Focus

The effects of climate change on productivity

- *Global warming stands to have quantitatively important effects on country productivity*
- *While most countries will apparently be affected negatively , some may see large gains*
- *Canada and Russia could see considerable increases in productivity*
- *India by contrast is set to be hit extremely hard; and the US too will incur losses*
- *The geopolitical consequences of these developments stand to be huge*

Introduction: acute v chronic climate change effects

The consequences of global warming, and thereby climate change, have many dimensions. Depending on the region, these include severe and more frequent heat waves, unprecedented wildfires, more frequent and severe storms and floods, and more.[1]

These 'acute', visible consequences are damaging – for humans, industry, agriculture, economies, and societies. The annual value of such events worldwide has been estimated, probably conservatively, as running currently at over $250 bn.[2]

'Chronic' climate change effects are hard to spot …

By contrast, however, 'chronic' consequences – those that result from the *gradual* effects of climate change – including rising temperature, rising sea level, changing rainfall patterns , and more – are less visible, day-to-day. But nevertheless they stand to shape developments over the long term, not least the productive potential of economies. This has led one scientist to observe that:

> *"…introducing climate change to the global economy is like having a headwind when you're flying: you might not notice it in any given year, but over the long run it can slow you down dramatically."* [3]

Quantifying chronic effects

… and just as hard to quantify …

The impacts of these slower-moving, 'chronic', changes are not easy to quantify, for various reasons:[4]

- Climate-change processes evolve,[5] given the inertia in geophysical systems;[6]
- Socioeconomic impacts differ between and within countries and societies; and
- Effects can be systemic: a discrete event can set off a chain of effects.

Early quantitative estimates of the 'chronic' economic impacts of climate change differed considerably, one from another.[7] More recently, the matter has been revisited: we consider below five prominent papers that seek to quantify *country-level* effects of global warming on economic growth.

A number of caveats are warranted. The five studies generally do not include any of the 'acute' climate risks (i.e., natural disasters), sea-level rise, or any non-market damages such as loss of life, conflicts and violence, biodiversity, and ecosystem damages. Hence their analysis is – unavoidably – partial. But some of their conclusions are so striking that they warrant consideration in their own terms.

Moreover, while some of the studies were estimated on subnational/district-level GDP data, we have focused on the country level results. This approach admittedly can mask significant intra-country differences.

Cross-country evidence from the literature

.. but the cumulative consequences can be enormous

The effects of climate change on output arise in various ways, ranging from changing agricultural yields, to reducing investment, labour supply, and/or productivity. And they are almost inevitably greater in some countries than in others – our particular interest in this paper.

A common feature of the five studies is that they employ econometric techniques to examine the historical relationship across countries between real GDP per capita growth on the one hand, and temperature and/or precipitation (or their deviation from their historical 'norms') on the other. In turn, as with any such relationship, the results can be projected into the future, given assumptions about emissions and/or temperatures.

Comparing the various results in the five studies is however not straightforward. While the authors address broadly the same issues, each asks somewhat different questions, and each employs somewhat different assumptions, variables, and time frames. (Summaries of each of the five studies are presented in *Appendix 1.*) Hence the results from the various studies cannot simply be compared or aggregated. Accordingly, we have undertaken a set of 'standardisation' calculations in order to be able to assess the findings on as broadly comparable a basis as possible.

This in turn makes it possible to present the results in a comprehensive 'country heatmap' (Figure 1), such that the key conclusions can be seen in a reasonably comparable and easy-to-digest format. (For details on how the heatmap has been constructed, see *Appendix 2*).

Basic results: the great geopolitical rotation

Slowly, some regions risk becoming uninhabitable …

Pooling the quantitative results across the 26 countries reveals some striking conclusions, which are also broadly consistent across the studies:

- First, climate change is threatening to make vast regions across the world less habitable, and drive the greatest migration of refugees in history.

… while others may see productivity increase considerably

- Second, however, for a few nations, climate change will present an unparalleled opportunity.

It is not an exaggeration to say that these developments stand to have potentially huge geopolitical consequences.

