BROWN BAG SEMINAR, UNIVERSITY OF MAINZ

Climate shift uncertainty and economic damages

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C3S Center for Critical Computational Studies

WÜBBEN STIFTUNG WISSENSCHAFT

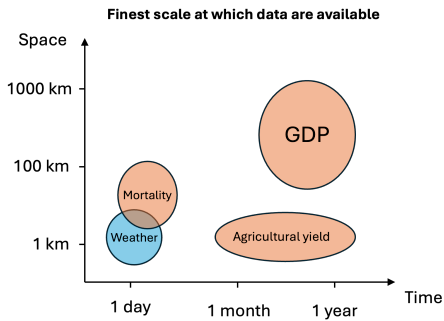
Motivation

Climate action requires information on climate impacts:

- Policies to mitigate climate change require information about the social costs of GHG emissions.
- Adaptation requires locally relevant information about future impacts.

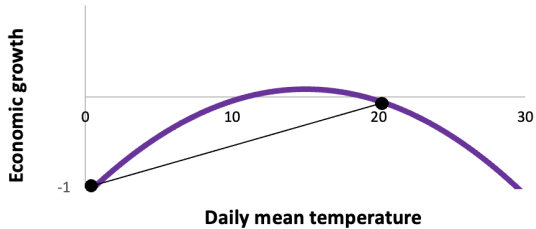
Data is widely available on past weather and socioeconomic outcomes with varying level of aggregation (time, space, sector, etc.).

How does **temporal aggregation** of weather (from days to years) affect our projections of the costs of climate change?



Aggregation of non-linear functions

Aggregation generally matters because of the concavity of most damage functions:



Non-linear damage function

Jensen's inequality:

g(Average [T]) > Average [g(T)]

Summary

METHODS

- We estimate the effect of daily temperature on annual economic growth rates (1950-2020).
- We use our estimates to project the costs of future climate change (2045-2054).
- We compare projections using the full distribution of **daily** temperature vs projections that shift the control distribution by the **annual** mean warming.

PREVIEW OF RESULTS

- Projections based on **annual** mean warming *underestimate* the costs of climate change by $\approx$ 16 % (0.052 pp).
- The omission comes from the **seasonal** pattern of warming.
- The omitted damages form a dipole: positive at Northern mid-latitudes, negative at high latitudes, close to zero in the tropics.

Contributions to the literature

(1) TEMPERATURE AND ECONOMIC GROWTH

- Earlier work relates *annual* mean temperature to annual economic growth rates: Dell 2011, Burke et al. 2015, Kalkuhl and Wenz 2020, Nath et al., and many others. Bilal and Kaenzig (2026) argue that *global* annual mean temperature shocks matter more than *local* shocks.
- Our results quantify the share of damages missing due to *temporal aggregation*.

(2) HETEROGENEOUS RESPONSES TO TEMPERATURE SHOCKS

- Earlier work provides evidence for large *spatial heterogeneity* in the response to temperature shocks (e.g. Linsenmeier et al. 2026).
- We estimate models of daily temperature with climate as moderator (income in robustness tests), accounting for some forms of adaptation.

(3) MODELING TEMPERATURE SHOCKS

- Other work focuses on temperature extremes (e.g. Waidelich et al. 2024), temperature variability (Kotz et al. 2020, Linsenmeier 2022).
- We integrate over the full distribution of daily temperature and show that the seasonal pattern of warming, not day-to-day variability, drives the result.

Data, model and estimation

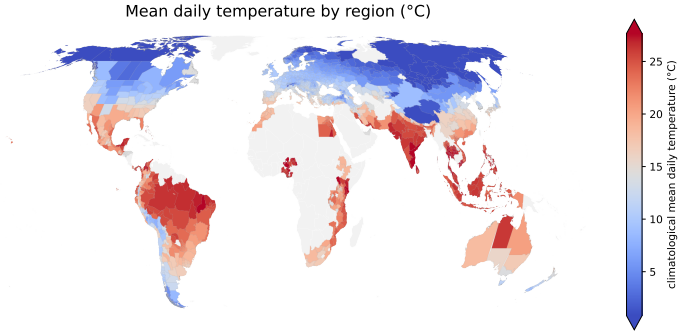
DATA

- We combine daily ERA5 reanalysis with regional annual GDP from DOSE (v2.14).
- Projections use bias-adjusted daily temperature from five CMIP6 climate models.

MODEL AND ESTIMATION

- We estimate a smooth model (restricted cubic splines) with region and country-year fixed effects.
- We identify the effect from temperature surprises, following Nath et al. (WP).

Data coverage



The sample covers 1,659 subnational regions over 1950-2020, with temporal coverage varying by region.

