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LETTER

Persistent effect of temperature on GDP identified from lower frequency temperature variability

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Abstract

It is well established that temperature variability affects a range of outcomes relevant to human welfare, including health, emotion and mood, and productivity across a number of economic sectors. However, a critical and still unresolved empirical question is whether temperature variation has a long-lasting effect on economic productivity and, therefore, whether damages compound over time in response to long-lived changes in temperature expected with climate change. Several studies have identified a relationship between temperature and gross domestic product (GDP), but empirical evidence as to the persistence of these effects is still weak. This paper presents a novel approach to isolate the persistent component of temperature effects on output using lower frequency temperature variation. The effects are heterogeneous across countries but collectively, using three different GDP datasets, we find evidence of persistent effects, implying temperature affects the determinants of economic growth, not just economic productivity. This, in turn, means that the aggregate effects of climate change on GDP may be far larger and far more uncertain than currently represented in integrated assessment models used to calculate the social cost of carbon.

1. Introduction

A large body of evidence now exists showing a relationship between temperature fluctuations and economic productivity [1–4]. Temperature has been shown to influence output at global [1, 2], national [5, 6], and regional scales [3], affecting a wide range of sectors in both high-income and low-income countries. The persistence of these impacts has first-order implications for the magnitude of climate change damages: if temperature fluctuations affect the determinants of economic growth (e.g. depreciation of capital or the total factor productivity growth rate), then they have a persistent impact on the level of economic output. In this case, climate change damages are cumulative and may be orders of magnitude larger than currently represented in models used for the cost–benefit analysis of climate change, which mostly assume non-persistent damages (for example, when temperature variations affect the productivity of labor or capital) with a few recent exceptions [7–14].

Despite its importance for determining the aggregate costs of climate change, evidence on the persistence of the impacts of temperature shocks is sparse and contradictory [15]. Dell *et al* [2] show that persistent and non-persistent effects can produce identical contemporaneous effects on the growth rate but can be distinguished using lagged temperature effects. Using global national accounts data, they fit a reduced-form model with lagged temperature terms and find evidence that effects of temperature shocks in poorer countries do not revert within ten years, implying large negative effects of higher temperatures on economic growth, at least in the medium-term. Burke *et al* [1] use a similar dataset to find robust evidence for a non-linear, hill-shaped relationship between contemporaneous temperature

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and GDP growth. However, evidence for persistent impacts on the economy is weaker since the sum of lagged effects has large standard errors with confidence intervals that include both zero and very large negative effects. In a model-selection exercise based on cross-validation, Newell *et al* [16] show that total climate damages are highly sensitive to the question of persistence and to the functional form of empirical models used to estimate effects, but also find that out-of-sample cross-validation tests are insufficiently powerful to disambiguate between alternate models of impact persistence. At a smaller spatial scale, Deryugina and Hsiang [5] found evidence of persistent but declining effects during the first ten years after a temperature shock in individual U.S. counties. Deryugina and Hsiang [5], and Colacito *et al* [17] found that increases in summer and fall temperature could have persistent effects on the gross state product of U.S. states.

A major empirical challenge is that estimating the sum of lagged effects, particularly for a non-linear function, can produce large standard errors and high uncertainty. For instance, in the quadratic specification used by Burke *et al*, identifying cumulative effects over ten years requires estimating and summing 20 regression coefficients [1]. The uncertainty around this statistic depends on the variance and covariance of all 20 parameter estimates. More recent empirical investigations of climate impacts on economic growth have focused on resolving detail at the subnational scale [3, 17, 18], or on resolving impacts on the production process [19]. While they suggest some persistence in temperature effects, the uncertainty around this key question relevant to understanding the aggregate costs of climate change remains largely unresolved.

2. Methods

Here, we propose a statistical test to identify the presence of persistent effects of temperature on output using lower-frequency temperature variation. We first use a simulation exercise to demonstrate the power of the test to discriminate between cases with and without persistent effects of temperature. Second, we implement this test on individual country-level temperature and economic growth time-series. The test complements previous approaches that have used either lagged temperatures or out-of-sample tests to attempt to resolve the question of impact persistence but which, as described above, have mostly produced ambiguous results.

The essence of the approach is that persistent and transient impacts on economic output can be distinguished using temperature variation occurring at different frequencies. Internal variability of the climate system gives rise to oscillations at different timescales. This is an intrinsic characteristic of non-linear dynamic systems like the Earth's climate [20]. While some of these fluctuations, such as El Nino Southern Oscillation with a period of two to seven years, are well understood [21], spectral analysis of atmospheric time series reveal fluctuations at all possible frequencies [22, 23]. Figure 1(a) shows this variability in the US temperature time series between 1960 and 2017 [24, 25]. We use a low-pass filter to successively remove high-frequency variation and obtain temperature time series that preserve only lower-frequency oscillations.

