Long-Term Macroeconomic Effects of Climate Change: A Cross-Country Analysis—Appendix A

Matthew E. Kahn[a], Kamiar Mohaddes[b*], Ryan N. C. Ng[c],
M. Hashem Pesaran[ad], Mehdi Raissi[e] and Jui-Chung Yang[f]

[a] Department of Economics, University of Southern California, USA; [b] Judge Business School & King's College, University of Cambridge, UK; [c] Faculty of Economics, University of Cambridge, UK; [d] Trinity College, Cambridge, UK; [e] International Monetary Fund, Washington DC, USA; [f] Department of Economics, National Taiwan University, Taiwan

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Abstract

This is the Appendix to the paper "Long-Term Macroeconomic Effects of Climate Change: A Cross-Country Analysis", published in *Energy Economics*. Appendix A.1 provides the economic theory that underlies the growth equation with weather shocks used in our empirical analysis. Appendix A.2 discusses how our specifications and econometric analyses relate to the literature. Appendix A.3 reports historical estimates of trend rises in temperature across 174 countries over the past half century. Appendix A.4 provides individual-country estimates of GDP per capita losses under the RCP 2.6 and RCP 8.5 scenarios over various horizons (by year 2030, 2050, and 2100).

*Corresponding author. Email address: km418@cam.ac.uk.

A Appendix

A.1 A Multi-Country Stochastic Growth Model with Weather and Climate Effects

Theoretical growth models generally focus on technological progress and permanent improvements in the efficiency with which factors of production are combined as the main drivers of long-term economic growth, and ignore the possible effects of weather patterns transformed by climate change. Examples include Merton (1975), Brock and Mirman (1972), Donaldson and Mehra (1983), Marimon (1989), and Binder and Pesaran (1999), who have developed stochastic growth models for single economies. We extend this literature and consider the growth process across N countries sharing a common technology but subject to different weather patterns.[18]

Consider a set of economies in which aggregate production possibilities are described by the following production function:

$$Y_{it} = \mathcal{F}\left(\Lambda_{it} L_{it}, K_{it}\right), \tag{A.1}$$

where L_{it} and K_{it} are labour and capital inputs, and Λ_{it} is a scale variable that determines labour productivity in economy i. We suppose that labour productivity is governed by technological factors, as well as by country-specific weather conditions. We consider temperature (T_{it}) and precipitation (P_{it}) as the main weather variables, but assume that labour productivity is affected by these variables only when they deviate from their historical norms (which also serve as country-specific but time-varying thresholds or climates). We express the historical norms by $T^*_{i,t-1}(m)$ and $P^*_{i,t-1}(m)$, respectively, where m denotes the number of years used in computations. Specifically, we set $T^*_{i,t-1}(m) = m^{-1}\sum_{s=1}^{m} T_{i,t-s}$ and $P^*_{i,t-1}(m) = m^{-1}\sum_{l=1}^{m} P_{i,t-l}$. In the theoretical derivations that follow we suppose that m is given and fixed, and address the choice of m in Section 2.

The horizon over which the historical norms are formed depends on the degree of adaptation to rising temperatures or precipitation. Small values of m represent high degrees of adaptation. We regard the historical norms as technologically neutral, in the sense that if temperature and precipitation remain close to their historical norms, they are not expected to have any effects on labour productivity. Recent research demonstrates that different regions of the U.S. have acclimated themselves to their own temperature niche. For instance, Heutel et al. (2016) document that heat waves (cold snaps) cause less deaths in warm (cold) places. Moreover, if temperature and precipitation deviate from their historical norms, the marginal effects on labour productivity could be different across climates, depending on the region under consideration. Accordingly, in what follows we also allow for an asymmetry in the effects of deviations from the historical norms on labour productivity, and introduce the following climate threshold variables:

$$\begin{aligned}\left[T_{it} - T^*_{i,t-1}(m)\right]^+ &= \left[T_{it} - T^*_{i,t-1}(m)\right] I\left(T_{it} - T^*_{i,t-1}(m) \geq 0\right), \\ \left[T_{it} - T^*_{i,t-1}(m)\right]^- &= -\left[T_{it} - T^*_{i,t-1}(m)\right] I\left(T_{it} - T^*_{i,t-1}(m) < 0\right),\end{aligned} \tag{A.2}$$

[18] See also Fankhauser and S.J. Tol (2005) and Dietz and Stern (2015) who discuss economic growth models with climate.

where $I(z) = 1$ if $z \geq 0$ and 0, otherwise. Similarly $\left[P_{it} - P^*_{i,t-1}(m)\right]^+$ and $\left[P_{it} - P^*_{i,t-1}(m)\right]^-$ can be defined for precipitation. By distinguishing between positive and negative deviations of the climate variables from their historical norms, we account for potential nonlinear effects of climate change on economic growth around country-specific thresholds.

Specifically, we adopt the following specification of changes in labour productivity in terms of temperature and precipitation:

$$\Lambda_{it} = A_{it} \exp\left(-\boldsymbol{\gamma}_i' \mathbf{x}_{it}(m)\right), \tag{A.3}$$

where A_{it} is the technology factor,

$$\mathbf{x}_{it}(m) = \begin{bmatrix} \left(T_{it} - T^*_{i,t-1}(m)\right)^+ \\ \left(T_{it} - T^*_{i,t-1}(m)\right)^- \\ \left(P_{it} - P^*_{i,t-1}(m)\right)^+ \\ \left(P_{it} - P^*_{i,t-1}(m)\right)^- \end{bmatrix}, \quad \boldsymbol{\gamma}_i = \begin{pmatrix} \boldsymbol{\gamma}_i^+ \\ \boldsymbol{\gamma}_i^- \end{pmatrix}.$$

$\boldsymbol{\gamma}_i^+ = (\gamma_{iT}^+, \gamma_{iP}^+)'$, and $\boldsymbol{\gamma}_i^- = (\gamma_{iT}^-, \gamma_{iP}^-)'$.

The historical norms can vary over time, but such variations are likely to be small in the short- to medium-term. One could also consider modelling the adverse effects of deviating from climatic norms, by using the quadratic formulation, for example, $\left[T_{it} - T^*_{i,t-1}(m)\right]^2$ instead of the threshold effects $\left(T_{it} - T^*_{i,t-1}(m)\right)^+$ and $\left(T_{it} - T^*_{i,t-1}(m)\right)^-$. But in cases where T_{it} is trended, which is the situation in almost all 174 countries in our sample (see Table A.5 and the discussion in Appendix A.3), the inclusion of $\gamma_i \left[T_{it} - T^*_{i,t-1}(m)\right]^2$ will induce a quadratic trend in equilibrium log per capita output (or equivalently a linear trend in per capita output growth) which is not desirable and can bias the estimates of the growth-climate change equation. Our focus on the deviations of temperature and precipitation from their historical norms marks a departure from the existing literature by implicitly modelling climate variability around country-specific long-term trends as well as adaptation.

We follow the literature and assume that labour input, L_{it}, and technology variables are exogenously given and can be approximated by the following linear processes

$$\log(L_{it}) = l_{i0} + n_i\, t + u_{ilt}, \tag{A.4}$$

$$\log(A_{it}) = \mathrm{a}_{i0} + g_i t + u_{iat}, \tag{A.5}$$

where l_{i0} and a_{i0} are economy-specific initial endowments of labour input and technology; n_i and g_i are the exogenously-determined rates of growth of labour input and technology, respectively; and u_{ilt} and u_{iat} are the stochastic components which could be driven by a combination of demand and supply shocks. Considering the long-run effects of weather patterns transformed by climate change on income growth, we do not attempt to identify such shocks, and assume that

$$\Delta u_{ilt} = -\left(1 - \rho_{il}\right) u_{il,t-1} + \varepsilon_{ilt}, \qquad |\rho_{il}| \leq 1,\ \varepsilon_{ilt} \sim iid\left(0, \sigma^2_{il}\right); \tag{A.6}$$

$$\Delta u_{iat} = -\left(1-\rho_{ia}\right) u_{ia,t-1} + \varepsilon_{iat}, \qquad |\rho_{ia}| \leq 1, \ \varepsilon_{iat} \sim iid\left(0, \sigma^2_{ia}\right). \tag{A.7}$$

Shocks to labour input, ε_{ilt}, could be correlated with the predictable part of weather conditions. For example, during heat waves, labour supply could fall before recovering in normal times. In such a setting, seasonal or cyclical changes in weather conditions might not have long-run growth effects, but can nevertheless lead to negative short-run correlations between labour input and weather shocks (as workers adapt their schedules to the changing weather conditions). It is, therefore, important to distinguish between short-run effects and the long-term impact of weather shocks transformed by climate change on income growth. The short-run correlation between weather and labour input shocks also renders the weather variable weakly exogenous, with important econometric implications for estimation of long-run growth effects of long-lasting shifts in weather patterns. The stochastic components of labour input and technology could follow unit-root processes. They also could be characterized as cross-sectionally correlated, for example, by common factor representations.

Finally, and most importantly, we assume the following specification for temperature and precipitation variables:

$$\mathbf{x}_{it}(m) = \boldsymbol{\mu}_{im} + \mathbf{v}_{it}(m), \ \mathbf{v}_{it}(m) \sim (\mathbf{0}, \boldsymbol{\Omega}_m), \tag{A.8}$$

where $\boldsymbol{\mu}_{im}$ are country-specific fixed effects representing the mean deviations of temperature and precipitation from their historical means, and $v_{it}(m)$ is the 4×1 vector of weather shocks, which could be correlated across countries. Since temperature and precipitation are measured as deviations from their historical norms in our analysis, they are unlikely to have unit roots or linear trends, although they could display short term drifts when m is relatively large and temperature increases faster than the economy's ability to adapt to the rising temperature or its increased variability (see Section 3). We acknowledge that our reduced form treatment of the temperature and precipitation variables abstract from explicitly modelling the feedback effects of Carbon dioxide (CO_2) emissions (caused by increased economic activity) to the climate variables. This is typically modelled explicitly in integrated assessment models, notably the DICE—see, for example, Nordhaus and Yang (1996), and Nordhaus (2008, 2013, 2017, 2018), and a recent paper by Ikefuji et al. (2019) which provides a stochastic treatment of a climate-economy model. However, we implicitly allow for such feedback effects on the projected future values of temperature and precipitation when we carry out our counterfactual exercises.

Having specified the exogenous processes, we follow Binder and Pesaran (1999) in deriving conditions under which the solution to the stochastic growth model is ergodic (stochastically stable). This property is essential for making long term inference between output per capita, technological innovation and the temperature and precipitation variables. We assume constant returns to scale, and write (A.1) as

$$Y_{it} = \Lambda_{it} L_{it}\, f\left(\kappa_{it}\right), \tag{A.9}$$

where κ_{it} denotes the ratio of physical capital to effective units of labour input, that is

$$\kappa_{it} = \frac{K_{it}}{\Lambda_{it} L_{it}}. \tag{A.10}$$

The physical capital stock depreciates in each period at a constant rate δ_i, and obeys the linear law of motion

$$K_{i,t+1} = (1-\delta_i)K_{it} + I_{it}, \qquad \delta_i \in (0,1). \tag{A.11}$$

The model specification is completed by assuming that households' aggregate saving is given by

$$S_{it} = s(\kappa_{it})\,Y_{it}, \tag{A.12}$$

where the saving function, $s(\cdot)$, is assumed to be continuously differentiable and $s_{it} \in (0,\ 1)$. In equilibrium, we have

$$S_{it} = I_{it} = s(\kappa_{it})\,Y_{it}, \tag{A.13}$$

hence

$$K_{i,t+1} = (1-\delta_i)K_{it} + s(\kappa_{it})\,Y_{it}. \tag{A.14}$$

Following the literature, we assume that that $f(\cdot)$ is twice continuously differentiable, is strictly increasing and concave, and satisfies $f(0) = 0$, as well as the Inada conditions $\lim_{\kappa\to 0} f^{'}(\kappa) = +\infty$, and $\lim_{\kappa\to\infty} f^{'}(\kappa) = 0$, for any given value of $\kappa_{it} = \kappa$.