Model and estimation

Moderated model of annual growth:

$$g_{i,t} = \sum_k \Big[\beta_k + \underbrace{\delta_k z_i}_{\text{climate}}\Big] u_{k,i,t} + \boldsymbol{\gamma}' \mathbf{p}_{i,t} + \mu_i + \nu_{c(i),t} + \varepsilon_{i,t}.$$

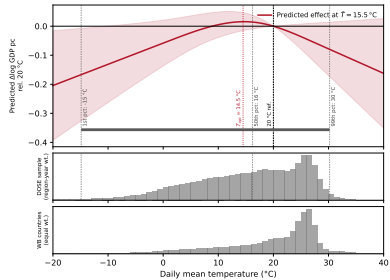
with residuals $u_{k,i,t}$ (“surprises”) from

$$\bar{b}_k(T)_{i,t} = a_{i,k} + \sum_{\ell=1}^{2} \boldsymbol{\pi}'_{i,\ell}\, \bar{\mathbf{b}}(T)_{i,t-\ell} + u_{k,i,t}.$$

and the temporally aggregated spline basis $\bar{b}(.)_{k,i,t}$

$$\bar{b}_k(T)_{i,t} = \frac{1}{|Y_{i,t}|} \sum_{d \in Y_{i,t}} b_k(T_{i,d}), \qquad k = 1, \ldots, K.$$

Result 1: “Inverted U” shape: heat and cold reduces economic growth



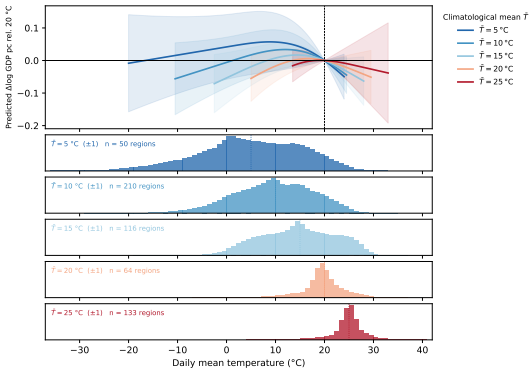
Economic growth is lowered by very cold and very high daily temperature (“inverted U”).

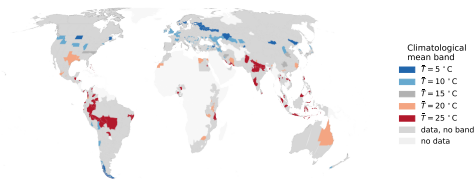
The overall shape of the curve is robust to alternative model specifications (splines with more knots, polynomial, region-specific trends instead of temperature surprises).

In the projected climate of 2050, annual GDP growth is 0.38 pp lower than in the pre-industrial climate (contemporaneous effect).

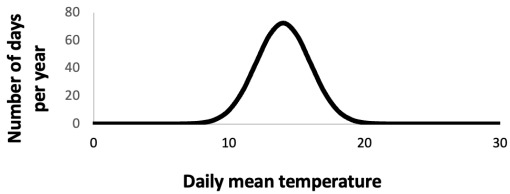
Result 2: Decline in output less steep in “better adapted” regions

Regions that have a warmer climate show a smaller decline in GDP in response to high temperature (analogously: colder climate and response to cold temperature).





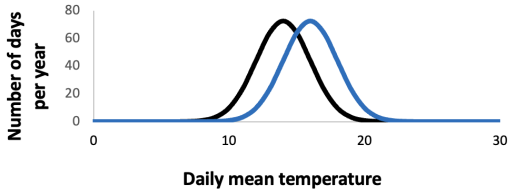
Scenarios (illustration)



Distribution of daily mean temperature:

Historical

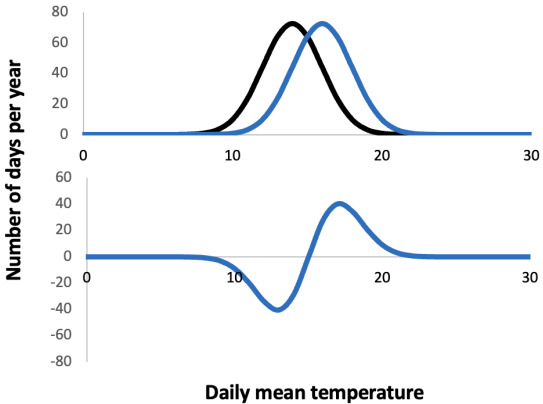
Scenarios



Distribution of daily mean temperature:

Historical
Future (shape-preserving)

Scenarios

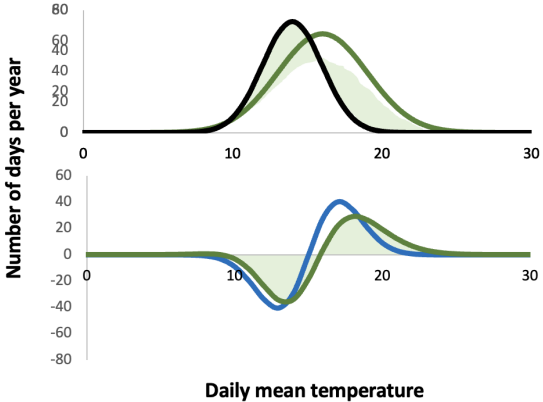


Distribution of daily mean temperature:

Historical
Future (shape-preserving)

Future (shape-preserving) minus **Historical**

Scenarios

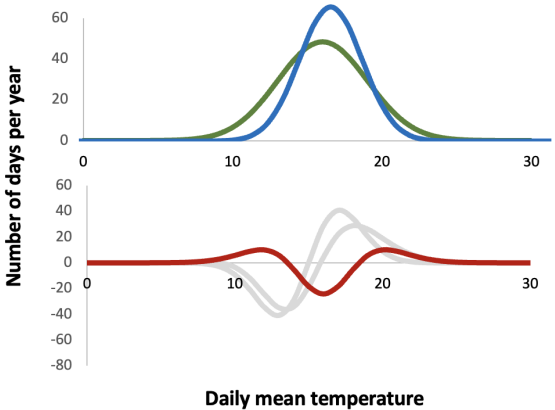


Distribution of daily mean temperature:

Historical
Future (shape-changing)