Temperature variability at different timescales will produce distinct economic dynamics depending on the persistence of economic impacts. This is illustrated in figure 1(b), which shows the change in GDP growth and GDP level expected under temperature shocks of different durations and alternate models of economic impact. Dell *et al* [2] derive a simple equation for a model that includes both non-persistent *level effects* (β) and persistent *growth effects* (γ), given baseline growth rate g:

$$g_t = g + \gamma T_t + \beta \Delta T_t \tag{1}$$

where T_t is the deviation in temperature from some mean value in period t and ΔT_t is the change in temperature between period t and $t-1$[4]. Although it is likely that some economies experience both levels and growth effects simultaneously, we use two stylized cases in figure 1(b) to illustrate how the timescale of temperature variation interacts with the models of economic impact. In the pure 'level effects' model we set the growth effect to zero (i.e. $\gamma = 0$) so that:

$$g_t = g + \beta \Delta T_t. \tag{2}$$

In the 'growth effects' model, we set the level effect to zero (i.e. $\beta = 0$) so that:

$$g_t = g + \gamma T_t. \tag{3}$$

A one-year temperature shock equally reduces GDP in a level effects model and in a growth effects model (figure 1(b), left column). However, when temperature returns to the baseline so does GDP in the level model, but not in the growth model (figure 1(b), bottom-left panel). The two models thus produce distinct long-term effects on GDP: growth effects on GDP keep accumulating as the duration of the temperature excursion increases, but level effects disappear when temperature returns to its baseline. It is this effect of past temperature shocks on the future level of GDP, occurring because temperature affects the determinants of economic growth, that we refer to in this manuscript as 'persistent' impacts.

[4] We inherit the taxonomy of 'levels effects' and 'growth effects' from [2]. While we focus on GDP growth, the terms originate in reference to effects on GDP. A level effect alters the level of GDP, and when temperature reverts to the baseline so does production. A growth effect alters the growth rate, thus its effects are cumulative and persistent.

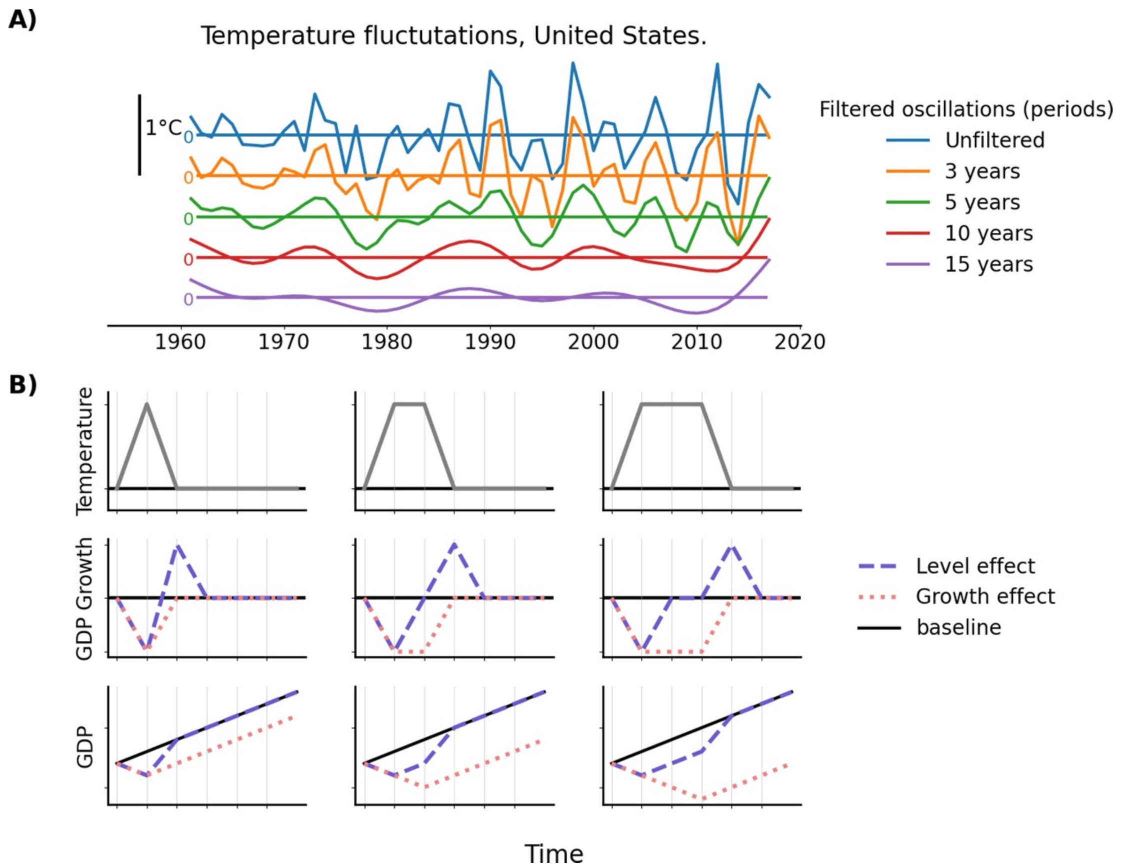

Figure 1. Temperature fluctuations (demeaned and detrended) and their effects on GDP. Panel (A). US population-weighted temperature fluctuations after detrending and filtering higher-frequency variation [24]. The top blue line shows the US temperature time series. Lower lines show the filtered time series, progressively expanding the periodicity range of the filter from 2 years up to 3, 5, 10, and 15 years. The time series are spread across the y-axis for visual purposes; all time series oscillate around zero because they were demeaned and detrended before filtering. Panel (B). Upper panel: temperature shocks at decreasing frequencies. Mid panel: effects of those shocks on GDP growth under levels and growth models. Lower panel: effects of temperature shocks on GDP.

Note that the effects illustrated in figure 1(b) do not include any variation in the impact of temperature shocks as a function of the shock duration. The question of whether longer-period temperature excursions, more analogous to the type of permanent warming expected from climate change, produce either larger (via compounding effects and intensification) or smaller (via adaptation) impacts compared to shorter temperature shocks has been widely debated [26–30]. The question of persistence—whether the level of GDP is affected by *past* temperature shocks—is distinct from this issue however. The distinction between persistent vs non-persistent impacts arises because of how temperature affects the economy; non-persistent effects arise through temporary effects on productivity (crop yield losses from extreme heat are one example) whereas persistent effects arise from impacts on factors that have a long-lived effect on economic production (destruction of capital in extreme events for instance). Adaptation or intensification would somewhat alter the shape of the responses shown in the right column of figure 1(b), but the levels and growth models would still produce qualitatively different dynamics, particularly in response to temperature shocks of different lengths.