The capital accumulation process, (A.14), can then be written as

$$\frac{K_{i,t+1}}{\Lambda_{i,t+1}L_{i,t+1}}\frac{\Lambda_{i,t+1}L_{i,t+1}}{\Lambda_{it}L_{it}} = (1-\delta_i)\frac{K_{it}}{\Lambda_{it}L_{it}} + s(\kappa_{it})\,\frac{Y_{it}}{\Lambda_{it}L_{it}},$$

which upon using (A.9) and (A.10) yields

$$\kappa_{i,t+1} = \exp\left[-\Delta\ln\left(\Lambda_{i,t+1}L_{i,t+1}\right)\right]\left[(1-\delta_i)\kappa_{it} + s(\kappa_{it})\,f(\kappa_{it})\right]. \tag{A.15}$$

Also, using equations (A.3), (A.4), and (A.5), we have

$$\Delta\ln\left(\Lambda_{i,t+1}L_{i,t+1}\right) = \Delta\ln\left(A_{i,t+1}\right) + \Delta\ln\left(L_{i,t+1}\right) - \boldsymbol{\gamma}_i'\Delta\mathbf{x}_{i,t+1}(m) = n_i + g_i + \xi_{i,t+1},$$

where

$$\xi_{i,t+1} = \triangle u_{i,l,t+1} + \triangle u_{i,a,t+1} - \boldsymbol{\gamma}_i'\Delta\mathbf{v}_{i,t+1} \tag{A.16}$$

and $u_{i,l,t+1}$, $u_{i,a,t+1}$ and $\mathbf{v}_{i,t+1}$ are defined by (A.6), (A.7) and (A.8), respectively. Hence

$$\frac{\kappa_{i,t+1}}{\kappa_{it}} = \exp\left(-n_i - g_i + \xi_{i,t+1}\right)\left[(1-\delta_i) + \frac{s(\kappa_{it})\,f(\kappa_{it})}{\kappa_{it}}\right].$$

Binder and Pesaran (1999) investigate the conditions under which the above dynamic stochastic non-linear equation has a steady state solution. They show that under standard regularity conditions on the saving rate, $s(\kappa)$, and assuming that $f(\kappa)/\kappa \to 0$, as $\kappa \to \infty$, the limiting distribution of κ_{it} (as $t \to \infty$) is ergodic in its r^{th} moment if $E\left|\xi_{i,t+1}\right|^r < \infty$, and most importantly, if large negative shocks are ruled out, such that

$$F_{\xi}\left[log(1-\delta_i) - n_i - g_i\right] = 0, \tag{A.17}$$

where $F_{\xi}(.)$ is the limiting cumulative distribution function of $\xi_{i,t+1}$, defined by (A.16). Since $n_i+g_i+\delta_i$ is relatively small, the above condition is likely to be satisfied for light-tailed distributions such as Gaussian or sub-Gaussian processes, but not when $\xi_{i,t+1}$ is heavy-tailed with a high level of volatility.[19] Suppose now condition (A.17) is met and the production technology is Cobb-Douglas. Then using (A.3), (A.9), (A.5), and (A.8), we have

$$y_{it} = \ln(Y_{it}/L_{it}) \approx y_{i0}^{*} + g_i t + u_{iat} - \boldsymbol{\gamma}_i' \mathbf{v}_{it}(m), \tag{A.18}$$

where

$$y_{i0}^{*} = \mathrm{a}_{i0} + \alpha_i \ln(\kappa_{i\infty}) - \boldsymbol{\gamma}_i' \boldsymbol{\mu}_{im},$$

α_i is the exponent of the capital input in economy i's production function; a_{i0} is the initial technological endowment; and $\kappa_{i\infty}$ is the steady state value of κ_{it}—see Binder and Pesaran (1999) for further details. The variations in the steady state value of y_{it} around its trend ($g_i t$) are determined by technology and weather shocks, u_{iat} and $\mathbf{v}_{it}(m)$, and vary across countries owing to differences in initial endowments, technological (α_i and g_i) and climate conditions, $\boldsymbol{\gamma}_i' \boldsymbol{\mu}_{im}$. The model can also generate a unit root in y_{it} by assuming that $log(A_{it})$ has a unit root, namely by setting $\rho_{ia}=1$ in (A.7). In this case, the growth rate of per capita output can be written as

$$\triangle y_{it} \approx g_i - \boldsymbol{\gamma}_i' \triangle \mathbf{v}_{it}(m) + \varepsilon_{iat}, \tag{A.19}$$

which reduces to the random walk model of output per capita if we abstract from the weather shocks (by setting $\gamma_i = 0$). In equilibrium, the mean per capita output growth is positively affected by technological progress, $g_i > 0$, and negatively impacted by deviations of the temperature and precipitation from their historical norms when $\gamma_i > 0$. This specification has the added advantage that $E(\triangle y_{it})$ does not inherit the strong trend in T_{it}, which the country/global temperatures have been subject to over the past 55 years (see Appendix A.3 and Table A.5).

The above theoretical derivation of output growth process requires that technology and weather shocks satisfy the truncation condition in (A.17). However, this condition is unlikely to be met in the presence of rare disaster events considered in the literature by Rietz (1988), Barro (2006, 2009) and Weitzman (2009), among others. To illustrate this point, let's abstract from demand and weather shocks and assume that the only remaining stochastic process, namely technology, has a unit root. Then $\xi_{i,t+1} = \varepsilon_{iat}$ and condition (A.17) reduces to (dropping the subscripts i)

$$F_{\varepsilon}\left[log(1-\delta) - n - g\right] = Pr\left(\varepsilon_t \le log(1-\delta) - n - g\right) = 0.$$

As in Barro (2009), suppose that $\varepsilon_t = u_t + v_t$, where u_t is $iidN(0, \sigma_u^2)$, and $v_{t+1} = 0$ with probability $1-p$ and $v_{t+1} = log(1-b)$ with probability p, where $p \ge 0$ is the probability of a disaster, and b

[19] See Ikefuji et al. (2019) who also show that within their stochastic dynamic economy-climate model, heavy-tailed risk is not compatible with power utility, and propose using the Pareto utility function instead.

$(0 < b < 1)$ is its size, measured as the fraction of output lost. Under this formulation

$$
\begin{aligned}
Pr\left[\varepsilon_t \leq log(1-\delta) - n - g\right] &= (1-p)\Phi\left(\frac{log(1-\delta) - n - g}{\sigma_u}\right) \\
&\quad + p\Phi\left(\frac{log(1-\delta) - n - g - log(1-b)}{\sigma_u}\right),
\end{aligned}
$$

where $\Phi(\cdot)$ is the cumulative distribution function of a standard normal variate. Also since $log(1-b) \approx -b$, and $log(1-\delta) \approx -\delta$, then the second term of the above expression could be far from zero if $b > \delta$, noting that $n+g$ is likely to be small, around 0.03. Therefore, in situations where $p > 0$, and b is much larger than the rate of capital depreciation, δ, the truncation condition will not be met even if we assume that non-disaster shocks are Gaussian. Consequently, the random walk model of output growth derived in (A.19), and assumed in the literature, might not be compatible with an equilibrium stochastic growth model, and in particular there is no guarantee for κ_{it} to converge to a time-invariant process, required for the validity of the random walk model of per capita output growth. Therefore, we cannot, and do not, claim that our empirical analysis allows for rare disaster events, whether technological or climatic. From this perspective, the counterfactual outcomes that we discuss in Section 3 should be regarded as conservative because they only consider scenarios where the climate shocks are Gaussian, without allowing for rare disasters.

Finally, in a panel data context, $\ln(\kappa_{it})$ can be approximated by a linear stationary process with possibly common factors, which yields the following Auto-Regressive Distributed Lag (ARDL) specification for y_{it}

$$\varphi_i(L)\Delta y_{it} = a_i + b_i(L)\boldsymbol{\gamma}_i' \triangle \mathbf{x}_{it}(m) + \varepsilon_{it}, \tag{A.20}$$

where $i = 1, 2, ..., N$; $t = 1, 2, ..., T$, $\varphi_i(L)$ and $b_i(L)$ are finite order distributed lag functions, a_i is the fixed effect, and ε_{it} is a serially uncorrelated shock.

A.2 Relation to the Literature

This annex explains how our approach to modelling the climate-macroeconomy relationship relates to the rapidly growing empirical literature on the topic. There are three main differences in model specifications: (a) whether temperature affects the level of GDP or its growth, allowing for lagged effects; (b) what functional form should be used for the relationship between output growth and temperature; and (c) how to account for latent factors in panel regressions. We focus on the studies of Dell et al. (2012), Burke et al. (2015), and Kalkuhl and Wenz (2020).

1. Dell et al. (2012)**,** or DJO for short, consider the following dynamic panel data model (equation A1.5 of their online Appendix II):

$$\Delta y_{it} = a_i + \sum_{\ell=1}^{p} \varphi_\ell \Delta y_{i,t-\ell} + \sum_{\ell=0}^{p+1} \psi_\ell T_{it-\ell} + \varepsilon_{it}. \tag{A.21}$$

where y_{it} is the log of real GDP per capita of country i in year t, a_i is the country-specific fixed effect, and T_{it} is the population-weighted average temperature of country i in year t. Suppose that

$$T_{it} = a_{Ti} + b_{Ti}t + v_{Ti,t} \tag{A.22}$$

where $b_{Ti} > 0$, $E\left(v_{Ti,t}\right) = 0$, and $E(v_{Ti,t}^2) = \sigma_{T_i}^2$. Substituting (A.22) in equation (A.21) yields

$$\Delta y_{it} = a_i + \sum_{\ell=1}^{p} \varphi_\ell \Delta y_{i,t-\ell} + \sum_{\ell=0}^{p+1} \psi_\ell \left(a_{Ti} + b_{Ti}\left(t-\ell\right) + v_{Ti,t-\ell}\right) + \varepsilon_{it}.$$

Taking expectations, we have

$$E\left(\Delta y_{it}\right) = \sum_{\ell=1}^{p} \varphi_\ell E\left(\Delta y_{i,t-\ell}\right) + c_i + b_{Ti}\left(\sum_{\ell=0}^{p+1} \psi_\ell\right) t,$$

where $c_i = a_i + a_{Ti}\left(\sum_{\ell=0}^{p+1} \psi_\ell\right) - b_{Ti}\sum_{\ell=0}^{p+1} \ell\psi_\ell$. To ensure that $E\left(\Delta y_{it}\right)$ exists, we suppose that the underlying growth processes are stable such that the roots of $1 - \sum_{\ell=1}^{p} \varphi_\ell z^{-i}$ all lie outside of the unit circle. Under this assumption $\left(1 - \sum_{\ell=1}^{p} \varphi_\ell L^\ell\right)^{-1} = \sum_{i=0}^{\infty} a_i L^i$ and we have

$$\begin{aligned} E\left(\Delta y_{it}\right) &= \frac{c_i}{1 - \sum_{\ell=1}^{p} \varphi_\ell} + b_{Ti}\left(\sum_{\ell=0}^{p+1} \psi_\ell\right)\left(\sum_{i=0}^{\infty} a_i L^i\right) t \\ &= \frac{c_i}{1 - \sum_{\ell=1}^{p} \varphi_\ell} + b_{Ti}\left(\sum_{\ell=0}^{p+1} \psi_\ell\right)\left(\sum_{i=0}^{\infty} a_i (t-i)\right), \end{aligned}$$

or after some simplifications, we have[20]

$$E\left(\Delta y_{it}\right) = \mu_i + \kappa_i t,$$

where

$$\mu_i = \frac{c_i}{1 - \sum_{\ell=1}^{p} \varphi_\ell} - \frac{b_{Ti}\left(\sum_{\ell=0}^{p+1} \psi_\ell\right)\sum_{\ell=1}^{p} \ell\varphi_\ell}{\left(1 - \sum_{\ell=1}^{p} \varphi_\ell\right)^2} \text{ and } \kappa_i = \frac{b_{Ti}\left(\sum_{\ell=0}^{p+1} \psi_\ell\right)}{1 - \sum_{\ell=1}^{p} \varphi_\ell}.$$

It is clear that the stability of the growth process does not, on its own, ensure that the mean growth is stable over time. For the latter, we also need to impose the additional restriction $b_{Ti}\left(\sum_{\ell=0}^{p+1} \psi_\ell\right) = 0$, so that $E\left(\Delta y_{it}\right)$ is time-invariant. One can obtain a stationary growth process if either $b_{Ti} = 0$ (no trend in temperature) and/or $\left(\sum_{\ell=0}^{p+1} \psi_\ell\right) = 0$. Under the latter restriction, the long term growth effect of rising temperature is given by

$$E\left(\Delta y_{it}\right) = \frac{c_i}{1 - \sum_{\ell=1}^{p} \varphi_\ell}$$

which is also compatible with $b_{Ti} = 0$. In short, to estimate growth regressions with rising temperature one needs to impose $\sum_{\ell=0}^{p+1} \psi_\ell = 0$ on equation (A.21).

[20] Note that $\sum_{i=0}^{\infty} a_i = \left(1 - \sum_{\ell=1}^{p} \varphi_\ell\right)^{-1}$ and $\sum_{i=0}^{\infty} i a_i = \left(1 - \sum_{\ell=1}^{p} \varphi_\ell\right)^{-2} \sum_{\ell=1}^{p} \ell\varphi_\ell$.