Broadly speaking, countries can be divided into three groups according to the effects:

The 'colder' countries. These countries – most notably Russia and Canada – are set to gain economically from higher temperatures:

- Russia's GDP per capita could, according to one study, quadruple by the end of the century under a 'business as usual' emissions scenario, relative to a 'no climate change' baseline.
- Canadians could be two and a half times richer in terms of per capita GDP.
- This happens essentially because, as the climate warms, Canada and Russia will move into the 'ecological sweet spot', with benefits coming from new Arctic transportation routes, an expanded capacity for farming, and access to offshore oil and gas reserves. Russia is already actively preparing for this likely 'great rotation' by declaring that remaking Russia's East:

  "… is our national priority for the entire 21st century."[8,9]

- In contrast, and under the same assumptions, the US national income per capita could shrink by one-third.[10]

The 'hotter' countries. These countries – and particularly India, Brazil, Saudi Arabia, and Indonesia – are likely to witness the sharpest reduction in productivity from a warmer climate.

- The country that stands out amongst the various studies as most adversely affected by a warmer climate is India, whose GDP per capita could be some 90% lower vis-à-vis a baseline of no climate change.[11]
- This is readily explicable: temperatures in parts of India have soared of late – to 50^{o} C last May, for example. A recent government report warned that by the end of the century India's average temperature is likely to have risen by 4.4^{o} C, the frequency of summer heatwaves to have risen 3 to 4 fold, and the duration of heatwaves to have doubled.[12]
- Given that some three-quarters of India's labour force is engaged in 'heat-exposed' activities, and produces around half of national output, the socio-economic consequences of a hotter climate could be dire.[13]

The 'middling' countries. Most of the studies conclude that the 'global sweet spot' for economic activity lies within countries whose average baseline temperature ranges between 10 and 15^{o} C, broadly the north temperate zone. These countries (e.g., France, Korea, Japan) see relatively little impact on productivity, or even some benefit.

Caveats

Many caveats apply to these results, and the following represent only some:

Aggregation. A number of the studies were conducted at the 'district' level, which is appropriate for countries with wide geographical ranges, such as Russia, China, and the US. Our averaging of country-wide results masks these intra-country variations.

Differences also stand to be large within some regions

- For Russia, for example, while the gross regional product (GRP) of Yakutia (a far Eastern state by the Arctic Ocean) could be about 8% higher under the 3.5° C warming scenario, the GRP of Chelyabinsk (a region near the Kazakhstan border) is projected to be some 14% lower by the end of the century.[14]
- Likewise, in the US, Louisiana's GRP could shrink by one-quarter, while that of Montana might be reduced by 'only' about 5%. This may be explained by the fact that the authors include average elevation, distance to coast, and navigable rivers in their analysis.[15]

Accounting for adaptation. Some of the impacts stand to be overestimated, given that there will inevitably be adaptation (technological advances, defensive investments etc). That said, there will have been at least some adaptation over the historical period over which these relationships were estimated, so some adaptation is included, by definition. However, adaptation comes at a cost: and it is often the most affected countries that can afford it the least.[16]

'Non-stationarity.' Not only will the values of the 'drivers' – most importantly greenhouse gas concentrations – change over time, it is also possible that the *way* in which they affect temperature will change, at least somewhat.

Partial analysis. While some estimates control for various possible slow-moving regional changes that affect growth (e.g., changes in technology, policy, institutions, demography, etc.),[17] others do not explicitly take such influences into account. While these slow-moving influences will doubtless prove important, at this stage how, and by how much, can only be guessed at.

Transition risks. The studies were primarily concerned with climate change physical risks,[18] yet transition risks stand to be equally important, particularly for fossil-fuel intensive economies.

Watch fors

The speed, and the extent, of the events described by the five studies summarised in this paper, and portrayed in the 'heat map' below, will depend importantly on the actions of the major emitters.

Furthermore, so considerable are the likely productivity, and perhaps also geopolitical, benefits to Russia in particular from global warning that it brings into question how Russia perceives its interests vis-à-vis the efforts by other countries to curb global warming.

