessment



results from empirical statistical models

Carelton & Hsiang (2016)

Example: Burke et al (2015)



- high profile
- well-done
- illustrative of our problem
- AND at least a couple of projects working to apply this damage function to solar geoengineering

Burke, Hsiang & Miguel (2015)

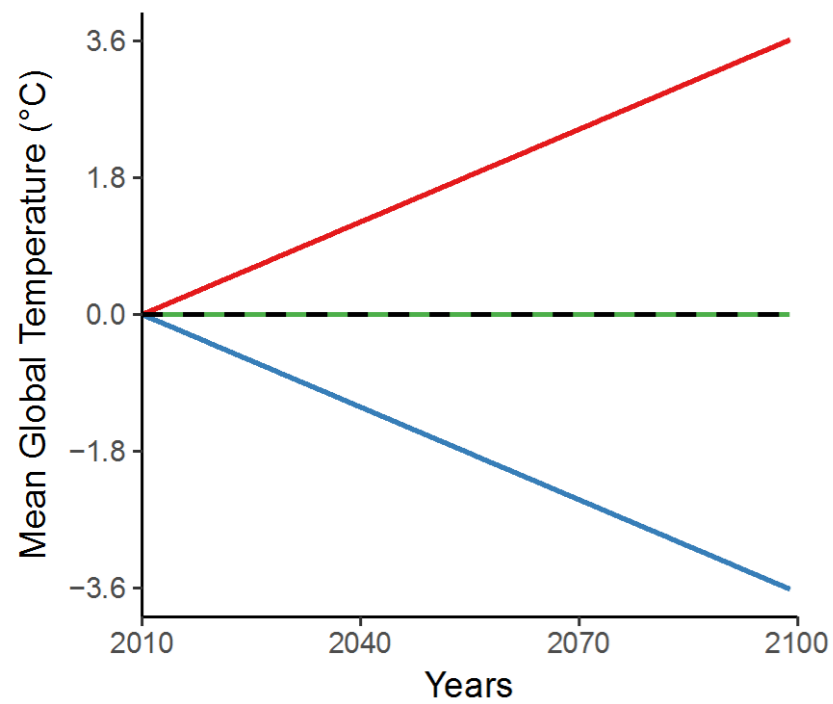
Problem:

What's lurking in your fixed effects?

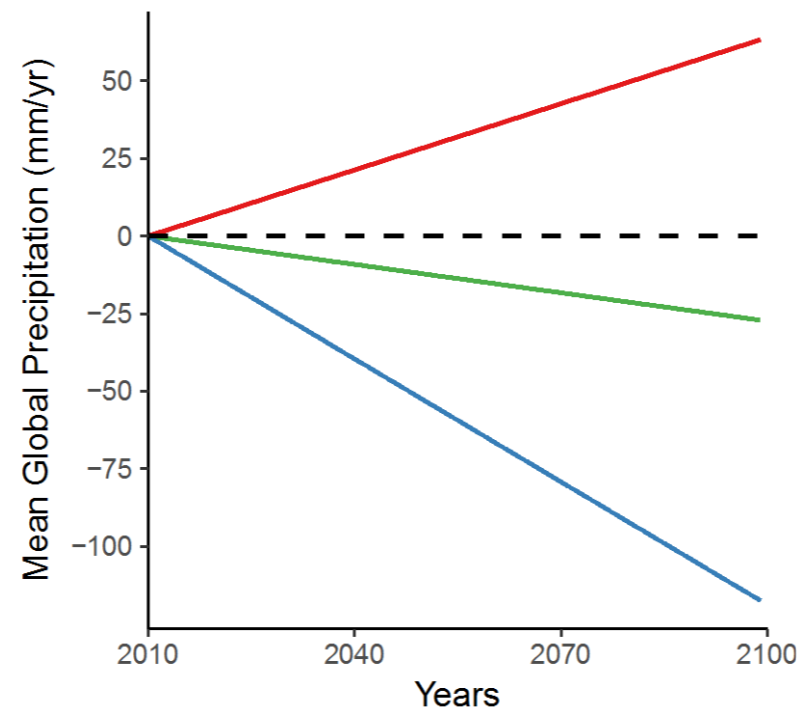
- The most important factors driving socio-economic change are not climate related (at least not at the moment)
- ...instead it's things like economic and political institutions matter
- To account for this source of heterogeneity, the empiricists use fixed effects models