In the main part of their paper, DJO assume that $\varphi_\ell = 0$ and estimate a distributed lagged model after adding region-year fixed effects, δ_{rt}:

$$\Delta y_{irt} = a_{ir} + \delta_{rt} + \sum_{\ell=0}^{L} \rho_\ell T_{ir,t-\ell} + \varepsilon_{irt}, \; L = 0, 1, 5, 10 \tag{A.23}$$

To investigate conditions under which the inclusion of region-year fixed effects solves the problem of working with trended temperature, we repeat the analysis above, and without loss of generality, for the baseline regressions of DJO for $L = 0$:

$$\Delta y_{irt} = a_{ir} + \delta_{rt} + \rho_0 T_{irt} + \varepsilon_{irt}, \tag{A.24}$$

with $T_{irt} = a_{Ti,r} + b_{Ti,r}t + v_{Ti,rt}$, where as before the temperature shocks, $v_{Ti,rt}$, for country i in region r, have zero means and finite variances. Then we have

$$E\left(\Delta y_{irt}\right) = \left(a_{ir} + \rho_0 a_{Ti,r}\right) + \delta_{rt} + \left(\rho_0 b_{Ti,r}\right) t.$$

$E\left(\Delta y_{irt}\right)$ is stationary if $\delta_{rt} + \rho_0 b_{Ti,r} t = 0$ for all i, r and t. In turn, this would either require $b_{Ti,r} = 0$ (no trend in temperature), a condition which does not hold given the historical data. Otherwise we must have exact cancellation of linear trends in temperature at the regional level with the region-year fixed effects, namely $\delta_{rt} + \rho_0 \bar{b}_{Tr} t = 0$, for all r, where $\bar{b}_{Tr} = n_r^{-1} \sum_{i=1}^{n_r} b_{Ti,r}$. Under $\delta_{rt} + \rho_0 \bar{b}_{Tr} t = 0$ the following restricted version of (A.24) needs to be considered for estimation:

$$\Delta y_{irt} = a_{ir} + \rho_0 \left(T_{irt} - \bar{b}_{Tr} t\right) + \varepsilon_{irt},$$

or

$$\Delta y_{irt} = a_{ir} + \psi_0 a_{Ti,r} + \rho_0 \left(b_{Ti,r} - \bar{b}_{Tr}\right) t + \rho_0 v_{Ti,rt} + \varepsilon_{irt},$$

One can potentially have steady state growth at the regional level but not at the country level, since $E\left(\Delta y_{irt}\right) = a_{ir} + \rho_0 a_{Ti,r} + \rho_0 \left(b_{Ti,r} - \bar{b}_{Tr}\right) t$, and $E\left(\Delta y_{irt}\right)$ will be stationary if either $\rho_0 = 0$ (no temperature effects on growth) or $b_{Ti,r} = \bar{b}_{Tr}$, for all r.

2. While the preferred model of DJO featured a linear temperature effect, that of Burke et al. (2015), or BHM for short, considers a quadratic equation, thus allowing for weather warming to boost growth in countries with cold climates and impede growth in countries with hot climates. This quadratic specification results in an optimal annual average temperature for GDP growth of 13°C. Deviations from this number in either direction generates changes in growth of equal magnitude but of opposite signs. Specifically, BHM consider the following model

$$\Delta y_{it} = a_i + \delta_t + \alpha T_{it} + \beta T_{it}^2 + \gamma_i t + \phi_i t^2 + \varepsilon_{it}. \tag{A.25}$$

where δ_t are the country time effects. $\gamma_i t$ and $\phi_i t^2$ are the country-specific linear time trend and quadratic time trend. It is clear that without further restrictions, the mean output growth, $E\left(\Delta y_{it}\right)$, in BHM's specification will be trended, which as we have argued is neither plausible on theoretical grounds nor supported empirically. But one cannot rule out that the upward trend in the temperature could cancel out—rendering $E(\Delta y_{it})$ without a trend. To investigate this possibility, we run country-specific regressions of output growth on its lagged value and a linear time trend ($\Delta y_{it} = a_i + \varphi_i \Delta y_{i,t-1} + \gamma_i t$), and report the statistical significance of the long-run trend coefficients, $\theta_i = \gamma_i/(1-\varphi_i)$, in Table A.1 for all countries in our sample. We find that at the 5% significance level, output growth is found to be upward trended in only 21 countries out of 174 in our sample and in the rest θ_i is either negative or not statistically different from zero.

Substituting (A.22) in (A.25) and taking expectations yields:

$$E(\Delta y_{it}) = c_i + E(\delta_t) + [(\alpha + 2\beta a_{Ti})\theta_i + \gamma_i] t + \left(\beta b_{Ti}^2 + \phi_i\right) t^2$$

where $c_i = a_i + \alpha a_{Ti} + \beta a_{Ti}^2 + \beta \sigma_{Ti}^2$. There are many types of restrictions that can be imposed to ensure that $E(\Delta y_{it})$ is not trended. Since δ_t is unobserved it seems most appropriate to set $E(\delta_t) = 0$, and then require that

$$(\alpha + 2\beta a_{Ti}) b_{Ti} + \gamma_i = 0, \text{ and } \beta b_{Ti}^2 + \phi_i = 0, \text{ for all } i. \tag{A.26}$$

A less restrictive set of conditions will be needed if we assume that $E(\delta_t) = \kappa_1 t + \kappa_2 t^2$, which is a fortuitous specification for $E(\Delta y_{it})$ to be trend-free. Under this specification, the following restrictions are needed

$$(\alpha + 2\beta a_{Ti}) b_{Ti} + \gamma_i = -\kappa_1 \text{ and } \beta b_{Ti}^2 + \phi_i = -\kappa_2, \text{ for all } i. \tag{A.27}$$

These restrictions can be equivalently written as

$$\beta b_{Ti}^2 + \phi_i = \beta b_{Tj}^2 + \phi_j, \text{ for all } i \neq j \tag{A.28}$$

and

$$(\alpha + 2\beta a_{Ti}) b_{Ti} + \gamma_i = (\alpha + 2\beta a_{Tj}) b_{Tj} + \gamma_j \text{ for all } i \neq j \tag{A.29}$$

Using the data set of BHM, we estimate equations (A.25) by the fixed effects (FE) estimator, with or without the time effects (TE), linear trends (LT) or quadratic trends (QT). The results are summarized in Table A.2 where in all its columns conditions (A.28) and (A.29) are not imposed correctly because temperature rises have not been uniform across countries.

3. Kalkuhl and Wenz (2020), or KW for short, adds two additional terms to BHM's specification, namely ΔT_{it} and the interaction term, $T_{it} \times \Delta T_{it}$, to allow for weather effects across climates:

$$\Delta y_{it} = a_i + \delta_t + \lambda \Delta T_{it} + \psi T_{it} \times \Delta T_{it} + \alpha T_{it} + \beta T_{it}^2 + \gamma_i t + \phi_i t^2 + \varepsilon_{it}, \tag{A.30}$$

Once again, substituting T_{it} from (A.22) in the above and taking expectations, we have

$$E(\Delta y_{it}) = c_i + E(\delta_t) + \left[\gamma_i + \alpha b_{Ti} + \psi b_{Ti}^2 + 2\beta b_{Ti} a_{Ti}\right] t + \left(\beta b_{Ti}^2 + \phi_i\right) t^2$$

Table A.1: Is Output Growth Trended?

Country	$\frac{\hat{\gamma}_i}{(1-\hat{\varphi}_i)}$	Country	$\frac{\hat{\gamma}_i}{(1-\hat{\varphi}_i)}$	Country	$\frac{\hat{\gamma}_i}{(1-\hat{\varphi}_i)}$
Afghanistan	-0.0117	Georgia	0.1060	Oman	-0.5250**
Albania	0.2640	Germany	-0.0400	Pakistan	-0.0439**
Algeria	-0.0423	Ghana	0.1250***	Panama	0.0384
Angola	0.3180	Greece	-0.1400***	Papua New Guinea	0.0167
Argentina	0.0127	Greenland	-0.0779	Paraguay	-0.0282
Armenia	0.2800	Guatemala	-0.0275	Peru	0.0594
Australia	-0.0211	Guinea	-0.0226	Philippines	0.0375
Austria	-0.0681***	Guinea-Bissau	-0.0502	Poland	-0.1260*
Azerbaijan	0.6040	Guyana	0.0774	Portugal	-0.1370***
Bahamas	-0.0703	Haiti	0.1560	Puerto Rico	-0.1210***
Bangladesh	0.1170***	Honduras	-0.0055	Qatar	-0.0590
Belarus	0.3030	Hungary	-0.0992	Romania	0.0112
Belgium	-0.0747***	Iceland	-0.0870*	Russian Federation	0.4340
Belize	-0.0498	India	0.1080***	Rwanda	0.0971
Benin	0.0184	Indonesia	0.0278	Saint Vincent and the Grenadines	0.0237
Bhutan	-0.0377	Iran	-0.0703	Samoa	-0.0060
Bolivia	0.0416	Iraq	-0.0046	Sao Tome and Principe	0.0011
Bosnia and Herzegovina	-2.2610**	Ireland	-0.0209	Saudi Arabia	-0.0272
Botswana	-0.1560**	Israel	-0.0597*	Senegal	0.0488**
Brazil	-0.0462	Italy	-0.1140***	Serbia	-0.1800
Brunei Darussalam	-0.0655	Jamaica	-0.0269	Sierra Leone	0.0549
Bulgaria	0.0837	Japan	-0.1440***	Slovakia	-0.1570
Burkina Faso	0.0366*	Jordan	-0.0673	Slovenia	-0.3550**
Burundi	-0.0929**	Kazakhstan	-0.0861	Solomon Islands	0.0895
Cabo Verde	-0.0492	Kenya	-0.0536	Somalia	0.0391
Cambodia	0.0600	Kuwait	0.1420	South Africa	-0.0409
Cameroon	-0.0228	Kyrgyzstan	0.3570	South Korea	-0.0864**
Canada	-0.0548**	Laos	0.2010***	South Sudan	0.5840
Central African Republic	-0.0487	Latvia	-0.5140	Spain	-0.0880**
Chad	0.1430*	Lebanon	-0.6390***	Sri Lanka	0.0690***
Chile	0.0470	Lesotho	-0.0352	Sudan	0.1160*
China	0.0666	Liberia	0.0664	Suriname	0.1440
Colombia	0.0092	Libya	-2.5570	Swaziland	-0.0377
Comoros	0.0090	Lithuania	-0.2490	Sweden	-0.0349
Congo	-0.0109	Luxembourg	-0.0142	Switzerland	-0.0061
Congo DRC	-0.0132	Macedonia	0.2310	Syria	-0.0644
Costa Rica	-0.0165	Madagascar	0.0172	Tajikistan	0.7840*
Côte d'Ivoire	-0.0507	Malawi	-0.0101	Tanzania	0.1920***
Croatia	-0.3280*	Malaysia	-0.0196	Thailand	-0.0508
Cuba	0.0335	Mali	-0.0160	Togo	-0.0652
Cyprus	-0.2440***	Mauritania	-0.0101	Trinidad and Tobago	0.0601
Czech Republic	-0.1200	Mauritius	0.0499	Tunisia	-0.0402
Denmark	-0.0626***	Mexico	-0.0650*	Turkey	-0.0126
Djibouti	0.4690***	Moldova	0.2730	Turkmenistan	0.6270**
Dominican Republic	-0.0059	Mongolia	0.3470**	Uganda	0.1250
Ecuador	-0.0078	Montenegro	0.1510	Ukraine	0.5570
Egypt	-0.0479	Morocco	-0.0133	United Arab Emirates	0.0007
El Salvador	0.0722	Mozambique	0.2710*	United Kingdom	-0.0327
Equatorial Guinea	0.0511	Myanmar	0.2030***	United States	-0.0508**
Eritrea	-0.5020	Namibia	0.2170***	Uruguay	0.0775
Estonia	-0.4300	Nepal	0.0636***	US Virgin Islands	0.3320
Ethiopia	0.3840***	Netherlands	-0.0701***	Uzbekistan	0.5720***
Fiji	-0.0185	New Caledonia	-0.1580	Vanuatu	-0.1070
Finland	-0.0664	New Zealand	-0.0060	Venezuela	-0.0023
France	-0.0840***	Nicaragua	0.0222	Vietnam	-0.0089
French Polynesia	-0.0159	Niger	0.0464	Yemen	-0.1610*
Gabon	-0.1380	Nigeria	0.0510	Zambia	0.0916**
Gambia	-0.0491	Norway	-0.0679***	Zimbabwe	-0.0628

Notes: Table reports OLS estimates of the coefficients based on the following country-specific regressions $\Delta y_{it} = a_i + \varphi_i \Delta y_{i,t-1} + \gamma_i t$. Asterisks indicate statistical significance at the 1% (***), 5% (**) and 10% (*).

