Global non-linear effect of temperature on economic production

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World Bank
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Motivation

- **Climate change** is one of the most important international development challenges of our time
  - Impacts are possible across a range of development areas, including agriculture, energy, health, migration, conflict, …

- Projections of future climate impacts matter for (potentially expensive) policy decisions today, e.g., December 2015 Paris climate conference

Motivation

- **Key policy question:** what is the cost of emitting a ton of carbon today?

Climate science

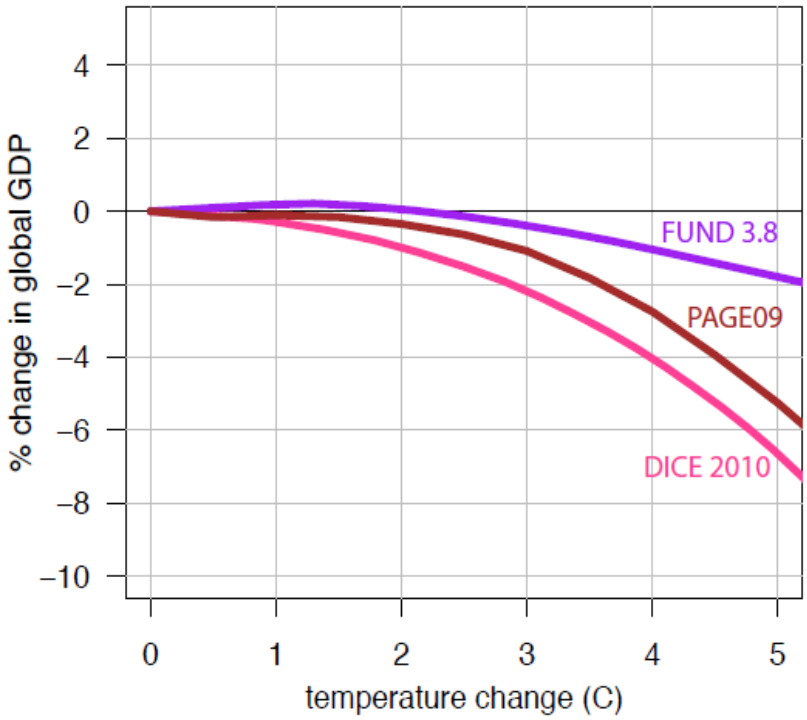
$$Social\ cost\ of\ carbon = \sum_{t=0}^{\infty} \underbrace{\delta^t \frac{\partial Damage}{\partial Temp_t}}_{\text{Economics}} \overbrace{\frac{\partial Temp_t}{\partial C02_t} \frac{\partial C02_t}{\partial Emissions_t}}^{\text{Climate science}}$$

- **Today's talk:** generate econometric estimates of the damage function with respect to economic growth

Damage functions in existing models

- Integrated assessment models (IAM's) are widely used in climate policy debates
- They assert that damages will be minimal up to 2-3 C, increasing beyond that

- Consider a -3% effect by 2100
- An economy growing 1% per year is 133% richer in 85 years
- With climate change of +4C, only 130% richer



Damage functions in existing models

- So, no need to worry? Many critiques of these models:

1) Pindyck (JEL, 2013): *"The damage functions used in most IAM's are completely made up, with no theoretical or empirical foundation."*
2) Revesz, Arrow, Goulder, et al. (Nature 2014): *"The models should be revised more frequently to accommodate scientific developments."*

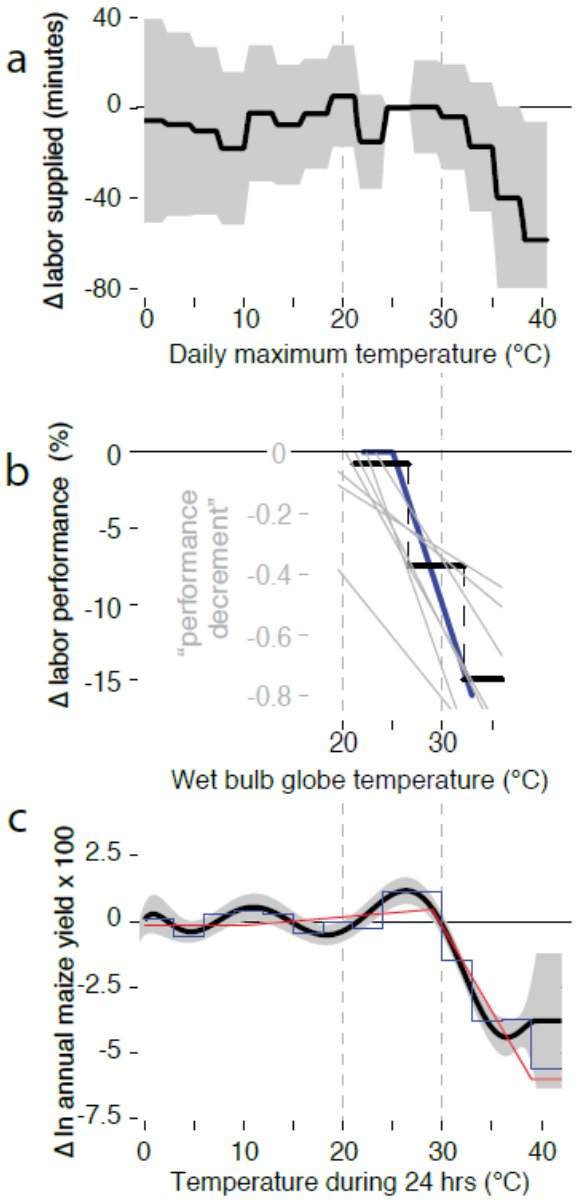
→ Limitations: developed in the 1990s; calibrated for moderate warming, not large changes; based mainly on out-of-date rich country estimates; ignore many plausible channels; do not allow for effects of climate on economic growth; ...

Recent micro-estimates of climate

Labor supply (Graff Zivin and Neidell 2014)

Labor productivity (Hsiang 2010)

Crop yields (Schlenker and Roberts 2009)

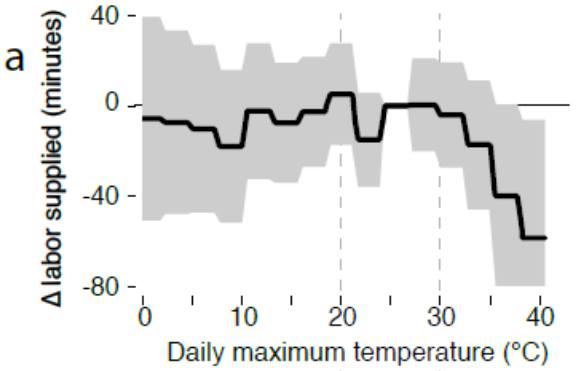


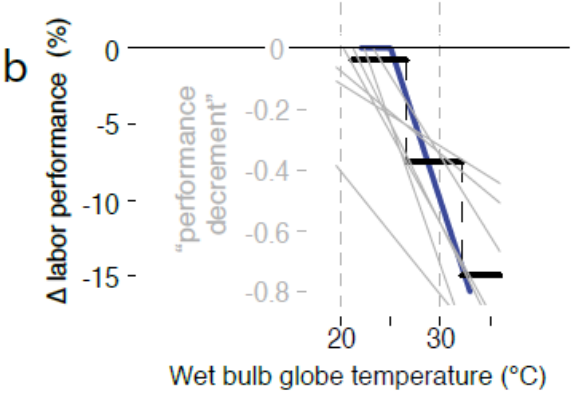
Linking micro-estimates to macro

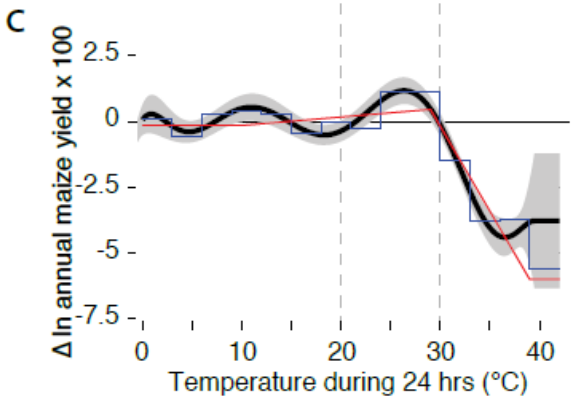
Labor supply (Graff Zivin and Neidell 2014)

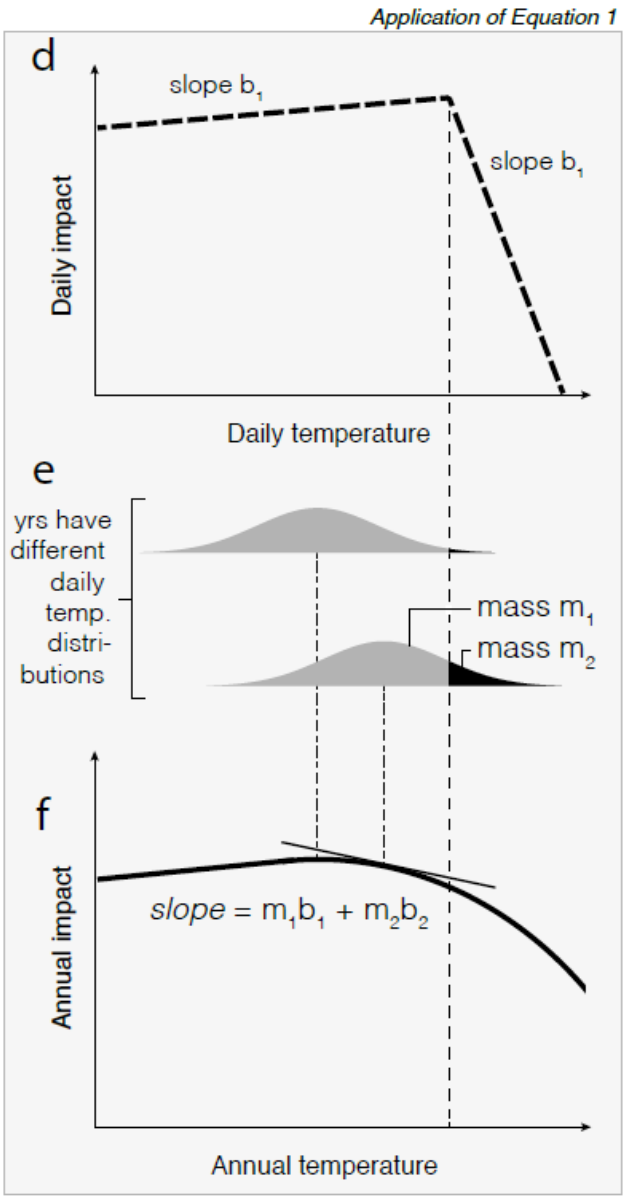
Labor productivity (Hsiang 2010)