Future (shape-changing) minus **Historical**

Scenarios

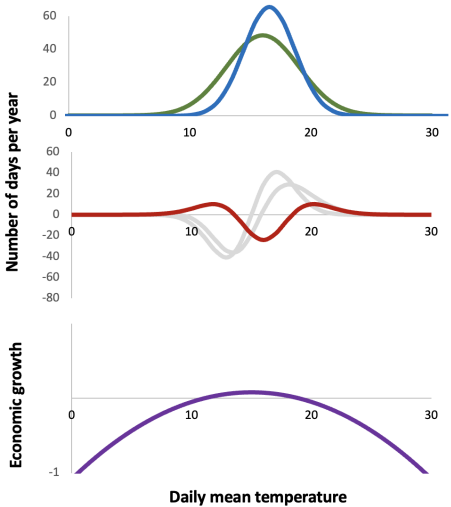


Distribution of daily mean temperature:

Future (shape-preserving)
Future (shape-changing)

Omitted days
(shape changing minus shape preserving)

Scenarios



Distribution of daily mean temperature:

Future (shape-preserving)
Future (shape-changing)a

Omitted days
(shape changing minus shape preserving)

Non-linear damage function

Projections

For every climate scenario and every climate model, we project the change in annual GDP growth relative to the pre-industrial control, $\Delta\hat{g}$ (in pp; negative when growth falls). We aggregate over regions (weighing by GDP) and average over the years 2045-2054.

We compare two projections and the difference between them:

$\Delta\hat{g}^{\text{mean}}$	**shape-preserving** (mean): control shifted by annual mean warming
$\Delta\hat{g}^{\text{full}}$	**shape-changing** (full): the climate model's daily temperatures
$\Delta\hat{g}^{\text{mean}} - \Delta\hat{g}^{\text{full}}$	**omitted damage**: missed by the mean projection (pp)
$\dfrac{\Delta\hat{g}^{\text{mean}} - \Delta\hat{g}^{\text{full}}}{-\Delta\hat{g}^{\text{mean}}}$	omitted damage as a fraction of the loss in the mean projection (in %)

$\Delta\hat{g}^{\text{mean}} - \Delta\hat{g}^{\text{full}} > 0$: the mean projection underestimates the costs.

Underestimation of global costs

The shape-preserving shift (*mean*) underestimates global costs:

	$\Delta\hat{g}^{\text{mean}}$ (pp)	$\Delta\hat{g}^{\text{full}}$ (pp)	$\Delta\hat{g}^{\text{mean}} - \Delta\hat{g}^{\text{full}}$ (pp)	$\frac{\Delta\hat{g}^{\text{mean}} - \Delta\hat{g}^{\text{full}}}{-\Delta\hat{g}^{\text{mean}}}$ (%)
SSP1-2.6	−0.2430	−0.3023	0.0594 [0.0153, 0.1024]	24.4 [6.3, 42.1]
SSP3-7.0	−0.3437	−0.3960	0.0523 [0.0150, 0.0886]	15.2 [4.4, 25.8]
SSP5-8.5	−0.4017	−0.4457	0.0440 [0.0126, 0.0746]	10.9 [3.1, 18.6]
mean of SSP	**−0.3295**	**−0.3813**	**0.0519** [0.0145, 0.0881]	**15.7** [4.4, 26.7]

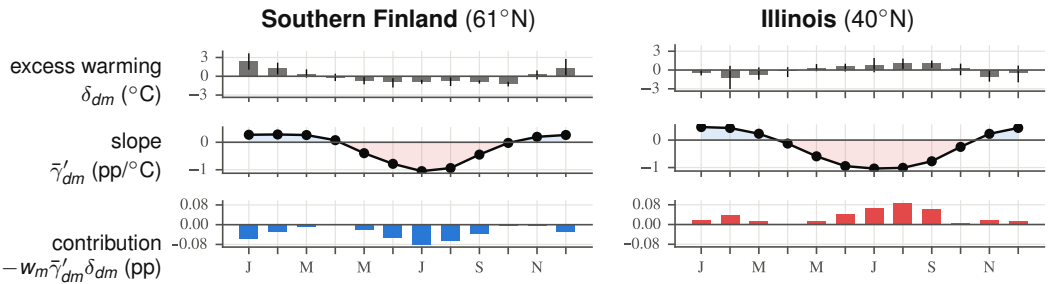
Mechanism: the seasonal pattern of warming

Second-order expansion of the omitted damage in region d:

$$\Delta\hat{g}_d^{\text{mean}} - \Delta\hat{g}_d^{\text{full}} \approx \underbrace{-\sum_m w_m\,\bar{\gamma}'_{dm}\,\delta_{dm}}_{=-\mathrm{Cov}_m(\bar{\gamma}'_{dm},\,\delta_{dm})} \underbrace{-\tfrac{1}{2}\sum_m w_m\,\bar{\gamma}''_{dm}\left(\delta_{dm}^2 + \Delta\sigma_{dm}^2\right)}_{\text{offset each other globally}}$$

- $\Delta\hat{g}_d^{\text{mean}}$, $\Delta\hat{g}_d^{\text{full}}$: change in annual GDP growth of region d in the mean and full projection (pp)
- w_m: share of the year's days in month m
- δ_{dm}: excess warming of month m over the year
- $\bar{\gamma}'_{dm}$, $\bar{\gamma}''_{dm}$: mean slope and curvature of the damage function γ_d over the days of month m
- $\Delta\sigma^2_{dm}$: change in the within-month variance of daily temperature

