THE ECONOMIC IMPACT OF GLOBAL WARMING

AN OXFORD ECONOMICS WHITE PAPER

DR JAMES NIXON

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To discuss the report further please contact:

James Nixon (jnixon@oxfordeconomics.com)

Oxford Economics

4 Milbank, London, SW1P 3JA

Tel: +44 207 803 1400

www.oxfordeconomics.com

The cover illustration shows the annual average temperature anomaly for Oxford from 1814-2018 using data from the UK Met Office. Known as 'Warming Stripes', these graphical representations of global warming were developed by Ed Hawkins of the Institute for Environmental Analytics and are available for a variety of geographical regions and locations. https://showyourstripes.info/

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EXECUTIVE SUMMARY

The impact of global warming is rarely included in standard macroeconomic forecasts, even over relatively long time horizons covering the next 20 or 30 years. In part, this reflects the perception that the economic effects of global warming are unlikely to become material until the second half of this century, when the effects of even significant warming are expected to be no more than a few percentage points of global GDP. Moreover, professional forecasters have so far tended to think it too hard to quantify the impact. This paper aims to remedy these two perceptions, as they are now outdated. This is done by comparing the scientific literature on the main impacts of global warming embedded in the IPCC's Special Report on Warming of 1.5°C with the economic literature on their likely economic cost.

The main point we highlight is that, if you want to forecast economic variables over the medium-to-long term (including horizons relevant for many businesses of 20-30 years), you need to take the effects of global warming into account, as they may subtract up to anywhere between 2.5% and 7.5% of world GDP by 2050. This will be distributed unevenly among countries, with the effects of climate change varying based on latitude, industrial structure and geography. India, Africa and Central America stand out in terms of the most significant effects of higher temperatures.

More generally, the largest effects are expected to be experienced in relatively poor countries, which are also usually the hottest and the least able to afford the costs of significant adaptation. On the other hand, China, India and SE Asia are likely to face the most serious risk of flooding from sea level rises and hence the still largely unquantified costs of building large-scale flood defences.

In addition, our literature review reveals that estimates of the economic damage of climate change have been consistently rising as more channels and/or data are taken into account. While damage estimates in 1990-2008 were in the range of a few percent of world GDP, more recent time-series estimates point to the costs being an order of magnitude higher. The point for professional forecasters to take away is that as more channels are taken into account in future studies, the estimated damages will rise. This may be especially true when one considers the potential value of items normally excluded from market estimates of GDP, such as natural capital and human mortality.

More concretely and directly relevant for strategic business planning and economic forecasting, this paper highlights that investment may rise in the short-to-medium term as efforts to mitigate and adapt to climate change are stepped up substantially. However, this investment is essentially unproductive as it goes toward replacement of existing capital stock due to higher depreciation. Hence, on top of the direct damages due to climate change mentioned above, growth will be lowered further as adaptation and mitigation investments reduce potential growth.

1. INTRODUCTION

Human influence on the climate has been the dominant cause of observed global warming since the mid-20th century. The temperature rise to date has already resulted in profound alterations to human and natural systems, including increases in drought, flooding, extreme weather, sea level rises and biodiversity loss. These changes are causing an unprecedented increase in climate-related risks, with people in low- and middle-income countries most severely affected. Some countries are already experiencing a decline in food security, which in turn is partly linked to rising poverty and international migration.

This conclusion, drawn from the Intergovernmental Panel on Climate Change (IPCC) Special Report on Global Warming of 1.5°C (SR1.5), suggests that climate change will have sufficiently sizeable economic effects to be of direct relevance to our long-term forecasts. Indeed, 2019 has already turned out to be another year of record-breaking temperatures, floods, and hurricanes,[1] which suggests that we are already experiencing the effects of climate change.

These events are part of a trend of rising global temperatures over the last half century that has left the global mean surface temperature (GMST) about 1°C higher than the pre-industrial average (defined as the average annual global temperature between 1850 and 1900). As a result, extreme weather events, such as heat waves, droughts, and floods, are likely to become more frequent, while melting ice sheets and thermal expansion of the oceans mean that sea levels will rise. Global warming is therefore pushing the world to new climatic extremes that are already having a significant economic impact.