Applying BHM to solar geoengineering

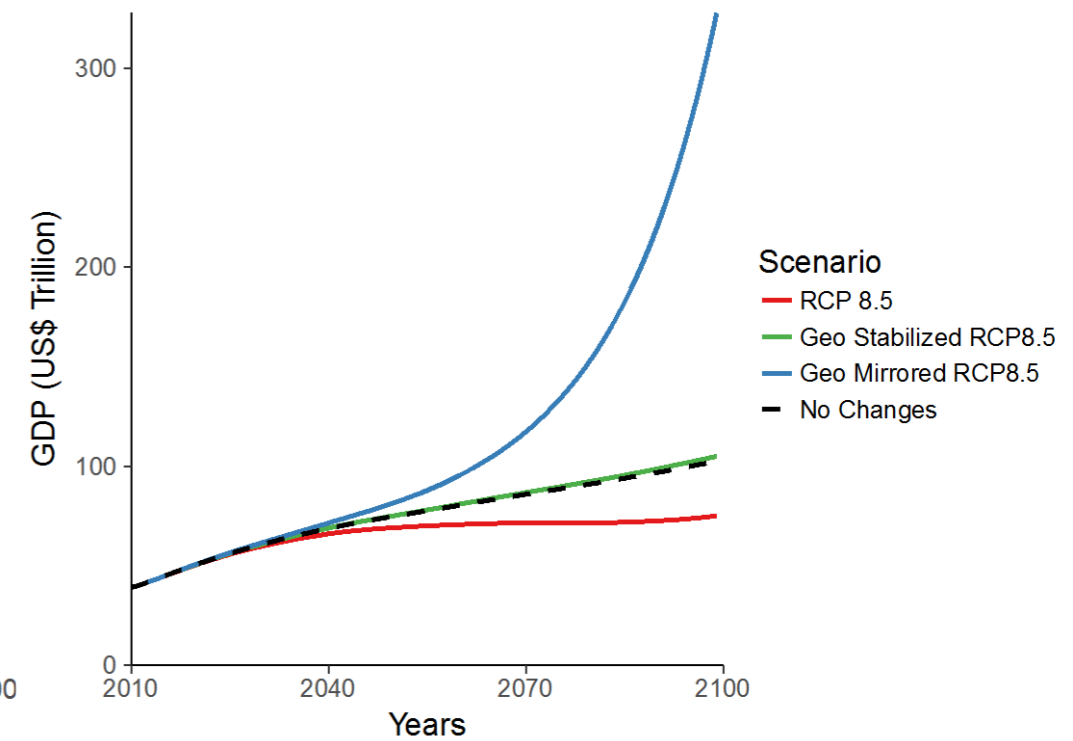
warming



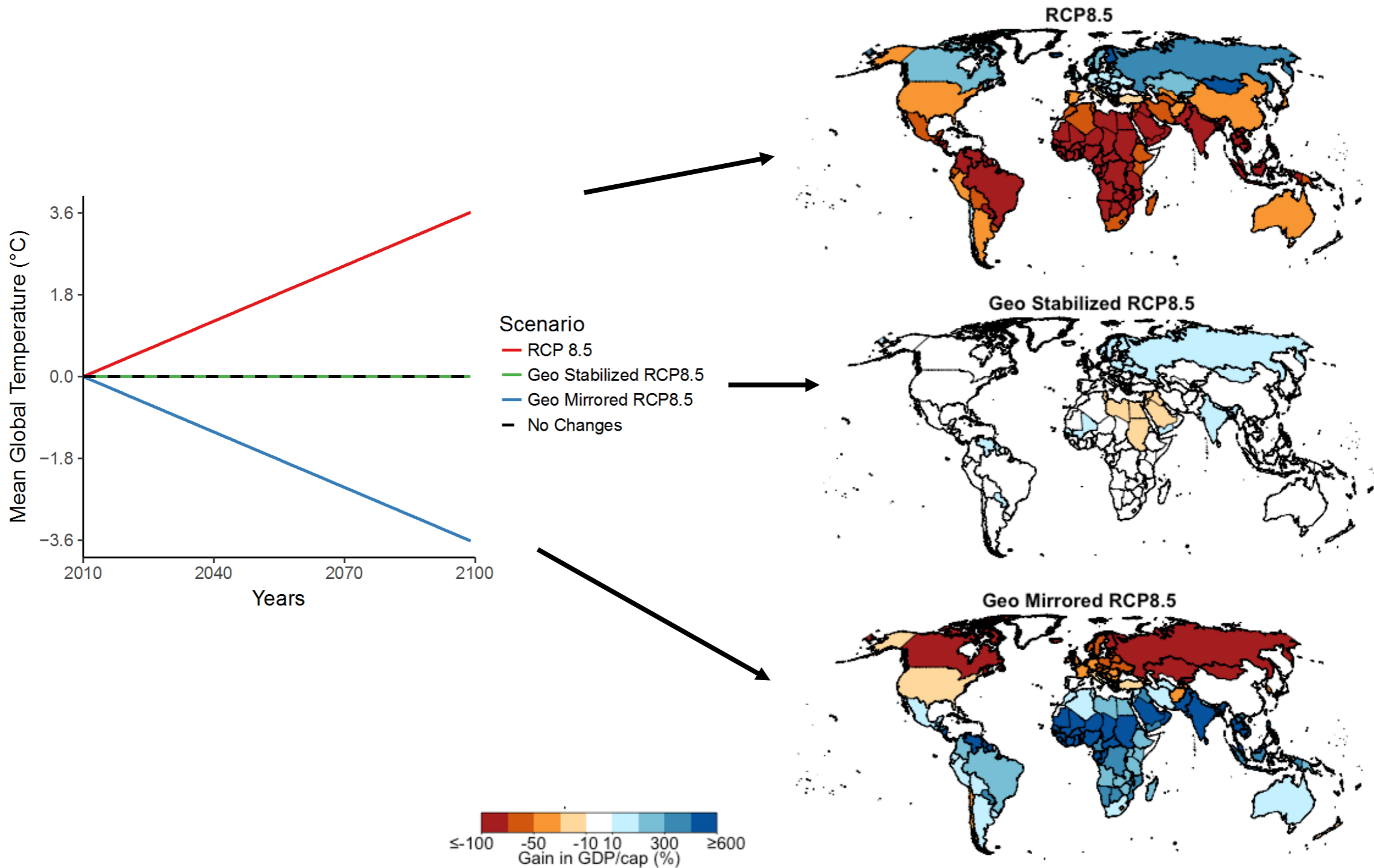
hydrology



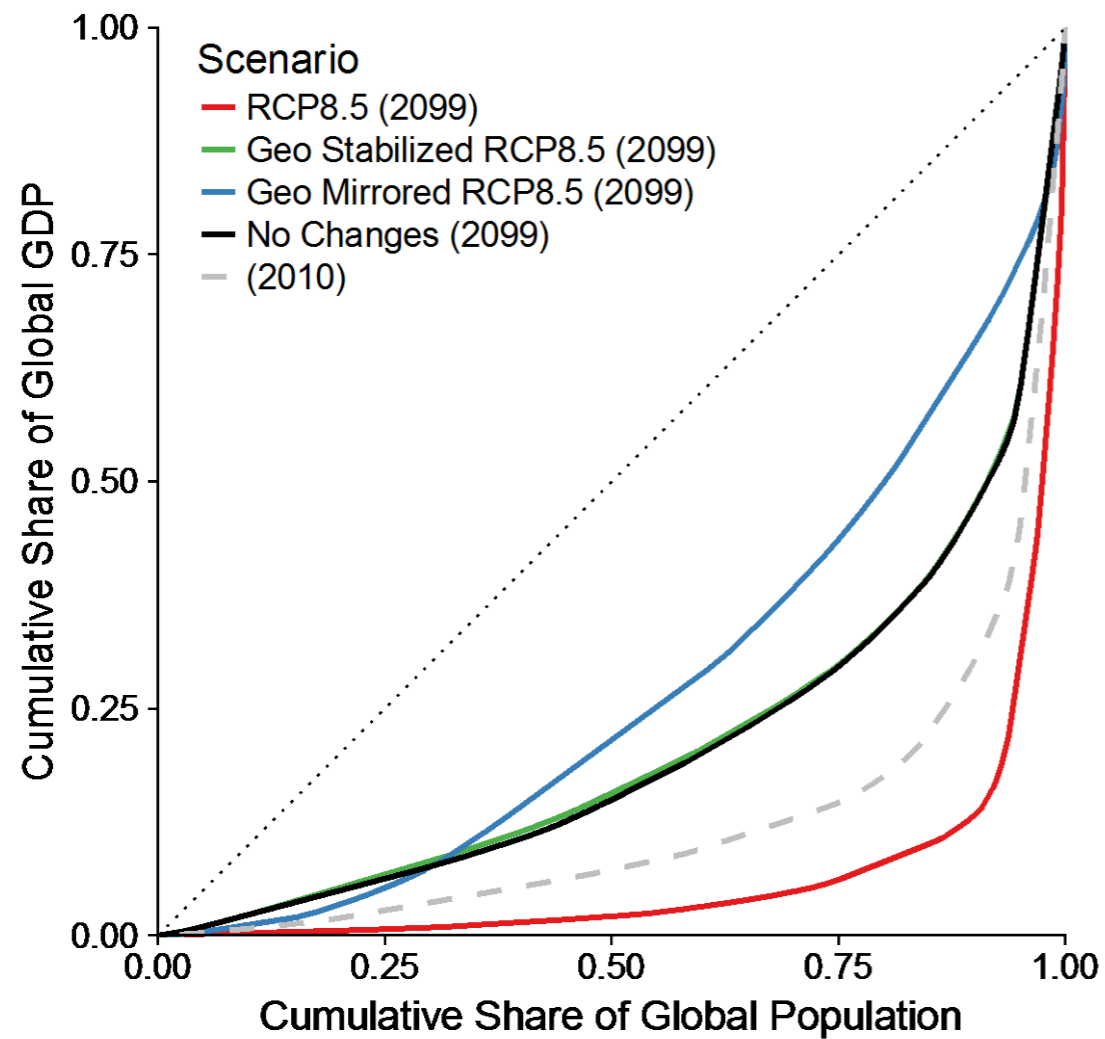
GDP



Paradoxical results



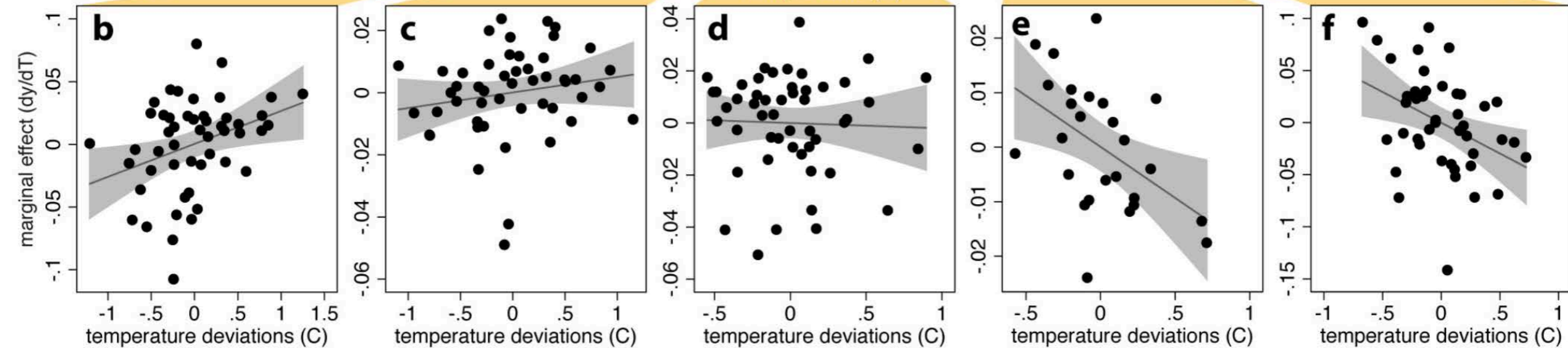
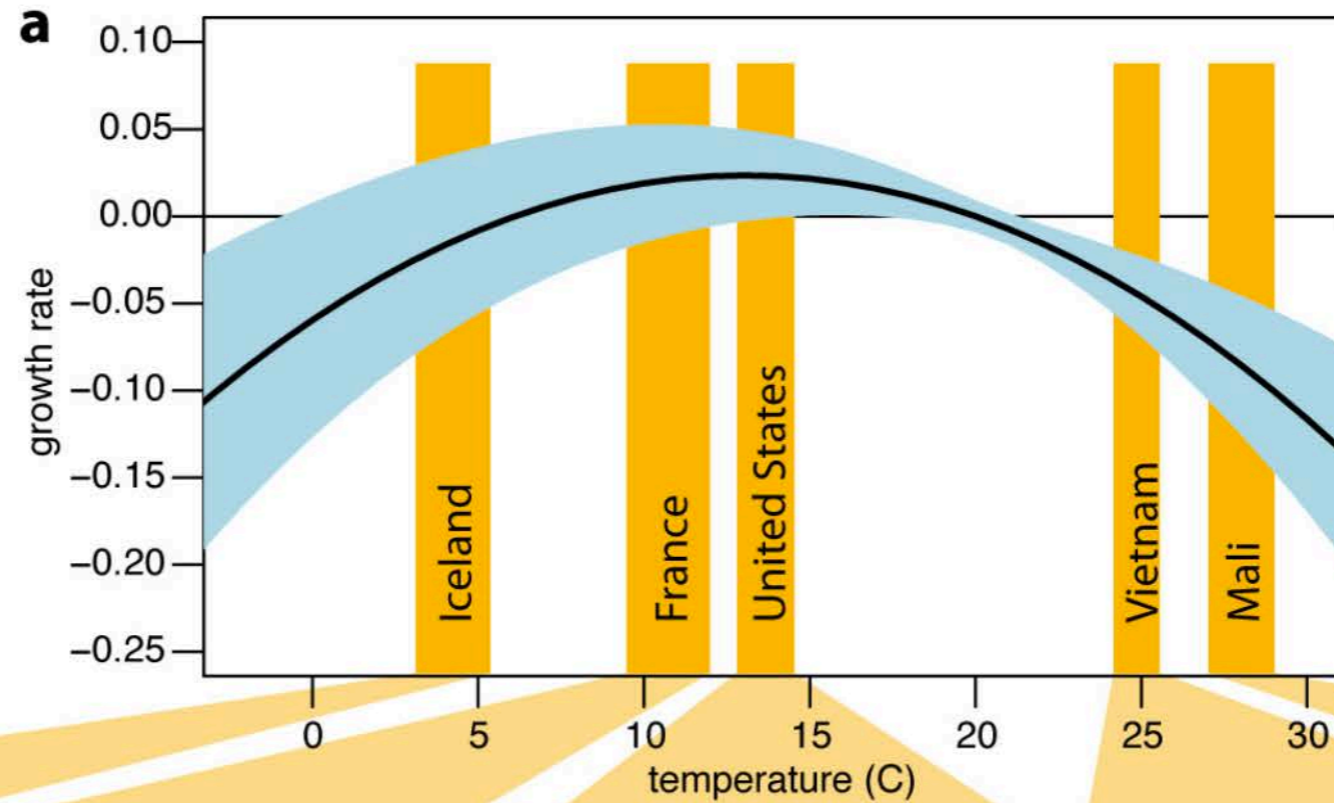
Paradoxical results