Hence watch for:

- The evolution of the emissions policies of the 'big' emitters, especially China and the US.
- Russia's activities in the Arctic.
- Policy in the developing countries. Collectively currently responsible for around 40% of global emissions,[19] willingness to curb their greenhouse gas emissions will be determined in part by whether the larger powers offer to compensate them for abstaining progressively from emitting greenhouse gases. ■

Figure 1: Climate change heatmap

Study	Research question	Model spec	Time horizon	CAN	RUS	NOR	SWE	CHE	CHN	USA	DEU	GBR	NZL	FRA	KOR	JPN	TUR	ITA	ARG	ZAF	MEX	AUS	HKG	IND	BRA	IDN	SAU	THA	SGP
				<0°C		0-5°C			5-10°C					10-15°C						15-20°C		20-25°C					25°C+		
	Average historic annual temperature (°C) →			-6.2	-6.0	1.4	2.3	4.9	6.7	6.9	8.5	8.7	10.2	10.6	11.1	11.2	11.2	12.2	14.4	17.5	20.4	21.7	23.0	24.0	24.5	25.4	25.5	26.2	26.8
Burke (2015)	Cumulative % change in GDP per capita vs world with no climate change		2100	247	419	249	210	121	-42	-36	63	42	-9	10	n.a.	-35	-17	-26	-53	-66	-73	-53	n.a.	-92	-83	-85	-96	-90	-87
Burke and Tanutama (2019)	Marginal effect of an 1°C increase in temp above the 2001-15 average temp on GDP per capita growth (in pp) under different versions of the model	0 lag	Historic relationship	0.7	0.7	0.3	0.2	0.0	-0.1	-0.1	-0.2	-0.2	-0.3	-0.3	-0.3	-0.3	-0.3	-0.4	-0.5	-0.8	-0.9	-1.0	-1.1	-1.1	-1.2	-1.2	-1.2	-1.2	-1.3
		1 lag		1.5	1.5	0.8	0.7	0.4	0.2	0.2	0.0	0.0	-0.1	-0.2	-0.2	-0.2	-0.2	-0.3	-0.6	-1.0	-1.2	-1.4	-1.5	-1.6	-1.7	-1.7	-1.8	-1.8	-1.9
		5 lags		4.8	4.8	3.1	2.8	2.1	1.6	1.6	1.1	1.1	0.8	0.6	0.6	0.6	0.6	0.3	-0.2	-1.2	-1.7	-2.2	-2.4	-2.7	-2.9	-2.9	-3.2	-3.2	-3.4
Kalkuhl (2020)	% change in GRP vs 8-12°C baseline temperature bin		2100	27.3	27.3	16.0	12.7	4.6	1.5	1.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-2.3	-12.4	-20.2	-24.2	-26.2	-28.3	-30.0	-30.0	-31.8	-31.8	-33.5
	Cumulative % change in GRP from 3.5°C warming vs no warming from 2015-19 temperature levels	Panel estimate	2100	-1.2	-7.4	-3.6	-4.7	-4.3	-7.2	-12.7	-4.9	-2.4	-4.3	-5.4	-7.0	-7.6	-10.1	-7.5	-10.4	-15.7	-12.9	-15.5	-9.1	-16.1	-17.2	-11.1	-18.2	-16.3	-11.3
Kompas et al (2018)	Impact on GDP (% change/year) from 3°C of warming		2050	0.2	0.0	0.0	0.1	0.0	-0.7	-0.1	0.1	0.1	0.1	0.1	-0.1	-0.2	0.0	0.2	-0.2	-0.4	-0.1	-0.2	-1.2	-3.2	-1.0	-4.0	-1.3	-2.5	-3.1
			Long-run	-0.2	-0.9	-0.6	-0.3	-0.4	-2.9	-0.6	-0.4	-0.4	-0.8	-0.5	-1.5	-1.3	-1.5	-0.6	-1.6	-2.5	-2.3	-1.1	-5.3	-10.4	-3.8	-13.3	-5.4	-9.2	-11.7
	From 4°C of warming		Long-run	-0.3	-1.4	-1.0	-0.5	-0.5	-4.6	-0.9	-0.6	-0.6	-1.3	-0.7	-2.7	-2.4	-2.5	-0.9	-2.6	-3.4	-4.0	-1.6	-7.7	-14.6	-6.8	-19.0	-7.8	-13.3	-16.6
Kahn et al (2019)	Cumulative percent change in GDP per capita (based on RCP 8.5 scenario vs historical trend warming)		2050	-4.4	-3.1	-0.6	-0.8	-4.3	-1.6	-3.8	-0.6	-1.2	-3.2	-1.9	-3.7	-3.7	-2.3	-2.6	-2.8	-2.5	-2.0	-2.3	n.a.	-3.6	-2.8	-2.8	-1.1	-1.1	n.a.
			2100	-13.1	-8.9	-1.8	-2.7	-12.2	-4.4	-10.5	-1.9	-4.0	-10.4	-5.8	-11.7	-10.7	-8.0	-7.0	-8.2	-7.6	-5.5	-6.9	n.a.	-9.9	-7.4	-7.5	-3.4	-4.0	n.a.