However, quantifying the economic consequences of climate change is conceptionally and computationally challenging.[2] Temperature increases of the magnitude that could occur over the next century − and many other aspects of climate change, such as the rapid rise in sea levels, ocean acidification, and increased incidence of flooding − sit well outside recent historical experience and will affect a large number of countries. Extrapolating from previously observed marginal changes is therefore problematic, as is the question of how to appropriately cost infrequent but potentially catastrophic tail risks.

In contrast to the science of global warming, the economic analysis of its effects is relatively undeveloped,[3] with the literature essentially split between a series of older empirical papers, which estimate the effects of even four or five degrees of warming at no more than a few percent of global GDP, and more recent long-dataset panel estimates, which place the economic impacts an order of magnitude higher. This is especially the case once one begins to consider the impact of environmental degradation on natural capital and the

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[1] July 2019 was the hottest month every recorded with record breaking temperatures experienced in Europe and parts of India. The US experienced its wettest 12 months on record amid weeks of record-setting floods throughout much of the central United States, while record temperatures in Alaska and Siberia contributed to an unprecedented loss of sea ice and a spate of forest fires in California.

[2] Hsiang et. al (2017).

[3] See for example the recent opinion piece by Oswald and Stern (2019).

risks to human health that are not included in market-based measures of GDP. There is therefore considerable uncertainty about the economic impact of climate change, with economists at risk of significantly underestimating it.[4] This white paper therefore reviews the existing literature on the economic costs of global warming with a view to considering whether we should be factoring the impact of global warming into our economic forecasts on horizons stretching to the next twenty or thirty years.

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[4] DeFries et.al. (2019)

2. THE IMPACT OF GLOBAL WARMING

In order to accurately assess the economic impact of global warming, it is necessary for economists to be cognizant of the science of global warming.[5] This paper therefore compares the scientific literature on the main impacts of global warming embedded in SR1.5 with the economic literature on the economic cost of global warming. This section reviews the observed and expected effects of global warming with a particular emphasis on the near term, with the aim of building a narrative through which the projected changes can be interpreted. While the earlier UN Assessment Reports have often focused on 2100 as a significant benchmark, our interest here is in the effects of global warming that we are likely to experience this side of 2050 and within the 1-2°C temperature range, which is the focus of SR1.5.

2.1 CLIMATE ZONES AND THE EFFECTS OF A WARMER WORLD

As a starting point, it may be worth appreciating that the Earth’s climate system is made up of several climate zones. These essentially form a number of ‘horizonal’ stripes that radiate poleward from the equator. It’s obviously hot at the equator, which leads to high rates of evaporation and typically sets up a process of convection whereby warm air rises, taking water vapour with it, and then cools, causing the vapour to fall as rain. We know these parts of the world as equatorial rain forests, which are in turn bounded by the savanna grasslands.

But the equator is not the warmest part of the world. Since the earth is tilted on its axis, the warmest summers are experienced by those parts of the globe where the sun is directly overhead in the summer. These are also the areas where the convection cell set up over the equator typically sees the now dry air descending. This forms the world’s tropical deserts (of which the Sahara is the most obvious example), which effectively band the tropical rain forests on either side of the equator. Moving poleward, one encounters the more temperate latitudes that characterise much of Europe and North America, before reaching the boreal climate zone that borders the polar regions.

An appreciation that the Earth is divided into a number of climate zones should begin to hint that not all parts of the world will experience global warming in the same way – some will be wetter; some will be drier. And while the Earth’s climate has always been naturally variable, the speed at which the climate has changed over the past 40–50 years appears to be unprecedented in the past 20,000 years. The issue is that this rapid, unidirectional change is taking place faster than the Earth’s natural ecosystems can adapt. As the Earth continues to warm, the climate zones will migrate poleward, with the temperate/tropical boundary that marks the limit of the tropical deserts advancing at something like 30 miles per decade[6].