The duration of temperature excursions from a mean value is key to identifying the presence of growth effects (figure 1(b) top row). The correlation between temperature and GDP growth in a growth effects model does not depend on the duration of the temperature anomaly, but breaks down in a level effects model as the length of the excursion grows (figure 1(b), middle row). This happens because there are no level effects if temperature is constant but away from the baseline.

Therefore it should be possible, in principle, to detect the presence of persistent effects in empirical data using different timescales of temperature variability. It is a common practice in signal processing problems to decompose time series into a sum of periodic components with varying frequencies, amplitudes and phases [31], widely used in a variety of fields like audio processing, electrical engineering, and climate science [32–34]. This approach allows the time-series to be reconstructed using a specific subsets of desired frequencies. A low-pass filter is a version of the time series that only preserves low

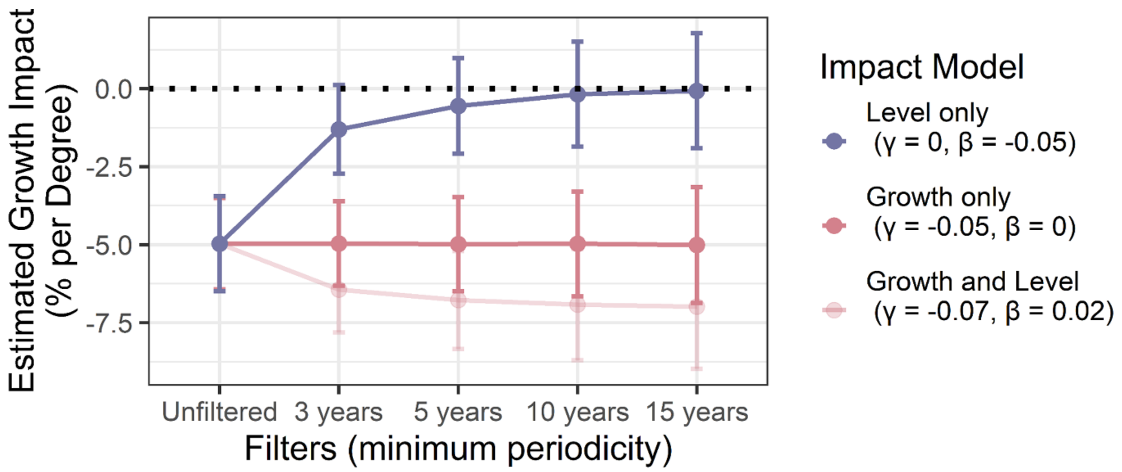

Figure 2. Simulation exercise demonstrating the divergence of regression results with increasing frequency filters under two alternate models of temperature impacts on economic production, a non-persistent 'level only' model (purple) and a fully persistent 'growth only' model (pink). A third semi-transparent pink line shows a combined model with opposite signs of growth and level effects.

frequency components. Following studies in the climate literature [35], we use a low-pass filter to remove inter-annual variations and obtain temperature time series that preserve only lower-frequency oscillations. If changes in temperature do not influence the underlying determinants of growth (levels only model), the estimated effect of low-frequency temperature anomalies on GDP growth should converge towards zero from the estimated effect of unfiltered temperature data. In contrast, if changes in temperature alter the determinants of growth (presence of persistent effects), the correlation between temperature and GDP growth should be detectable after the temperature data is filtered.

Figure 2 demonstrates this effect in a simulation exercise. It shows results from time series regressions of simulated economic growth on simulated temperature at different levels of filtering under two stylized cases—one in which there are only non-persistent damages (i.e. the level effects-only model, purple line) and one with only persistent damages (i.e. the growth effects-only model, pink line), following equations (2) and (3) respectively. Additionally, to illustrate one of the many possible combinations, another semi-transparent line shows a simulation with mixed growth and level effects with opposite signs.

The random temperature time series used in the simulations preserve the frequency distribution of the Earth's natural oscillations by matching the spectral decomposition on 1500 years of pre-industrial global temperatures based on the Last Millennium Reanalysis [36]. Using this decomposition we generate 10 000 random 350 year temperature time series that preserve this frequency distribution but with random phase shifts [37] and then simulate economic dynamics for each temperature time series under the two alternate impacts models using equations (2) and (3), and the combined effect using equation (1), adding an independent and identically distributed noise component. We regress the simulated economic growth data on temperature after filtering out varying ranges of frequencies from the temperature time series, and adjusting the regression estimate to avoid a small bias introduced by the changing amplitude of temperature variations at lower frequency filters (Supplementary material 2).

Figure 2 shows the mean value of the estimated coefficients and its confidence interval for all the simulations. Without any filtering using only contemporaneous temperatures, growth and level impacts are indistinguishable, as originally pointed out by Dell *et al* [2]. But filtering out high frequencies in the temperature data produces divergent effects: the estimated effect under the growth only model remains detectable while the coefficients in the level model attenuates markedly. In other words, the different patterns in figure 2 mean that these two possible worlds—one with and one without persistent temperature impacts—could potentially be distinguished using this method. In essence, a statistical test on the coefficient for the filtered data is a test for the presence of growth effects, and is independent of the presence, or sign, of level effects.