Table A.2: Effects of Temperatures and Precipitations on per Capita Real GDP Growth: Variations of Burke et al. (2015) Specifications

	(1) FE+TE +LT+QT	(2) FE +LT+QT	(3) FE+TE	(4) FE
α	0.0127***	0.0102***	0.0083**	0.0093**
	(0.0037)	(0.0038)	(0.0040)	(0.0045)
β	-0.0005***	-0.0004***	-0.0003**	-0.0002**
	(0.0001)	(0.0001)	(0.0001)	(0.0001)
N	166	166	166	166
$\max T$	50	50	50	50
avg$T$	39.66	39.66	39.66	39.66
$\min T$	8	8	8	8
$N \times T$	6584	6584	6584	6584

Notes: Column (1) uses the fixed effects (FE), time effects (TE), country-specific linear time trends (LT) and quadratic time trends (QT). Column (2) uses the FE, LT and QT. Column (3) uses the FE and TE. Column (4) uses only the FE. The standard errors are clustered at the country level. Asterisks indicate statistical significance at the 1% (***), 5% (**) and 10% (*).

where $c_i = a_i + \lambda b_{Ti} + \alpha a_{Ti} + \psi a_{Ti} b_{Ti} + \beta \left(a_{Ti}^2 + \sigma_{Ti}^2\right)$. As before, to ensure a trend-free $E\left(\Delta y_{it}\right)$, one possibility would be to set $E(\delta_t) = 0$ and impose the following restrictions

$$\gamma_i + \alpha b_{Ti} + \psi b_{Ti}^2 + 2\beta b_{Ti} a_{Ti} = 0, \text{ and } \beta b_{Ti}^2 + \phi_i = 0, \text{ for all } i.$$

Other related restrictions can be obtained depending on what is assumed about $E\left(\delta_t\right)$. In effect, KW's generalization of BHM's specification does not resolve the trend problem that surrounds the output growth specifications used in the literature.

Our specification: We consider the following panel ARDL model

$$\Delta y_{it} = a_i + \sum_{\ell=1}^{p_y} \varphi_\ell \Delta y_{i,t-\ell} + \sum_{\ell=0}^{p_{\tilde{T}}+1} \psi_\ell \tilde{T}_{it-\ell}\left(m\right) + \varepsilon_{it}, \tag{A.31}$$

where y_{it} is the log of real GDP per capita of country i in year t, a_i is the country-specific fixed effect, $\tilde{T}_{it}\left(m\right) = \left(\frac{2}{m+1}\right)\left[T_{it} - T_{i,t-1}^*(m)\right]$ is a measure of temperature relative to its historical norm per annum, T_{it} is the population-weighted average temperature of country i in year t, and $T_{i,t-1}^*(m) = \frac{1}{m}\sum_{\ell=1}^{m} T_{i,t-\ell}$ is the time-varying historical norm of temperature relative to the preceding m years. We set $m = 30$ in the baseline, given that climate norms are typically formed using 30-year moving averages, but we also check the robustness of our results using $m = 20$ and 40. We also allow for heterogeneous slopes and consider augmenting the panel ARDL model with global and regional output growth to allow for common latent effects.

The above specification has a number of distinct features that differ from the literature and are worth highlighting.

Feature #1. Our specification differs from BHM in modeling a subtle form of nonlinearity at the country level (e.g., by focusing on deviations of T_{it} from country-specific and time-varying norms) and from DJO in using $\tilde{T}_{it}(m)$ in lieu of T_{it}. This modeling choice is supported by Mendelsohn (2016) who argues that researchers should focus on the deviation of T_{it} from its mean, $T^*_{i,t-1}(m)$, to estimate unbiased weather effects in panel data studies. Such a transformation also introduces an interaction between weather and climate, and an implicit model of adaptation (see Tol (2021) for details).

To show the benefits of this variable transformation formally, let's take

$$\begin{aligned}\tilde{T}_{it-\ell}(m) &= \left(\frac{2}{m+1}\right)\left[T_{it-\ell} - T^*_{i,t-\ell}(m)\right] \\ &= \left(\frac{2}{m+1}\right)\left(T_{it} - m^{-1}\sum_{s=1}^{m} T_{i,t-s-\ell}\right)\end{aligned}$$

and use $T_{it} = a_{Ti} + b_{Ti}t + v_{Ti,t}$. We then have

$$\begin{aligned}\tilde{T}_{it-\ell}(m) &= a_{Ti} + b_{Ti}(t-\ell) + v_{Ti,t-\ell} - m^{-1}\sum_{s=1}^{m}\left[a_{Ti} + b_{Ti}(t-s-\ell) + v_{Ti,t-s-\ell}\right] \\ &= v_{Ti,t-\ell} - m^{-1}\sum_{s=1}^{m} v_{Ti,t-s-\ell},\end{aligned}$$

and it readily follows that $E\left[\tilde{T}_{it-\ell}(m)\right] = b_{Ti}$. Hence taking expectations of (A.31), it follows that

$$E(\Delta y_{it}) = a_i + \sum_{\ell=1}^{p_y}\varphi_\ell E(\Delta y_{i,t-\ell}) + \left(\sum_{\ell=0}^{p_{\tilde{T}}+1}\psi_\ell\right) b_{Ti},$$

which yields the following time-invariant long-term growth effects from temperature increases

$$E(\Delta y_{it}) = \frac{a_i + \left(\sum_{\ell=0}^{p_{\tilde{T}}+1}\psi_\ell\right) b_{Ti}}{1 - \sum_{\ell=1}^{p}\varphi_\ell}.$$

Therefore, our ARDL specification with $\tilde{T}_{it}(m)$ instead of T_{it}, results in stationary mean growth rates without imposing additional restrictions on b_{Ti} across countries. Also, under growth convergence $a_i + \left(\sum_{\ell=0}^{p_{\tilde{T}}+1}\psi_\ell\right) b_{Ti} = a_j + \left(\sum_{\ell=0}^{p_{\tilde{T}}+1}\psi_\ell\right) b_{Tj}$, countries with a larger trend temperature rise (larger b_{Ti}) must have a higher level of intrinsic (technology induced) output growth to compensate for the larger negative impact from global warming (assuming $\sum_{\ell=0}^{p_{\tilde{T}}+1}\psi_\ell < 0$). In the absence of such compensating effects, we might end up with more divergent growth paths across countries with global warming.

Feature #2. To distinguish between level and growth effects, we re-write equation (A.31) as:

$$\Delta y_{it} = a_i + \sum_{\ell=1}^{p_y}\varphi_\ell \Delta y_{i,t-\ell} + \left(\sum_{\ell=0}^{p_{\tilde{T}}}\psi_\ell\right)\tilde{T}_{it-1}(m) + \sum_{\ell=0}^{p_{\tilde{T}}}\beta_\ell \Delta\tilde{T}_{it-\ell}(m) + \varepsilon_{it}, \tag{A.32}$$

If temperature shocks, $\tilde{T}_{it-\ell}(m)$, were to have long-term growth effects, the coefficient of $\tilde{T}_{it-1}(m)$

in the above equation, namely $\sum_{\ell=0}^{p_{\tilde{T}}+1} \psi_\ell$, must be non-zero. The ARDL specification we use is sufficiently flexible and allows us to test this restriction.

In our empirical investigation, we also estimate (A.32) using the absolute value of $\tilde{T}_{it}(m)$, namely $\left|\tilde{T}_{it}(m)\right|$, which has the added advantage of accounting for climate variability as discussed in the main part of the paper. One could also allow for asymmetry in the effects of $\tilde{T}_{it}(m)$ on growth by estimating

$$\begin{aligned} \Delta y_{it} \quad = \quad & a_i + \sum_{\ell=1}^{p_y} \varphi_\ell \Delta y_{i,t-\ell} + \left(\sum_{\ell=0}^{p_{\tilde{T}}} \psi_\ell^+ \right) \tilde{T}_{it-1}^+(m) + \left(\sum_{\ell=0}^{p_{\tilde{T}}} \psi_\ell^- \right) \tilde{T}_{it-1}^-(m) \\ & + \sum_{\ell=0}^{p_{\tilde{T}}} \beta_{1\ell}^+ \Delta \tilde{T}_{it-\ell}^+(m) + \sum_{\ell=0}^{p_{\tilde{T}}} \beta_{1\ell}^- \Delta \tilde{T}_{it-\ell}^-(m) + \varepsilon_{it}, \end{aligned} \tag{A.33}$$

where

$$\tilde{T}_{it}^+(m) = \tilde{T}_{it}(m) I\left[\tilde{T}_{it-\ell}(m) \geq 0\right] \text{ and } \tilde{T}_{it}^-(m) = -\tilde{T}_{it}(m) I\left[\tilde{T}_{it-\ell}(m) < 0\right]$$

The same logic applies in distinguishing between level and growth effects when using $\left|\tilde{T}_{it}(m)\right|$ or estimating the asymmetric effects in equation (A.33). The estimation results are reported in Table A.3 for different values of m. None of the estimated coefficients on $\tilde{T}_{it-1}(m)$, $\left|\tilde{T}_{it-1}(m)\right|$, $\tilde{T}_{it-1}^+(m)$, and $\tilde{T}_{it-1}^-(m)$ are statistically significant at 10% level regardless of m. This finding suggests that temperature shocks, $\tilde{T}_{it-\ell}(m)$ are more likely to affect the level of GDP—a result that is consistent with the microeconomic evidence (see Auffhammer (2018) and Newell et al. (2021) for details) and the growth model developed in this paper. This result is consistent with DJO as they report growth effects of lagged temperature for poor countries only. Moreover, the sign reversal on temperature lags in DJO is indicative of level effects. When BHM estimate their distributed lag models with 1–5 lags of the quadratic temperature polynomial, they find that cumulative temperature effects on growth is not statistically distinguishable from zero. Moreover, as in DJO, lagged temperature effects exhibit sign reversals (see Newell et al. (2021) for details). Thus, we drop $\tilde{T}_{it-1}(m)$, $\left|\tilde{T}_{it-1}(m)\right|$, $\tilde{T}_{it-1}^+(m)$, and $\tilde{T}_{it-1}^-(m)$ from all regressions in the main text. Note that there could be long-term growth effects if temperature keeps rising above its country-specific time-varying norms owing to climate change, $\left(\sum_{\ell=0}^{p_{\tilde{T}}} \psi_\ell\right) \neq 0$ and $\sum_{\ell=0}^{p_{\tilde{T}}} \beta_\ell \neq 0$ in equation (A.32).[21]

Feature #3. To test the impact of weather shocks across climates, we consider a heterogenous panel data model where the coefficients of lagged output growth and temperature variables are allowed to vary across countries, and report the mean group (MG) estimates of marginal weather effects for different regions (e.g., hot and cold). We believe this is an improvement over Kalkuhl and Wenz (2020), who allow for heterogeneity by using interaction terms such as $\tilde{T}_{it}(m) \times \bar{T}_i$ where $\bar{T}_i$ measures the average temperature in country i over 1960–2014.

Feature #4. We exclude time effects or time trends from most regressions in this paper as they could result in overfitting and worse out-of-sample predictions. The inferior statistical performance of models with trends is also confirmed by model cross-validation of Newell et al. (2021). To treat

[21] As an example, while the stock of capital will determine the level of GDP, capital accumulation affects GDP growth.

Table A.3: Level Effects? Long-Run Impact of Temperature Shocks on per Capita Real GDP Growth, 1960–2014

Historical Norm:	$m = 20$		$m = 30$		$m = 40$	
	(a) FE	(b) HPJ-FE	(a) FE	(b) HPJ-FE	(a) FE	(b) HPJ-FE
(a) Specification 1						
$\tilde{T}_{it-1}(m)$	-0.0176	0.0011	-0.0270	0.0016	-0.0360	0.0281
	(0.0302)	(0.0416)	(0.0397)	(0.0587)	(0.0478)	(0.0718)
(b) Specification 2						
$\left\|\tilde{T}_{it-1}(m)\right\|$	-0.0174	-0.0221	-0.0140	-0.0037	-0.0031	0.0260
	(0.0779)	(0.0843)	(0.1085)	(0.1249)	(0.1316)	(0.1543)
(c) Specification 3						
$\tilde{T}^{+}_{it-1}(m)$	-0.0212	-0.0057	-0.0106	0.0370	0.0068	0.1023
	(0.0780)	(0.0861)	(0.1093)	(0.1240)	(0.1333)	(0.1526)
$\tilde{T}^{-}_{it-1}(m)$	0.0185	0.0222	0.0575	0.1410	0.1132	0.2930
	(0.1006)	(0.0996)	(0.1425)	(0.1503)	(0.1792)	(0.1939)
$N \times T$	6714	6674	6714	6674	6714	6674

Notes: Specification 1 is given by $\Delta y_{it} = a_i + \sum_{\ell=1}^{p_y} \varphi_\ell \Delta y_{i,t-\ell} + \left(\sum_{\ell=0}^{p_{\tilde{T}}} \psi_\ell\right) \tilde{T}_{it-1}(m) + \sum_{\ell=0}^{p_{\tilde{T}}} \beta_\ell \Delta \tilde{T}_{it-\ell}(m) + \varepsilon_{it}$, where y_{it} is the log of real GDP per capita of country i in year t, $\tilde{T}_{it}(m) = \left(\frac{2}{m+1}\right)\left[T_{it} - T^*_{i,t-1}(m)\right]$ is a measure of temperature relative to its historical norm per annum, T_{it} is the population-weighted average temperature of country i in year t, and $T^*_{i,t-1}(m) = \frac{1}{m}\sum_{\ell=1}^{m} T_{i,t-\ell}$ is the time-varying historical norm of temperature over the preceding m years in each t. Specification 2 estimates the same model with $\left|\tilde{T}_{it}(m)\right|$ and specification 3 allows for asymmetry in the effects of $\tilde{T}_{it}(m)$ on growth by using $\tilde{T}^{+}_{it}(m) = \tilde{T}_{it}(m) I\left[\tilde{T}_{it-\ell}(m) \geq 0\right]$ and $\tilde{T}^{-}_{it}(m) = -\tilde{T}_{it}(m) I\left[\tilde{T}_{it-\ell}(m) < 0\right]$ in regressions. Columns labelled (a) report the FE estimates and columns labelled (b) report the half-panel jackknife FE (HPJ-FE) estimates, which corrects the bias in columns (a). The standard errors are estimated by the estimator proposed in Proposition 4 of Chudik et al. (2018). Asterisks indicate statistical significance at the 1% (***), 5% (**), and 10% (*) levels.

unobserved factors, instead we augment the ARDL panel regressions with lagged world output growth (regional output growth could also be used), and estimated the following augmented ARDL specification:

$$\Delta y_{it} = a_i + \omega \Delta \bar{y}_{w,t-1} + \sum_{\ell=1}^{p_y} \varphi_\ell \Delta y_{i,t-\ell} + \sum_{\ell=0}^{p_{\tilde{T}}} \beta \Delta \left| \tilde{T}_{it-\ell}(m) \right| + \varepsilon_{it},$$

where $\bar{y}_{wt}$ is the log of world's real GDP per capita in year t (capturing common time effects). The results are reported in Table A.4.