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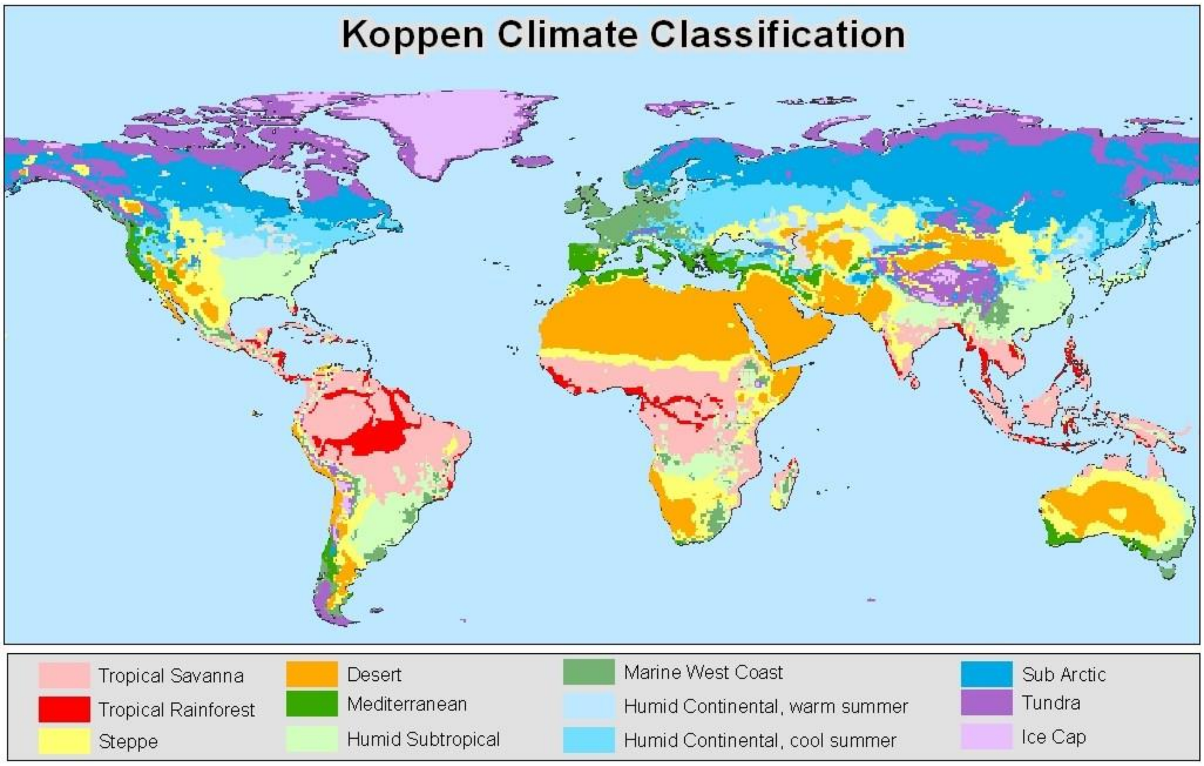
[5] See the excellent primer by Hsiang & Kopp (2018)

[6] See for example Nicola Jones, “Redrawing the Map: How the World’s Climate Zones Are Shifting”, Yale Environment 360, 23 October 2018. https://e360.yale.edu/features/redrawing-the-map-how-the-worlds-climate-zones-are-shifting. An instructive visualisation of how the climate zones will move poleward is available at http://koeppen-geiger.vu-wien.ac.at/



Source: http://koeppen-geiger.vu-wien.ac.at/

If one wanted to make a distinction between global warming and climate change, one could say that the planet as a whole will experience global warming, while individual localities (and hence the people on the ground) will experience climate change as the climate zones march poleward. Warming will be greatest in the polar regions where temperature increases will typically be three times greater than those experienced at the equator.

Hence, the parts of the world where drought is most likely to become a problem are those parts into which the subtropical deserts are likely to expand – chiefly the western United States and eastern Australia, but also Southern Mediterranean Europe, Central Southern Africa, India, southern China and subtropical Latin America. These are the parts of the world on the climate change front line.

By the same token, the poleward move of temperate climate zones into boreal regions will have far-reaching consequences in countries like Russia and Canada. The existing tropical regions, meanwhile, are likely to experience even heavier rainfall with an associated increase in the incidence of flooding, while today's temperate (and densely populated regions) will experience proportionately large increases in average temperatures and will perhaps face the biggest challenges in terms of adaptation. By virtue of its Atlantic location, the UK will be both warmer and wetter.[7]