Crop yields (Schlenker and Roberts 2009)









This study

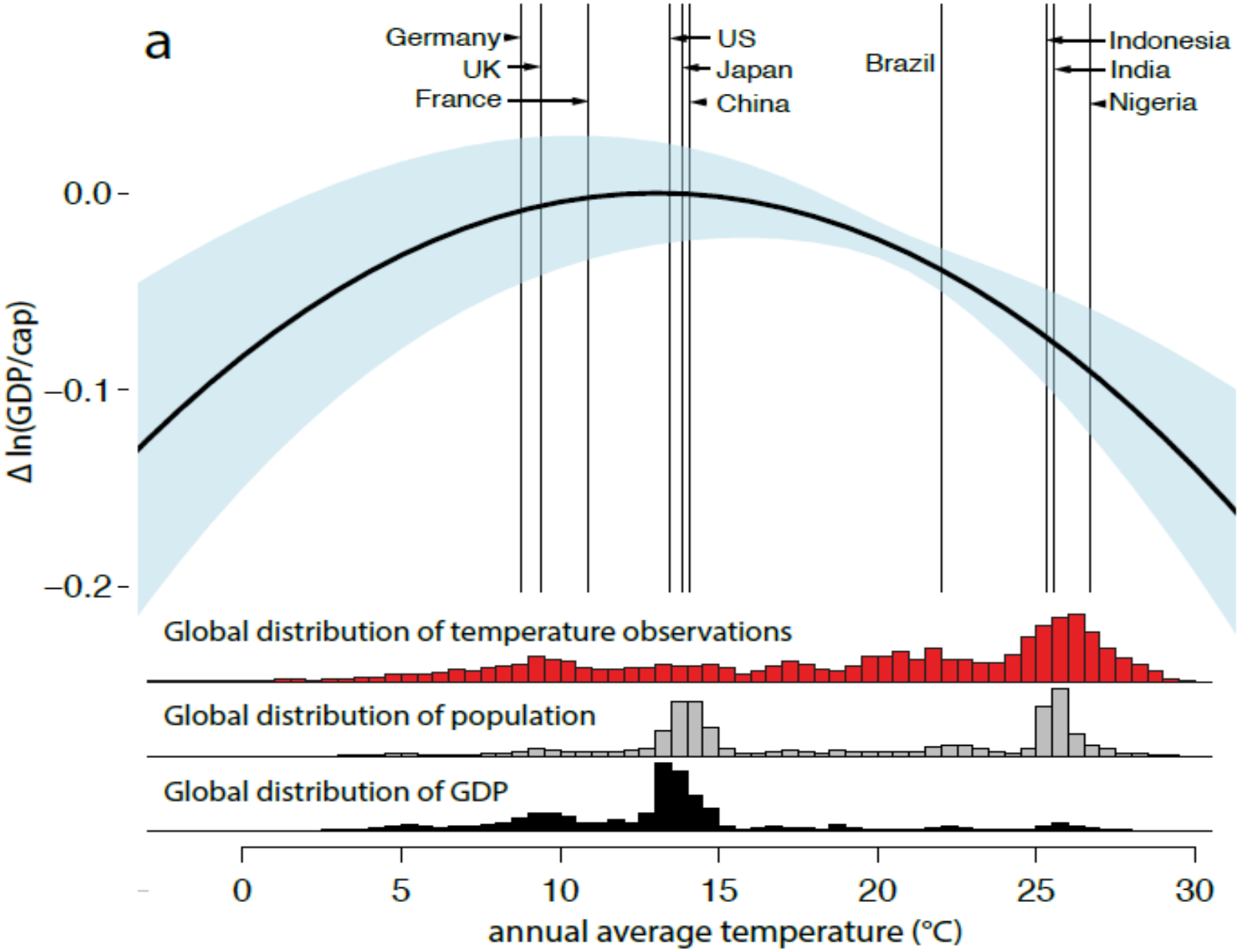
- Estimate climate impacts on economic growth, allowing for non-linearities in the relationship
- Annual data for 166 countries for 1960-2010
- WDI for growth, U Delaware for temperature/precipitation:

$$\Delta Y_{it} = g(T_{it}) + \lambda_1 P_{it} + \lambda_2 P_{it}^2 + \mu_i + \gamma_t + \theta_{1i} t + \theta_{2i} t^2 + \varepsilon_{it}$$

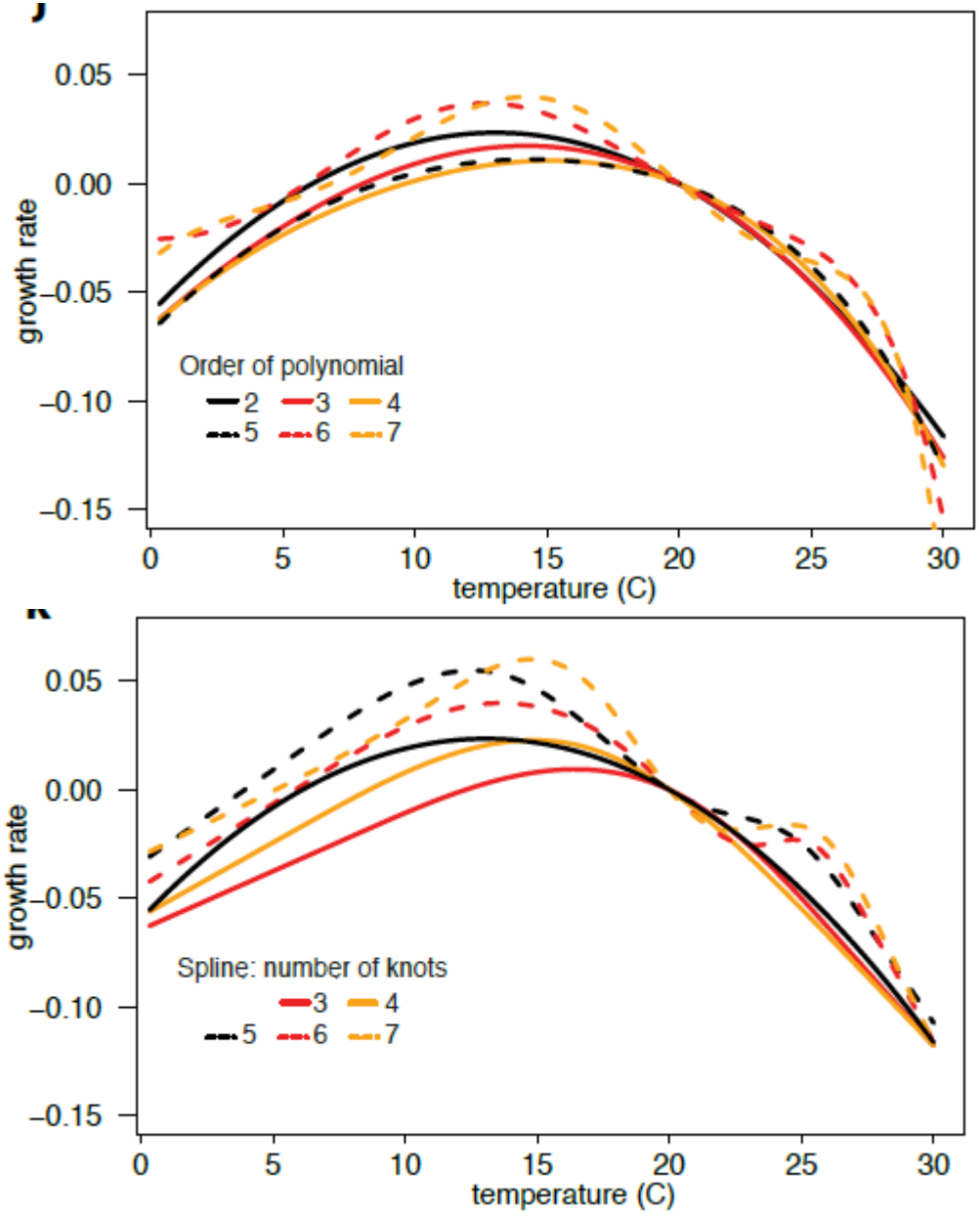
- Also include additional lags of temperature to estimate persistent growth effects

- Builds on the seminal work by Dell, Jones and Olken (2012); earlier Miguel et al. (2004), Barrios et al. (2010), and others show growth sensitive to climate.