Source: Llewellyn Consulting based on results from respective academic studies as cited above.
Notes: Standardised variables are colour-coded. Dark green indicates a country with the least negative (or even a positive) impact on growth/productivity from warmer temperatures, dark red with the most negative impact (i.e., exceeding +/-1.5 standard deviations from the mean); Country groupings into temperature brackets done by LLC – these may not correspond with the authors; GRP – Gross Regional Product.
We take full responsibility for any misinterpretation of these academic results.

The results from Kahn et al (2019) are markedly different from other studies. We believe the difference can be explained by the following, quoting the authors: "Our focus on the deviations of temperature and precipitation from their historical norms also marks a departure from the literature, as changes in the distribution of weather patterns (not only averages of climate variables but also their variability) are modelled explicitly." The authors also explain: For example, while the level of temperature in Canada is low, the country is warming up twice as fast as rest of the world and therefore is being affected by climate change (including from damages to its physical infrastructure, coastal and northern communities, human health and wellness, ecosystems and fisheries).

Appendix 1: Summaries of the five studies

Burke et al. (2015) *Global non-linear effect of temperature on economic production*[20]

- A landmark study that provided the first evidence that economic activity in all regions is coupled with global climate, and established a new empirical foundation for modelling economic loss in response to climate change.
- The authors tested their hypothesis using data on economic production for 166 countries over the period 1960–2010. In essence, they analyse whether country-specific deviations from growth trends are non-linearly related to country-specific deviations from temperature and precipitation trends, after accounting for any shocks common to all countries.
- They conclude that overall economic productivity is indeed non-linear in temperature for all countries, with productivity peaking at an annual average temperature of 13° C, and declining strongly at higher temperatures.
- The authors also conclude that the relationship is globally generalisable; unchanged since 1960; and evident for agricultural and non-agricultural activity, in both rich and poor countries.
- While much of global economic production is clustered near the estimated temperature optimum, rich and poor countries alike exhibit similar non-linear responses to temperature. Poor tropical countries however exhibit larger responses – mainly because they are hotter, rather than because they are poorer.
- The authors do not find that technological advances, or the accumulation of wealth and experience since 1960, have fundamentally altered the relationship between productivity and temperature.
- They conclude that unmitigated warming would be likely, in and of itself, to reduce average global incomes by around 23% by 2100, as well as widen global income inequality.
- Differences in the projected impact of warming are mainly a function of countries' baseline temperatures, given that warming raises productivity in cool countries. In particular, Europe could benefit from increased average temperatures. Because warming harms productivity in countries with already-high average temperatures, incomes in poor regions are projected "*with high confidence*" to fall relative to a situation of no climate change.

Burke, Tanutama (2019) *Climatic Constraints on Aggregate Economic Output*[21]

- The authors undertake regression analysis at the 'district level' (sub-state level in the US, for example) across a historical dataset of 37 countries (11,000 districts in total) over the 2001-15 period.
- They find that district-level economic production is concave in temperature exposure, with a negative slope throughout nearly all the observed temperature distribution, and increasingly steep at higher temperatures.
- Interestingly, they also find that the impacts of a given temperature exposure do not differ meaningfully between rich and poor regions; but exposure to damaging temperatures is much more common in poor regions.
- These results suggest that additional warming will exacerbate inequality, particularly across countries, and that economic development alone would be unlikely to reduce damages, in contrast to what is commonly hypothesised.
- The authors estimate that, since 2000, warming has already cost both the US and the EU $4 tr or more in lost output, and tropical countries are more than 5% poorer than they would have been without this warming.