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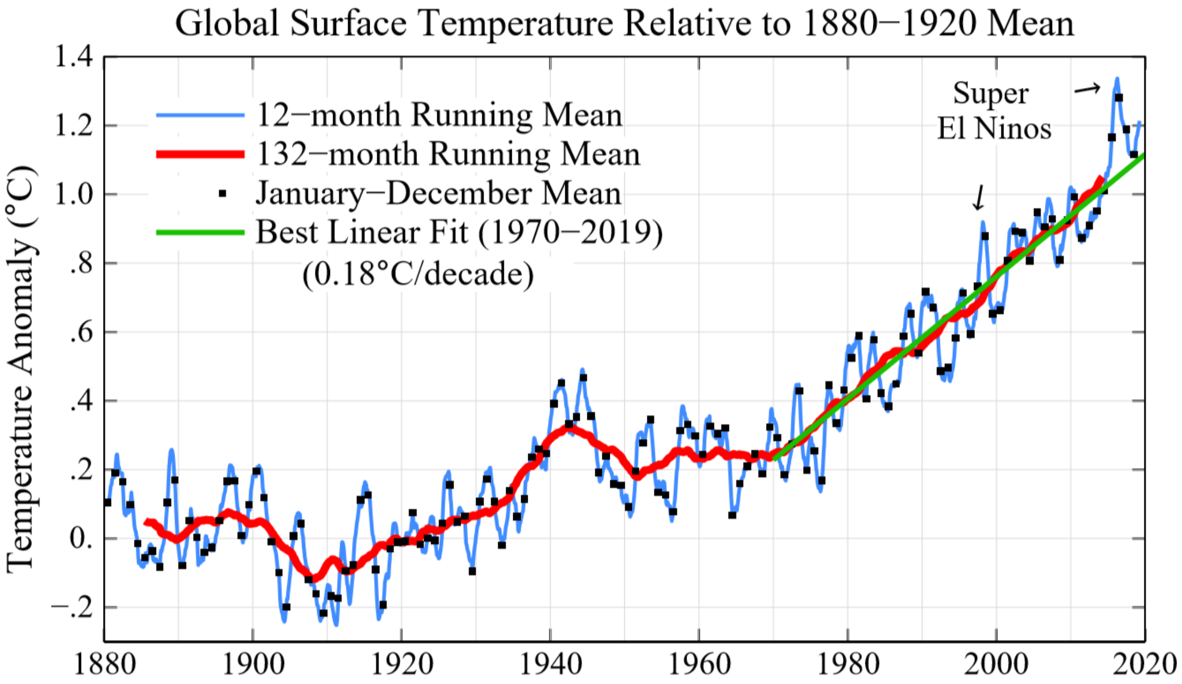
[7] Met Office UK Climate Projections

2.2 HOW MUCH HAS THE EARTH WARMED SO FAR

The global land and ocean surface temperature departure from average for September 2019 tied with 2015 as the highest for the month of September according to the 140-year global temperature dataset record maintained by the US National Oceanic and Atmospheric Administration (NOAA), which dates back to 1880. The year-to-date temperature for September 2019 was the second warmest on record.[8] Last year (2018) was the fourth warmest on record, with the last four years collectively being the hottest period on Earth since modern measurements began. Overall, the global mean surface temperature (GMST) is currently about 1°C above the pre-industrial average (taken here to be the average temperature between 1850-1900), with most of that warming taking place in the last 50 years.

It is now virtually certain (at least 99 percent probability) that the observed warming trend exceeds the bounds of natural variability. The IPCC in its Fifth Assessment Report (AR5) concluded that “it is extremely likely [at least 95% probability] that human influence has been the dominant cause of the observed warming since the mid-20th century.”

In the absence of efforts to reduce emissions of greenhouse gases, the Earth will continue to warm. At the current rate of warming, the average global temperature will increase by about 1°C every 50 years. Extrapolating the current rate of increase into the future suggests that the Earth is on course to hit 1.5°C by 2045 and 2°C by around 2070.



Source: http://www.columbia.edu/~mhs119/Temperature/

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[8] NOAA: Assessing the Global Climate in September 2019.

To derive precise estimates of future warming, there are a multitude of climate modelling research programmes that maintain and run global climate models. For the IPCC assessments, the model results are compared in what is known as the Coupled Model Inter-comparison Project (CMIP).[9] To ensure that model outputs are comparable with each other, a standardised set of emissions scenarios has been constructed to provide a common set of inputs. These emissions scenarios are known as representative concentration pathways (RCPs) and exogenously prescribe a future flow of emissions.

These emissions scenarios are labelled according to the overall amount of heating, known as 'radiative forcing', (measured in watts per m2) that will be generated by 2100 in each scenario:[10]

- **RCP 8.5** has the strongest forcing, with CO_2 emissions nearly doubling from their current levels by 2050 and continuing to rise thereafter.