While previous literature used lagged temperature estimates to test for growth effects, we show through a simulation that using a low-pass filter is more efficient in distinguishing between levels and growth effects at the medium to long term in a context where data is limited to 70 years. Supplementary figure 1 compares the coefficients estimated with the filtering approach (left panel) and the sum of the lagged coefficients for a full distributed lag model (middle) and a more parsimonious version that reduces the number of estimated coefficients by imposing smoothness on the lag structure (right). The distributed lag model is as powerful at distinguishing levels from growth effects when the number of lags and the length of filtering are small. However, filtering grows more efficient for greater number of lags and longer filters, as the distributed lag model becomes increasingly noisy. This suggests that the low-pass filtering test can be a helpful complement to existing approaches using lagged temperature in investigating the persistence of effects over the medium to long run in data scarce contexts.

We use our test to investigate the persistence of temperature effects on economic production. We use GDP data from the World Bank covering 217 countries from 1961 to 2017 [38], merging this dataset with population-weighted temperature and rainfall data from University of Delaware [24, 25]. To identify whether country-level temperature impacts have persistent effects we performed the following regression for each country and length of filter:

$$g_t = \theta_f T_{t,f} + \pi_f P_{t,f} + \epsilon_t \quad (4)$$

where $T_{t,f}$ and $P_{t,f}$ are the population-weighted temperature and rainfall in year t after demeaning, detrending, and filtering out frequencies higher than f. The filters f are low-pass filters that filter-out any oscillations with periods shorter than 3, 5, 10, and 15 years, or $f = unfiltered$ when no filter was applied. The low-pass filter algorithm requires data that spans at least twice the upper bound periodicity, which results in some countries not having estimates for all the levels of filtering due to missing data at earlier time periods. Country-specific quadratic time trends are removed from all variables (growth, temperature and rainfall) prior to analysis to address concerns of non-stationarity in the weather and economic time-series. Excluding rainfall from equation (4) would bias the estimate of θ, since rainfall is known to correlate with both GDP growth [39] and temperature [40]. However, we restrict the analysis to temperature and leave the discussion of results on precipitation to the supplementary material.

Given the lack of strong prior empirical evidence for the persistence of temperature effects, or strong theoretical or empirical evidence regarding drivers of heterogeneity in the response, the analysis focuses at the country level to give more flexibility and allow estimates to differ across countries. On the other hand, this comes at the cost of larger statistical uncertainty. We analyze the evidence for persistence across all countries at the global scale by separately pooling the positive and negative estimates of θ_f and estimating the following regression model

$$\hat{\theta}_{f,c} = F_f + \epsilon_{f,c} \quad (5)$$

where the value of the temperature coefficient estimate in country c at filtering level f is regressed on a vector of indicators of the level of filtering, clustering standard errors at the continent level.

3. Results and discussion

The behavior of the estimates $\hat{\theta}_f$ for each country contains information about the persistence of temperature effects on the economy. In particular, non-zero low-frequency estimates signal presence of growth effects, as shown in the simulations (figure 2). We find that 39 countries have low-frequency estimates that are statistically different from zero at the 90% confidence level (of which 18 might be expected as false positives given the number of comparisons). Further, looking across all countries there is not strong evidence for systematic trends in coefficients towards zero at lower frequency variation, as would be expected if impacts operated only through non-persistent level effects.

Figure 3(A) shows the values of $\hat{\theta}_f$ for all countries at different levels of filtering, binned into two broad categories: a converging-towards-zero effect (blues), where the absolute value of $\hat{\theta}_f$ decreases at lower frequencies (as expected by the presence of level effects only, or by the combination of a level effect and a smaller growth effect), and a not-converging-towards-zero effect (oranges), where the absolute value of $\hat{\theta}_f$ increases at lower frequencies (explained only by the presence of persistent effects). In addition, there is a third category we describe as 'unclassified' (grey) where the absolute value of $\hat{\theta}_f$ increases but changes sign between the unfiltered and the most filtered estimates. This behavior could be explained by levels and growth effects of opposite signs; yet, these countries are conservatively not classified as either converging or not converging. Within the two groups of converging and not converging countries, we further identify subsets of countries where the filtered estimates are either *statistically* larger (i.e. intensifying; dark orange) or smaller (converging; dark blue) from the unfiltered estimates.

Figure 3(B) tracks features of countries' estimates that are key to detect the presence of growth and levels effects. The left column divides countries based on the statistical significance of the unfiltered estimate, the middle column shows the statistical significance of the countries' most filtered estimate, and the right column shows whether estimates show converging, not converging, or intensifying effects. Among the 27 countries whose unfiltered estimate is statistically different from zero, the 15 year filtered coefficients of 18 countries are not statistically different from zero, meaning only level effects were detected in those countries (purple lines in figure 3(B)). Presence of growth effects (figure 3(B), pink lines) is detected in the remaining 9 countries and in 30 other countries whose unfiltered estimate was not statistically different from zero.