Kalkuhl, M. and Wenz, L. (2020) *The impact of climate conditions on economic production. Evidence from a global panel of regions*[22]

- The authors use a panel of subnational GDP data – Gross Regional Product (GRP) – that allows the depiction of local weather as well as climate conditions, on various time scales, across the globe (covering more than 1,500 regions). They use climate and economic data at the subnational level for the years 1900 to 2014.
- Non-market damages including loss of life, conflicts and violence, biodiversity and ecosystem damages are not captured.
- The authors find robust evidence that GRP responds to annual temperature shocks, as well as to long-run temperature levels (climate). With respect to precipitation, however, the evidence is less robust.
- Consistent with existing evidence on labour productivity and agricultural yields, the authors find strong evidence that changes in annual mean temperatures have a non-linear effect on economic output.
  - Increases in temperature tend to increase GRP in cold regions (where annual mean temperature is below 5° C) and reduce GRP in hot regions.

  - Their panel specification suggests that a permanent increase in temperature would lead to a permanent loss in economic output in hot regions. This loss is considerable: a 1^0 C temperature increase in a region with an annual mean temperature of 25^0 C, reduces GRP by about 3.5% in that region.

- This heterogeneity of climate damages is correlated with baseline GRP, i.e. poorer regions tend to suffer more from global warming. This is understandable, given that the marginal effect of warming is stronger in hot regions, which also tend to be poor regions.

  - Applying the panel and cross-sectional results to projected warming levels for a high-warming scenario (i.e. an increase in global mean surface temperature by about 3.5^0 C until the end of the century), would reduce global output by 7%–14% in 2100 compared with a scenario of no further warming.

  - The projected damages are even higher for tropical and poor regions, for which output losses of up to 20% are suggested.

- **Summary table.** The authors present the table below, which provides an overview of damage estimates both from their work and that involving others' panel and cross-sectional regressions:

GRP losses of a 1°C temperature increase – overview of findings from the literature. Table shows different estimates from the literature for the effect of a 1 °C temperature increase on reductions of economic output and compares them to our results. Upper rows refer to findings from annual panel models, lower rows to those from cross-sectional models. For non-linear annual panel specifications, marginal effects at 25 °C are given. Studies differ in regional scope and modeling choice, as detailed in the main text.

Study	Finding
	Annual panel models
Dell et al. (2012)	1–1.3% for poor countries, no significant effect for full sample
Burke et al. (2015) (0 lag)	−0.3% at 10 °C and 1.2% at 25 °C temperature
Burke et al. (2015) (5 lags)	0.6% at 10 °C and 0.9% at 25 °C temperature
García-León (2015)	0.03–0.06% for EU NUTS regions
Burke and Tanutama (2019) (0 lag)	0.1% at 10 °C and 1.7% at 25 °C temperature
Burke and Tanutama (2019) (5 lags)	0.8% at 10 °C and 2.9% at 25 °C temperature
Our study: temperature change (preferred; 1 lag)	0.8% at 10 °C and 3.5% at 25 °C temperature
Our study: temperature level (0 lag)	0.5% at 10 °C and 2.6% at 25 °C temperature
Our study: temperature level (5 lags)	2.4% at 10 °C and 2.6% at 25 °C temperature
	Cross-sectional models
Dell et al. (2009)	1.2–1.9% for Latin American municipalities
García-León (2015)	1.6–2.2% for EU NUTS regions
Our study	2.0–4.3%

Source: Kalkuhl (2020)

- The authors note that all these studies report similar marginal effects of a 1^0 C temperature increase. Given that these studies regress growth on temperature levels, they imply permanent growth rate impacts after a one-time 1^0 C temperature increase.

- Marginal effects in the authors' study tend to be slightly larger, in particular at higher temperature levels, even though they use a comparable econometric specification that is based on temperature levels rather than temperature changes.

Kompas et al (2018) ***The Effects of Climate Change on GDP by Country and the Global Economic Gains From Complying With the Paris Climate Accord*** [23]

- The authors' work extends a large dimensional intertemporal Computable General Equilibrium (CGE) trade model to account for the various effects of global warming (e.g. loss in agricultural productivity, sea level rise, and health effects) on Gross Domestic Product (GDP) growth and levels for 139 countries, by decade and over the long term, where producers 'look forward' and adjust price expectations and capital stocks to account for future climate effects.

- The results depict effects of global warming that vary by time, region, and economic sector, but tend to increase over time.

  - The effects also become much greater in relatively poor African and Asian nations, where the loss in GDP, as indeed in all countries near the equator, is particularly severe.

- Over the medium term, and notwithstanding some minor gains in a few European countries, the losses from global warming (at 3° C) dominate a major part of the world.