Mechanism: Southern Finland and Illinois

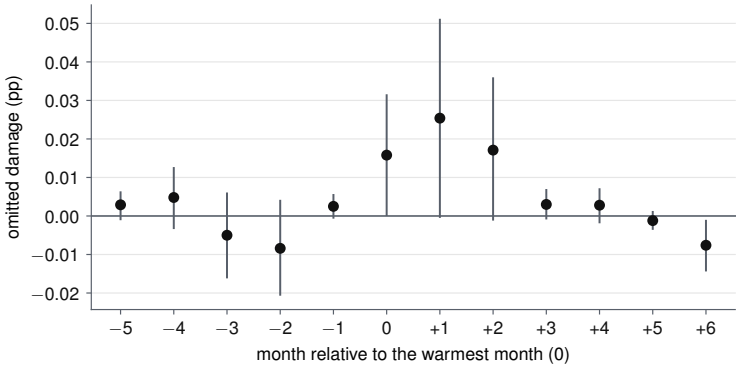


- In Southern Finland, winter warms faster than the year when warming helps growth, so the mean projection overstates the damage (omitted damage -0.41 pp).
- In Illinois, late summer warms faster than the year when warming hurts growth, so the mean projection understates the damage (omitted damage $+0.40$ pp).

SSP3-7.0, 2050

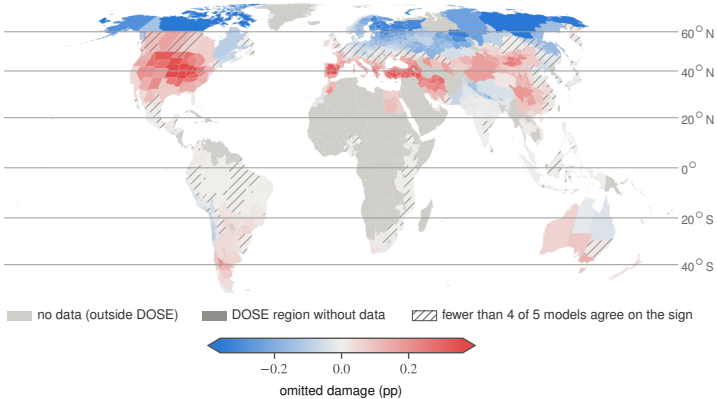
Mechanism: the omission arises in the warm season

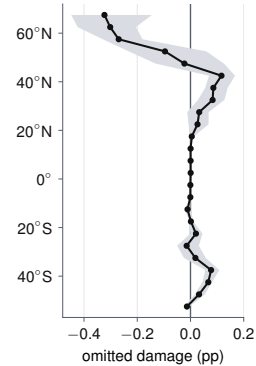
The omission peaks one month after the warmest month.



All regions, SSP3-7.0; 5–95 % over the damage-function draws

Omitted damages by latitude

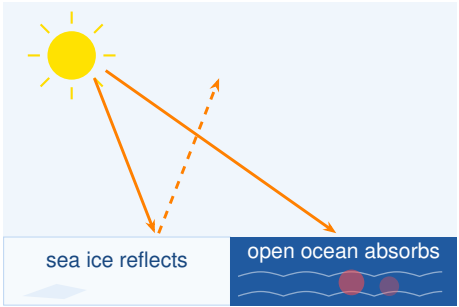




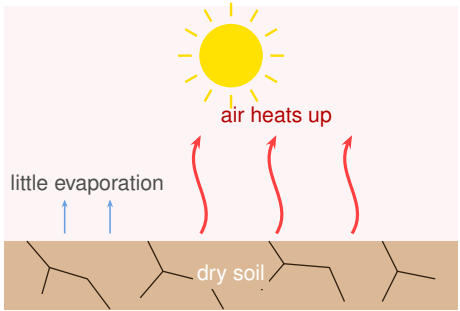
Map: all SSP. Right: SSP3-7.0; band: 5–95 % across climate models

Physical drivers of the dipole

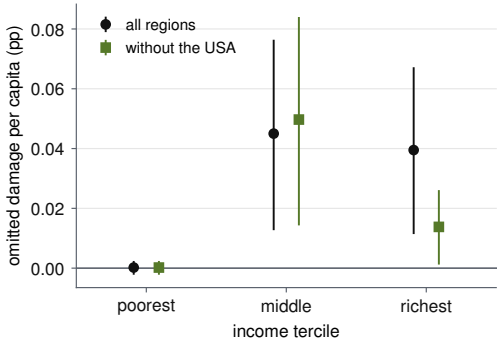
Far north: winters warm most



Mediterranean: summers warm most



Omitted damages by income



Omitted damages are concentrated in the middle- and high-income terciles.

All SSP; 5–95 % over the damage-function draws

Assumptions about the data generating process

We assume that daily temperature affects daily economic activity (e.g. labour productivity).

We allow for non-linearity in this relationship. We also allow for the relationship to differ by climate.

But:

- We ignore time-cumulative effects (e.g. prolonged heat waves).
- We ignore possibly heterogeneous responses over the annual cycle.

Summary and robustness

- Projecting damages with annual mean warming understates growth damages by about a sixth in 2050.
- The results differ more by climate model than by SSP because the models differ in the seasonal patterns of warming. Dropping one climate model at a time, the share stays between 12.1 % and 18.1 %.
- These effects are calculated within the sample of regions in DOSE. Adding regions for the rest of the world (1.52 billion people) lowers the omitted damages from 15.7 % to 15.2 %.