The middle column of figure 3(B) shows that in 18 countries where growth effects have been detected the filtered estimates are statistically *larger* than the

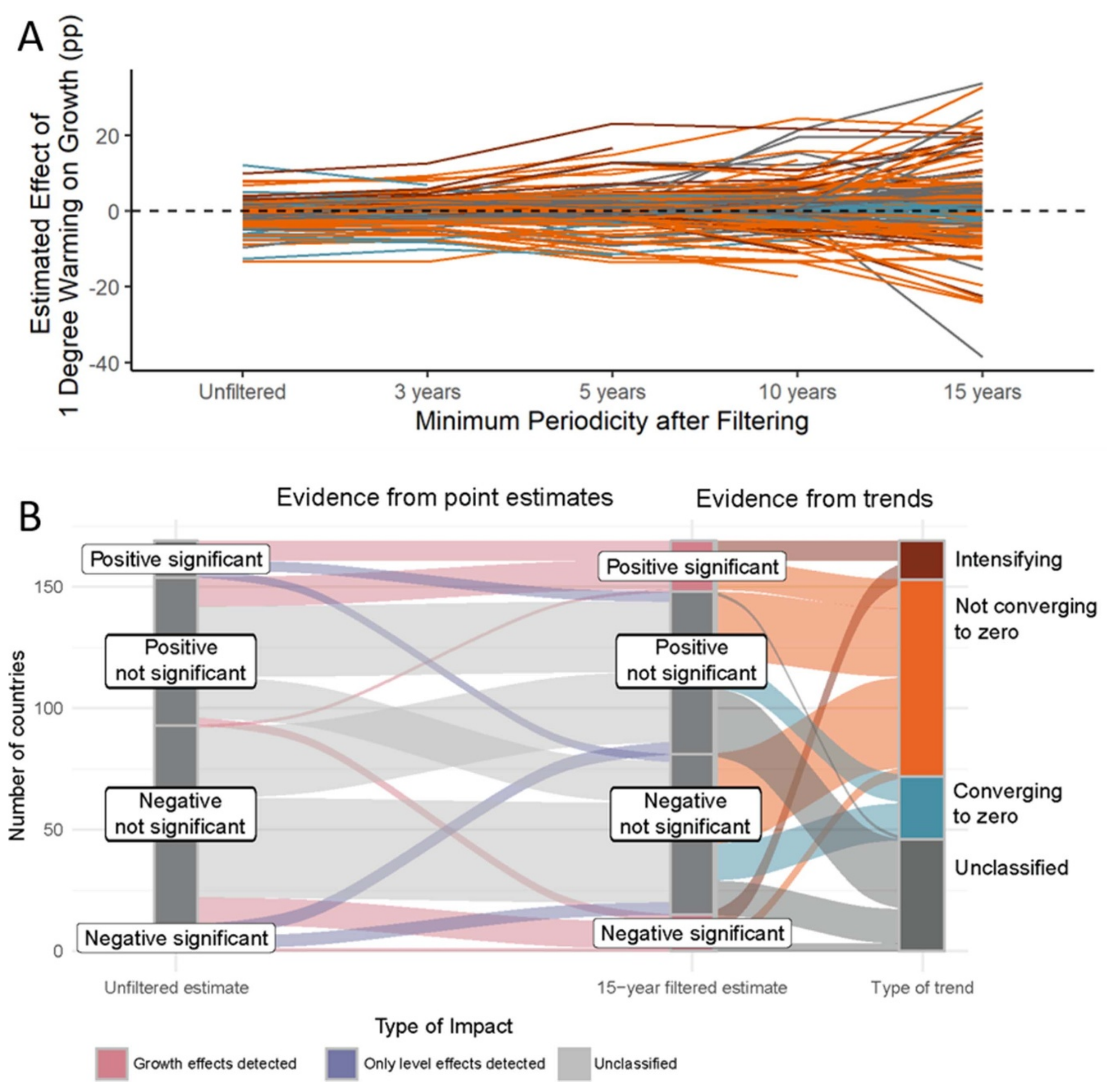

Figure 3. Panel (A) Country-level estimates of the temperature effect on economic growth. For visualization purposes only, each line connects the estimated coefficients from regressions at different levels of filtering of the temperature data. Lines are color coded depending on the trend from the unfiltered to the most filtered estimate: orange when the absolute value of coefficients increases with filtering ('*Not converging to zero*'); dark orange when the difference between unfiltered and most filtered is significant at 10% ('*Intensifying*'); blue when the absolute value of coefficients decreases with filtering ('*Converging to zero*'), and dark blue when the trend is statistically significant at 10% ('**Converging to zero*'; not found in this results); grey when the most filtered estimate is larger than the unfiltered but with opposite sign. The graph only shows countries with estimates below the 99th percentile for readability. Panel (B) The left-hand side of the chart displays the number of countries for which there is evidence of growth effects, in pink, and evidence of level effects, in purple. The right-hand side classifies 15 year filtered estimates by the type of trend using the same color code as panel (A).

unfiltered estimates (i.e. 'intensifying effect'), a pattern that is consistent with level and growth effects of opposite sign. Among the remaining 137 countries that do not attain conventional statistical significance of the most filtered estimate, more countries have non-converging estimates ($n = 65$, orange lines) than converging estimates ($n = 27$, blue lines). There is no country where the filtered estimate is significantly smaller than the unfiltered estimate.

We performed the same analysis using two alternative economic growth datasets that span a longer time period but include fewer countries. Firstly we used the Barro-Ursua dataset, with annual data on economic growth of 43 countries starting as early as 1790–2009, developed to examine the persistence of macroeconomic shocks [41, 42]. Secondly, we use the Maddison Project database that standardizes country-level GDP per capita for 170 countries for several centuries [43]. Due to the sparsity of temperature and rainfall records pre-1900, we use only post-1900 data for both datasets. Supplementary figure 4 replicates figure 3 for these two alternate datasets covering different subsets of countries and much longer time-periods than the World Bank data. We again fail to find strong evidence that estimates systematically converge towards zero using lower frequency variation, as would be expected if impacts to the economy operated only through non-persistent levels effects.