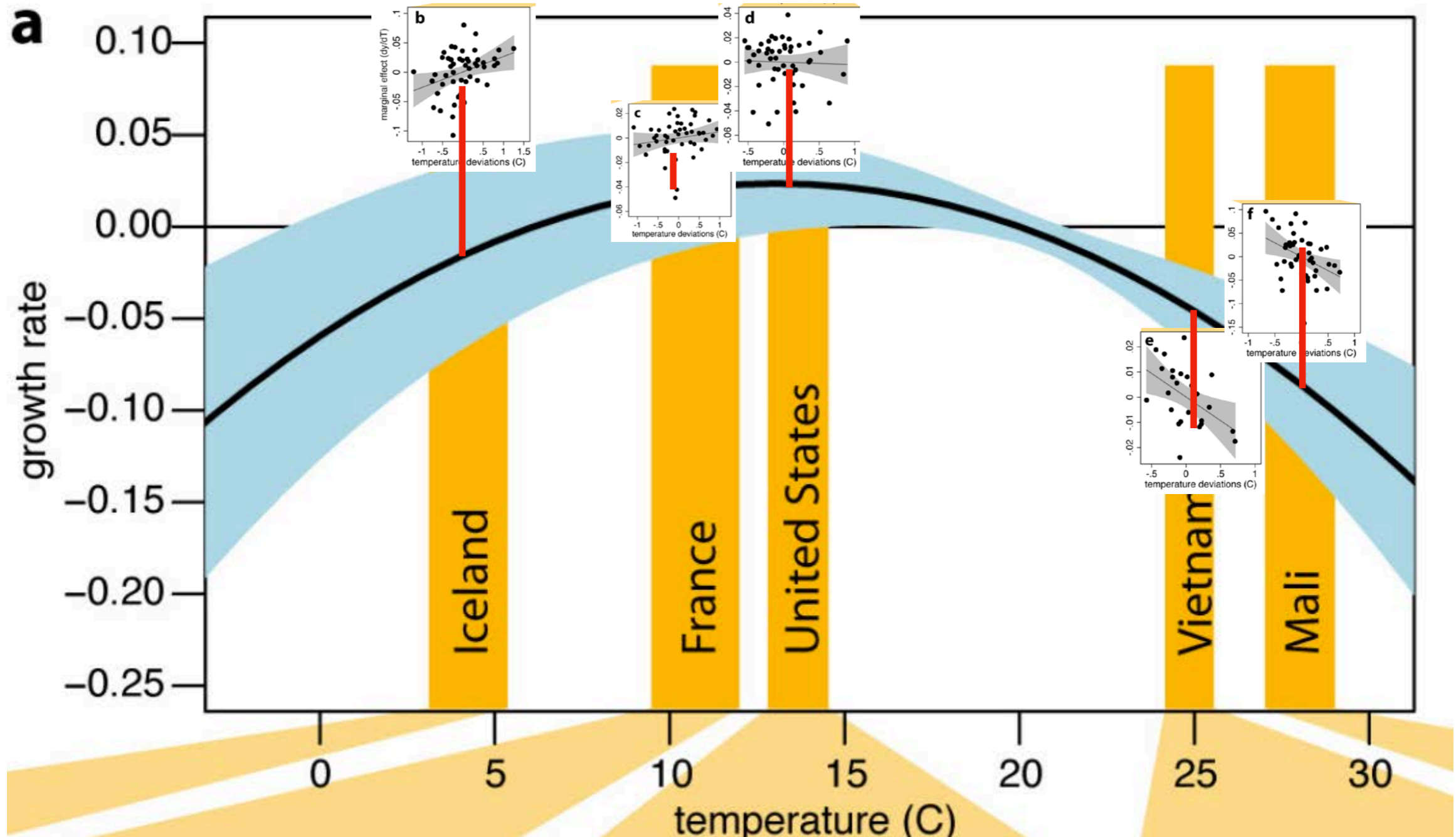
Solar geoengineering to cool the planet beyond recent past fixes income inequality

(hooray!)