*Quadratic temperature term, P < 0.01



Robustness to functional form of *g(T)*



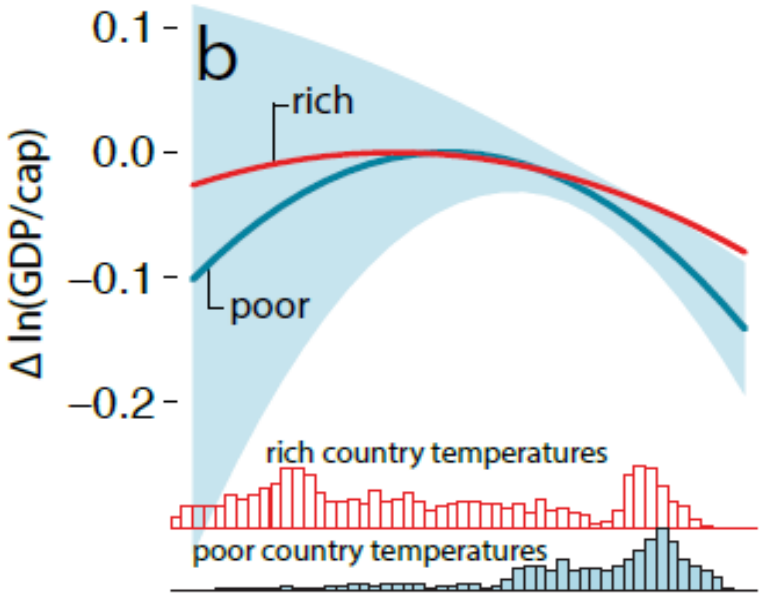
How solid is conventional wisdom?

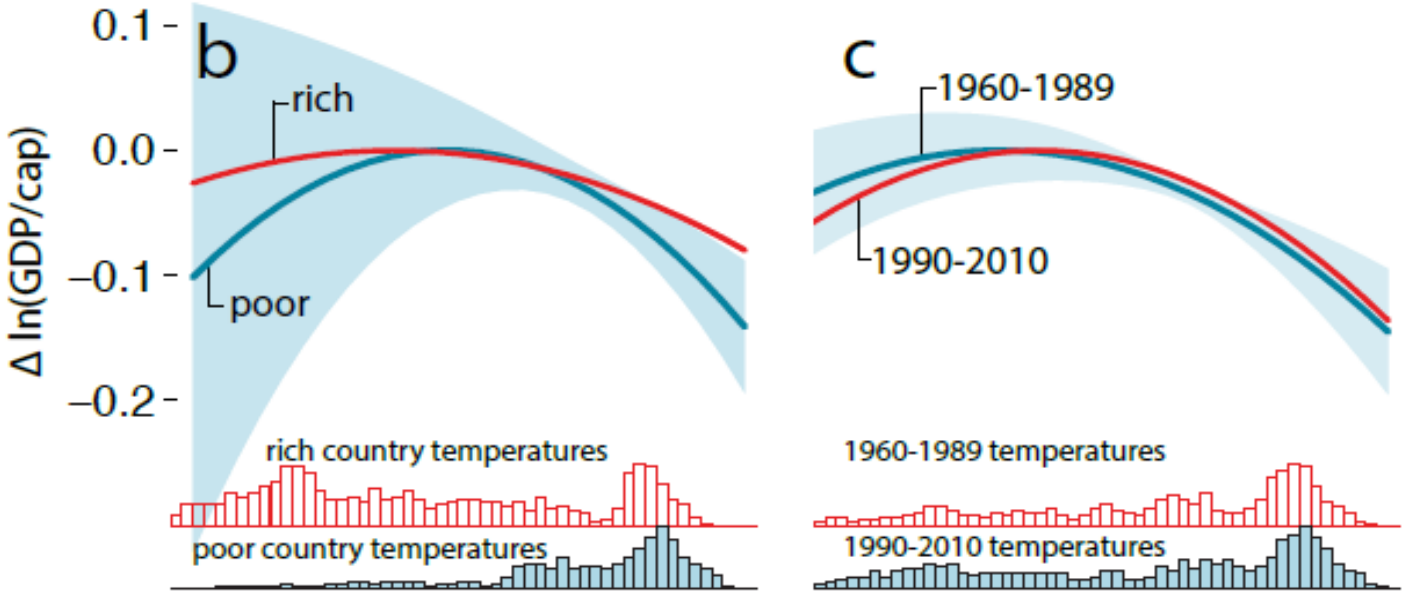
- Conventional wisdom in economics (sometimes built in IAM's):

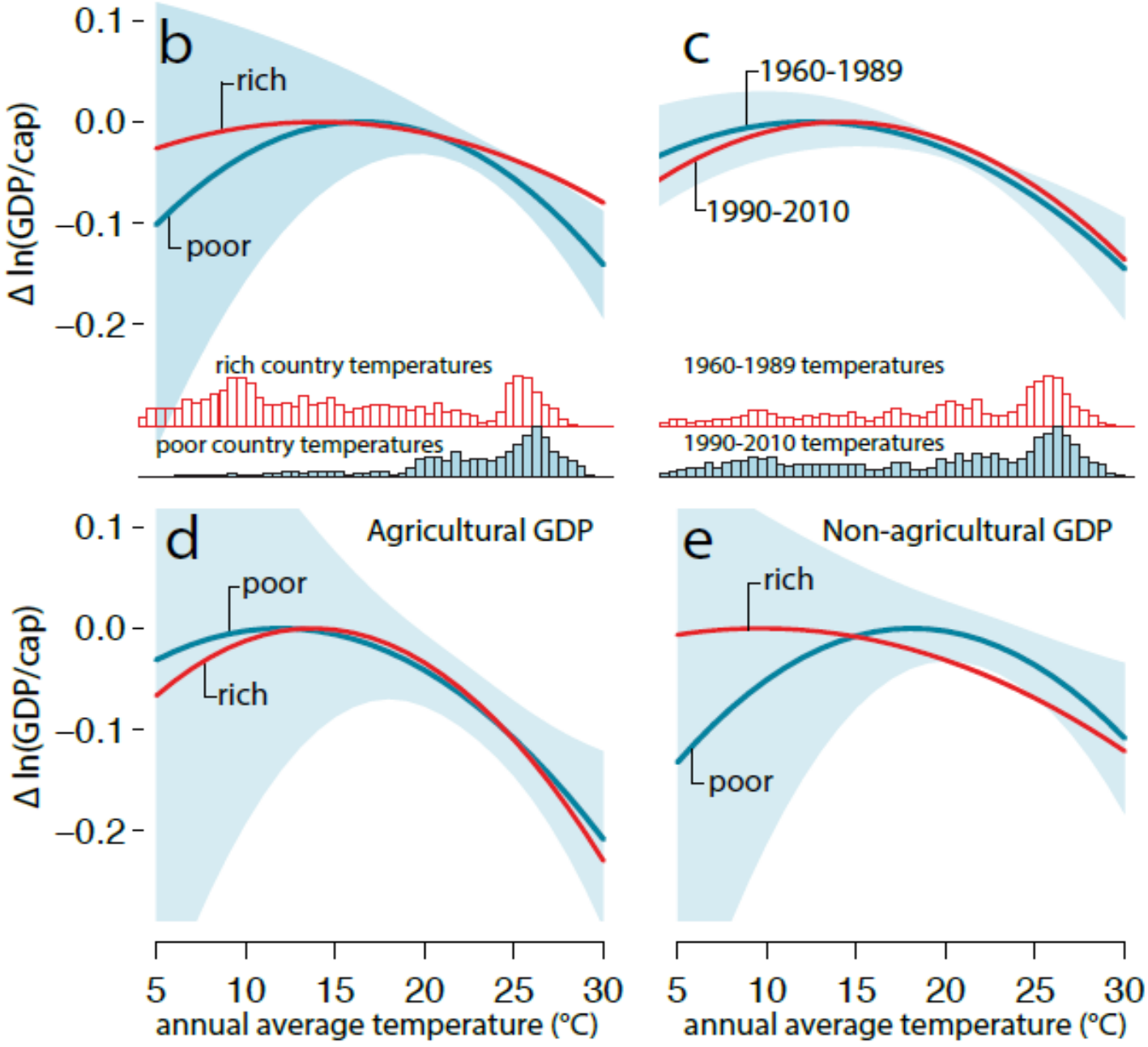
1) Wealth insulates societies from the effects of climate

2) Economic productivity has become less sensitive to climate over time (adaptation)

3) Agriculture is sensitive to climate but not other sectors


b
0.1
0.0
–0.1
–0.2
Δ ln(GDP/cap)
rich
poor
rich country temperatures
poor country temperatures


b
c
rich
poor
1960-1989
1990-2010
Δ ln(GDP/cap)
0.1
0.0
–0.1
–0.2
rich country temperatures
poor country temperatures
1960-1989 temperatures
1990-2010 temperatures


b
rich
poor
Δ ln(GDP/cap)
0.1
0.0
–0.1
–0.2
rich country temperatures
poor country temperatures
c
1960-1989
1990-2010
1960-1989 temperatures
1990-2010 temperatures
d
Agricultural GDP
poor
rich
e
Non-agricultural GDP
rich
poor
5
10
15
20
25
30
annual average temperature (°C)

How solid is conventional wisdom?