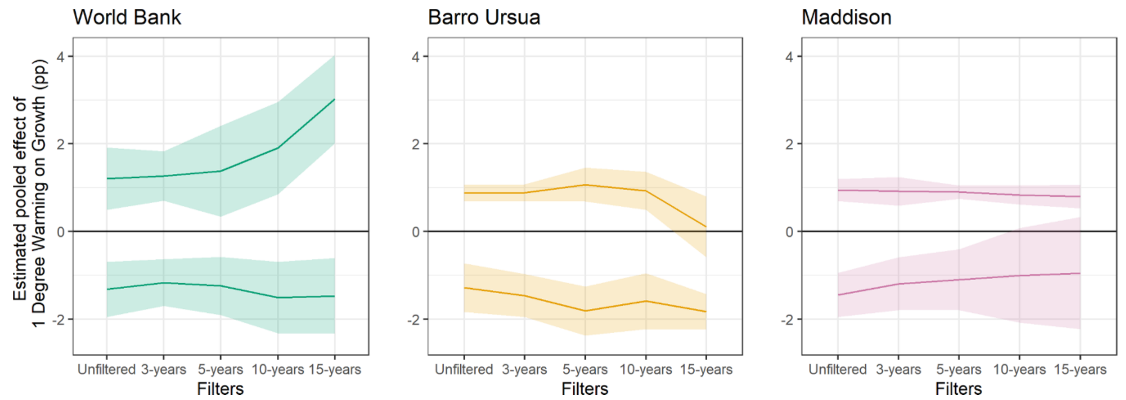

Figure 4. Pooled estimates of countries with positive and negative unfiltered coefficients across different levels of filtering using three alternative datasets.

Pooling estimates from all countries, we are able to evaluate evidence, at the global level, for converging estimates at lower frequency filters. We thus estimate equation (5). Where the temperature coefficient estimate $\hat{\theta}_{f,c}$ in country c at filtering level f is regressed on a vector with the levels of filtering F, clustering standard errors at the continent level to allow for cross-country correlation and weighting the observations by the inverse standard error. Patterns such as divergence or convergence towards zero as filtering increases would cancel out if, as it shown in figure 3, upper panel, there are both positive and negative effects. We therefore perform the analysis separately for countries with positive and negative unfiltered estimates. If only non-persistent level effects were present, we would expect to see the negative (positive) estimates converging towards zero, resulting in a positive (negative) coefficient estimate on the filtering variables F.

Figure 4 shows the cumulative estimated effect for each level of filtering, and shows that, across all countries, we do not see evidence for this attenuating effect. Instead, the regression results show evidence of persistent effect where the average value estimated using lower frequency temperature variation is similar to the value estimated using unfiltered data (see supplementary table 1).

Finally, supplementary figure 5 examines evidence for heterogeneity in the marginal effect of temperature between countries, specifically whether they are associated with either per capita GDP or mean temperature. Using only estimates significantly different from zero at the unfiltered and 15 year filter levels (i.e. countries for which evidence of persistent effects is strongest), we find some evidence that impacts are negatively correlated with countries' mean temperature as found in previous studies [1], but no systematic differences in the estimated effects between rich and poor countries (supplementary figure 8 shows a similar pattern resulting from a distributed lag non-linear model under a panel analysis).

4. Discussion

The question of the persistence of climate damages is a first-order problem for climate change economics. Studies that allow climate change to affect the determinants of economic growth tend to produce far larger aggregate climate change costs than studies that impose only level effects on production [11, 13–15]. In response to the permanent shifts in temperature expected with climate change, persistent impacts operate via effects on the growth rate compound over time, producing far larger aggregate damages over the long time frames relevant for assessing climate change costs. Yet, impacts have been modeled as non-persistent by the numerous integrated assessment studies that since the 1990s have calculated climate damages and evaluated optimal climate policy.

In contrast with previous literature that models non-linear effects of temperature on growth, we analyze the temperature-growth relationship with country-level regressions. The smaller temperature ranges allow us to accurately model the effects using a linear approximation (see supplementary material and supplementary figure 2). In addition, instead of using high-frequency, year-to-year temperature variation to estimate climate impacts on the economy, here we use lower frequency variation. Our identification strategy focuses on the persistent effect of temperature by adjusting for time trends and country-specific dynamics (via demeaning and detrending) but uses lower-frequency temperature variability instead of lags to distinguish between growth and levels effects. Using a low-pass filter instead of lags avoids adding noise terms together that could prevent identifying medium run persistent effects (see supplementary material and supplementary figure 1).

Applying this test to three different datasets of economic growth, we fail to find strong evidence of only non-persistent effects. There are two key pieces of evidence. First, we found statistically significant persistent temperature impacts on economic growth in 22% (19%; 8%) of the countries using the World Bank (Maddison Project; Barro-Ursua) dataset. Significant effects in these regressions implies the persistence of temperature impacts at least over the 15 year period of our lowest-frequency regressions. Secondly, we examine how regression estimates change using lower frequency temperature variation. The lack of persistent effects, as posited by the vast majority of integrated assessment studies estimating climate damages, would imply convergence of these estimates towards zero. But we fail to find evidence of such convergence. At the individual country level, only 15% (21%; 34%) of countries have effects that converge towards zero. For many more countries, the estimated effects either do not converge towards zero or intensify over time, an effect that could be due to adaptation or coping dynamics, competing growth and levels effects with different signs, or a reduction in attenuation bias with longer filter lengths (though this effect is likely small, as described more fully in supplementary figure 6). Pooling evidence from across all countries produces stable effect sizes with lower frequency variation for all three datasets, at least over the 10–15 year period. Therefore, the evidence suggests a sensitivity of aggregate economic output to temperature shocks persisting over at least the 10–15 year time frame and a conspicuous absence of evidence for fully non-persistent levels impacts.