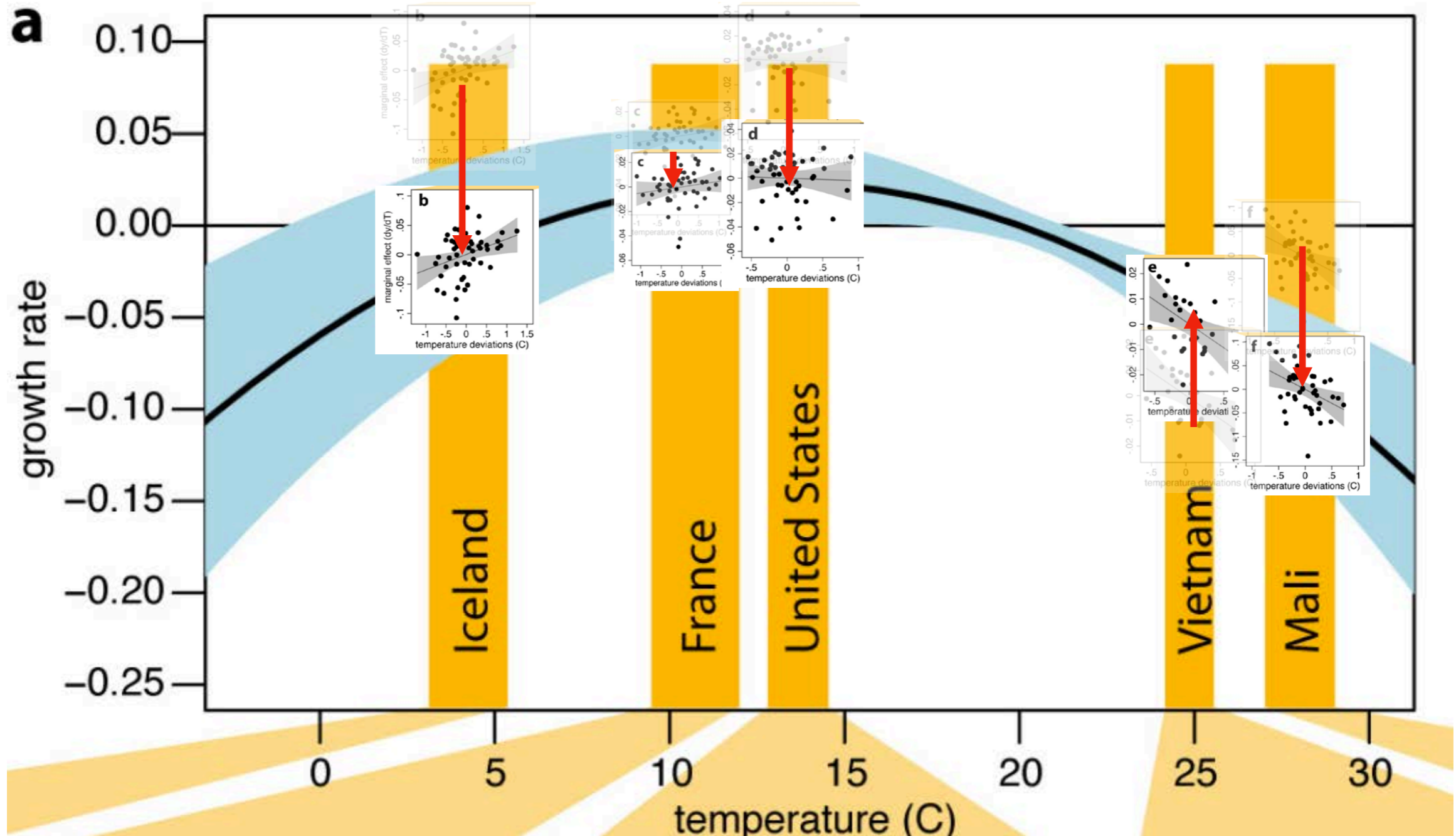
what is a fixed effects model



what is a fixed effects model



what is a fixed effects model



Nice p-values

	(1) Base	(2) >20yrs	(3) No oil	(4) No US/China	(5) ContYr FE	(6) ContYr + noTrend
Temp.	0.0127*** (0.0038)	0.0135*** (0.0038)	0.0128*** (0.0036)	0.0128*** (0.0038)	0.0142*** (0.0037)	0.0133*** (0.0034)
Temp. sq.	-0.0005*** (0.0001)	-0.0005*** (0.0001)	-0.0005*** (0.0001)	-0.0005*** (0.0001)	-0.0005*** (0.0001)	-0.0004*** (0.0001)
Precip.	0.0145 (0.0100)	0.0148 (0.0100)	0.0130 (0.0101)	0.0148 (0.0101)	0.0124 (0.0106)	0.0084 (0.0098)
Precip. sq.	-0.0047* (0.0026)	-0.0049* (0.0026)	-0.0040 (0.0025)	-0.0048* (0.0026)	-0.0041 (0.0027)	-0.0021 (0.0023)
Constant	1.4575** (0.6444)	0.0740 (0.0633)	1.4522** (0.6228)	1.4707** (0.6507)	-0.0362 (0.0411)	-0.0819** (0.0370)
Observations	6584	6477	6090	6484	6584	6584
R squared	0.286	0.278	0.275	0.284	0.367	0.267
Optimum	13.06	13.39	12.64	13.09	14.92	17.40

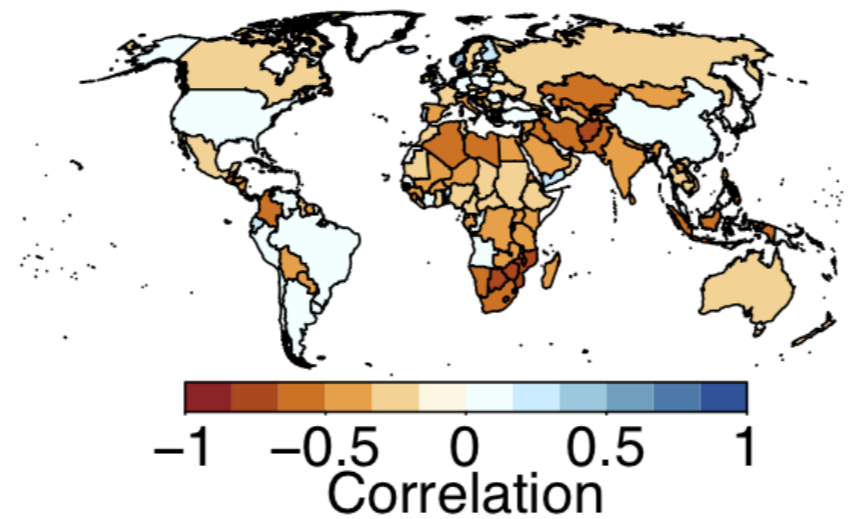
Unless otherwise indicated, all models include country fixed effects, year fixed effects, and quadratic country time trends, with in metres. Columns: (1) main specification, (2) as in column 1 but excluding countries with fewer than 20 years of growth data; dropping United States and China, (5) as in column 1 but adding continent-by-year fixed effects, (6) as in column 1 but adding but dropping year fixed effects, (8) as in column 1 but only linear time trend, (9–10) as in column 1 but adding 1 or 3 lags of pe growth data from Penn World Tables. Asterisks indicate statistical significance at the 1% (***), 5% (**), and 10% (*) levels.

Why is temperature showing up as the only important thing?

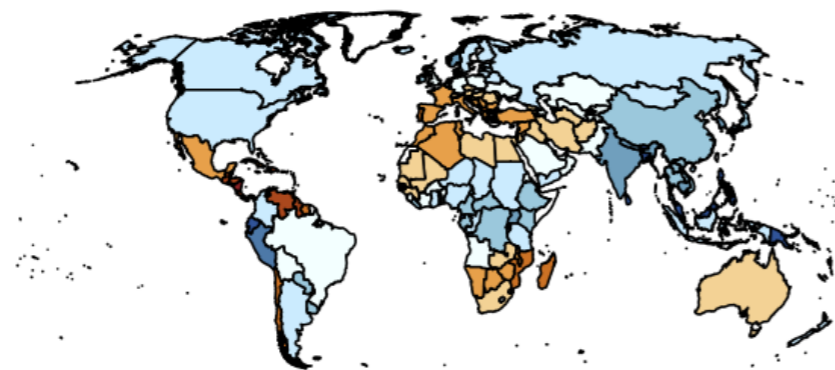
- Problems: Correlates that are insignificant because they're
 - Noisy?
 - Heterogeneity is aggregated out of variables due to positive and negative changes? and
 - Correlations do not have much cross-sectional variation compared to future trends, etc.