A.3 Climate Change: Historical Patterns

This appendix examines how global temperature has evolved over the past half century (1960–2014) as well as over a longer period (1900–2014). Allowing for the significant heterogeneity that exists across countries with respect to changes in temperature over time, we estimate country-specific regressions

$$T_{it} = a_{Ti} + b_{Ti} t + v_{Ti,t}, \text{ for } i = 1, 2, ..., N = 174, \tag{A.34}$$

where T_{it} denotes the population-weighted average temperature of country i at year t. The per annum average increase in land temperature for country i is given by b_{Ti}, with the corresponding global measure defined by $b_T = N^{-1} \Sigma_{i=1}^{N} b_{Ti}$. Individual country estimates of b_{Ti} together with their standard errors are summarized in Table A.5. The estimates range from -0.0044 (Samoa) to 0.0390 (Afghanistan). For 169 countries (97.1% of cases), these estimates are positive; out of which, the estimates in 161 countries (95.3% of cases) are statistically significant at the 5% level. There are only five countries for which the estimate, $\widehat{b}_{Ti}$, is not positive: Bangladesh, Bolivia, Cuba, Ecuador and Samoa, but none of them are statistically significant at the 5% level. See also Figure A.2 which illustrates the increase in temperature per year for the 174 countries over 1960–2014.

Table A.6 presents estimates of b_{Ti} over a longer time horizon (1900–2014). The country-specific estimates of b_{Ti} for the 174 countries over this longer sample period range from -0.0008 (Greece) to 0.0190 (Haiti). In 172 countries (98.9% of the cases) these estimates are positive and in 156 countries (90.7% of cases) they are statistically significant at the 5% level. There are only two countries for which the estimate of b_{Ti} is not positive: Greece and Macedonia but these are not statistically significant. The estimated results over 1900–2014 echo those obtained over the 1960–2014 period. Temperature has been rising for pretty much all of the countries in our sample, indicating that T_{it} is trended. As discussed in the main text, the econometric specifications in the literature involve real GDP growth rates and the level of temperature, T_{it}, and in some cases also T_{it}^2; see, for instance, Dell et al. (2012) and Burke et al. (2015). But in cases where T_{it} is trended, which is the situation in almost all the countries in the world (based on both the 1900–2014 and the 1960–2014 samples), inclusion of T_{it} in the regressions will induce a quadratic trend in equilibrium log per capita output (or equivalently a linear trend in per capita output growth) which is not desirable and can bias the estimates of the growth-climate change equation.

The above country-specific estimates are also in line with the average increases in global tem-

Table A.4: Long-Run Effects of Climate Change on per Capita Real GDP Growth, 1960–2014 (Using Absolute Value of Deviations of Climate Variables from their Historical Norm)

	Specification 1						Specification 2					
	$m=20$		$m=30$		$m=40$		$m=20$		$m=30$		$m=40$	
	(a) FE	(b) HPJ-FE	(a) FE	(b) HPJ-FE	(a) FE	(b) HPJ-FE	(a) FE	(b) HPJ-FE	(a) FE	(b) HPJ-FE	(a) FE	(b) HPJ-FE
$\widehat{\theta}_{\Delta\lvert\tilde{T}_{it}(m)\rvert}$	-0.313**	-0.456**	-0.494**	-0.728***	-0.602**	-0.859**	-0.317**	-0.461**	-0.495**	-0.733***	-0.605**	-0.873**
	(0.141)	(0.191)	(0.197)	(0.270)	(0.248)	(0.344)	(0.140)	(0.191)	(0.197)	(0.270)	(0.249)	(0.344)
$\widehat{\theta}_{\Delta\lvert\tilde{P}_{it}(m)\rvert}$	-0.0653	-0.109	-0.0014	-0.0845	-0.198	-0.333	-	-	-	-	-	-
	(0.233)	(0.323)	(0.466)	(0.508)	(0.635)	(0.684)	-	-	-	-	-	-
$\widehat{\phi}$	0.690***	0.625***	0.690***	0.625***	0.690***	0.624***	0.691***	0.625***	0.691***	0.625***	0.691***	0.625***
	(0.0506)	(0.0452)	(0.0505)	(0.0453)	(0.0504)	(0.0453)	(0.0506)	(0.0453)	(0.0505)	(0.0453)	(0.0504)	(0.0453)
ω	0.312***	0.313***	0.307***	0.302***	0.310***	0.307***	0.312***	0.311***	0.308***	0.304***	0.309***	0.304***
	(0.0413)	(0.0532)	(0.0414)	(0.0534)	(0.0413)	(0.0533)	(0.0413)	(0.0532)	(0.0413)	(0.0532)	(0.0414)	(0.0535)
N	174	174	174	174	174	174	174	174	174	174	174	174
$\max T$	50	50	50	50	50	50	50	50	50	50	50	50
avg$T$	38.36	38.36	38.36	38.36	38.36	38.36	38.36	38.36	38.36	38.36	38.36	38.36
$\min T$	2	2	2	2	2	2	2	2	2	2	2	2
$N \times T$	6714	6674	6714	6674	6714	6674	6714	6674	6714	6674	6714	6674

Notes: Specification 1 is given by $\Delta y_{it} = a_i + \omega\Delta\bar{y}_{w,t-1} + \sum_{\ell=1}^{p_y}\varphi_\ell\Delta y_{i,t-\ell} + \sum_{\ell=0}^{p_{\tilde{T}}}\beta_{1\ell}\left|\tilde{T}_{it-\ell}(m)\right| + \sum_{\ell=0}^{p_{\tilde{T}}}\beta_{2\ell}\left|\tilde{P}_{it-\ell}(m)\right| + \varepsilon_{it}$, where y_{it} is the log of real GDP per capita of country i in year t, $\bar{y}_{wt}$ is the log of world's real GDP per capita in year t, $\tilde{T}_{it}(m) = \left(\frac{2}{m+1}\right)\left[T_{it} - T^*_{i,t-1}(m)\right]$ and $\tilde{P}_{it}(m) = \left(\frac{2}{m+1}\right)\left[P_{it} - P^*_{i,t-1}(m)\right]$ are measures of temperature and precipitation relative to their historical norms per annum, T_{it} and P_{it} are the population-weighted average temperature and of precipitation country i in year t, and $T^*_{i,t-1}(m) = \frac{1}{m}\sum_{\ell=1}^{m} T_{i,t-\ell}$ and $P^*_{i,t-1}(m) = \frac{1}{m}\sum_{\ell=1}^{m} P_{i,t-\ell}$ are the time-varying historical norms of temperature and precipitation over the preceding m years in each t. The long-run effects, θ_i , are calculated from the OLS estimates of the short-run coefficients in equation (1): $\theta_1 = \phi^{-1}\sum_{\ell=0}^{p}\beta_{1\ell}$ and $\theta_2 = \phi^{-1}\sum_{\ell=0}^{p}\beta_{2\ell}$, where $\phi = 1 - \sum_{\ell=1}^{p}\varphi_\ell$. Specification 2 drops the precipitation variables from the baseline model. The standard errors are estimated by the estimator proposed in Proposition 4 of Chudik et al. (2018). Asterisks indicate statistical significance at the 1% (***), 5% (**), and 10% (*) levels.

Table A.5: Individual Country Estimates of the Average Yearly Rise in Temperature Over the Period 1960–2014

Country	$\widehat{b}_{Ti}$	Country	$\widehat{b}_{Ti}$	Country	$\widehat{b}_{Ti}$
Afghanistan	0.0390***	Georgia	0.0159***	Oman	0.0082***
Albania	0.0240***	Germany	0.0229***	Pakistan	0.0096***
Algeria	0.0288***	Ghana	0.0184***	Panama	0.0169***
Angola	0.0193***	Greece	0.0112***	Papua New Guinea	0.0074***
Argentina	0.0070***	Greenland	0.0381***	Paraguay	0.0047
Armenia	0.0140**	Guatemala	0.0276***	Peru	0.0065**
Australia	0.0094***	Guinea	0.0166***	Philippines	0.0068***
Austria	0.0170***	Guinea-Bissau	0.0237***	Poland	0.0255***
Azerbaijan	0.0188***	Guyana	0.0029	Portugal	0.0104***
Bahamas	0.0195***	Haiti	0.0163***	Puerto Rico	0.0059**
Bangladesh	-0.0007	Honduras	0.0207***	Qatar	0.0271***
Belarus	0.0316***	Hungary	0.0163***	Romania	0.0186***
Belgium	0.0261***	Iceland	0.0206***	Russian Federation	0.0348***
Belize	0.0114***	India	0.0095***	Rwanda	0.0158***
Benin	0.0180***	Indonesia	0.0053***	Saint Vincent and the Grenadines	0.0124***
Bhutan	0.0143***	Iran	0.0229***	Samoa	-0.0044*
Bolivia	-0.0000	Iraq	0.0244***	Sao Tome and Principe	0.0240***
Bosnia and Herzegovina	0.0373***	Ireland	0.0151***	Saudi Arabia	0.0207***
Botswana	0.0260***	Israel	0.0168***	Senegal	0.0255***
Brazil	0.0162***	Italy	0.0283***	Serbia	0.0155***
Brunei Darussalam	0.0096***	Jamaica	0.0204***	Sierra Leone	0.0161***
Bulgaria	0.0124***	Japan	0.0133***	Slovakia	0.0197***
Burkina Faso	0.0191***	Jordan	0.0146***	Slovenia	0.0298***
Burundi	0.0186***	Kazakhstan	0.0240***	Solomon Islands	0.0096***
Cabo Verde	0.0181***	Kenya	0.0176***	Somalia	0.0213***
Cambodia	0.0167***	Kuwait	0.0254***	South Africa	0.0073***
Cameroon	0.0117***	Kyrgyzstan	0.0280***	South Korea	0.0081*
Canada	0.0300***	Laos	0.0091***	South Sudan	0.0308***
Central African Republic	0.0099***	Latvia	0.0304***	Spain	0.0260***
Chad	0.0181***	Lebanon	0.0247***	Sri Lanka	0.0107***
Chile	0.0102***	Lesotho	0.0099**	Sudan	0.0295***
China	0.0230***	Liberia	0.0094***	Suriname	0.0042
Colombia	0.0061**	Libya	0.0333***	Swaziland	0.0174***
Comoros	0.0062*	Lithuania	0.0277***	Sweden	0.0210***
Congo	0.0146***	Luxembourg	0.0281***	Switzerland	0.0183***
Congo DRC	0.0150***	Macedonia	0.0129***	Syria	0.0225***
Costa Rica	0.0173***	Madagascar	0.0214***	Tajikistan	0.0002
Côte d'Ivoire	0.0131***	Malawi	0.0234***	Tanzania	0.0104***
Croatia	0.0247***	Malaysia	0.0133***	Thailand	0.0055**
Cuba	-0.0006	Mali	0.0214***	Togo	0.0185***
Cyprus	0.0151***	Mauritania	0.0243***	Trinidad and Tobago	0.0243***
Czech Republic	0.0192***	Mauritius	0.0216***	Tunisia	0.0368***
Denmark	0.0195***	Mexico	0.0117***	Turkey	0.0141**
Djibouti	0.0135***	Moldova	0.0202***	Turkmenistan	0.0255***
Dominican Republic	0.0152***	Mongolia	0.0276***	Uganda	0.0198***
Ecuador	-0.0031	Montenegro	0.0196***	Ukraine	0.0263***
Egypt	0.0272***	Morocco	0.0211***	United Arab Emirates	0.0158***
El Salvador	0.0319***	Mozambique	0.0148***	United Kingdom	0.0129***
Equatorial Guinea	0.0275***	Myanmar	0.0200***	United States	0.0147***
Eritrea	0.0178***	Namibia	0.0262***	Uruguay	0.0151***
Estonia	0.0330***	Nepal	0.0176***	US Virgin Islands	0.0226***
Ethiopia	0.0219***	Netherlands	0.0240***	Uzbekistan	0.0214***
Fiji	0.0115***	New Caledonia	0.0118***	Vanuatu	0.0279***
Finland	0.0304***	New Zealand	0.0018	Venezuela	0.0160***
France	0.0215***	Nicaragua	0.0286***	Vietnam	0.0054**
French Polynesia	0.0236***	Niger	0.0075	Yemen	0.0345***
Gabon	0.0177***	Nigeria	0.0163***	Zambia	0.0190***
Gambia	0.0234***	Norway	0.0232***	Zimbabwe	0.0139***

Notes: $\widehat{b}_{Ti}$ is the OLS estimate of b_{Ti} in the country-specific regressions $T_{it} = a_{Ti} + b_{Ti}t + v_{T,it}$, where T_{it} denotes the population-weighted average temperature (°C). Asterisks indicate statistical significance at the 1% (***), 5% (**) and 10% (*) levels.