- Conventional wisdom in economics (sometimes built in IAM's):

1) Wealth insulates societies from the effects of climate

   → Perhaps partially: there is a somewhat flatter response for rich countries but not statistically distinguishable from the poor

2) Economic productivity has become less sensitive to climate over time (adaptation)

   → Not for this outcome

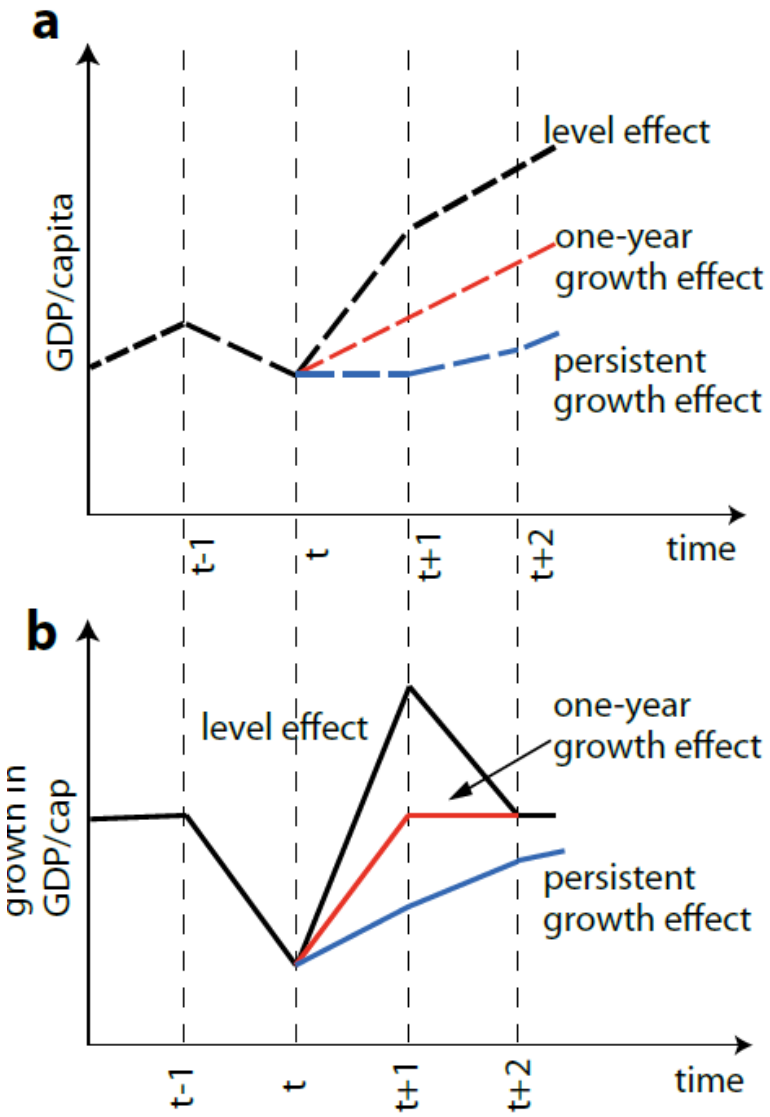
3) Agriculture is sensitive to climate but not other sectors

   → Not really: both appear sensitive to temperature, with agriculture somewhat more so (consistent with micro findings)

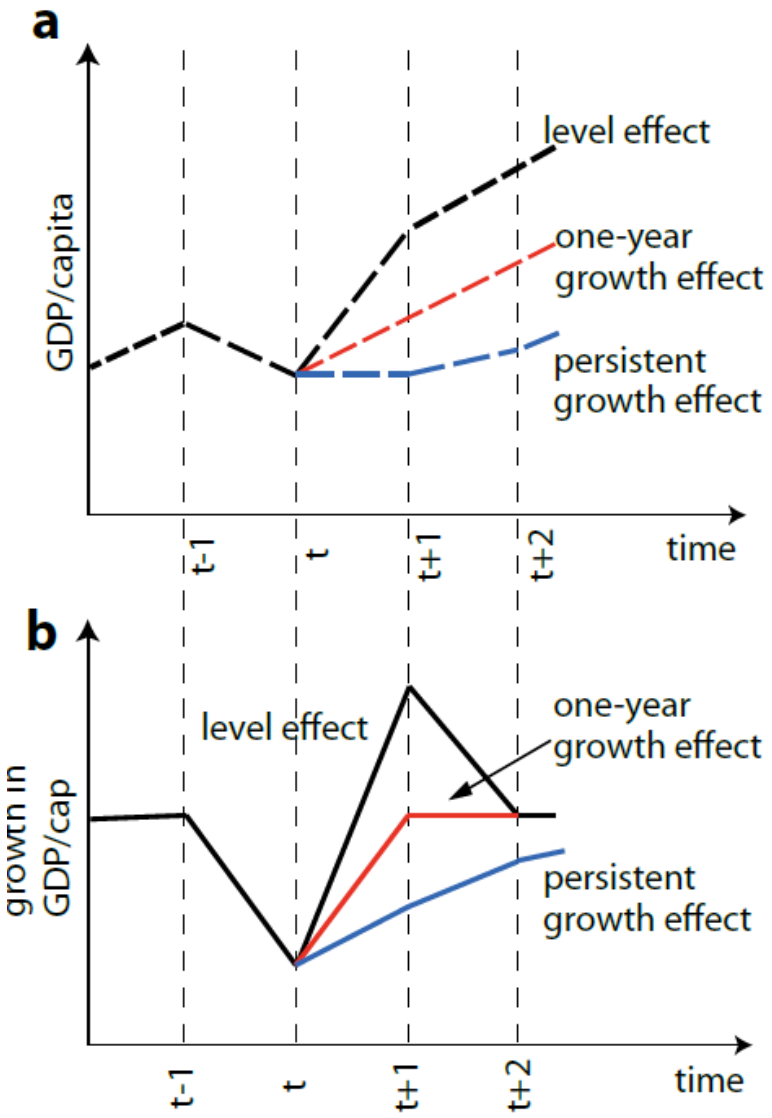
Are there persistent growth effects?

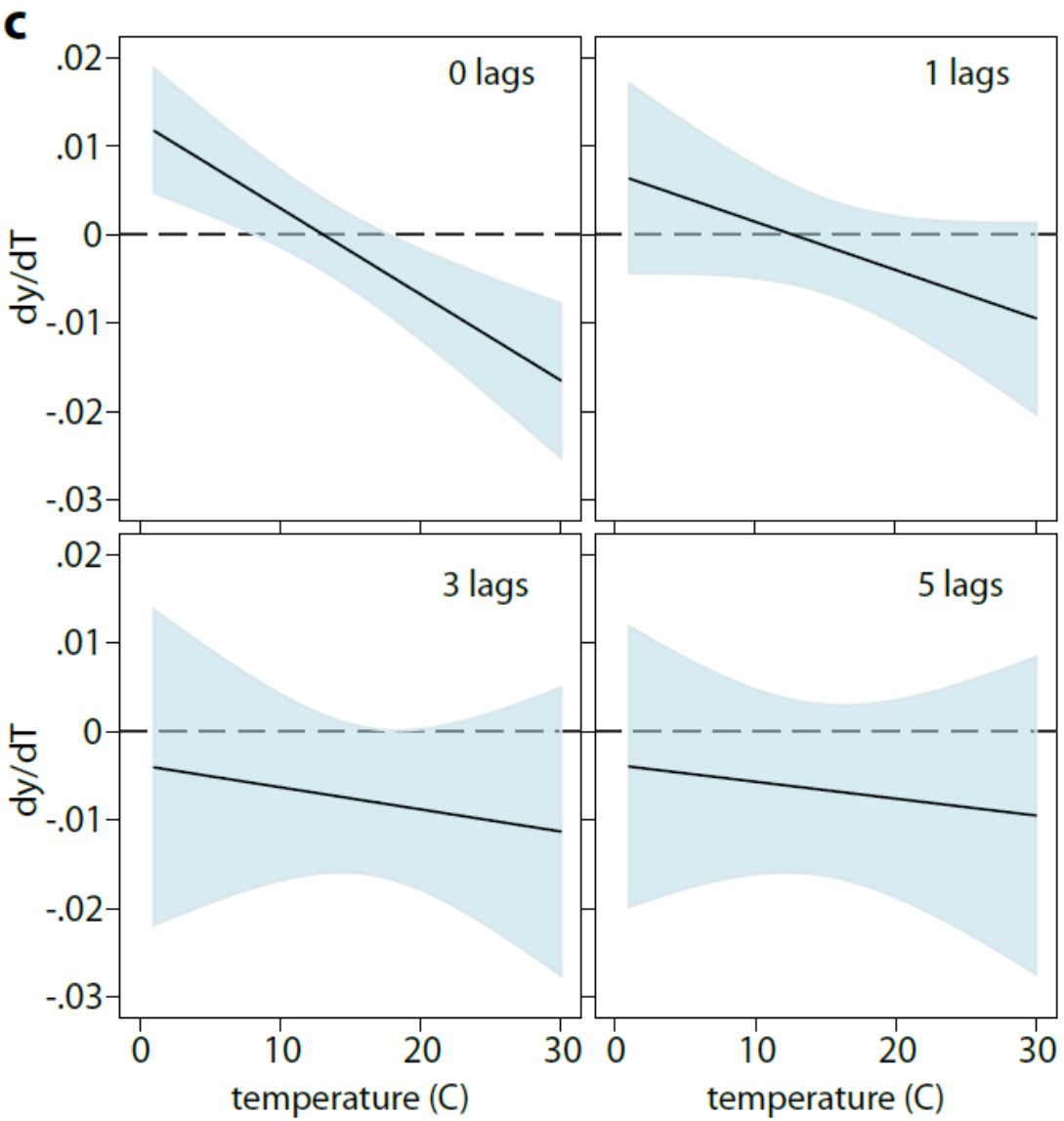
- Test for growth effects by summing up contemporaneous and lagged terms (for us, to t-5 years)
- “Temporary” level effects: effects in year t and t+1 are equal in magnitude and opposite sign

Growth effects of climate



Growth effects of climate





Are there persistent growth effects?