This is a problem EQUALLY for GHG and SG climate change

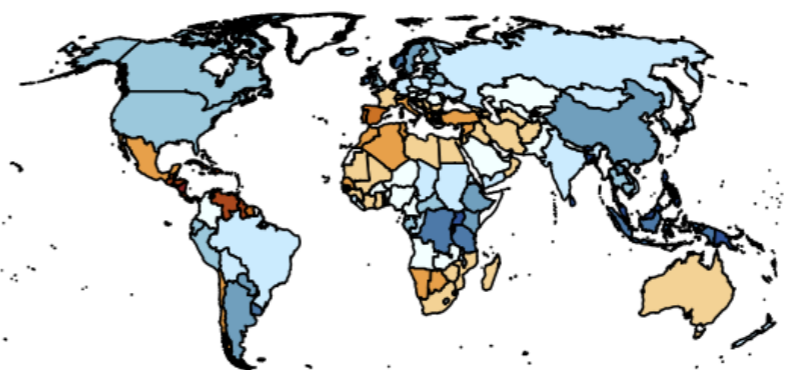
(a) **Historical Correlation**



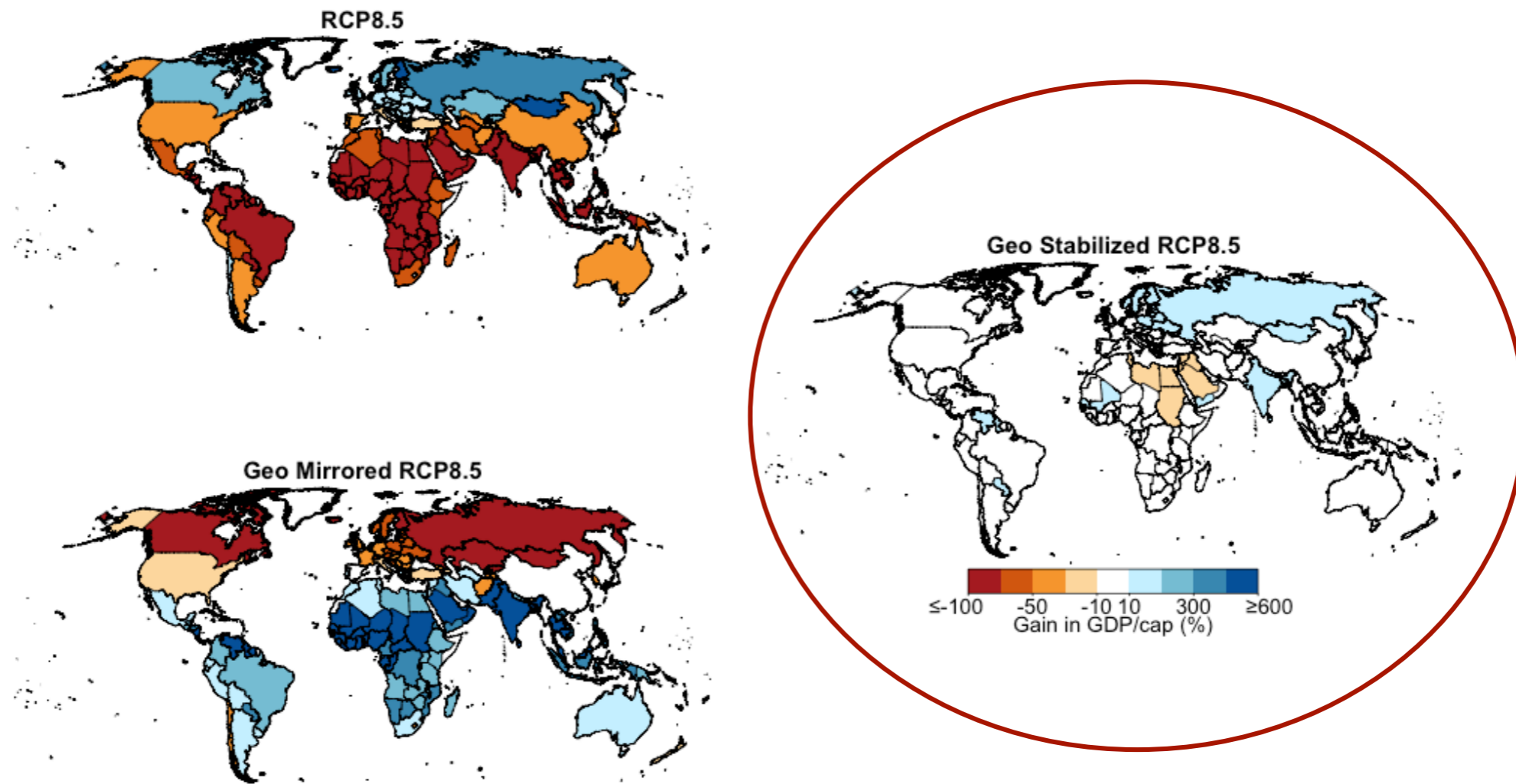
(b) **RCP8.5**



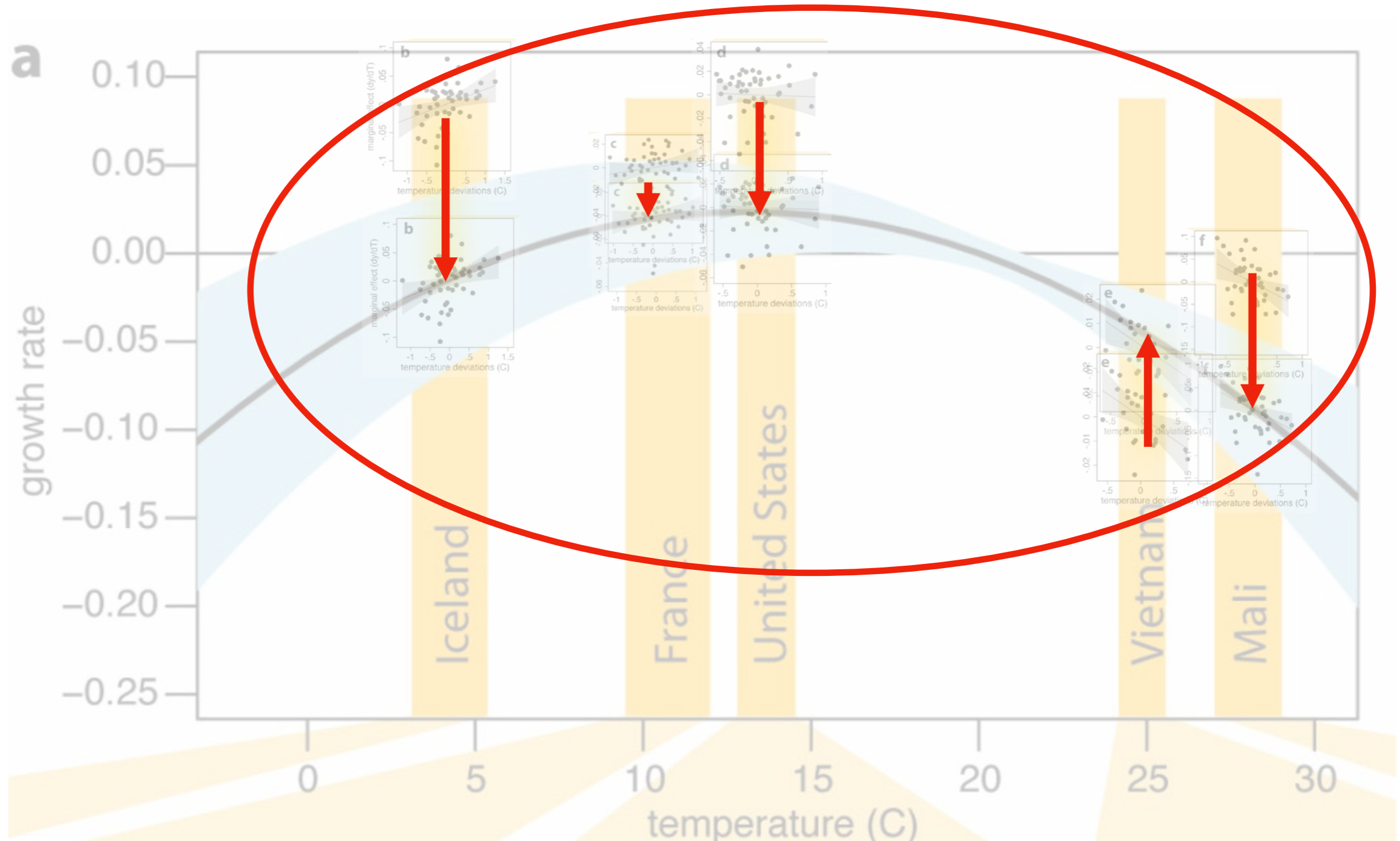
(c) **Geoengineering**



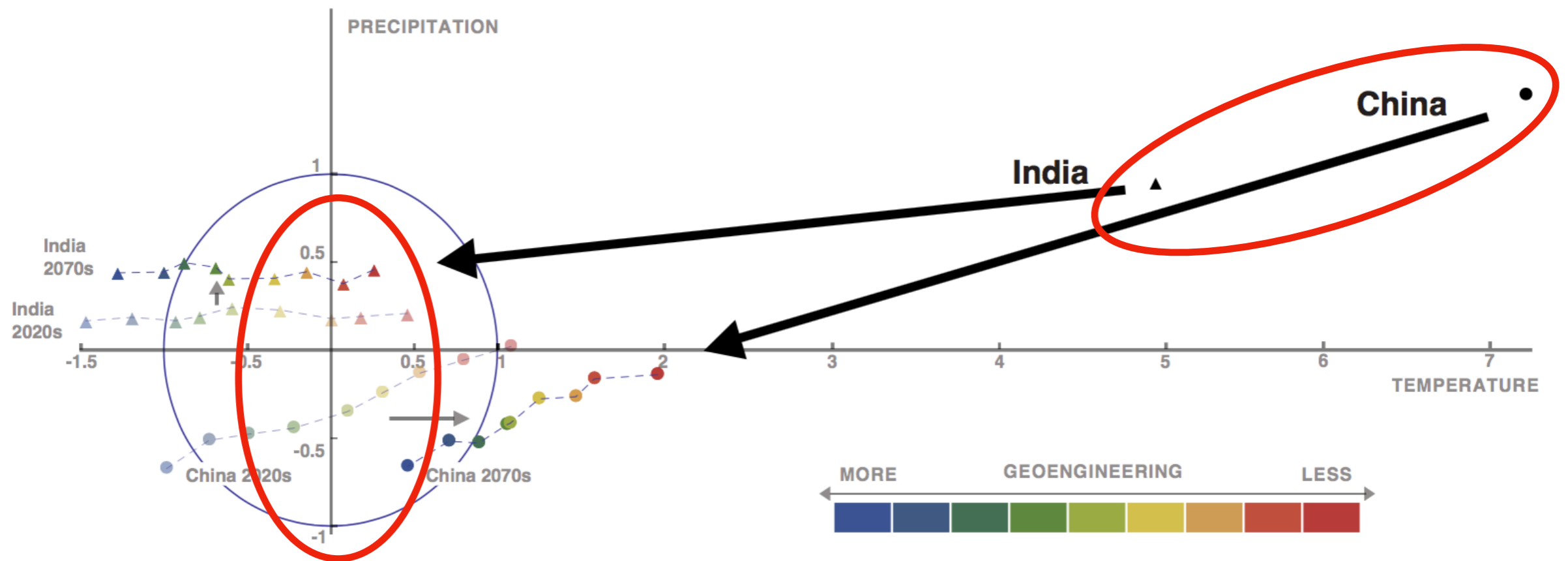
Applying BHM to solar geoengineering



What's in these really?