– The largest losses in all cases, and for all temperature increases, occur in Sub-Saharan Africa, India, and Southeast Asia.

Kahn et al. (2019) *Long-Term Macroeconomic Effects of Climate Change: A Cross-Country Analysis*[24]

- The authors use a panel data set of 174 countries over the years 1960 to 2014.
- They conclude that a persistent change in climate conditions has a long-term negative effect on per capita GDP growth.
  – Specifically, they find that a temperature rise (fall) above (below) its historical norm by 0.01° C annually, reduces (increases) income growth by 0.0543 percentage points per year. (Note: Global average temperature has risen on average by 0.0181 degrees Celsius per year over the past half century (1960-2014).
- The authors' empirical findings pertain to poor or rich, hot or cold, countries alike, economic growth being affected not only by higher temperatures but also by the *degree of climate variability*.
  – The authors' results suggest, for example, that Canada will be one of the biggest 'losers' from further warming. [Our understanding is that, to an extent at least, this result is driven by the *speed* of warming, i.e. Canada has been warming twice as fast as the rest of the world, and this 'trend warming' is one of the variables in the authors' equation.]
  – This conclusion runs contrary to most of the literature, which finds that temperature increases have uneven macroeconomic effects, with adverse consequences in countries with hot climates, such as low-income countries.
- The authors also find that an increase in average global temperature of 0.04° C per year corresponding to the Representative Concentration Pathway (RCP) 8.5 scenario stands to reduces world real GDP per capita by 7.2 percent by 2100.
  – Limiting the increase to 0.01° C per year, which corresponds to the December 2015 Paris Agreement, would reduce the output loss substantially to just 1.07 percent.

Appendix 2: Constructing the heatmap

Data

- Our main research effort to date has been to quantify effects of climate change on economic growth and productivity across countries.
- To this end we have been particularly interested in academic papers that present numerical, country-level estimates. Sometimes the results were public, but we have also contacted authors to obtain further information.
- Coefficients were often given in respect of 'temperature brackets', i.e. for a country with an average 'baseline temperature' of X° C, each additional degree of warming would imply output/productivity loss of Y percentage points by a point in time in the future.
- Assumptions on 'baseline temperatures' are therefore crucial – these determine which econometric coefficients from empirical studies to apply for each country.
- Where the results were presented for 'temperature brackets', we had to 'assign' our sample countries into respective temperature ranges based on historic temperature data. To do this we calculated average annual temperatures for the countries in the sample for 1950-80 from Berkeley Earth, available at: http://berkeleyearth.lbl.gov/country-list/ . [Accessed 10 July 2020]
  - For comparison, we also consulted the average annual temperatures as published by Kahn et al., 2019.
  - A note of caution: a different time frame for average annual temperatures would perforce yield somewhat different conclusions.
- On occasion we had to average district-level data to obtain country-level figures, and interpolate given econometric coefficients to cover a full range of temperatures in the sample.
- There is inevitable subjectivity involved in many of these steps: we take full responsibility for any misinterpretation of these academic results.