- **RCP 6.0** is an intermediate scenario consistent with a continued heavy reliance on fossil fuels but with intermediate energy intensity. It envisages increasing use of croplands (and hence a shift to a more vegetarian diet) and declining use of grasslands. CO_2 emissions peak in 2060 at 75% above today's levels, then decline to 25% above today.

- **RCP 4.5** has a moderate forcing, with CO_2 emissions stabilising at close to their current levels through the middle of the century and declining thereafter, reaching about 40% of their current levels by 2080.

- **RCP 2.6** has the weakest forcing, with CO_2 emissions declining immediately to less than a third of the current levels by 2050 and becoming net-negative during the 2080s.

In assessing future climate change, it may be useful to label these pathways as 'high', 'moderate' and 'low' emissions scenarios. RCP 4.5 might be thought of as consistent with efforts to be carbon neutral by 2050, while RCP 8.5 can be described as a relatively high emissions scenario, "with with low income, high population and high energy demand, due to only modest improvements in energy intensity[11]." Atmospheric CO_2 concentrations are currently 412 ppm[12].

Table 1: RCPs and projected temperature outcomes

	2050 ± 10 yrs		2090 ± 10 yrs	
	CO_2e emissions	GMST Change	CO_2e emissions	GMST Change
Scenario	ppm.	°C	ppm.	°C
RCP 2.6	455	1.6 ± 0.6	431	1.6 ± 0.7
RCP 4.5	526	2.0 ± 0.6	577	2.4 ± 0.8
RCP 6.0	505	1.9 ± 0.6	699	2.8 ± 0.9
RCP 8.5	628	2.6 ± 0.6	1091	4.3 ± 1.1

Source: Oxford Economics\Table TS1 AR5;\ RCP database

2.3 THE EFFECTS OF FURTHER WARMING

Human-induced global warming is increasingly responsible for a broad pattern of climate change, which is driving an increased incidence of heatwaves and drought, flooding and extreme weather. Last year, in order to highlight the growing impact of increasing CO_2 concentrations, the IPCC published its Special Report on Global Warming of 1.5°C (SR1.5). This report concluded that human-induced global warming had already caused multiple changes in the climate system, which include more frequent heatwaves and an increase in the frequency and intensity of heavy precipitation events. More broadly, SR1.5 identified 10 channels through which future global warming is likely to have an impact both on the natural world but also on the human activities that depend on affected ecosystems.

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1. Temperatures changes

The amount of global warming experienced in the future will depend on the future rate of emissions. Central temperature projections for 2050 vary between 1.6°C for a low emissions scenario and 2.6°C for a high emissions scenario (with uncertainty of roughly 0.5°C in either direction). Larger temperature increases and proportionately bigger effects could be experienced after 2050 depending on the future path of emissions.

As a central case, SR1.5 suggests that we are likely to reach 1.5°C of warming by around 2040. However, this average global temperature increase masks significant variation on a country-by-country basis, with temperature increases a function of latitude. Warming in mid-to-high latitudes will be significantly greater than this global average.

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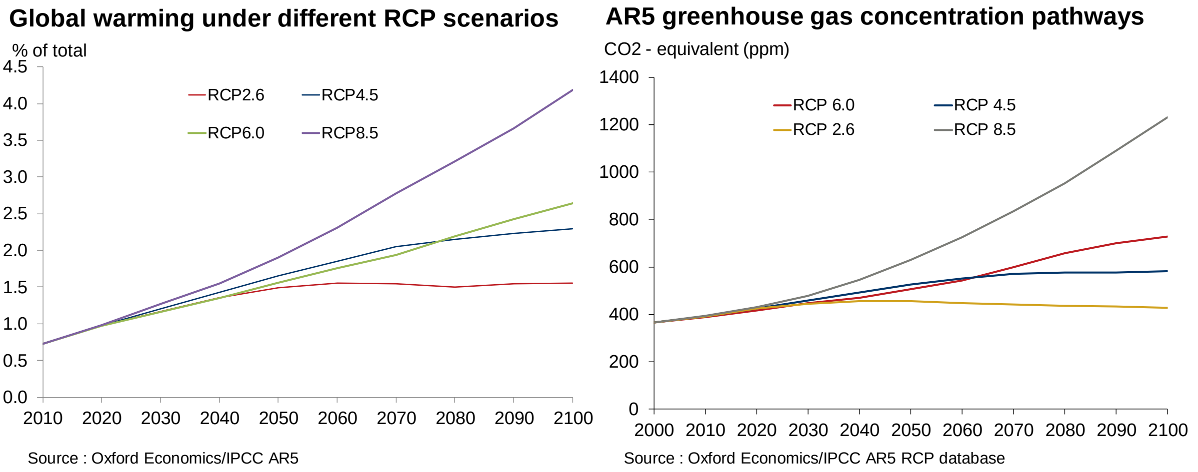
[9] The most recent comparison is ubiquitously known as CMIP 5 - see Taylor, Stouffer, and Meehl (2012).