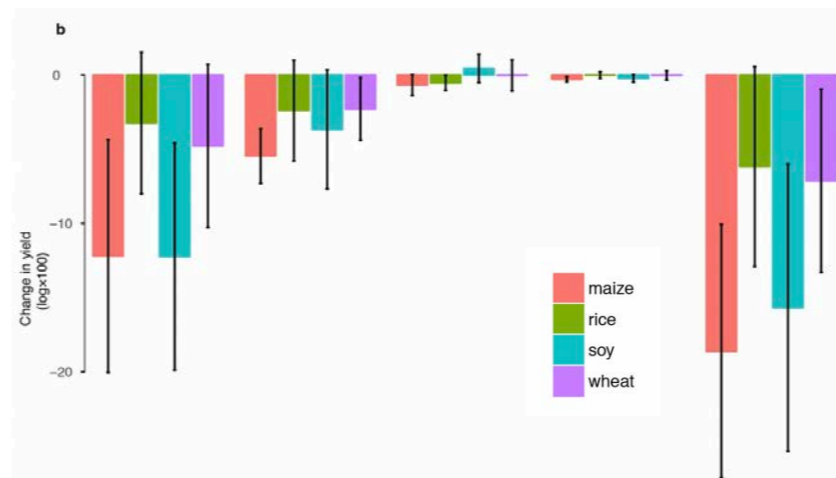
Back to SRM...



Is this really only a problem for SRM?

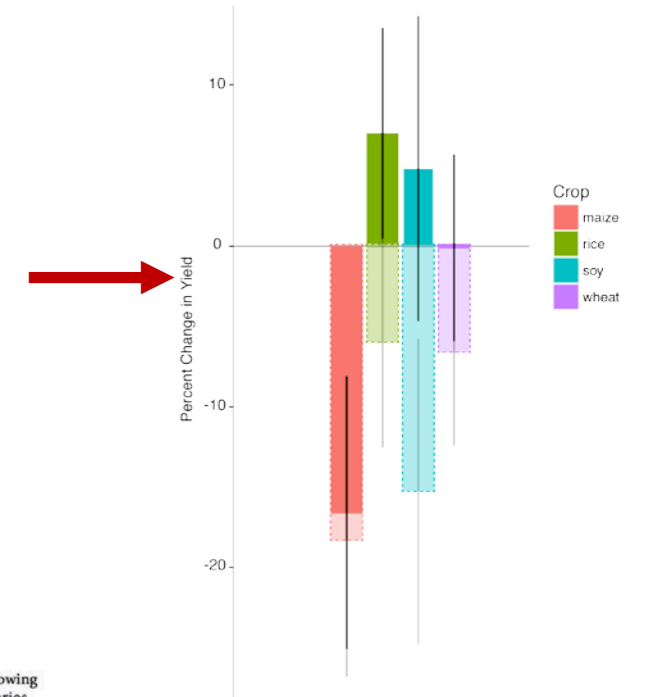
- reason for getting such very significant effects in pooled response models: country fixed effects
- with climate, because countries also happen to be geographically contiguous, climatological factors are also probably captured by fixed effects
 - i.e., the value of the current climate regime
- SRM impacts science hasn't created this problem so much as rendered it obvious

First SG Nature cover



Extended Data Fig. 7 | Effects of climate change and SRM relative to an historical scenario. a, As in Fig. 4e, but comparing a climate change scenario (RCP 4.5) to an historical scenario (Supplementary Information, section IV.3). b, As in Fig. 4e, but comparing a climate-change-with-SRM scenario to an historical scenario. Note that these calculations consider

only climatological and sunlight-mediated effects; changes in yields owing to carbon fertilization, or other factors that may differ between scenarios, are not included. Error bars show 95% confidence intervals around the estimated mean effect.

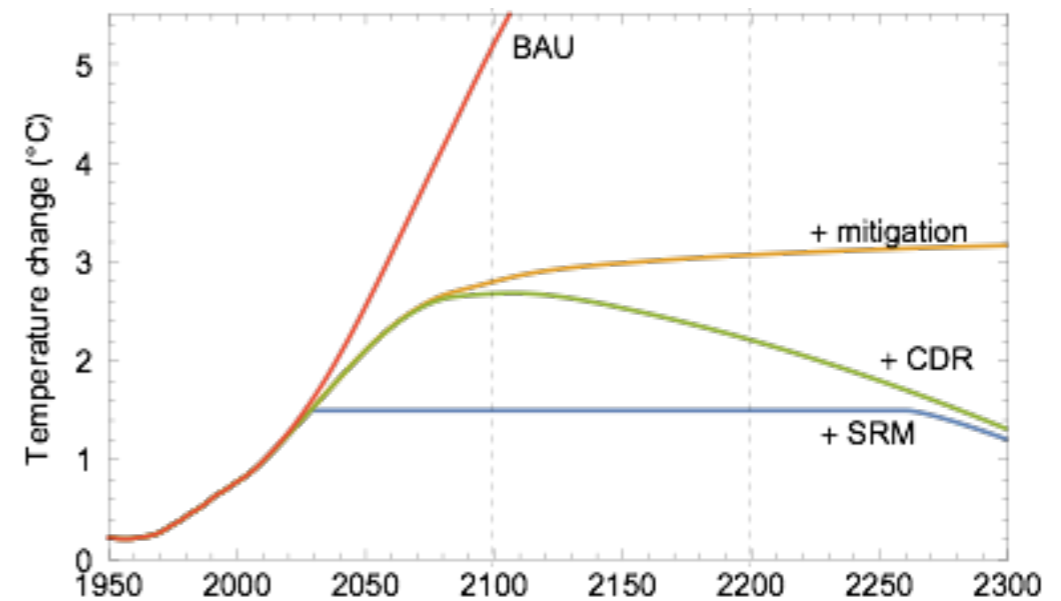
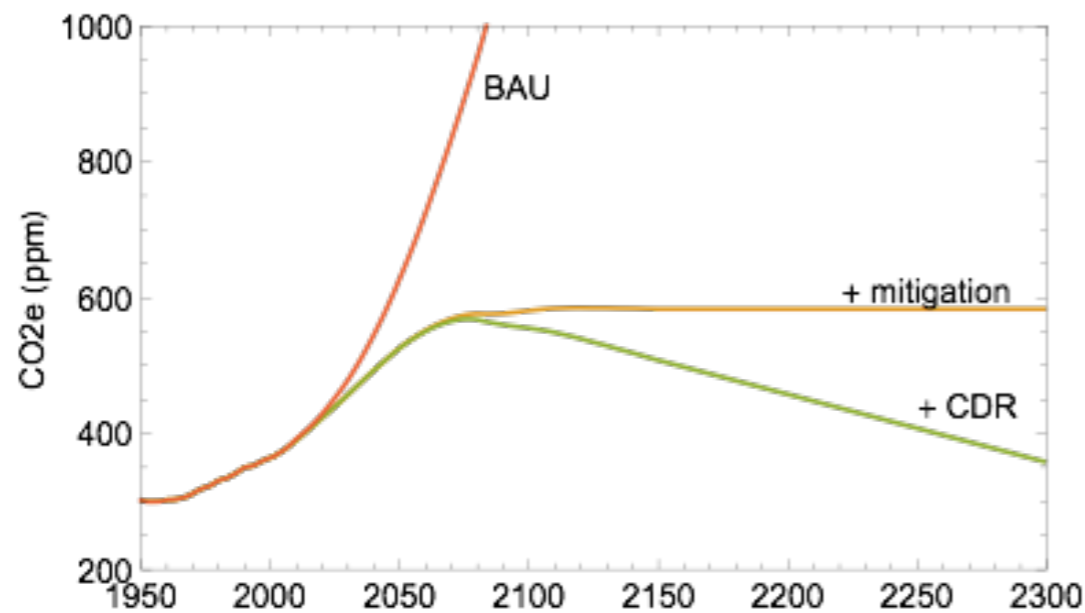


Worried about a SG empirical revolution...



- Fixed effects
- interannual temperature variability is strongly correlated with interannual variability in hydrological variables (annual temperature and precipitation are negatively correlated almost everywhere over land, for reasons Kevin Trenberth articulates well in this paper: <https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2005GL022760>), whereas the pattern of correlation between temperature and precipitation in the forced response is not the same for either GHG-driven change or solar geoengineering. Projections made using empirical models have a major shortcoming given this covariate problem.