Table A.6: Individual Country Estimates of the Average Yearly Rise in Temperature Over the Period 1900–2014

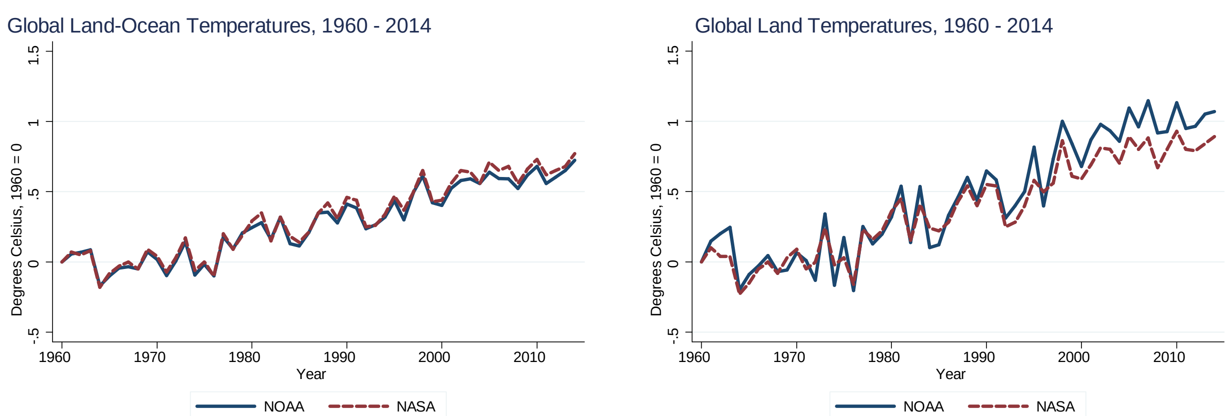
Country	$\widehat{b}_{Ti}$	Country	$\widehat{b}_{Ti}$	Country	$\widehat{b}_{Ti}$
Afghanistan	0.0136***	Georgia	0.0044**	Oman	0.0047***
Albania	0.0036**	Germany	0.0063***	Pakistan	0.0043***
Algeria	0.0067***	Ghana	0.0035***	Panama	0.0060***
Angola	0.0099***	Greece	-0.0008	Papua New Guinea	0.0026**
Argentina	0.0038***	Greenland	0.0110***	Paraguay	0.0032**
Armenia	0.0056**	Guatemala	0.0065***	Peru	0.0039***
Australia	0.0041***	Guinea	0.0028***	Philippines	0.0048***
Austria	0.0056***	Guinea-Bissau	0.0051***	Poland	0.0063***
Azerbaijan	0.0064***	Guyana	0.0051***	Portugal	0.0051***
Bahamas	0.0048***	Haiti	0.0190***	Puerto Rico	0.0023***
Bangladesh	0.0033***	Honduras	0.0086***	Qatar	0.0125***
Belarus	0.0094***	Hungary	0.0033*	Romania	0.0043**
Belgium	0.0057***	Iceland	0.0034*	Russian Federation	0.0111***
Belize	0.0041***	India	0.0029***	Rwanda	0.0050***
Benin	0.0032***	Indonesia	0.0025***	Saint Vincent and the Grenadines	0.0050***
Bhutan	0.0055***	Iran	0.0072***	Samoa	0.0050***
Bolivia	0.0011	Iraq	0.0083***	Sao Tome and Principe	0.0071***
Bosnia and Herzegovina	0.0106***	Ireland	0.0057***	Saudi Arabia	0.0070***
Botswana	0.0098***	Israel	0.0047***	Senegal	0.0074***
Brazil	0.0061***	Italy	0.0045***	Serbia	0.0038**
Brunei Darussalam	0.0002	Jamaica	0.0134***	Sierra Leone	0.0031***
Bulgaria	0.0012	Japan	0.0099***	Slovakia	0.0061***
Burkina Faso	0.0045***	Jordan	0.0032*	Slovenia	0.0062***
Burundi	0.0075***	Kazakhstan	0.0122***	Solomon Islands	0.0020**
Cabo Verde	0.0039***	Kenya	0.0026***	Somalia	0.0071***
Cambodia	0.0045***	Kuwait	0.0091***	South Africa	0.0051***
Cameroon	0.0039***	Kyrgyzstan	0.0146***	South Korea	0.0101***
Canada	0.0110***	Laos	0.0028***	South Sudan	0.0102***
Central African Republic	0.0020**	Latvia	0.0094***	Spain	0.0080***
Chad	0.0048***	Lebanon	0.0030*	Sri Lanka	0.0050***
Chile	0.0017**	Lesotho	0.0026**	Sudan	0.0102***
China	0.0064***	Liberia	0.0018**	Suriname	0.0012
Colombia	0.0098***	Libya	0.0076***	Swaziland	0.0103***
Comoros	0.0053***	Lithuania	0.0080***	Sweden	0.0064**
Congo	0.0064***	Luxembourg	0.0050***	Switzerland	0.0046***
Congo DRC	0.0051***	Macedonia	-0.0000	Syria	0.0055***
Costa Rica	0.0031*	Madagascar	0.0018*	Tajikistan	0.0099***
Côte d'Ivoire	0.0013	Malawi	0.0162***	Tanzania	0.0026***
Croatia	0.0039**	Malaysia	0.0014*	Thailand	0.0012
Cuba	0.0021***	Mali	0.0057***	Togo	0.0023**
Cyprus	0.0080***	Mauritania	0.0083***	Trinidad and Tobago	0.0035**
Czech Republic	0.0040**	Mauritius	0.0053***	Tunisia	0.0087***
Denmark	0.0044**	Mexico	0.0060***	Turkey	0.0045**
Djibouti	0.0057***	Moldova	0.0089***	Turkmenistan	0.0092***
Dominican Republic	0.0111***	Mongolia	0.0111***	Uganda	0.0048***
Ecuador	0.0091***	Montenegro	0.0070***	Ukraine	0.0089***
Egypt	0.0056***	Morocco	0.0041***	United Arab Emirates	0.0055***
El Salvador	0.0050**	Mozambique	0.0134***	United Kingdom	0.0038***
Equatorial Guinea	0.0093***	Myanmar	0.0051***	United States	0.0036***
Eritrea	0.0046***	Namibia	0.0093***	Uruguay	0.0064***
Estonia	0.0093***	Nepal	0.0039***	US Virgin Islands	0.0069***
Ethiopia	0.0049***	Netherlands	0.0043**	Uzbekistan	0.0096***
Fiji	0.0045***	New Caledonia	0.0006	Vanuatu	0.0043***
Finland	0.0070**	New Zealand	0.0043***	Venezuela	0.0152***
France	0.0069***	Nicaragua	0.0086***	Vietnam	0.0015*
French Polynesia	0.0062***	Niger	0.0009	Yemen	0.0154***
Gabon	0.0074***	Nigeria	0.0044***	Zambia	0.0033**
Gambia	0.0046***	Norway	0.0054**	Zimbabwe	0.0066***

Notes: $\widehat{b}_{Ti}$ is the OLS estimate of b_{Ti} in the country-specific regressions $T_{it} = a_{Ti} + b_{Ti}t + v_{T,it}$, where T_{it} denotes the population-weighted average temperature (°C). Asterisks indicate statistical significance at the 1% (***), 5% (**) and 10% (*) levels.

perature published by the *Goddard Institute for Space Studies* (GISS) at National Aeronautics and Space Administration (NASA), and close to the estimates by the *National Centers for Environmental Information* (NCEI) at the National Oceanic and Atmospheric Administration (NOAA). The right panel in Figure A.1 plots the global land temperatures between 1960 and 2014 recorded by NOAA and NASA; clearly showing that T_t is trended. IPCC (2013) also estimates similar trends using various datasets and over different sub-periods. For instance, the trend estimates of global land-surface air temperature (in °C per decade) over the 1951-2012 period, based on data from the Climatic Research Unit's *CRUTEM4.1.1.0*, NOAA's *Global Historical Climatology Network Version 3* (GHCNv3), and *Berkeley Earth*, are reported as 0.175 (±0.037), 0.197 (±0.031), and 0.175 (±0.029), respectively with 90% confidence intervals in brackets; see Chapter 2 of IPCC (2013).

Using the individual country estimates in Table A.5, the average rise in global temperature over the 1960-2014 period is given by $\hat{b}_{\mathcal{T}} = 0.0181(0.0007)$ degrees Celsius per annum, which is statistically highly significant.[22] In comparison, according to NASA observations global land temperature has risen by 0.89°C between 1960 and 2014, or around 0.0165°C per year, and based on NCEI data the global land-surface air temperature has risen by 1.07°C over the same period, or around $0.0198°C$ per year. Thus our global estimate of $0.0181°C$ lies in the middle of these two estimates, but has the added advantage of having a small standard error, noting that it is a pooled estimate across a large number of countries.

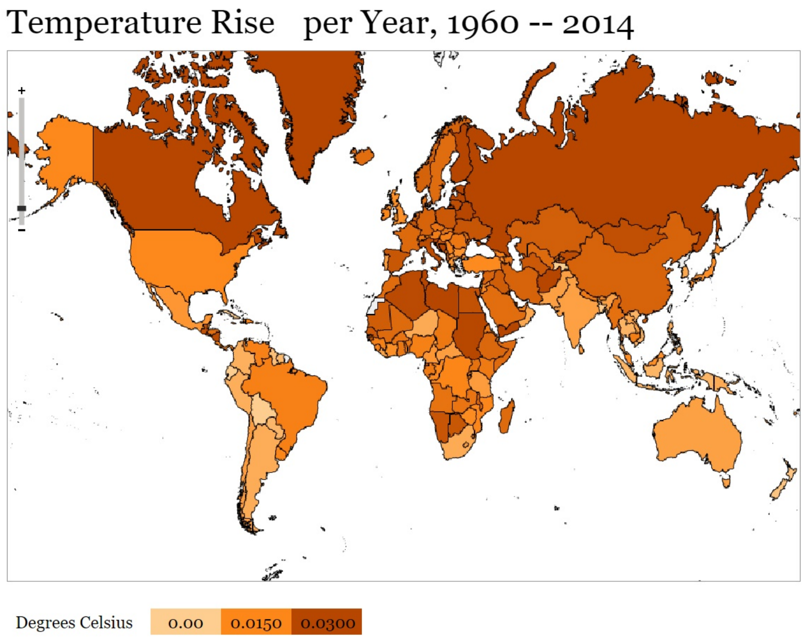
Figure A.1: Global Land-Surface Air and Sea-Surface Water Temperatures (Degrees Celsius, 1960 = 0)



Note: The left panel shows the global land-surface air and sea-surface water temperatures, and the right panel shows the global land-surface air temperatures, both over the 1960–2014 period. The blue lines show the temperatures observed by the *National Centers for Environmental Information* (NCEI) at the National Oceanic and Atmospheric Administration (NOAA); and the broken red lines show the temperatures observed by the *Goddard Institute for Space Studies* (GISS) at National Aeronautics and Space Administration (NASA). The temperatures in 1960 are standardised to zero.

[22] The standard error of $\hat{b}_{\mathcal{T}} = N^{-1}\Sigma_{i=1}^{N}\hat{b}_{\mathcal{T}i}$, given in round brackets, is computed using the mean group approach of Pesaran and Smith (1995).

Figure A.2: Temperature Increase per year for the 174 Countries, 1960–2014



We also plot the global land-surface air and sea-surface water temperatures in the left panel of Figure A.1. We observe an upward trend using data from NOAA (a rise of 0.72°C) or data from NASA (a rise of 0.77°C) between 1960 and 2014; equivalent to 0.0134°C and 0.0143°C per year, respectively. Note that the land-surface air temperature has risen by more than the sea-surface water temperature over this period, because oceans have a larger effective heat capacity and lose more heat through evaporation.