[10] A variety of both natural and anthropogenic substances and processes possess the ability to alter the Earth's energy balance and drive global warming. Radiative forcing, measured in units of watts per square metre (W/m^2), quantifies the change in energy caused by different drivers and is the amount of heating received, on average, by the Earth's surface, per second, per meter.

[11] Riahi et. al. (2011)

[12] https://climate.nasa.gov/

Future global warming under different emissions scenarios



Source: Oxford Economics\Table TS1 AR5;\ RCP database

SR1.5 warns that the strongest summer warming is expected to occur at mid latitudes, with increases of up to 3°C for a 1.5°C increase in average global temperatures. Winter temperatures in the high-latitude polar regions are likely to rise by 4.5°C for a 1.5°C increase in average global temperatures.

Higher temperatures are projected to result in net reductions in the yields of some of the world’s major food crops, including maize, rice, wheat and other cereal crops, especially in sub-Saharan Africa, Southeast Asia and Central and South America. Equally, the poleward migration of biomes that results from higher temperatures is expected to facilitate the spread of invasive species, pests and diseases. Above 1.5°C, the expansion of desert terrain and vegetation that is likely to occur in the Mediterranean will cause changes unparalleled in the last 10,000 years.

Numerous changes to many of the Earth’s ecosystems have been observed that can be directly related to climate change. In many locations, terrestrial organisms are migrating towards higher latitudes and altitudes, while fish are migrating so they can stay within preferred water temperatures. Under moderate or high emissions scenarios, many slow-moving species may be unable to track the poleward movement of climate zones. While high-latitude ecosystems are likely to be transformed by the invasion of species from lower latitudes, species extinctions may be common in lower latitudes resulting in a significant loss of biodiversity.

SR1.5 reports that 18% of all insect species, 16% of plants and 8% of vertebrates are expected to lose half of their climatically determined range at 2°C of warming. The global terrestrial land area projected to experience an ecosystem transformation is 13% for 2°C of warming, with wetland ecosystems especially vulnerable. In high-latitude tundra and boreal areas, significantly warmer winter temperatures are already allowing shrubs to encroach.

2. Temperature extremes

Higher temperatures will bring a variety of problems, especially when compounded by higher humidity, which makes it more difficult for the human body to cool itself. Apart from the obvious effects of heat, the chief challenge is that rates of evaporation will increase markedly at hotter temperatures, significantly exacerbating the effects of drought. According to SR1.5, the biggest increase in heat extremes is projected to occur in central and eastern North America, Central and Southern Europe, the Mediterranean (including Southern Europe, Northern Africa and the Near East), Western and Central Asia and Southern Africa.) Some 14% of the world's population is projected to be exposed to severe heatwaves at least once every five years at 1.5°C of warming, increasing to 37% at 2°C.[13]

India in particular appears to be on the front line in terms of temperature extremes, which will have a significant impact by virtue of its relatively large population. A new study by the Climate Impact Lab suggests that by 2100, around 1.5 million more people will die in India as a result of climate change under a high emissions scenario – a rate as high as the death rate from all infectious diseases in India today.

It's important to appreciate that it's not just heat extremes or drought that can have negative impacts. Warmer winters in mid to sub-tropical latitudes, for example, may mean fewer nights when the temperature falls below zero, which encourages the spread of pests and diseases that do not normally survive the winter. This will have a potentially dramatic impact on agricultural productivity.[14]

From an economic point of view, one of the major challenges will be that in many developing nations, subsistence farming is an important source of livelihood in the absence of formal social security systems. Torch the agricultural sector in these countries and the ability of subsistence farmers to manage is significantly reduced, creating an incentive to move off the land. As a result, migration out of agriculturally dependent communities is likely and significantly associated with global temperature. According to the OCED's international migration database, a 1°C increase in average temperatures is associated with a 1.9% increase in bilateral migration flows from 142 sending countries. Increased migration and the likely political pressure to contain large-scale population movements are set to be one of the persistent and increasing impacts of climate change, with large populations in countries like India likely to be most affected.