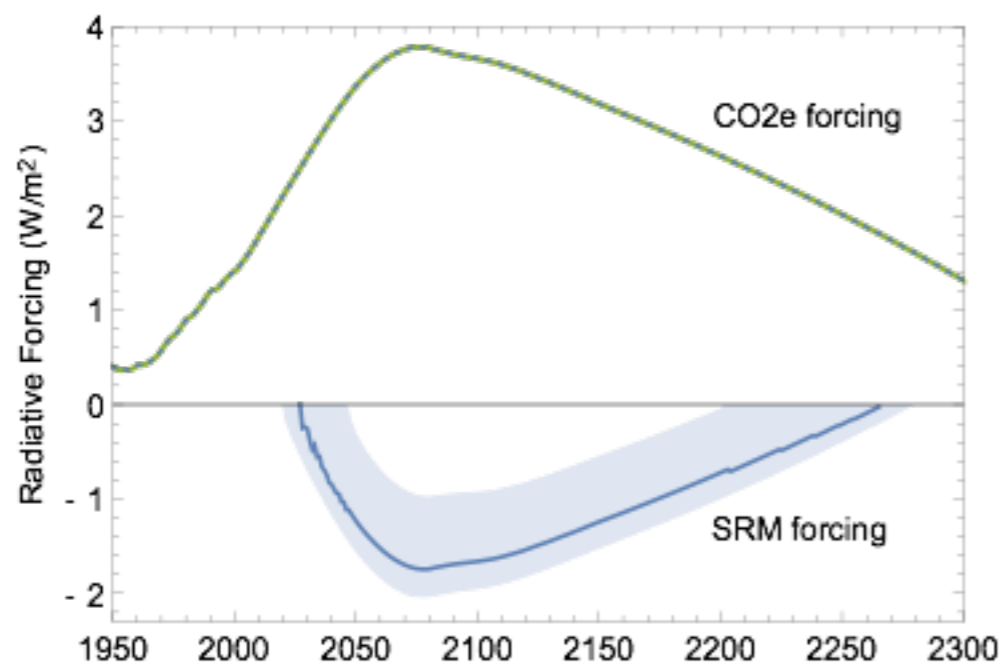
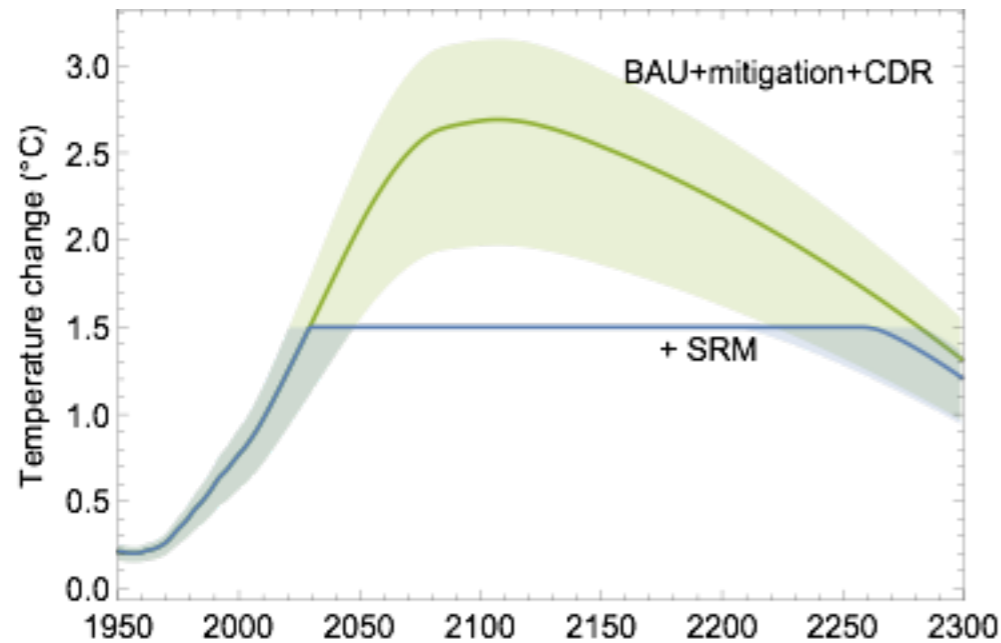
When we analyze quasi-realistic solar geoengineering ...



~1.7 W/m² (~3 TgS/year as H₂SO₄ or 5+ TgS as SO₂)

MacMartin, Ricke & Keith (in press)

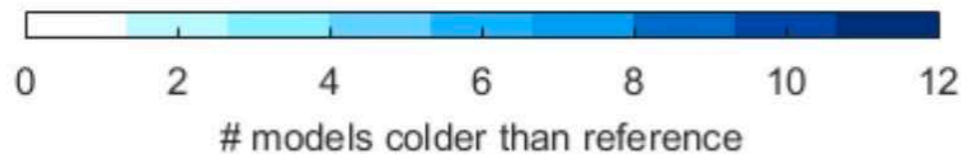
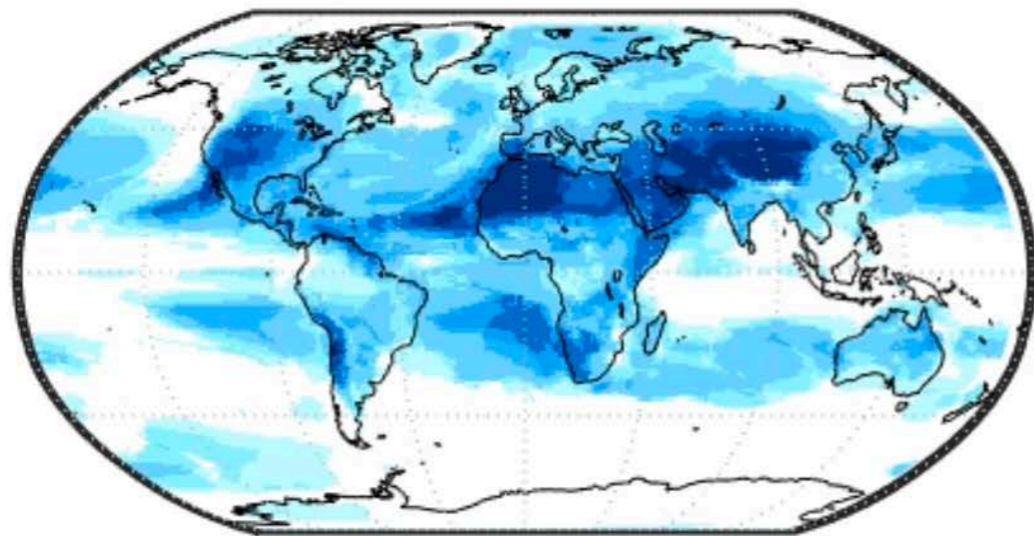
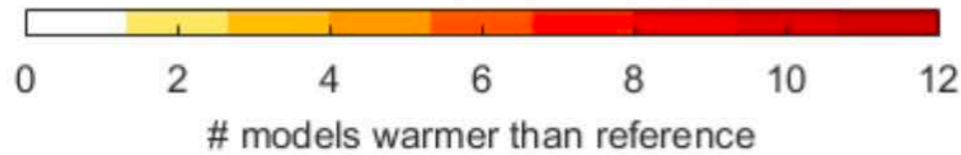
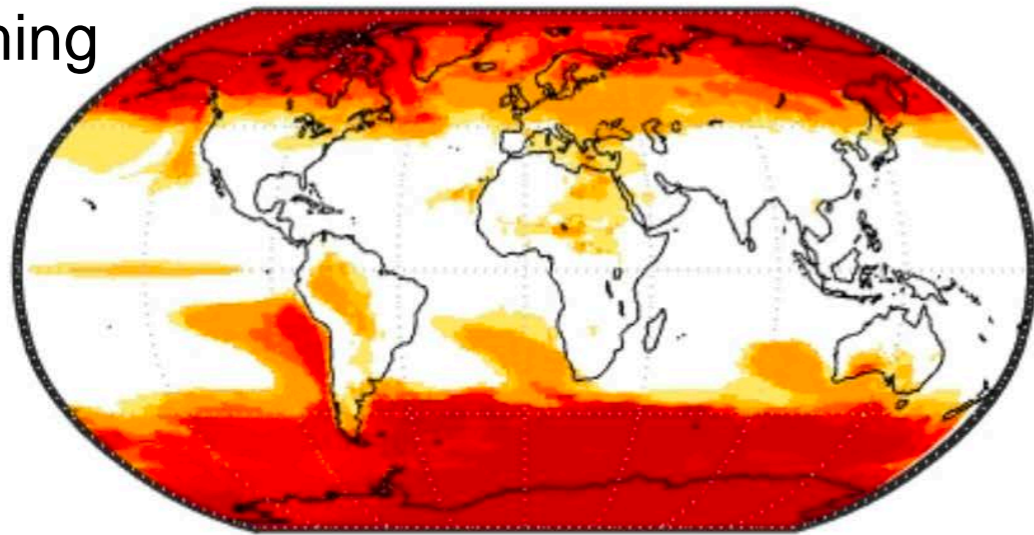
Solar geo can help manage uncertainty about climate sensitivity, the range of temperature outcomes