Thank you

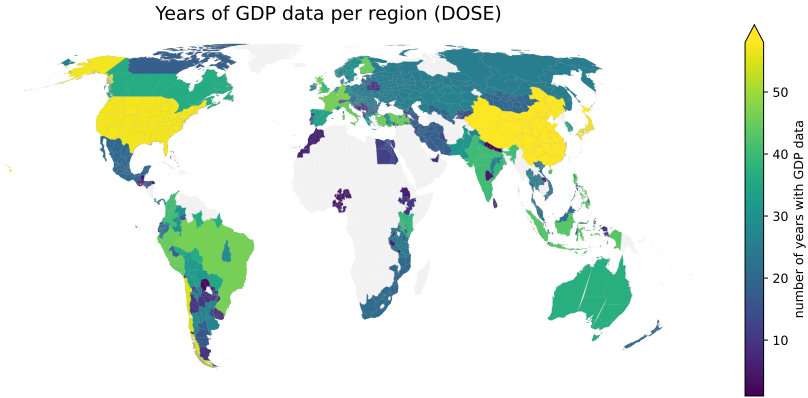
Working Paper: https://mlinsenmeier.com/research/

Comments welcome.

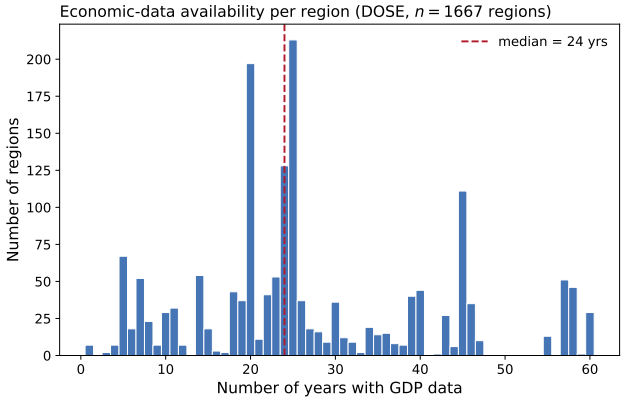
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Appendix

DOSE data availability



DOSE data availability II



Climate models

Five climate models (CMIP6)

- GFDL-ESM4
- IPSL-CM6A-LR
- MPI-ESM1-2-HR
- MRI-ESM2-0
- UKESM1-0-LL

Binned model

Fixed effects model with bins of daily temperature:

$$g_{it} = \alpha_i + P_{it}\beta + \sum_{b=1}^{B} n_{bit}\gamma_b + \mu_{ct} + \epsilon_{it}$$

- g_{it} annual growth rate in region i in year t
- n_{bit} number of days with temperature in bin b (width: 2 degrees C; winsorized at 99 %)
- P_{it} annual precipitation (also daily bins in robustness check)
- α_i region fixed effects
- μ_{ct} country-year fixed effects

We estimate this model by climate region. We fit a smooth curve into the coefficients γ_b.

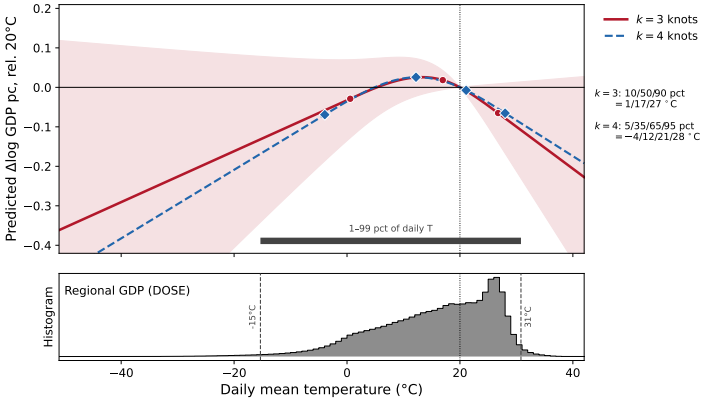
Smooth model

Fixed effects model with splines of daily temperature:

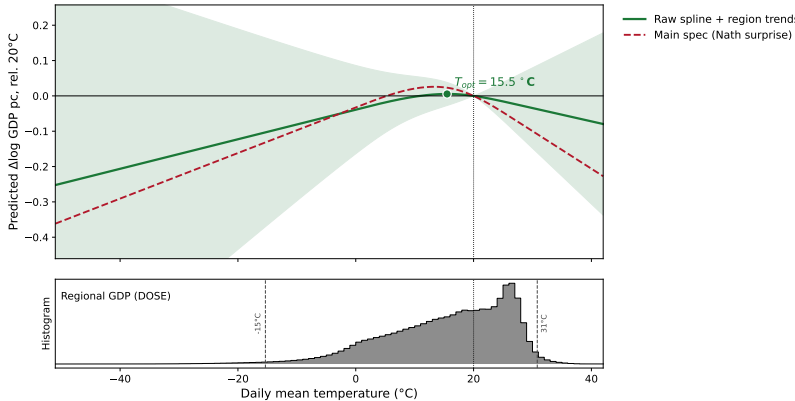
$$g_{it} = \alpha_i + f(P_{it}; \beta) + g(T_{it}; \gamma) + \mu_{ct} + \epsilon_{it}$$

- g_{it} annual growth rate in region i in year t
- T_{it} daily temperature
- P_{it} daily precipitation
- α_i region fixed effects
- μ_{ct} country-year fixed effects