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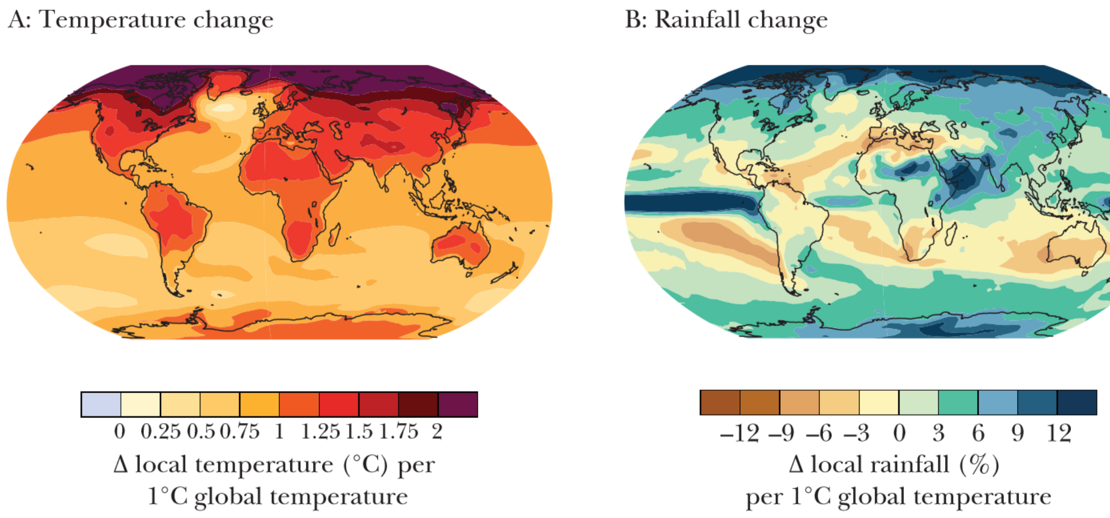
[13] Dosio et. al. (2018)

[14] A good recent example being the increase in leaf rust on coffee plants in central America. See "The unseen driver behind the migrant caravan: climate change," The Guardian, 30 October 2018.

Projected Change in Local Average Temperatures and Local Average Rainfall



Source: Hsiang & Kopp (2018) from Collins, Knutti, et. al. (2013).

3. Heavy Precipitation

A warmer atmosphere is capable of holding more water vapour, leading to an increase in overall precipitation. However, because of the complexities of atmospheric dynamics and the direction of prevailing winds, there is significant heterogeneity in projected precipitation changes, with some locations getting wetter and others becoming drier. The figure above illustrates average changes in rainfall for each 1°C of warming. SR1.5 argues that the regions likely to experience the biggest increase in heavy precipitation include high-latitude regions (including Alaska, Canada, Northern Europe and North-Eastern Asia), mountainous regions like Tibet (with an increased risk of flooding downstream), Eastern Asia (including China and Japan), and Eastern North America.

4. Dryness and Drought

Prolonged hot and dry periods are projected to become substantially more frequent in many savanna grassland areas. Higher rates of evaporation and longer periods without rainfall will exacerbate the effects of growing population in some areas. Areas in the Andes and northern India, which depend on glacial meltwater, are likely to be exposed to increasing water scarcity. The global stock of land available for livestock farming is expected to decline by 7-10% at 2°C with considerable economic consequences for many communities and regions. The Mediterranean, Southern Africa and western Australia are expected to experience increased intensity and frequency of drought

5. Runoff and river flooding

Warmer temperatures will increase rates of evaporation, leading to increased rainfall in some regions. This may lead to an increase in flooding in many of the world’s major river basins. This year’s flooding across the Mississippi in the midwestern and southern United States, for example, is reported to have affected 14 million people and cost $2bn in damages to infrastructure alone.[15]

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[15] “The Great Flood of 2019: A Complete Picture of a Slow-Motion Disaster”, New York Times, 11 September 2019.