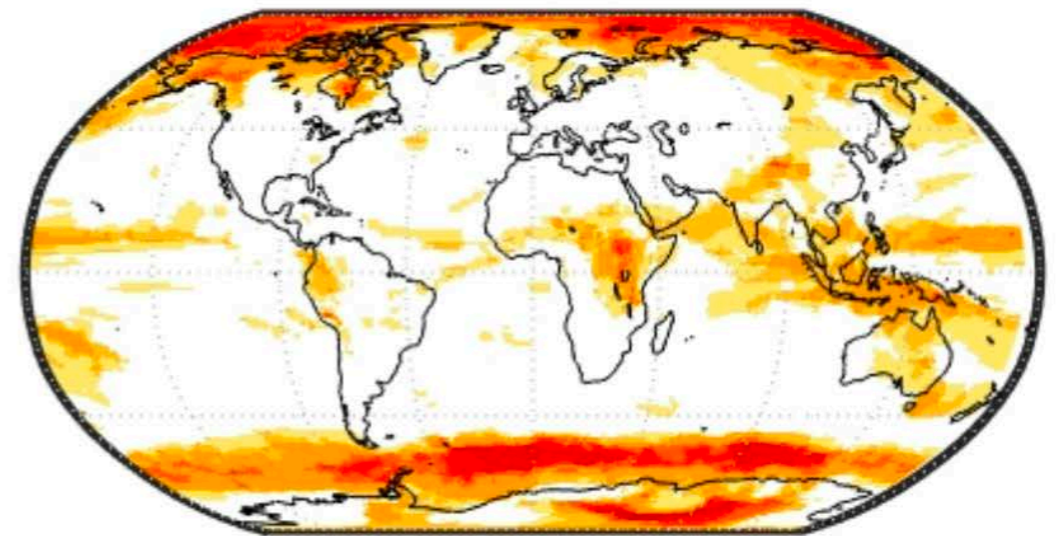
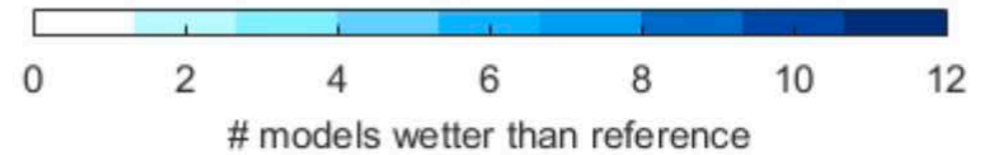
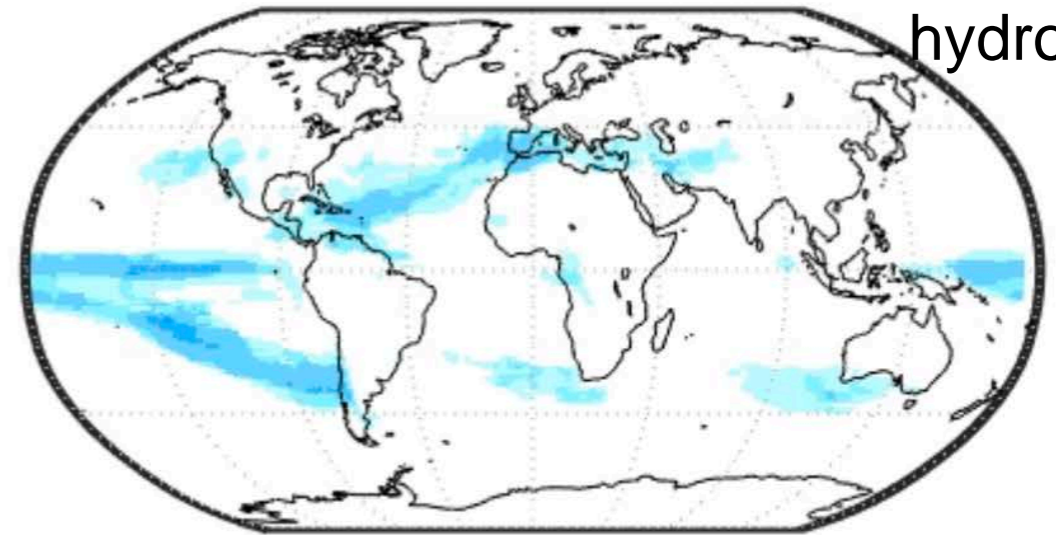
Solar geoengineering increases the certainty of being able to achieve a target.

1.5°C-Geo compared to 1.5°C-NoGeo (statistically significant differences)

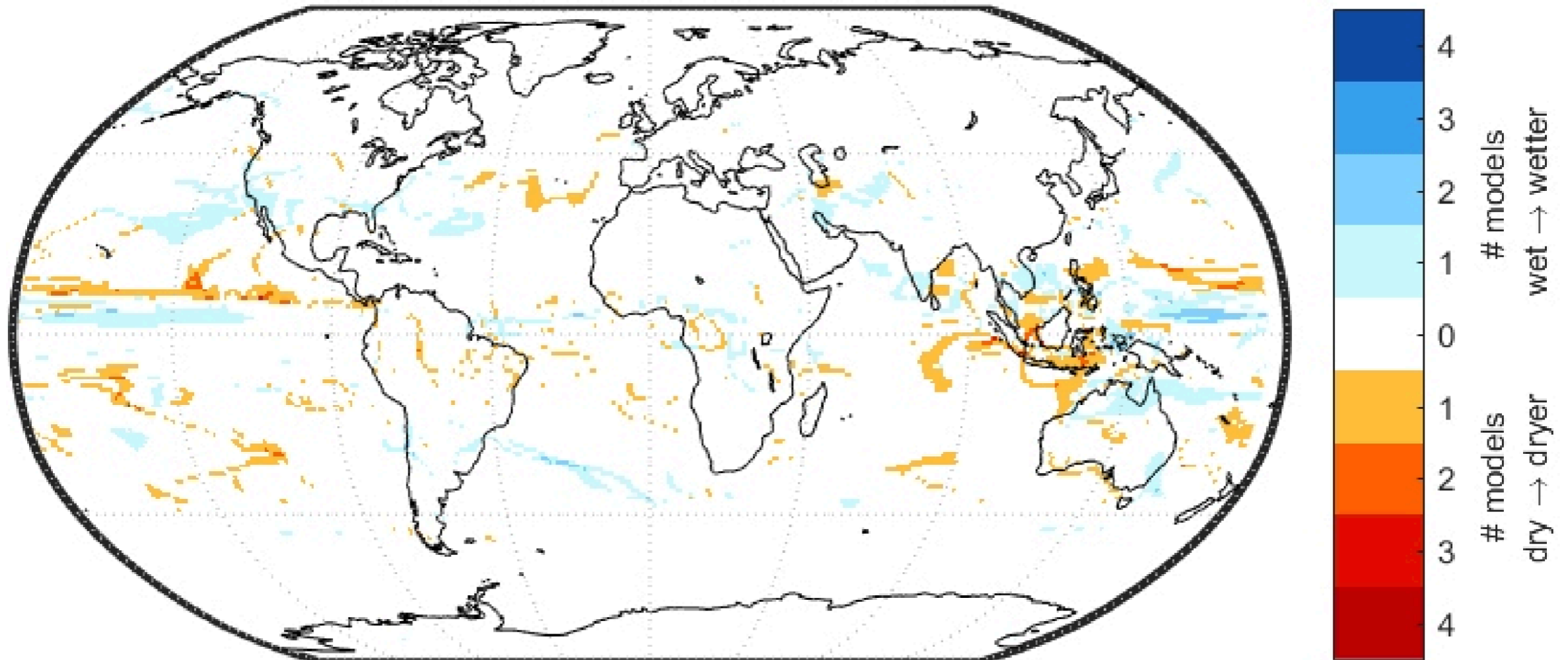
warming



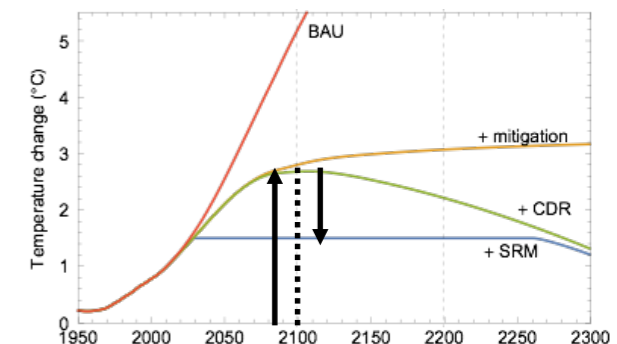
hydrology



Damages from solar geoengineering will be indistinguishable from residual CO2 damages



... maybe not for, e.g., particles in Arctic, but almost certainly for drought in Amazon



How to fix this

???