Knots

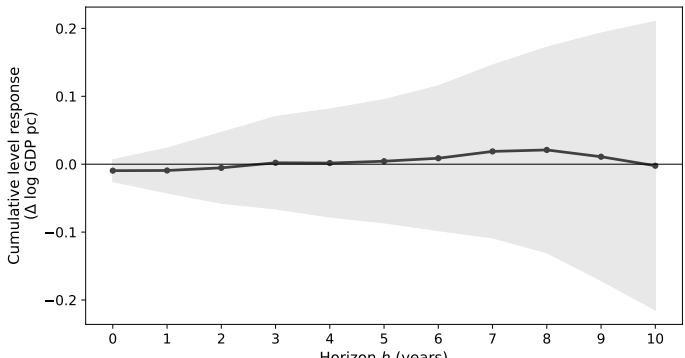

Predicted Δlog GDP pc, rel. 20°C
0.2
0.1
0.0
−0.1
−0.2
−0.3
−0.4
k = 3 knots
k = 4 knots
k = 3: 10/50/90 pct
= 1/17/27 °C
k = 4: 5/35/65/95 pct
= −4/12/21/28 °C
1–99 pct of daily T
Histogram
Regional GDP (DOSE)
15°C
31°C
−40
−20
0
20
40
Daily mean temperature (°C)

Trends


Raw spline + region trends
Main spec (Nath surprise)
Predicted Δlog GDP pc, rel. 20°C
0.2
0.1
0.0
−0.1
−0.2
−0.3
−0.4
T_{opt} = 15.5 °C
Regional GDP (DOSE)
Histogram
-15°C
31°C
−40
−20
0
20
40
Daily mean temperature (°C)

Weak evidence for a level effect

The level of GDP seems to recover from a temporary increase in temperature, but statistical uncertainty is *very* large.



The figure shows the response to a 1 ℃ increase at 30 ℃ in a temperate region.

Persistence of the omitted damage

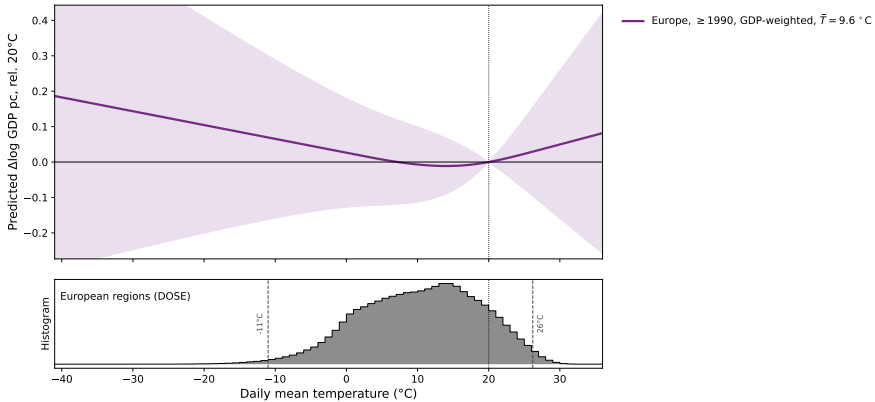
The growth effect in 2050 is 0.052 pp. How much of it persists is open:

- Without persistence, the omission costs US$34.5 billion, one year on 2015 GDP.
- With full persistence, GDP in 2050 is 1.07 % lower.

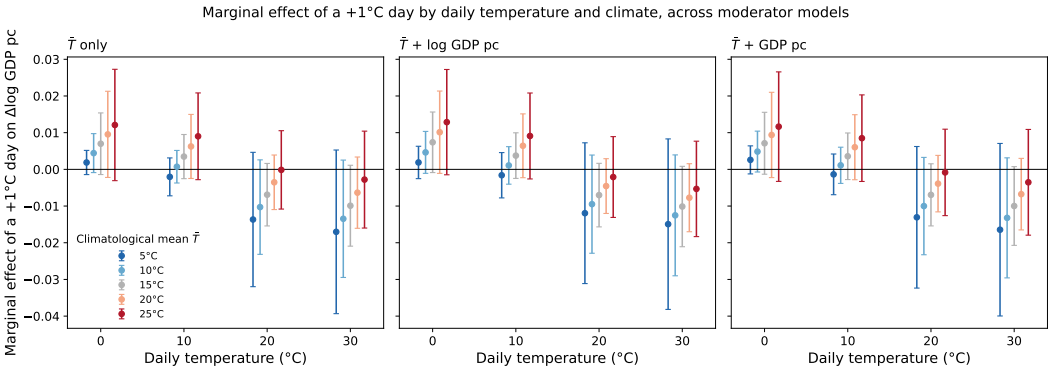
These two figures probably bracket the range between a pure level and a pure growth effect.

With ten annual lags, the contemporaneous omission is the same. Ten years on, the cumulative omission is about two fifths of it, with an interval that includes both no and full persistence.