- Test for growth effects by summing up contemporaneous and lagged terms (for us, to t-5 years)
- "Temporary" level effects: effects in year t and t+1 are equal in magnitude and opposite sign

- There is some evidence or persistent growth effects: lagged terms sometimes statistically significant

→ Why? Shocks could reduce investment, hurting future productivity; investments may go towards adaptation measures as the climate changes (rather than productive capital); economic shocks could trigger violence and political instability that lowers productivity (Hsiang, Burke and Miguel 2013)

Projecting climate change impacts

- Project future GDP per capita for country i (Y_{it}) to 2100 as a function of the estimated temperature effects, *g(T)*:

$$Y_{it} = Y_{it-1} * \{1 + \eta_{it} + [g(T_{it}^{+}) - g(\bar{T})]\}$$

- Projected temperature T_{it}^{+} is the median of the Coupled Model Intercomparison Project (CMIP5) ensemble, under the "business as usual" **RCP8.5 scenario** of high GHG emissions

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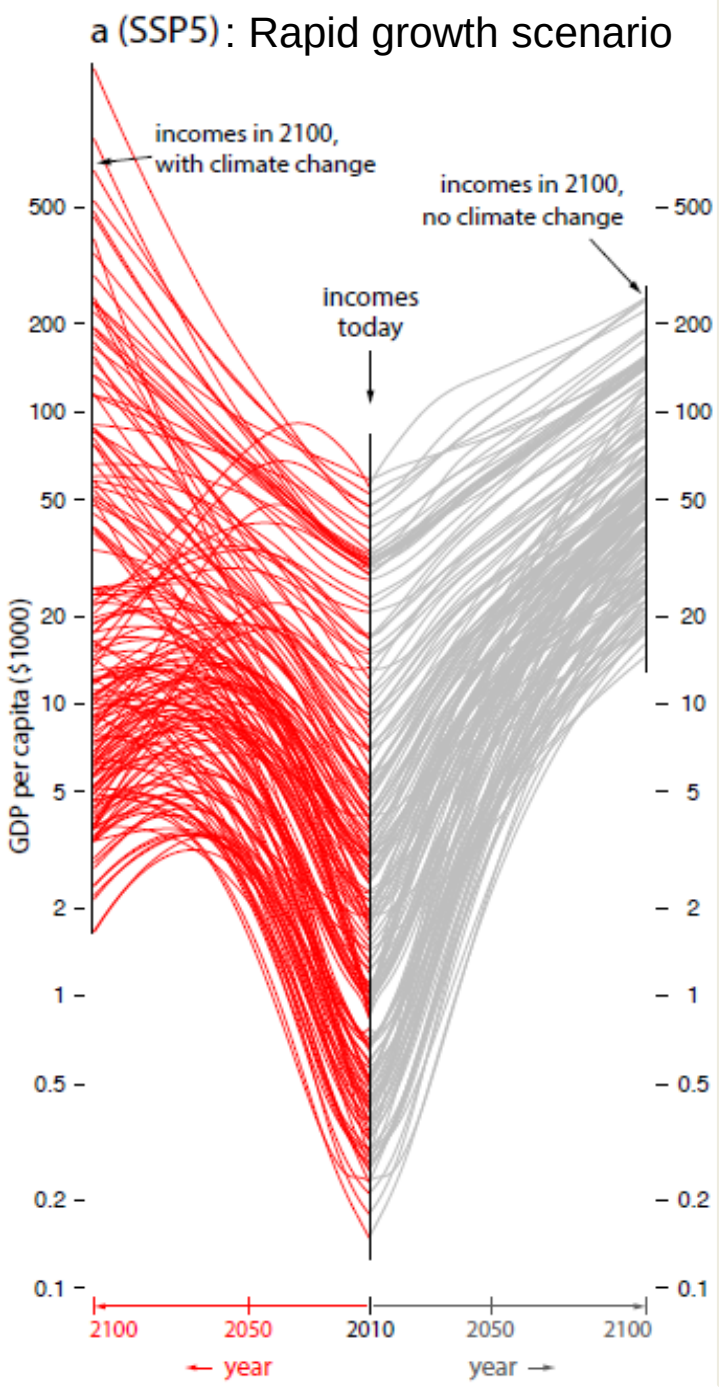
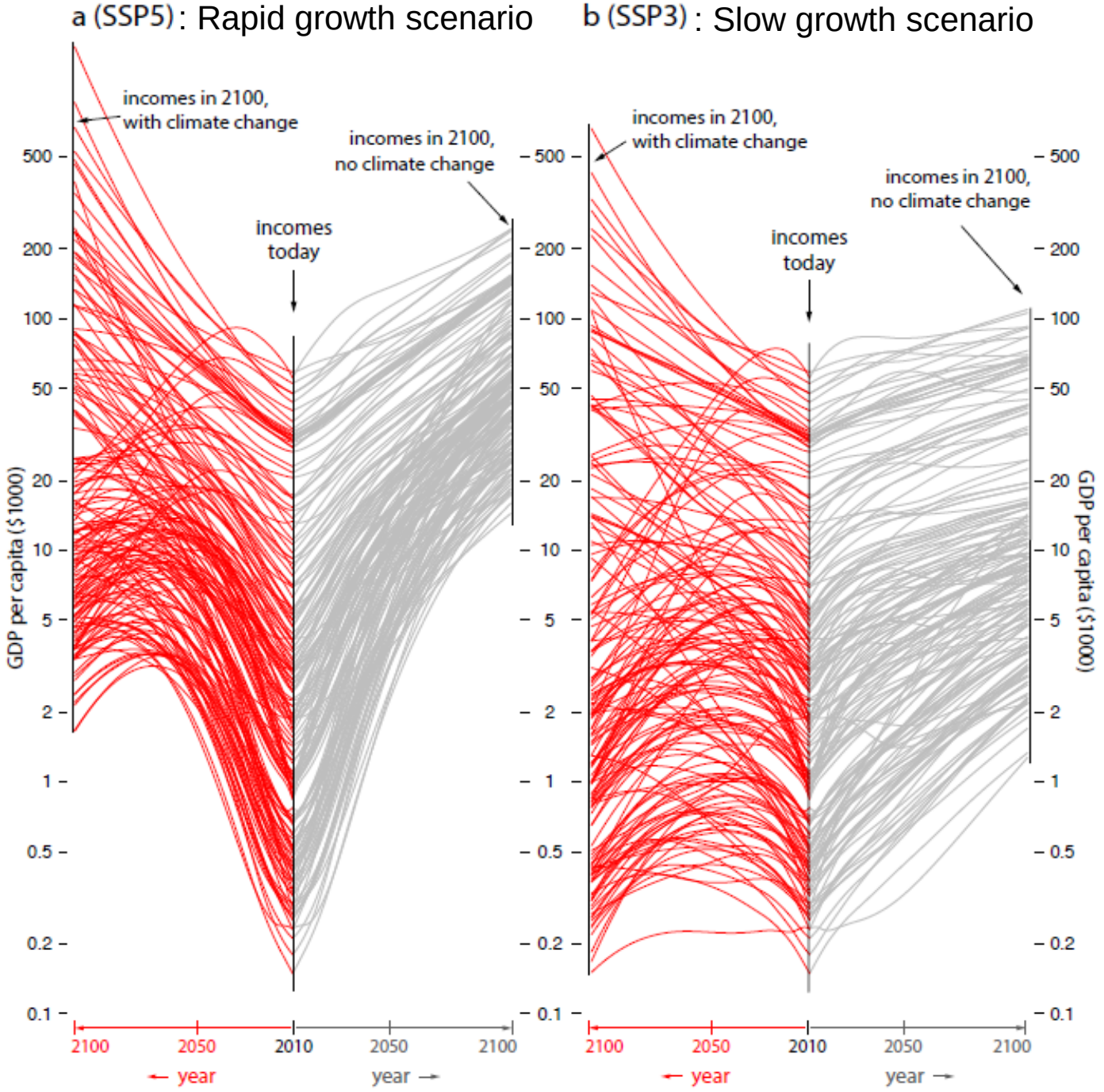
- The "baseline" growth rate η_{it} is computed either as the average over 1980-2010, or using the "Shared Socioeconomic Pathways" (SSP's) developed by the climate community
- SSP3 (slow growth, ~1% per annum); SSP5 (rapid growth, ~3%)


a (SSP5): Rapid growth scenario
incomes in 2100, with climate change
incomes in 2100, no climate change
incomes today
GDP per capita ($1000)
500
200
100
50
20
10
5
2
1
0.5
0.2
0.1
2100
2050
2010
2050
2100
year
year