A.4 Additional Results

We reported the real GDP per capita losses arising from global warming under the RCP 2.6 and RCP 8.5 scenarios, compared to the reference case, in country heat maps and for the year 2100 only in the main text. In Table A.7 we make available all of the 174 country-specific estimates over various horizons (by year 2030, 2050, and 2100).

Table A.7: Percent Loss in GDP per capita by 2030, 2050, and 2100 under the RCP 2.6 and RCP 8.5 Scenarios

	Key Variables in Equation (13)					Percent Loss in GDP per capita					
	$\bar{T}i$	$\widehat{b}^{0}_{Ti}$	$\widehat{\sigma}_{Ti}$	d_i		RCP 2.6 Scenario			RCP 8.5 Scenario		
				RCP 2.6	RCP 8.5	2030	2050	2100	2030	2050	2100
Afghanistan	12.35	0.039	0.61	-0.0005	0.0009	-0.35	-0.78	-1.18	0.70	1.96	5.54
Albania	12.94	0.024	0.48	0.0002	0.0014	0.15	0.42	1.22	1.03	3.13	8.86
Algeria	23.02	0.029	0.41	-0.0009	0.0004	-0.59	-0.94	1.33	0.34	0.92	2.56
Angola	21.90	0.019	0.34	-0.0002	0.0009	-0.14	-0.31	-0.52	0.71	2.09	5.84
Argentina	14.14	0.007	0.29	0.0005	0.0013	0.20	0.71	2.50	0.79	2.78	8.17
Armenia	7.82	0.014	0.82	0.0000	0.0012	-0.01	-0.02	-0.05	0.42	1.57	6.03
Australia	21.69	0.009	0.35	0.0002	0.0011	0.06	0.17	0.56	0.64	2.25	6.93
Austria	6.94	0.017	0.54	0.0001	0.0013	0.06	0.16	0.46	0.71	2.39	7.58
Azerbaijan	12.99	0.019	0.65	-0.0008	0.0004	-0.21	-0.23	1.25	0.18	0.54	1.80
Bahamas	25.59	0.020	0.28	-0.0008	-0.0001	-0.50	-0.52	2.34	-0.08	-0.20	-0.44
Bangladesh	25.55	-0.001	0.26	0.0005	0.0014	0.06	0.42	2.15	0.55	2.68	8.59
Belarus	6.21	0.032	0.83	-0.0003	0.0009	-0.12	-0.28	-0.54	0.52	1.58	5.04
Belgium	9.45	0.026	0.64	-0.0005	0.0004	-0.23	-0.47	-0.29	0.25	0.71	2.17
Belize	25.54	0.011	0.27	-0.0001	0.0008	-0.04	-0.09	-0.18	0.55	1.75	5.10
Benin	27.38	0.018	0.25	-0.0003	0.0007	-0.22	-0.48	-0.50	0.59	1.65	4.43
Bhutan	7.84	0.014	0.36	0.0016	0.0026	1.18	3.70	10.33	2.23	6.64	17.76
Bolivia	21.47	0.000	0.33	0.0003	0.0015	0.02	0.15	0.90	0.53	2.64	8.82
Bosnia and Herzegovina	8.96	0.037	0.58	0.0004	0.0015	0.27	0.74	2.07	1.24	3.56	9.75
Botswana	21.96	0.026	0.62	-0.0003	0.0011	-0.13	-0.30	-0.53	0.67	2.07	6.37
Brazil	24.45	0.016	0.24	0.0000	0.0011	0.02	0.06	0.15	0.99	2.79	7.35
Brunei Darussalam	26.84	0.010	0.27	-0.0005	0.0003	-0.15	-0.07	1.41	0.16	0.50	1.65
Bulgaria	9.97	0.012	0.51	0.0009	0.0021	0.39	1.39	4.84	1.24	4.41	13.16
Burkina Faso	28.40	0.019	0.29	-0.0004	0.0007	-0.26	-0.53	-0.26	0.60	1.72	4.71
Burundi	20.28	0.019	0.43	0.0001	0.0012	0.08	0.21	0.59	0.81	2.56	7.46
Cabo Verde	21.02	0.018	0.46	0.0002	0.0009	0.10	0.27	0.80	0.57	1.80	5.54
Cambodia	26.95	0.017	0.29	-0.0007	0.0001	-0.36	-0.38	1.84	0.10	0.26	0.74
Cameroon	24.43	0.012	0.29	-0.0003	0.0006	-0.13	-0.23	0.08	0.39	1.23	3.75
Canada	-6.20	0.030	0.77	0.0004	0.0021	0.20	0.56	1.68	1.37	4.40	13.08
Central African Republic	25.30	0.010	0.32	-0.0001	0.0008	-0.05	-0.11	-0.15	0.49	1.65	5.12
Chad	27.57	0.018	0.46	-0.0009	0.0002	-0.31	-0.18	2.65	0.11	0.31	0.92
Chile	8.16	0.010	0.31	0.0008	0.0017	0.50	1.68	5.18	1.23	3.97	11.08
China	6.68	0.023	0.30	-0.0006	0.0007	-0.45	-0.80	0.45	0.58	1.62	4.35
Colombia	24.65	0.006	0.28	0.0000	0.0010	0.00	-0.01	-0.03	0.52	1.93	6.02
Comoros	25.08	0.006	0.40	0.0004	0.0012	0.11	0.39	1.57	0.49	1.97	6.71
Congo	24.63	0.015	0.25	-0.0002	0.0008	-0.12	-0.27	-0.40	0.62	1.81	4.99
Congo DRC	23.92	0.015	0.26	-0.0001	0.0009	-0.09	-0.22	-0.41	0.73	2.13	5.81
Costa Rica	23.41	0.017	0.35	0.0007	0.0015	0.49	1.47	4.33	1.20	3.64	9.95
Côte d'Ivoire	26.35	0.013	0.27	-0.0003	0.0006	-0.15	-0.29	-0.09	0.45	1.37	3.96
Croatia	11.27	0.025	0.58	-0.0002	0.0009	-0.10	-0.24	-0.46	0.59	1.79	5.52
Cuba	25.39	-0.001	0.28	0.0005	0.0013	0.06	0.44	2.26	0.44	2.28	7.68
Cyprus	18.67	0.015	0.48	-0.0001	0.0009	-0.02	-0.05	-0.12	0.50	1.66	5.37
Czech Republic	7.47	0.019	0.64	-0.0002	0.0009	-0.07	-0.16	-0.28	0.41	1.33	4.52
Denmark	7.90	0.019	0.74	-0.0005	0.0004	-0.13	-0.24	-0.02	0.16	0.49	1.63
Djibouti	28.00	0.013	0.35	-0.0009	0.0001	-0.25	0.17	3.62	0.03	0.08	0.22
Dominican Republic	25.19	0.015	0.37	-0.0002	0.0006	-0.08	-0.18	-0.31	0.35	1.06	3.31
Ecuador	22.32	-0.003	0.39	0.0005	0.0014	0.00	0.19	1.49	0.27	1.94	7.70
Egypt	22.20	0.027	0.44	-0.0004	0.0008	-0.29	-0.61	-0.69	0.63	1.79	5.06
El Salvador	24.59	0.032	0.37	-0.0001	0.0008	-0.05	-0.12	-0.31	0.76	2.08	5.50
Equatorial Guinea	24.32	0.027	0.45	-0.0007	0.0002	-0.40	-0.76	-0.02	0.14	0.36	1.00
Eritrea	25.95	0.018	0.50	-0.0002	0.0009	-0.07	-0.16	-0.29	0.53	1.70	5.42
Estonia	5.22	0.033	0.89	-0.0007	0.0005	-0.27	-0.54	-0.33	0.28	0.80	2.47
Ethiopia	22.58	0.022	0.25	-0.0004	0.0006	-0.30	-0.66	-0.72	0.56	1.52	4.00
Fiji	24.45	0.011	0.27	0.0004	0.0011	0.25	0.77	2.39	0.81	2.54	7.12
Finland	1.47	0.030	0.96	-0.0011	0.0003	-0.35	-0.46	1.48	0.12	0.34	1.02
France	10.55	0.022	0.50	-0.0001	0.0010	-0.03	-0.07	-0.17	0.62	1.92	5.82
French Polynesia	23.83	0.024	0.30	0.0005	0.0011	0.43	1.17	3.16	1.03	2.83	7.43
Gabon	24.44	0.018	0.32	-0.0002	0.0007	-0.10	-0.24	-0.45	0.55	1.61	4.56
Gambia	26.43	0.023	0.32	0.0002	0.0012	0.20	0.53	1.44	1.15	3.20	8.43

Notes: We consider persistent increases in temperatures based on the RCP 2.6 and RCP 8.5 scenarios. The losses are based on $\Delta_{ih}(d_i)$, see equation (13), with $h = 16$, 36, and 86 (corresponding to the year 2030, 2050, and 2100, respectively) and $m = 30$.

Table A.7: Percent Loss in GDP per capita by 2030, 2050, and 2100 under the RCP 2.6 and RCP 8.5 Scenarios (continued)