Heatmap

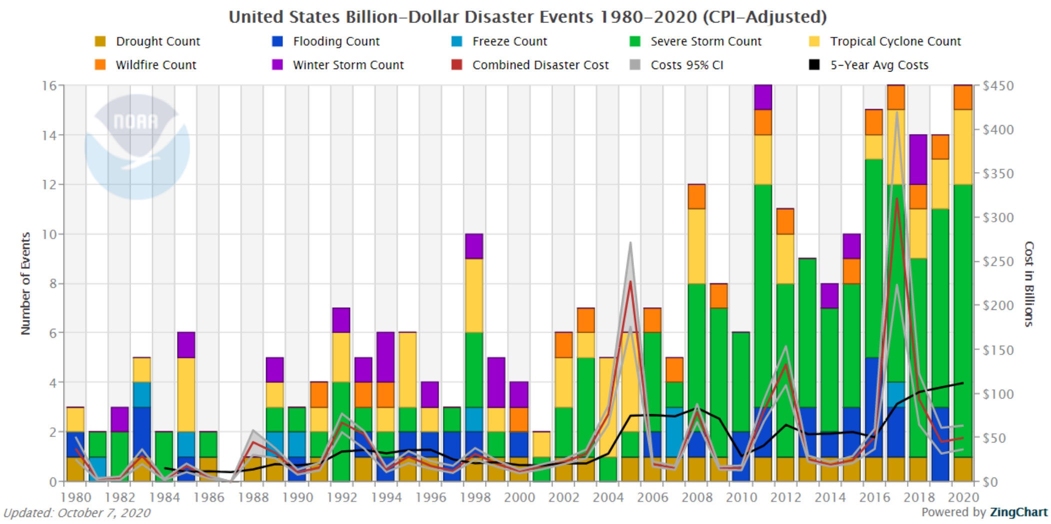
- Given that different studies pose somewhat different questions, the heatmap is at base an adaptation of authors' results. The aim here has been to construct a simple visual summary of how individual countries' economic growth/productivity is likely to be affected by higher temperatures.
- The first step was to order countries by their historic average temperatures, from the 'coldest' to 'warmest'.
- The left-most column lists the five studies (with their different model specifications), from which we extracted or inferred individual country results.
- The results were then standardised and colour-coded, based on the following thresholds (in similar fashion to the method that we employ when constructing to our structural/fiscal heatmaps):
  - **Dark green** indicates a country with the least negative (or even a positive) impact on growth/productivity from warmer temperatures, **dark red** with the most negative impact (i.e. exceeding +/-1.5 standard deviations from the mean);
  - **Light green/red indicates** somewhat more/less negative impact on growth from climate change than that of the darker shaded countries (between +/-0.5 and +/-1.5 standard deviations from the mean);
  - **Grey** indicates results that are near the mean (between +0.5 and -0.5 standard deviations from the mean).

[1] For a summary presentation of the effects by broad region, see Briozzo, S., and Llewellyn, J., 2019. *Climate change: consequences by region*. Llewellyn Consulting, November. Available on request.

[2] Globally, it has been estimated that there were 416 natural-catastrophe events in 2020, resulting in $268bn worth of economic damages, 8% above the average annual losses for this century. See Seekings, C., 2021. *Natural disasters expose huge insurance protection gap*. The Actuary [online]. Available at: https://www.theactuary.com/2021/01/26/natural-disasters-expose-huge-insurance-protection-gap. [Accessed: 31 March 2021]

In the US, the number of billion-dollar weather and climate disasters has increased 7-fold since 1980 (Figure 1 below). The U.S. has experienced 285 weather and climate disasters since 1980 where overall damages/costs reached or exceeded $1 billion (including CPI adjustment to 2020). The total cost of these 285 events exceeds $1.875 trillion. The total cost over the last 5 years (2016-2020) exceeds $600 billion — averaging more than $120 billion/year — both new records.

Figure 1: US billion-dollar disaster events, 1980-2020



Source: National Centers for Environmental Information

Full link to data: https://www.ncdc.noaa.gov/billions/time-series

[3] Marshall Burke, Associate Professor, Dept. of Earth System Science, and Deputy Director, Center on Food Security and the Environment, Stanford University.

[4] McKinsey Global Institute, 2020. Climate risk and response: Physical hazards and socioeconomic impacts, [online]. Available at: https://www.mckinsey.com/business-functions/sustainability/our-insights/climate-risk-and-response-physical-hazards-and-socioeconomic-impacts [Accessed: 20 May 2020]

[5] In other words, they tend to be 'non-stationary'. 'Stationarity', by which is meant that not only do the values (in this case of temperature and its various determinants) change over time, but also the *ways* in which they change themselves change over time.

[6] Moreover, this is likely to continue to be the case even if net-zero targets ultimately are met.

[7] For example, impacts of 5^0 C warming have been estimated to reduce global GDP by anywhere between 0 and 20%. See Stern, Nicholas (2008). *The Economics of Climate Change*. American Economic Review: Papers & Proceedings 2008, 98:2, 1–37. Available at: https://pubs.aeaweb.org/doi/pdfplus/10.1257/aer.98.2.1. [Accessed 17 March 2021] Reference made in Kalkuhl, et al., 2020.