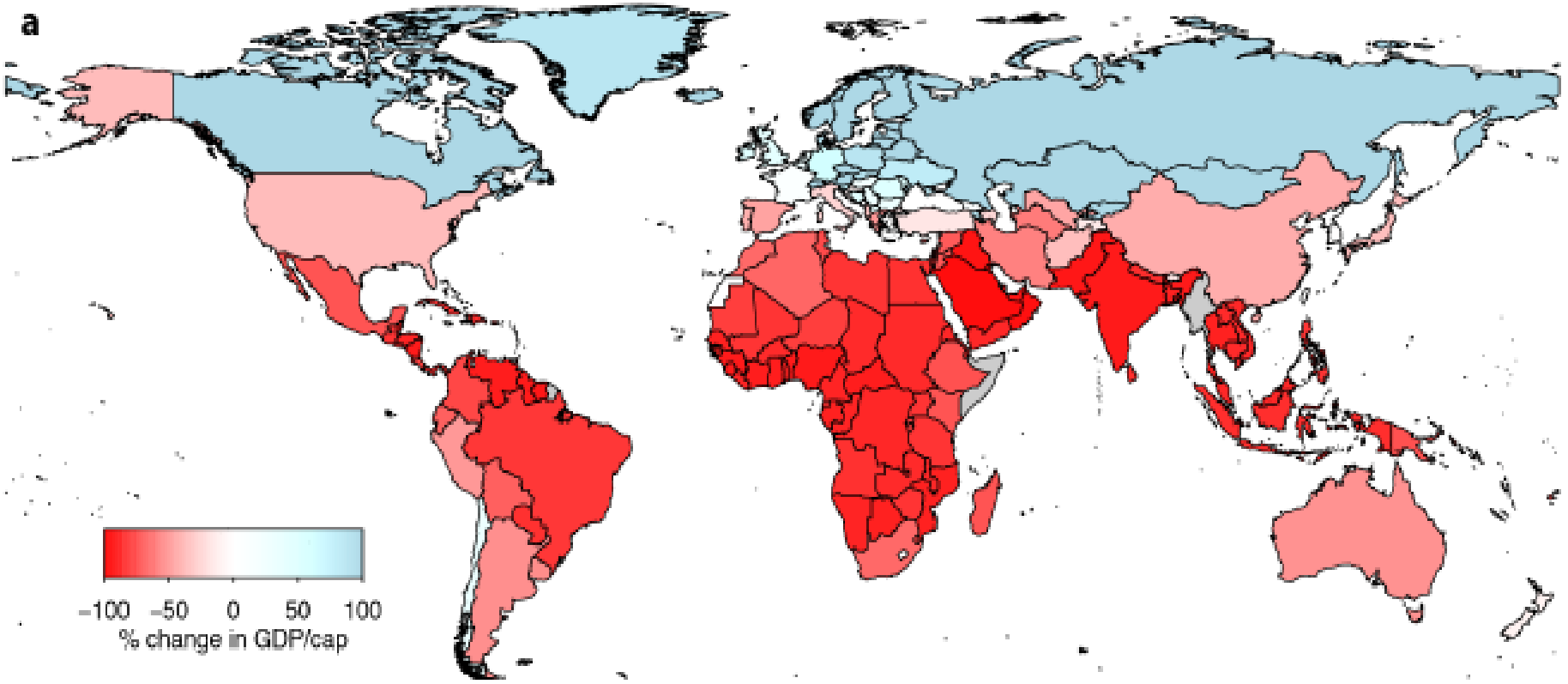
WB-2015


a (SSP5) : Rapid growth scenario
b (SSP3) : Slow growth scenario
incomes in 2100, with climate change
incomes in 2100, no climate change
incomes today
GDP per capita ($1000)
500
200
100
50
20
10
5
2
1
0.5
0.2
0.1
2100
2050
2010
2050
2100
year

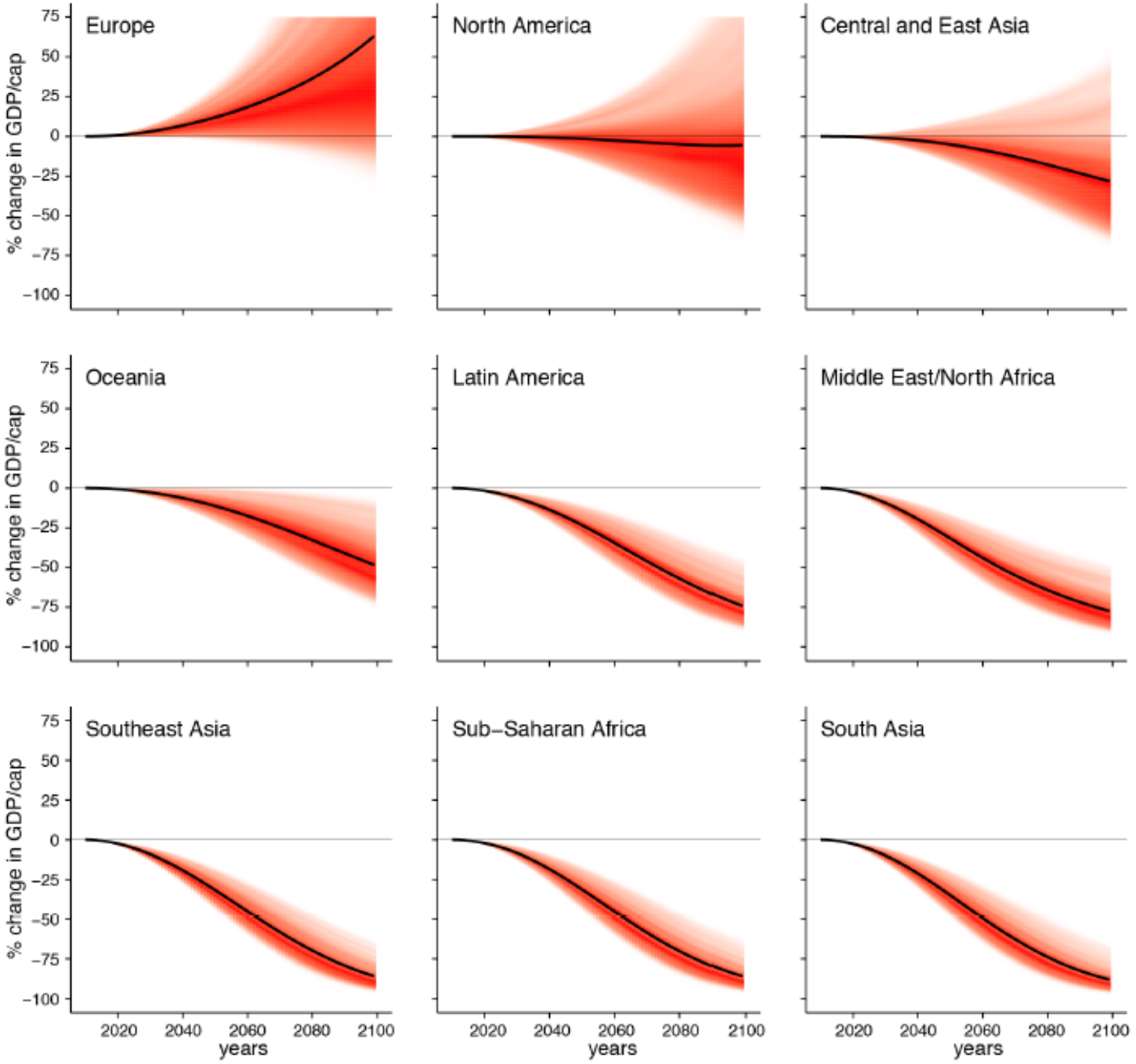
High likelihood of negative impacts

Statistic	Projected impacts under alternate scenarios of future population/income growth *% impact relative to world without climate change*		
	base	SSP3	SSP5
point est.	-36	-26	-23
5th	-65	-60	-58
25th	-50	-42	-39
50th	-35	-24	-21
75th	-16	2	5
95th	27	67	66
% runs < 0	85	73	71
% runs < -10	79	66	63
% runs < -20	71	56	51