Like previous work, we find both positive and negative effects of temperature on different countries. It should be remarked that decade-long temperature excursions used to estimate the effects here are very small in amplitude (the median amplitude for 15 year filtered temperature is 0.11 °C). While figure 3 shows the effect of 1 °C increase in temperature, the actual magnitude of temperature variation over this time-scale is much smaller and it is an open question whether these effect sizes can be extrapolated to much larger changes in temperature expected with climate change.

This highlights a fundamental empirical challenge in estimating the effects of climate change. Climate change will produce large (∼2 °C–4 °C) and sustained changes in temperature. The historical record contains both large but short temperature excursions and much smaller but longer temperature variation. Previous papers [1, 2] have examined the effect of high frequency variation, raising the question of whether these estimates can be extrapolated to longer-lasting temperature changes (e.g. due to effects of adaptation, compounding effects, or the dynamics of persistent vs transient economic impacts). Here we instead focus on the opposite—lower-frequency but much smaller variation (at least in the filtered estimates). This gives more confidence that effects estimated are representative of impacts of sustained temperature change, at least over the medium run, while raising questions about whether these can be extrapolated to much larger levels of warming expected with climate change.

Finally, we note that our approach is not able to distinguish between a levels effect that continues compounding over the 15 year time-frame of our lowest-frequency estimates but then subsequently reverses, and a 'pure' growth effect in which there is no subsequent reversal. Differentiating these two types of effects is a question of what happens in time-frames longer than 15 years, which is an inherently difficult empirical question due to the relatively short time span of data available. However, either interpretation of the filtered results (i.e. 15 years of continuously worsening levels effects followed by reversal or a fully persistent effect) implies persistence of damages over time periods longer than a decade. Either interpretation would imply larger aggregate climate damages than the standard approach to representing climate change costs in integrated assessment models, which assumes no persistence or compounding effects.

While providing evidence of persistent impacts of temperature shocks on growth, our framework does not isolate the mechanisms by which they arise. Past studies have modeled persistent impacts as resulting from a slow-down in total factor productivity growth [11, 12], changes to the capital depreciation rate [11], or impacts to the stock of natural capital [44]. Other studies leave the mechanism of growth rate impacts unspecified [9, 13]. Letta and Tol [19] investigate this question and suggest impacts arise through effects on total factor productivity growth, but more work is needed to understand exactly how these impacts manifest.

A consistent and unsurprising finding from past work is that allowing for persistent damages, because of their compounding nature, vastly increases the uncertainty in climate change impact projections. For instance, Newell *et al* [16] estimate confidence intervals on damage estimates that allow for growth-rate effects orders of magnitude larger than those that restrict impacts to only the level of GDP. Similarly, in a recent modeling study, Kikstra *et al* [45] show that the persistence of economic damages is the most important parameter determining aggregate climate change costs. Our findings do not show strong evidence for the presence of only non-persistent impacts and instead suggest compounding effects over at least a decadal time frame. Therefore, restricting modeling of climate change damages to only non-persistent levels effects likely greatly under-states both the uncertainty and the downside risk associated with climate change.

Data availability statement

The code to replicate the analysis and figures is in: https://github.com/BerBastien/TempEffectGDP.

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Author contributions

Conceptualization and supervision: F C M
Methodology: B A B O, F C M, F G
Coding: B A B O
Investigation: B A B O, F C M, F G
Writing: B A B O, F C M, F G

Conflict of interest

Authors declare that they have no competing interests.