	Key Variables in Equation (13)					Percent Loss in GDP per capita					
	$\bar{T}i$	$\widehat{b}^0_{Ti}$	$\widehat{\sigma}_{Ti}$	d_i		RCP 2.6 Scenario			RCP 8.5 Scenario		
				RCP 2.6	RCP 8.5	2030	2050	2100	2030	2050	2100
Georgia	8.73	0.016	0.67	-0.0004	0.0008	-0.09	-0.18	-0.05	0.33	1.12	4.01
Germany	8.47	0.023	0.65	-0.0006	0.0004	-0.22	-0.39	0.08	0.21	0.61	1.92
Ghana	27.14	0.018	0.24	-0.0004	0.0005	-0.31	-0.61	-0.10	0.43	1.18	3.17
Greece	13.82	0.011	0.49	0.0008	0.0019	0.35	1.26	4.45	1.12	4.04	12.21
Greenland	-19.71	0.038	0.73	-0.0008	0.0007	-0.42	-0.85	-0.52	0.49	1.39	4.10
Guatemala	23.56	0.028	0.28	-0.0002	0.0008	-0.16	-0.40	-0.89	0.80	2.12	5.48
Guinea	25.53	0.017	0.25	-0.0002	0.0008	-0.12	-0.28	-0.50	0.71	2.03	5.45
Guinea-Bissau	26.74	0.024	0.28	-0.0002	0.0007	-0.20	-0.47	-0.88	0.70	1.91	5.02
Guyana	25.98	0.003	0.33	0.0003	0.0013	0.07	0.27	1.21	0.56	2.42	7.89
Haiti	24.55	0.016	0.53	0.0001	0.0009	0.04	0.10	0.27	0.45	1.49	4.95
Honduras	25.27	0.021	0.35	-0.0003	0.0006	-0.19	-0.42	-0.57	0.46	1.33	3.78
Hungary	10.33	0.016	0.64	-0.0002	0.0009	-0.07	-0.15	-0.20	0.41	1.41	4.96
Iceland	1.10	0.021	0.65	-0.0007	0.0003	-0.23	-0.32	0.83	0.12	0.33	1.00
India	23.99	0.009	0.25	0.0004	0.0015	0.26	0.81	2.57	1.16	3.62	9.90
Indonesia	25.40	0.005	0.15	0.0003	0.0011	0.19	0.61	1.92	0.91	2.79	7.51
Iran	17.33	0.023	0.52	-0.0001	0.0012	-0.04	-0.10	-0.23	0.83	2.59	7.65
Iraq	22.11	0.024	0.67	-0.0008	0.0006	-0.28	-0.44	0.73	0.29	0.86	2.74
Ireland	9.34	0.015	0.41	0.0001	0.0008	0.03	0.09	0.26	0.46	1.47	4.62
Israel	20.31	0.017	0.55	-0.0004	0.0007	-0.12	-0.24	-0.08	0.36	1.15	3.87
Italy	12.21	0.028	0.43	0.0000	0.0011	0.01	0.02	0.05	0.89	2.56	7.01
Jamaica	25.18	0.020	0.35	0.0000	0.0007	0.01	0.04	0.09	0.59	1.71	4.80
Japan	11.18	0.013	0.40	0.0006	0.0017	0.33	1.06	3.47	1.12	3.72	10.70
Jordan	18.56	0.015	0.62	0.0002	0.0015	0.08	0.22	0.70	0.72	2.61	8.69
Kazakhstan	6.00	0.024	0.80	0.0010	0.0023	0.46	1.48	5.02	1.35	4.65	14.33
Kenya	24.46	0.018	0.31	-0.0005	0.0004	-0.29	-0.48	0.50	0.29	0.82	2.39
Kuwait	25.61	0.025	0.54	-0.0008	0.0006	-0.35	-0.58	0.60	0.39	1.14	3.46
Kyrgyzstan	1.75	0.028	0.52	0.0003	0.0017	0.18	0.48	1.36	1.31	3.91	10.85
Laos	23.20	0.009	0.39	-0.0004	0.0005	-0.09	-0.07	0.78	0.19	0.65	2.34
Latvia	5.82	0.030	0.85	-0.0004	0.0007	-0.18	-0.40	-0.52	0.36	1.08	3.46
Lebanon	15.19	0.025	0.59	0.0009	0.0019	0.53	1.63	5.06	1.36	4.30	12.35
Lesotho	11.75	0.010	0.46	0.0008	0.0020	0.36	1.30	4.61	1.16	4.22	12.60
Liberia	25.66	0.009	0.22	0.0001	0.0009	0.03	0.09	0.26	0.66	2.07	5.76
Libya	22.34	0.033	0.36	-0.0012	0.0000	-0.91	-1.31	2.50	0.03	0.07	0.19
Lithuania	6.42	0.028	0.84	-0.0003	0.0008	-0.12	-0.27	-0.45	0.41	1.26	4.16
Luxembourg	9.07	0.028	0.65	-0.0006	0.0003	-0.29	-0.56	-0.12	0.19	0.54	1.60
Macedonia	10.31	0.013	0.54	0.0007	0.0019	0.28	0.96	3.46	1.08	3.92	12.04
Madagascar	22.87	0.021	0.28	-0.0003	0.0006	-0.20	-0.45	-0.75	0.55	1.54	4.14
Malawi	22.26	0.023	0.34	-0.0004	0.0007	-0.29	-0.62	-0.57	0.62	1.76	4.81
Malaysia	25.30	0.013	0.21	-0.0002	0.0006	-0.15	-0.31	-0.34	0.53	1.51	4.12
Mali	28.70	0.021	0.38	-0.0004	0.0009	-0.24	-0.50	-0.38	0.67	1.96	5.53
Mauritania	27.68	0.024	0.44	-0.0004	0.0008	-0.26	-0.54	-0.47	0.63	1.86	5.33
Mauritius	23.92	0.022	0.30	-0.0005	0.0002	-0.38	-0.70	0.15	0.13	0.34	0.92
Mexico	20.43	0.012	0.25	-0.0002	0.0009	-0.10	-0.21	-0.23	0.64	1.97	5.54
Moldova	9.37	0.020	0.78	0.0004	0.0016	0.17	0.50	1.68	0.81	2.85	9.51
Mongolia	0.15	0.028	0.66	-0.0003	0.0011	-0.16	-0.35	-0.57	0.68	2.11	6.52
Montenegro	8.54	0.020	0.48	0.0015	0.0026	1.05	3.33	9.64	2.09	6.42	17.50
Morocco	18.77	0.021	0.44	-0.0003	0.0009	-0.18	-0.38	-0.44	0.65	1.97	5.80
Mozambique	24.20	0.015	0.33	-0.0004	0.0007	-0.16	-0.31	-0.02	0.47	1.46	4.35
Myanmar	22.98	0.020	0.30	-0.0005	0.0004	-0.34	-0.61	0.25	0.29	0.80	2.24
Namibia	19.57	0.026	0.50	0.0004	0.0015	0.27	0.77	2.26	1.20	3.58	9.99
Nepal	15.13	0.018	0.38	0.0009	0.0020	0.59	1.82	5.34	1.61	4.86	13.15
Netherlands	9.71	0.024	0.65	-0.0006	0.0003	-0.24	-0.43	0.13	0.15	0.42	1.27
New Caledonia	21.43	0.012	0.36	0.0008	0.0015	0.44	1.45	4.62	1.02	3.39	9.73
New Zealand	10.16	0.002	0.39	0.0009	0.0017	0.23	1.17	4.78	0.70	3.18	10.35
Nicaragua	26.18	0.029	0.34	-0.0007	0.0001	-0.57	-1.05	0.32	0.08	0.22	0.58
Niger	27.60	0.008	0.57	-0.0007	0.0005	-0.05	0.13	1.74	0.14	0.51	2.12
Nigeria	26.87	0.016	0.30	-0.0004	0.0006	-0.23	-0.42	0.08	0.42	1.24	3.56
Norway	1.35	0.023	0.75	-0.0008	0.0004	-0.23	-0.36	0.62	0.19	0.56	1.80

Notes: We consider persistent increases in temperatures based on the RCP 2.6 and RCP 8.5 scenarios. The losses are based on $\Delta_{ih}(d_i)$, see equation (13), with $h = 16$, 36, and 86 (corresponding to the year 2030, 2050, and 2100, respectively) and $m = 30$.

Table A.7: Percent Loss in GDP per capita by 2030, 2050, and 2100 under the RCP 2.6 and RCP 8.5 Scenarios (continued)

	Key Variables in Equation (13)					Percent Loss in GDP per capita					
	$\bar{T}i$	$\widehat{b}^0_{Ti}$	$\widehat{\sigma}_{Ti}$	d_i		RCP 2.6 Scenario			RCP 8.5 Scenario		
				RCP 2.6	RCP 8.5	2030	2050	2100	2030	2050	2100
Oman	26.79	0.008	0.31	0.0002	0.0013	0.08	0.26	0.87	0.81	2.83	8.31
Pakistan	20.43	0.010	0.40	0.0002	0.0015	0.08	0.26	0.88	0.88	3.16	9.55
Panama	25.12	0.017	0.31	0.0000	0.0008	0.01	0.02	0.05	0.63	1.87	5.27
Papua New Guinea	23.80	0.007	0.19	0.0003	0.0011	0.15	0.45	1.44	0.82	2.55	6.99
Paraguay	23.72	0.005	0.50	0.0003	0.0014	0.06	0.23	1.02	0.49	2.21	8.01
Peru	19.96	0.007	0.32	0.0002	0.0012	0.05	0.16	0.55	0.66	2.46	7.61
Philippines	25.42	0.007	0.20	0.0005	0.0013	0.29	0.98	3.05	0.98	3.09	8.46
Poland	7.84	0.026	0.76	-0.0003	0.0008	-0.12	-0.27	-0.43	0.38	1.16	3.83
Portugal	15.20	0.010	0.42	0.0002	0.0013	0.07	0.22	0.72	0.68	2.46	7.75
Puerto Rico	23.53	0.006	0.30	0.0006	0.0013	0.24	0.89	3.16	0.71	2.62	7.92
Qatar	26.79	0.027	0.51	-0.0004	0.0008	-0.25	-0.54	-0.62	0.60	1.77	5.15
Romania	8.91	0.019	0.62	0.0002	0.0014	0.10	0.27	0.83	0.77	2.64	8.47
Russian Federation	-5.96	0.035	0.68	-0.0002	0.0014	-0.14	-0.34	-0.71	1.03	3.08	8.93
Rwanda	19.93	0.016	0.35	0.0001	0.0011	0.06	0.15	0.42	0.80	2.49	7.12
St. Vincent & Grenadines	26.69	0.012	0.29	-0.0005	0.0002	-0.19	-0.26	0.70	0.13	0.38	1.16
Samoa	26.24	-0.004	0.28	0.0008	0.0014	0.02	0.66	3.64	0.31	2.31	8.31
Sao Tome and Principe	25.69	0.024	0.29	-0.0001	0.0007	-0.04	-0.11	-0.27	0.69	1.88	4.97
Saudi Arabia	25.51	0.021	0.55	-0.0007	0.0006	-0.26	-0.38	0.78	0.34	1.05	3.35
Senegal	28.29	0.026	0.35	-0.0004	0.0006	-0.31	-0.67	-0.73	0.53	1.46	4.01
Serbia	9.96	0.016	0.54	0.0002	0.0014	0.09	0.25	0.78	0.79	2.74	8.66
Sierra Leone	26.20	0.016	0.24	-0.0004	0.0005	-0.25	-0.47	-0.03	0.41	1.16	3.22
Slovakia	7.64	0.020	0.61	0.0001	0.0013	0.06	0.17	0.50	0.71	2.36	7.54
Slovenia	7.80	0.030	0.59	0.0003	0.0015	0.22	0.61	1.76	1.10	3.33	9.50
Solomon Islands	26.85	0.010	0.18	0.0002	0.0009	0.12	0.35	1.04	0.77	2.23	5.98
Somalia	26.65	0.021	0.32	-0.0006	0.0003	-0.37	-0.65	0.41	0.22	0.59	1.66
South Africa	17.52	0.007	0.33	0.0001	0.0012	0.04	0.11	0.35	0.67	2.46	7.56
South Korea	11.07	0.008	0.49	0.0008	0.0019	0.30	1.15	4.34	0.96	3.73	11.68
South Sudan	27.35	0.031	0.43	-0.0008	0.0004	-0.52	-0.98	0.05	0.32	0.87	2.40
Spain	13.31	0.026	0.45	-0.0001	0.0010	-0.08	-0.19	-0.43	0.77	2.26	6.39
Sri Lanka	27.11	0.011	0.21	-0.0001	0.0006	-0.07	-0.17	-0.27	0.50	1.51	4.23
Sudan	27.34	0.029	0.38	-0.0009	0.0002	-0.63	-1.04	1.21	0.19	0.51	1.38
Suriname	26.21	0.004	0.34	0.0003	0.0012	0.07	0.26	1.06	0.54	2.26	7.42
Swaziland	20.33	0.017	0.43	-0.0008	0.0002	-0.29	-0.23	2.14	0.09	0.24	0.71
Sweden	2.27	0.021	0.89	-0.0005	0.0007	-0.14	-0.24	0.07	0.24	0.76	2.67
Switzerland	4.88	0.018	0.49	0.0008	0.0019	0.46	1.45	4.60	1.32	4.27	12.24
Syria	17.88	0.022	0.65	-0.0005	0.0007	-0.19	-0.37	-0.07	0.37	1.12	3.67
Tajikistan	3.08	0.000	0.57	0.0003	0.0017	0.01	0.06	0.38	0.43	2.38	9.35
Tanzania	22.65	0.010	0.31	-0.0003	0.0008	-0.09	-0.17	0.02	0.46	1.54	4.73
Thailand	26.22	0.005	0.31	-0.0002	0.0007	-0.03	-0.05	0.06	0.29	1.12	3.98
Togo	26.41	0.018	0.25	-0.0001	0.0008	-0.07	-0.18	-0.41	0.76	2.13	5.64
Trinidad and Tobago	25.62	0.024	0.30	-0.0005	0.0003	-0.36	-0.76	-0.56	0.24	0.64	1.74
Tunisia	20.08	0.037	0.43	-0.0011	0.0001	-0.82	-1.40	1.21	0.08	0.21	0.53
Turkey	11.24	0.014	0.70	0.0002	0.0014	0.07	0.20	0.64	0.60	2.26	7.98
Turkmenistan	15.67	0.025	0.67	0.0000	0.0012	0.00	-0.01	-0.01	0.72	2.30	7.19
Uganda	22.84	0.020	0.31	-0.0004	0.0005	-0.28	-0.56	-0.17	0.42	1.19	3.32
Ukraine	8.17	0.026	0.81	0.0002	0.0014	0.08	0.22	0.63	0.73	2.39	7.82
United Arab Emirates	27.22	0.016	0.48	0.0002	0.0015	0.08	0.22	0.65	0.92	3.10	9.31
United Kingdom	8.69	0.013	0.46	-0.0001	0.0007	-0.02	-0.05	-0.11	0.34	1.16	3.97
United States	6.94	0.015	0.36	0.0004	0.0016	0.20	0.60	1.88	1.20	3.77	10.52
Uruguay	17.49	0.015	0.35	0.0002	0.0009	0.09	0.24	0.70	0.65	2.05	6.00
US Virgin Islands	26.79	0.023	0.45	-0.0009	-0.0002	-0.41	-0.50	1.89	-0.13	-0.30	-0.54
Uzbekistan	12.84	0.021	0.69	0.0007	0.0019	0.30	0.93	3.11	1.11	3.79	11.72
Vanuatu	24.75	0.028	0.33	-0.0005	0.0002	-0.38	-0.83	-0.87	0.21	0.55	1.48
Venezuela	25.00	0.016	0.30	0.0000	0.0010	0.00	0.00	-0.01	0.82	2.45	6.74
Vietnam	23.20	0.005	0.32	0.0000	0.0009	0.00	0.01	0.02	0.38	1.51	5.15
Yemen	24.56	0.035	0.60	-0.0007	0.0004	-0.40	-0.82	-0.61	0.27	0.74	2.12
Zambia	21.17	0.019	0.47	0.0003	0.0015	0.18	0.51	1.56	1.06	3.40	9.82
Zimbabwe	21.24	0.014	0.47	0.0001	0.0013	0.04	0.12	0.35	0.76	2.62	8.15

Notes: We consider persistent increases in temperatures based on the RCP 2.6 and RCP 8.5 scenarios. The losses are based on $\Delta_{ih}(d_i)$, see equation (13), with $h = 16$, 36, and 86 (corresponding to the year 2030, 2050, and 2100, respectively) and $m = 30$.

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