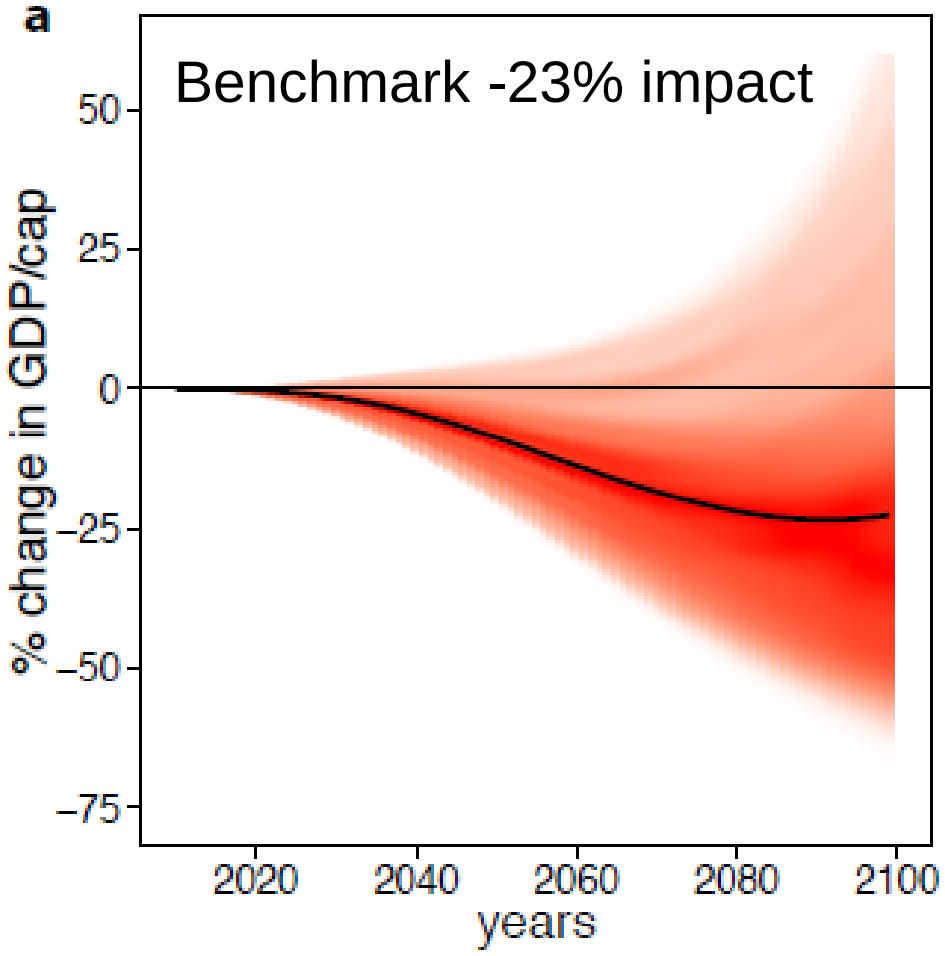
Relative to no climate change

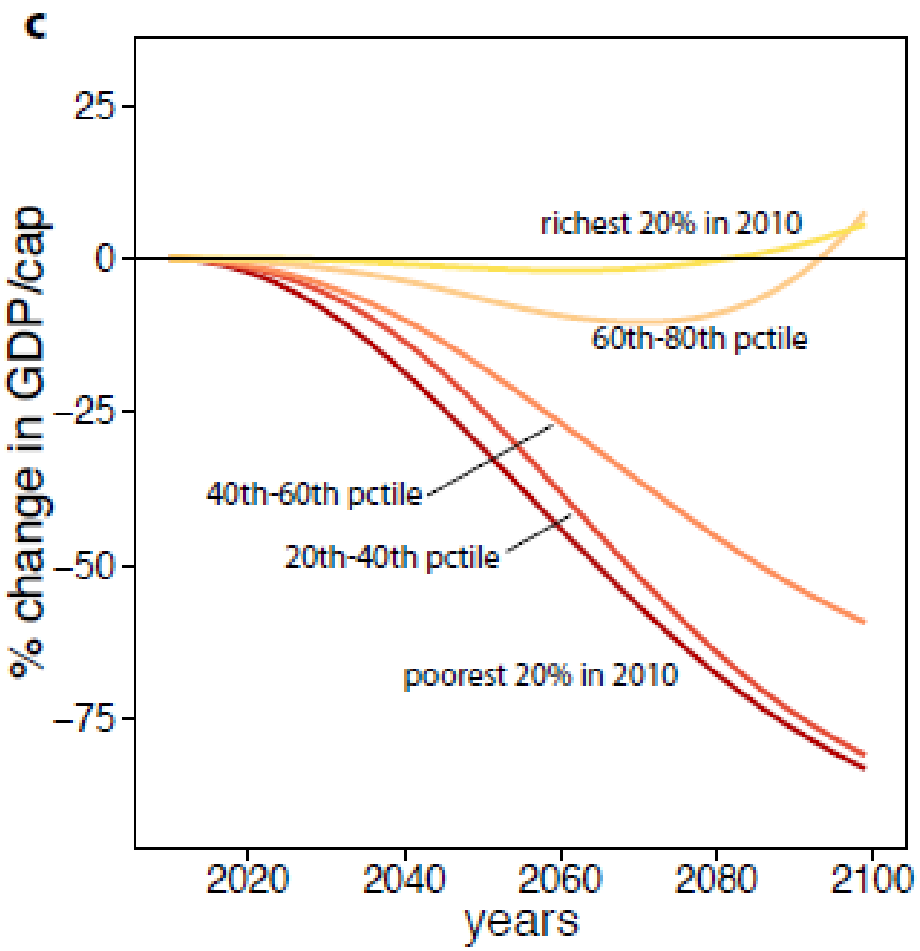


>75% countries worse off


Europe
North America
Central and East Asia
Oceania
Latin America
Middle East/North Africa
Southeast Asia
Sub−Saharan Africa
South Asia
% change in GDP/cap
75
50
25
0
−25
−50
−75
−100
2020
2040
2060
2080
2100
years

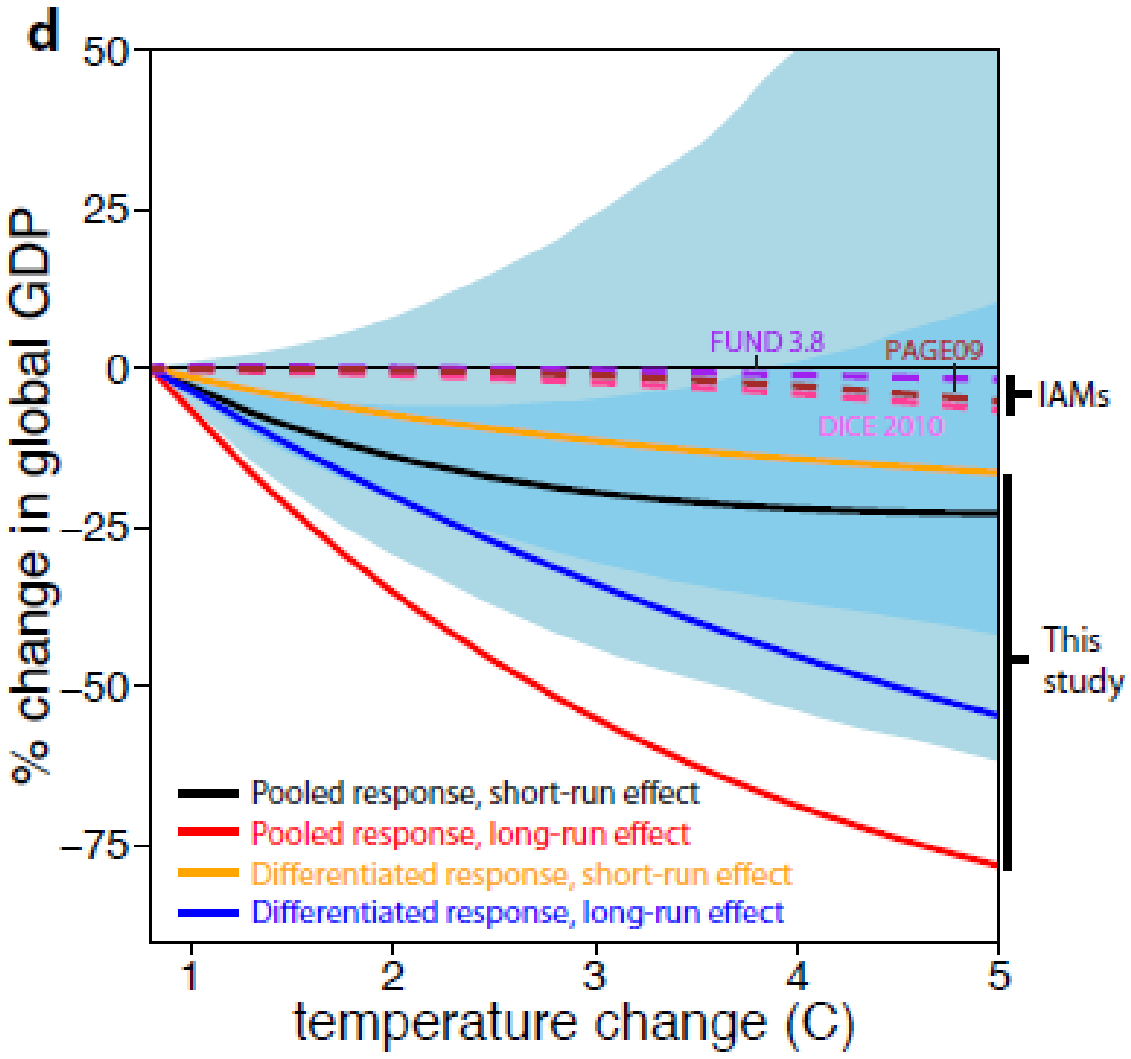
Risk of rising global income inequality





Projected effects far larger than IAM's

Economic growth effects are a key difference



Comparison to Dell, Jones, Olken 2012

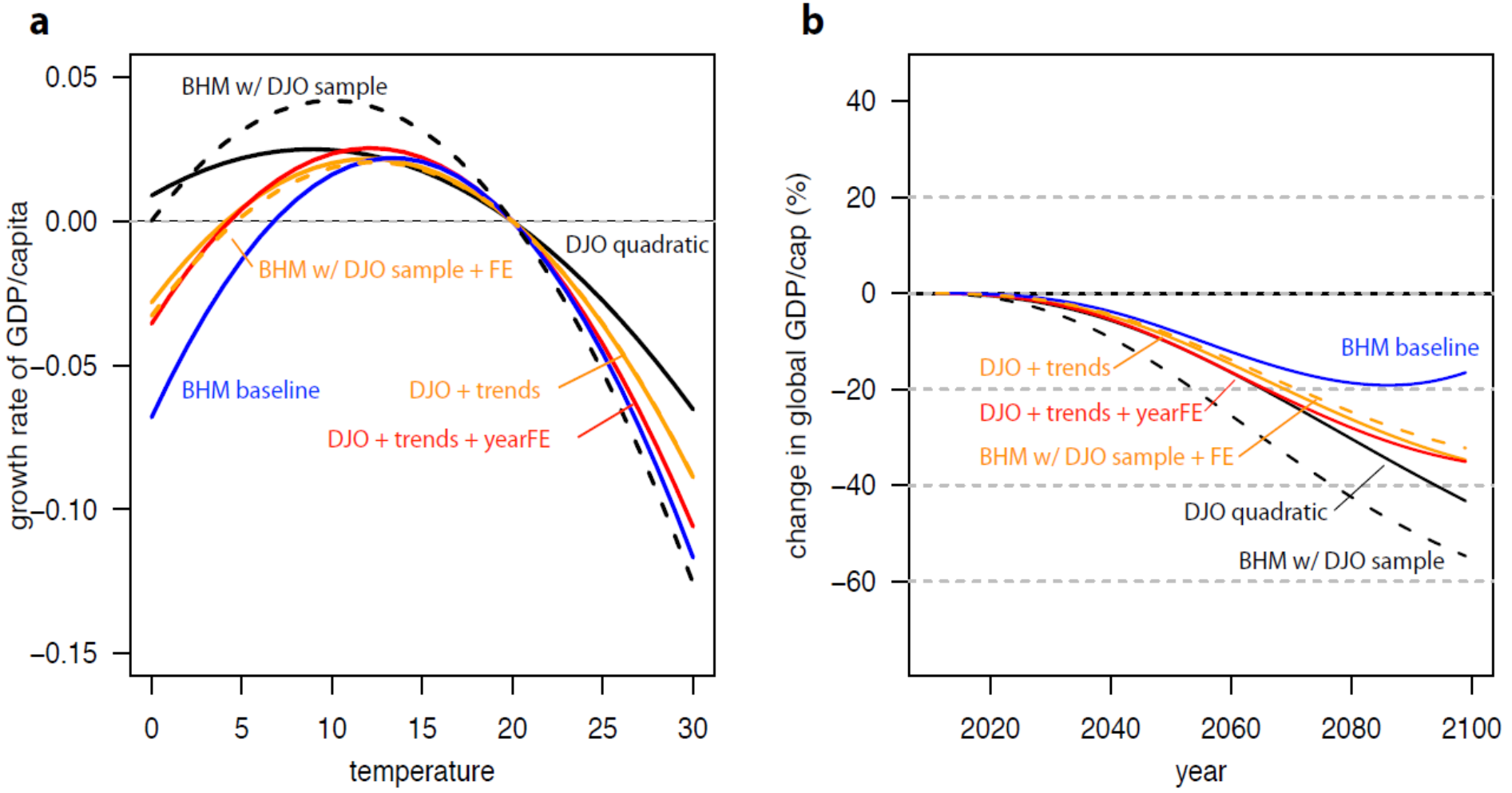
- We use slightly longer time series, and updated data; and slightly different empirical specification than DJO 2012