Europe

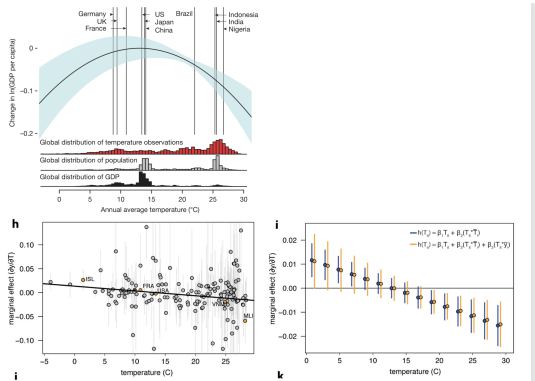

Europe, ≥ 1990, GDP-weighted, $\bar{T} = 9.6$ °C
Predicted Δlog GDP pc. rel. 20°C
0.4
0.3
0.2
0.1
0.0
−0.1
−0.2
European regions (DOSE)
Histogram
-11°
26°
−40
−30
−20
−10
0
10
20
30
Daily mean temperature (°C)

Moderation by income



Burke et al

Non-linear specification in Burke et al. (2015) and country-heterogeneity

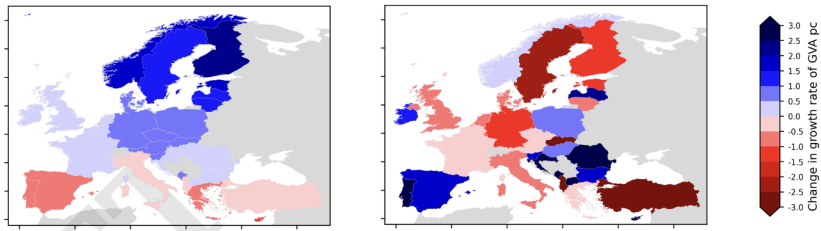


Burke, Hsiang & Miguel (2015), *Nature*

Linsenmeier et al

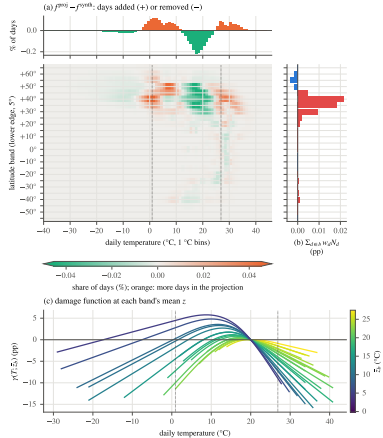
Left: model specification of Burke et al. (2015)

Right: country-specific coefficients of annual mean temperature



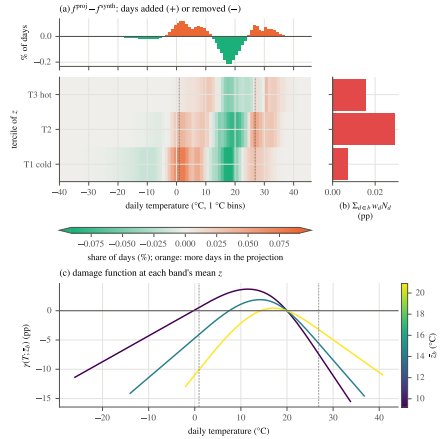
Linsenmeier, Groom & Roth (2026), *Nature Communications*

Days added and removed by the projection

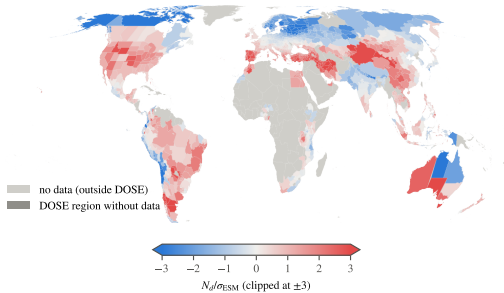


Mean of the 15 model × scenario cells

Days added and removed, by mean climate

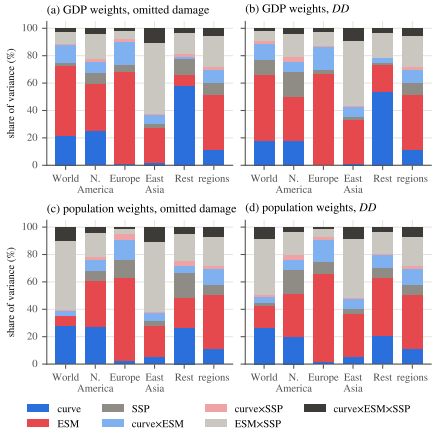


Signal-to-noise across climate models



Ensemble mean over standard deviation across the five models. Regions with $|SNR| > 1$ hold 37.4 % of world GDP and carry 85 % of the global omission.

Variance decomposition



Second-order split of the omitted damage

	omitted (pp)	(a)	(b)	(c)	(d)	(e)
World, GDP weights	0.0523	93	23	−24	−1	10
World, population weights	0.0280	85	27	−20	−1	9
$\lvert\text{lat}\rvert > 50^\circ$	−0.0796	80	−20	52	4	−16
$23.5^\circ < \lvert\text{lat}\rvert \leq 50^\circ$	0.0853	91	15	−11	0	5
$\lvert\text{lat}\rvert \leq 23.5^\circ$	0.0087	34	24	37	1	4

Shares of the omitted damage (%). (a) first-order term; (b) squared excess warming; (c) change in within-month variance; (d) cross term; (e) remainder. Latitude groups by centroid, GDP weights.

SSP3-7.0, mean of five models, point estimate

Derivation (1/2): decomposing the omitted damage

Write region d's growth effect month by month, relative to the pre-industrial control, with w_m the month's share of days and $E_m^C[\cdot]$ the mean over the month's days in climate C:

$$\Delta\hat{g}_d^C = \sum_m w_m \Big(E_m^C\big[\gamma_d(T)\big] - E_m^{\text{ctrl}}\big[\gamma_d(T)\big] \Big)$$

The control term is the same in both projections and cancels in their difference. Month m warms by Δ_{dm}, the year by $\bar{\Delta}_d$. The **excess warming** of the month is $\delta_{dm} = \Delta_{dm} - \bar{\Delta}_d$, with $\sum_m w_m \delta_{dm} = 0$.