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References

[1] Burke M, Hsiang S M and Miguel E 2015 Global non-linear effect of temperature on economic production *Nature* **527** 235
[2] Dell M, Jones B F and Olken B A 2012 Temperature shocks and economic growth: evidence from the last half century *Am. Econ. J.* **4** 66–95
[3] Kalkuhl M and Wenz L 2020 The impact of climate conditions on economic production. Evidence from a global panel of regions *J. Environ. Econ. Manage.* **1** 102360
[4] Carleton T A and Hsiang S M 2016 Social and economic impacts of climate *Science* **353** 6304
[5] Deryugina T and Hsiang S 2017 The marginal product of climate *Report No.: w24072* (Cambridge, MA: National Bureau of Economic Research) p w24072 (available at: www.nber.org/papers/w24072.pdf) (Accessed 10 December 2020)
[6] Schlenker W and Roberts M J 2009 Nonlinear temperature effects indicate severe damages to US crop yields under climate change *Proc. Natl Acad. Sci.* **106** 15594–8
[7] Dietz S and Stern N 2015 Endogenous growth, convexity of damage and climate risk: how Nordhaus' framework supports deep cuts in carbon emissions *Econ. J.* **125** 574–620
[8] Gazzotti P *et al* 2021 Persistent inequality in economically optimal climate policies *Nat. Commun.* **12** 3421
[9] Glanemann N, Willner S N and Levermann A 2020 Paris Climate Agreement passes the cost-benefit test *Nat. Commun.* **11** 110
[10] Hänsel M C *et al* 2020 Climate economics support for the UN climate targets *Nat. Clim. Change* **10** 781–9
[11] Moore F C and Diaz D B 2015 Temperature impacts on economic growth warrant stringent mitigation policy *Nat. Clim. Change* **5** 127
[12] Moyer E J, Woolley M D, Matteson N J, Glotter M J and Weisbach D A 2014 Climate impacts on economic growth as drivers of uncertainty in the social cost of carbon *J. Legal Stud.* **43** 401–25
[13] Ricke K, Drouet L, Caldeira K and Tavoni M 2018 Country-level social cost of carbon *Nat. Clim. Change* **8** 895
[14] Estrada F, Tol R S J and Gay-García C 2015 The persistence of shocks in GDP and the estimation of the potential economic costs of climate change *Environ. Model. Softw.* **1** 155–65
[15] Piontek F, Drouet L, Emmerling J, Kompas T, Méjean A, Otto C, Rising J, Soergel B, Taconet N and Tavoni M 2021 Integrated perspective on translating biophysical to economic impacts of climate change *Nat. Clim. Change* **11** 563–72
[16] Newell R G, Prest B C and Sexton S E 2021 The GDP-temperature relationship: implications for climate change damages *J. Environ. Econ. Manage.* **1** 102445
[17] Colacito R, Hoffmann B and Phan T 2019 Temperature and growth: a panel analysis of the United States *J. Money Credit Bank* **51** 313–68
[18] Damania R, Desbureaux S and Zaveri E 2020 Does rainfall matter for economic growth? Evidence from global sub-national data (1990–2014) *J. Environ. Econ. Manage.* **102** 102335
[19] Letta M and Tol R S J 2019 Weather, climate and total factor productivity *Environ. Resour. Econ.* **73** 283–305
[20] Lorenz E N 1963 Deterministic nonperiodic flow *J. Atmos. Sci.* **20** 130–41
[21] Imbers J, Lopez A, Huntingford C and Allen M R 2013 Testing the robustness of the anthropogenic climate change detection statements using different empirical models *J. Geophys. Res.* **118** 3192–9
[22] Hasselmann K 1976 Stochastic climate models Part I. Theory *Tellus* **28** 473–85
[23] Mann M E, Steinman B A and Miller S K 2020 Absence of internal multidecadal and interdecadal oscillations in climate model simulations *Nat. Commun.* **11** 49
[24] Matsuura K and Willmott C J 2018 Terrestrial air temperature: 1900–2017 gridded monthly time series (Newark, DE: University of Delaware) (available at: http://climategeogudeledu/∼climate/html_pages/Global2017/READMEGlobalTsT2017.html)
[25] Matsuura K and Willmott C J 2018 *Terrestrial Precipitation: 1900–2017 Gridded Monthly Time Series* (Newark, DE: Electronic Department of Geography, University of Delaware) p 19716
[26] Moore F C and Lobell D B 2014 Adaptation potential of European agriculture in response to climate change *Nat. Clim. Change* **4** 610–4
[27] Burke M and Emerick K 2016 Adaptation to climate change: evidence from US agriculture *Am. Econ. J.* **8** 106–40
[28] Mérel P and Gammans M 2018 Climate econometrics: can the panel approach account for long-run adaptation? *American Journal of Agricultural Economics* **103** 1207–38
[29] Taraz V 2017 Adaptation to climate change: historical evidence from the Indian monsoon *Environ. Dev. Econ.* **22** 517–45
[30] Kolstad C D and Moore F C 2020 Estimating the economic impacts of climate change using weather observations *Rev. Environ. Econ. Policy* **14** 1–24
[31] Duhamel P and Vetterli M 1990 Fast Fourier transforms: a tutorial review and a state of the art *Signal Process.* **19** 259–99
[32] Bergland G 1969 Fast Fourier transform hardware implementations—an overview *IEEE Trans. Audio Electroacoust.* **17** 104–8
[33] Ghil M 2002 Advanced spectral methods for climatic time series *Rev. Geophys.* **40** 1003
[34] Smith J O 2007 *Mathematics of the Discrete Fourier Transform (DFT): With Audio Applications* (CA: W3k Publishing) p 323

[35] Mann M E, Steinman B A and Miller S K 2014 On forced temperature changes, internal variability, and the AMO *Geophys. Res. Lett.* **41** 3211–9

[36] Tardif R, Hakim G J, Perkins W A, Horlick K A, Erb M P, Emile-Geay J, Anderson D M, Steig E J and Noone D 2019 Last millennium reanalysis with an expanded proxy database and seasonal proxy modeling *Clim. Past* **15** 4

[37] Figwer J 1997 A new method of random time-series simulation *Simul. Pract. Theory* **5** 217–34

[38] World Bank 2021 World Bank open data (available at: https://data.worldbank.org/)

[39] Kotz M, Levermann A and Wenz L 2022 The effect of rainfall changes on economic production *Nature* **601** 223–7

[40] Fischer E M and Knutti R 2016 Observed heavy precipitation increase confirms theory and early models *Nat. Clim. Change* **6** 986–91

[41] Barro R J and Ursúa J F 2008 Macroeconomic crises since 1870 *National Bureau of Economic Research* wp 13940 (available at: https://doi.org/10.3386/w13940) (Accessed 25 July 2022)

[42] Barro R and Ursua J 2010 Barro-Ursua macroeconomic data (available at: https://scholar.harvard.edu/barro/publications/barro-ursua-macroeconomic-data)

[43] Bolt J and van Zanden J L 2020 Maddison style estimates of the evolution of the world economy. A new 2020 update p 44

[44] Bastien-Olvera B A and Moore F C 2021 Use and non-use value of nature and the social cost of carbon *Nat. Sustain.* **4** 101–8

[45] Kikstra J S, Waidelich P, Rising J, Yumashev D, Hope C and Brierley C M 2021 The social cost of carbon dioxide under climate-economy feedbacks and temperature variability *Environ. Res. Lett.* **16** 094037