- The quadratic temperature term in DJO 2012 is only marginally significant and they focus on linear specifications, separately for rich and poor countries

→ Results using a quadratic specification are very similar regardless of data series and other econometric modeling choices

→ Their linear specification yields much more "optimistic" projections of future climate impacts, in part because the point estimate for rich countries is positive (but small, not significant)

Comparison to Dell, Jones, Olken 2012



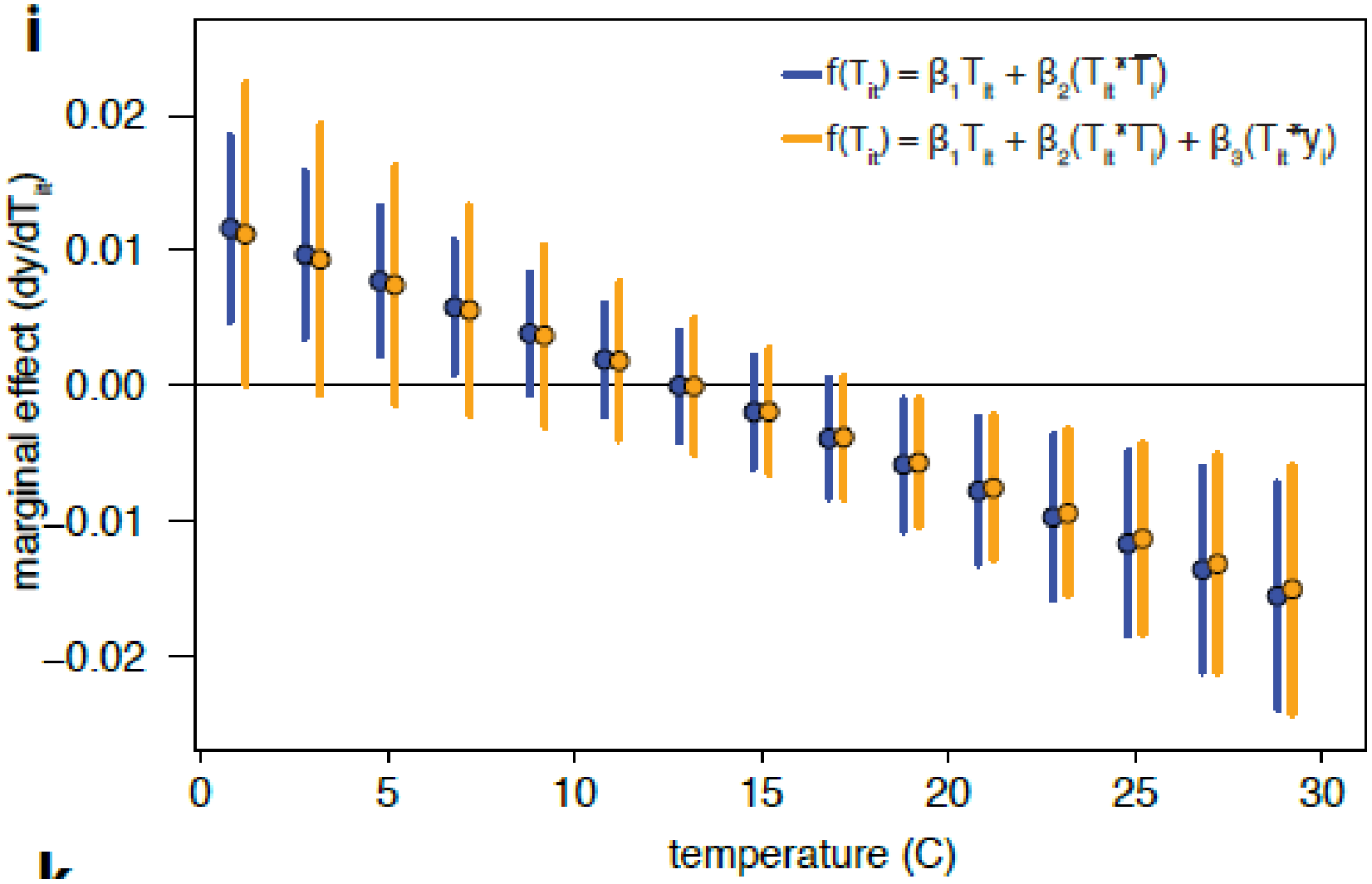
Conclusions

1. A non-linear effect of temperature on growth historically
   - No significant differences between rich and poor countries
   - No evidence of meaningful adaptation over time
2. High likelihood of large losses under future climate change
   - Under "business as usual" emissions, 51-71% odds global income per capita is >20% lower by 2100
   - Low income regions are at greatest risk
3. Loss estimates are far larger than existing damage functions, despite fact that our effects only work through temperature
   - Losses an order of magnitude larger than leading IAM's

→ Much more investment in mitigation is likely to be optimal

END – EXTRA SLIDES

Non-linearity, conditional on income



Robustness of non-linearity

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

Robustness of non-linearity (2)

	(6) ContYr + noTrend	(7) No YrFE	(8) LinearTime	(9) LDV 1lag	(10) LDV 3lags	(11) PWT
Temp.	0.0133***	0.0103***	0.0128***	0.0087**	0.0062*	0.0072*
	(0.0034)	(0.0039)	(0.0043)	(0.0039)	(0.0038)	(0.0039)
Temp. sq.	-0.0004***	-0.0004***	-0.0005***	-0.0004***	-0.0003***	-0.0004***
	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)
Precip.	0.0084	0.0159	0.0137	0.0165*	0.0201**	0.0195*
	(0.0098)	(0.0107)	(0.0100)	(0.0095)	(0.0098)	(0.0109)
Precip. sq.	-0.0021	-0.0045*	-0.0035	-0.0047*	-0.0052**	-0.0038
	(0.0023)	(0.0026)	(0.0023)	(0.0024)	(0.0024)	(0.0028)
Constant	-0.0819**	-0.8024**	-0.7693***	-11.3227***	-28.3451***	0.0643
	(0.0370)	(0.3366)	(0.0517)	(0.7957)	(2.0763)	(0.0467)
Observations	6584	6584	6584	6418	6086	6627
R squared	0.267	0.240	0.219	0.286	0.289	0.220
Optimum	17.40	12.74	13.40	11.92	9.98	9.88

No significant rich-poor difference

	(1) Base	(2) poor-yr FE	(3) >20Yrs
Temperature (β_1)	0.0089**	0.0069	0.0085*
	(0.0044)	(0.0050)	(0.0044)
Temperature sq. (β_2)	-0.0003*	-0.0003	-0.0003
	(0.0002)	(0.0002)	(0.0002)
Temperature * 𝟙[poor] (β_3)	0.0165	0.0193	0.0246
	(0.0182)	(0.0187)	(0.0186)
Temperature sq. *𝟙[poor] (β_4)	-0.0005	-0.0005	-0.0006
	(0.0004)	(0.0004)	(0.0004)
Observations	6452	6452	6345
R squared	0.291	0.299	0.284
$\beta_1 + \beta_3$	0.0254	0.0262	0.0332
se($\beta_1 + \beta_3$)	0.0177	0.0180	0.0181
$\beta_2 + \beta_4$	-0.0008	-0.0008	-0.0009
se($\beta_2 + \beta_4$)	0.0004	0.0004	0.0004
Rich-country optimum (C)	14.1	12.2	14.2
Poor-country optimum (C)	16.5	17.2	17.8

No significant rich-poor difference (2)

	(4) >20Yrs+poor-yr FE	(5) ContYr FE	(6) ContYr + noTren
Temperature (β_1)	0.0063	0.0099*	0.0146***
	(0.0050)	(0.0054)	(0.0052)
Temperature sq. (β_2)	-0.0003	-0.0003	-0.0005***
	(0.0002)	(0.0002)	(0.0002)
Temperature * 𝟙[poor] (β_3)	0.0275	0.0115	0.0016
	(0.0191)	(0.0147)	(0.0147)
Temperature sq. *𝟙[poor] (β_4)	-0.0007	-0.0004	0.0001
	(0.0004)	(0.0004)	(0.0003)
Observations	6345	6452	6452
R squared	0.293	0.372	0.270
$\beta_1 + \beta_3$	0.0338	0.0215	0.0162
se($\beta_1 + \beta_3$)	0.0184	0.0130	0.0123
$\beta_2 + \beta_4$	-0.0009	-0.0007	-0.0004
se($\beta_2 + \beta_4$)	0.0004	0.0003	0.0003
Rich-country optimum (C)	12.2	19.2	15.1
Poor-country optimum (C)	18.3	16.2	20.6

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