Between the two climates, we insert each month of the mean projection, shifted by its own excess warming δ_{dm}:

$$\Delta\hat{g}_d^{\text{full}} - \Delta\hat{g}_d^{\text{mean}} = \underbrace{\sum_m w_m \Big(E_m^{\text{mean}}\big[\gamma_d(T+\delta_{dm})\big] - E_m^{\text{mean}}\big[\gamma_d(T)\big] \Big)}_{\text{(A) shift: each month moves by its excess warming}} + \underbrace{\sum_m w_m \Big(E_m^{\text{full}}\big[\gamma_d(T)\big] - E_m^{\text{mean}}\big[\gamma_d(T+\delta_{dm})\big] \Big)}_{\text{(B) shape: same monthly mean, different spread}}$$

The omitted damage is therefore $\Delta\hat{g}_d^{\text{mean}} - \Delta\hat{g}_d^{\text{full}} = -(A) - (B)$.

Derivation (2/2): second-order expansion

(A) SHIFT

Expand γ_d day by day, $\gamma_d(T+\delta) = \gamma_d(T) + \gamma_d'(T)\,\delta + \frac{1}{2}\gamma_d''(T)\,\delta^2 + O(\delta^3)$, and average over the month's days:

$$(A) \approx \sum_m w_m \left(\bar{\gamma}_{dm}'\,\delta_{dm} + \tfrac{1}{2}\,\bar{\gamma}_{dm}''\,\delta_{dm}^2 \right)$$

with $\bar{\gamma}_{dm}' = E_m^{\text{mean}}[\gamma_d']$ and $\bar{\gamma}_{dm}'' = E_m^{\text{mean}}[\gamma_d'']$ the mean slope and curvature of the damage function over the month's days.

(B) SHAPE

The two months have the same mean and differ in their variance by $\Delta\sigma_{dm}^2$. Since $E[\gamma(X)] \approx \gamma(\mu) + \frac{1}{2}\gamma''(\mu)\,\mathrm{Var}(X)$:

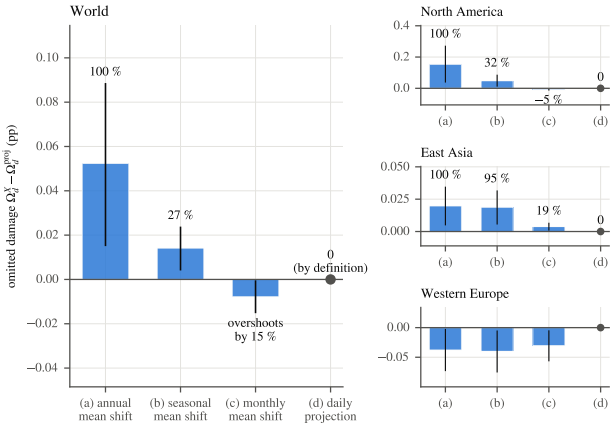
$$(B) \approx \sum_m w_m\, \tfrac{1}{2}\,\bar{\gamma}_{dm}''\,\Delta\sigma_{dm}^2$$

COMBINE

$$\Delta\hat{g}_d^{\text{mean}} - \Delta\hat{g}_d^{\text{full}} = -(A) - (B) \;\approx\; -\sum_m w_m\,\bar{\gamma}_{dm}'\,\delta_{dm} \;-\; \tfrac{1}{2}\sum_m w_m\,\bar{\gamma}_{dm}''\left(\delta_{dm}^2 + \Delta\sigma_{dm}^2\right)$$

The remainder collects third-order terms, higher moments within months, and a small cross term (appendix table).

Mechanism: twelve monthly means suffice globally



- Globally, a seasonal shift removes about three quarters of the omission, and a monthly shift removes all of it, overshooting by 15 %.
- Day-to-day variability within months works slightly in the opposite direction.
- In Western Europe, the omission is negative, and a monthly shift removes only about a fifth of it.

SSP3-7.0

Coverage: units outside DOSE

	outside DOSE			share omitted, % (DOSE → all)	
	people (M)	omitted (pp)	DOSE (pp)	population	GDP
Africa	830	0.0124 [0.0034, 0.0212]	0.0256	4.8 → 2.9	5.9 → 6.4
Asia	549	0.0419 [0.0092, 0.0743]	0.0248	6.1 → 6.7	7.8 → 8.7
Europe	11	−0.0190 [−0.0879, 0.0566]	−0.0050	−1.8 → −1.9	4.2 → 4.0
North America	68	0.0007 [0.0001, 0.0013]	0.1004	22.3 → 18.7	29.5 → 28.5
South America	53	0.0027 [−0.0009, 0.0062]	0.0159	2.6 → 2.4	4.6 → 4.5
Oceania	12	0.0008 [0.0002, 0.0015]	0.0489	17.0 → 7.2	15.8 → 14.6
All	1,523	0.0219 [0.0050, 0.0384]	0.0274	6.6 → 6.0	15.7 → 15.2

- Outside DOSE, the omission sits in the northern subtropics and is close to zero in the tropics, including sub-Saharan Africa.
- The result outside DOSE leans more on extrapolation: the flat damage function keeps 54 % of the omission there, against 83 % in DOSE.

Omitted damage: pp of annual growth