[8] The steady melting of the Arctic sea ice will open a new shipping lane that would cut transit times from Southeast Asia to Europe by up to 40 percent and also shorten travel time to the United States, positioning Russia to profit by controlling this route between China and the West. For more, see Lustgarten, A., 2020. *How Russia wins the climate crisis*. The New York Times Magazine [online]. Available at: https://www.nytimes.com/interactive/2020/12/16/magazine/russia-climate-migration-crisis.html [Accessed 7 March 2021]

[9] *"We believe navigation can be made year-round and we're not waiting until it happens climate-wise,"* Chekunkov said. *"We're building the most powerful fleet of nuclear icebreakers in the world."* All-year navigation could be a reality by mid-century. For more, see Lombrana, L., 2021. Where Climate Scientists See Danger, Russia Sees an Opportunity. Bloomberg [online]. Available at: https://www.bloomberg.com/news/articles/2021-03-15/where-climate-scientists-see-danger-russia-sees-an-opportunity [Accessed 17 March 2021]

[10] Burke, M. et. al (2015). *Global non-linear effect of temperature on economic production*. Nature [online]. Available at: https://web.stanford.edu/~mburke/climate/BurkeHsiangMiguel2015.pdf. [Accessed 17 July 2020] Numeric country-specific results available at: https://web.stanford.edu/~mburke/climate/

[11] Ibid.

[12] Pakrasi, S., 2020. *Temperature over India likely to rise by over 4 degrees Celsius by end of 21st century: Govt report*, [online]. Available at: https://www.hindustantimes.com/india-news/temperature-over-india-likely-to-rise-by-over-4-degress-celsius-by-end-of-21st-century-govt-report/story-ZsXcDjcYv7DiHWG7F8egGO.html [Accessed: 31 March 2021]

[13] McKinsey Global Institute, 2020.

[14] Kalkuhl, M., Wenz, L. (2020): *The impact of climate conditions on economic production. Evidence from a global panel of regions*. Journal of Environmental Economics and Management, 103, 102360. Available at: The impact of climate conditions on economic production. Evidence from a global panel of regions - ScienceDirect [Accessed: 30 September 2020]

[15] Ibid.

[16] See, for example, the IMF, 2021. Asia-Pacific, the Gigantic Domino of Climate Change. Available at: Asia-Pacific, the Gigantic Domino of Climate Change – IMF Blog. [Accessed: 25 March 2021]

[17] Kalkuhl et al., 2020, for example, include region-specific polynomial time trends which control for various possible slow-moving regional changes that affect growth (e.g. technological change, institutional change, demographic change, etc. As the cross-sectional regressions suggest a negative relationship between temperature and GRP that is stable over different decades, they conclude that technological change has not reduced the temperature sensitivity of economies.

Kahn et al., 2019, for example, postulate in their theoretical model that labour productivity in each country is affected by a common technological factor and country specific climate variables, which they take to be average temperature, and precipitation, in addition to other country-specific idiosyncratic shocks.

[18] Kalkuhl et al., 2020, include cumulative oil and gas reserves in their analysis.

[19] Note that for these purposes we do not include China among the developing economies. For more, see Centre for Global Development, 2015. Developing Countries Are Responsible for 63 Percent of Current Carbon Emissions. Available at: Developing Countries Are Responsible for 63 Percent of Current Carbon Emissions | Center For Global Development (cgdev.org) [Accessed 7 April 2021]

[20] Burke, M. et. al., 2015.

[21] Burke, Tanutama, 2019. *Climatic Constraints on Aggregate Economic Output*. NBER Working Paper 25779. Available at: http://web.stanford.edu/~mburke/papers/BurkeTanutama_NBER_w25779.pdf#:~:text=Climatic%20Constraints%20on%20Aggregate%20Economic%20Output%20Marshall%20Burke,specific%20case%20studies%20and%20simulations%20have%20suggested%20that [Accessed: 20 June 2020]

[22] Kalkuhl, M., Wenz, L., 2020.

[23] Kompas, T., Pham, V. H., & Che, T. N.(2018). The effects of climate change on GDP by country and the global economic gains from complying with the Paris Climate Accord Available at: The Effects of Climate Change on GDP by Country and the Global Economic Gains From Complying With the Paris Climate Accord - Kompas - 2018 - Earth's Future - Wiley Online Library [Accessed: 15 July 2020]

[24] Kahn et al., 2019. *Long-Term Macroeconomic Effects of Climate Change: A Cross-Country Analysis*. The IMF. Available at: Long-Term Macroeconomic Effects of Climate Change: A Cross-Country Analysis (imf.org) [Accessed: 30 August 2020]