For 2°C of warming, an increase in runoff is projected for much of the high northern latitudes, South East Asia, East Africa, and North-Western Europe (including the UK). Decreases in river runoff are anticipated in the Mediterranean, southern Australia, Central America and central and southern South America, which may result in significantly reduced river flow, especially in areas where there are major dams upstream.[16]

6. Tropical Storms

As the Earth's climate system becomes more energised, it seems intuitive to expect an increase in the intensity and frequency of tropical storms and there is some evidence that this is true for the Atlantic.[17] The IPCC Special Report on the Ocean and the Cryosphere in a Changing Climate (SROCC) notes that anthropogenic climate change has increased the observed precipitation winds and storm surges associated with some tropical cyclones. It also notes that there is emerging evidence that storms are becoming stronger and tracking further towards the poles as sea surface temperatures rise.

7. Ocean circulation and temperature

SR1.5 argues that it is virtually certain that the upper layers of the ocean (0-700m) have been increasing in temperature, with isotherms (lines of equal temperature) of sea surface temperature shifting to higher latitudes at rates of up to 40km per year. Marine organisms are already responding by shifting their biographical ranges to higher latitudes, which has consequently affected the structure of biodiversity and food webs. These trends are expected to become more pronounced as warming proceeds, with a decrease in biodiversity at the equator offset by increases at higher latitudes. While the impact of shifting species ranges will be mostly negative for human communities and industries, fisheries in high latitudes in the northern hemisphere may expand temporarily as the extent of summer sea ice recedes (and net primary productivity increases).

Coral reefs – home to more than a million species – and kelp forests are threatened by both higher temperatures and ocean acidification.[18] The majority (70-90%) of tropical coral reefs that exist today are expected be completely destroyed even if warming is limited to 1.5%.

8. Sea Ice Extent

Over the last two decades, global warming has led to widespread shrinking of the cryosphere, with mass losses of ice sheets and glaciers, reductions in snow cover and Arctic sea ice extent and thickness, and melting permafrost.[19] Nevertheless, although Arctic ocean summer sea ice has been retreating rapidly in recent decades, the Arctic is not expected to be completely ice free until temperatures are about 2°C above pre-industrial levels. SR1.5 concludes that the probability of a sea-ice-free Arctic ocean during the summer is substantially higher at 2°C than at 1.5°C, with one ice-free summer expected

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[16] See for example "Mekong levels at lowest on record as drought and dams strangle river," phys.org, 31 October 2019.

[17] Walsh et. al. (2016).

[18] Hoegh-Guldberg et. al. (2007)

[19] IPCC Special Report on the Ocean and Cryosphere in a Changing Climate.

every 10 years at 2°C. This falls to one every 100 years if warming is limited to 1.5°C.

9. Sea level rise

Global warming contributes to rising sea levels by two processes: thermal expansion of the oceans and the melting of land-based ice sheets. The remaining ice sheets in Greenland and the Antarctic, together with glaciers world-wide, have experienced a significant loss in mass. Between 2006 and 2015, the Greenland ice sheet experienced surface melting at a rate of 278 Gt/yr. The Antarctic lost mass at an average rate of 155 Gt/yr, mostly due to rapid thinning and retreat of major glaciers draining the West Antarctic Ice Sheet. Glaciers world-wide outside of Greenland and the Antarctic have retreated at an average rate of 220 Gt/yr.

Since 1902, global sea levels have increased by about 16cm, with the rise since 1990 being about 2.5 times faster than in the first 90 years of the 20th century. The latest estimates from satellite altimetry suggest that the sea level is currently rising by 3.6mm per year. The rise in sea level is getting faster due to the combined increase in ice loss from the Greenland and Antarctic ice sheets. Mass loss from the Antarctic over the period 2007-2016 tripled relative to 1997-2006, while ice loss from Greenland doubled in the same period.

Economically, the main threat from rising sea levels stems from coastal flooding and the costs of adaptation through improved flood defences. Some coastal areas will be permanently inundated, while the increased frequency of wave and tide driven flooding is expected to render some low-lying island states uninhabitable[20]. SR1.5 suggests that at least 136 megacities (coastal cities with a population greater than 1 million) are at risk of flooding due to the magnitude of sea level rises associated with a 1.5-2°C increase in global temperatures, with many of these cities located in South-East Asia.

Historically, the oceans and ice sheets have been modelled as having a slow response time to rising temperatures (it takes time for the ice to melt and for warmer surface waters to mix with the deep ocean) with the result that sea-level rises have been seen as relatively insensitive to alternative emission scenarios in the first half of this century. Horton et. al. (2018) find that median projections for future sea levels are for another 20-30cm increase before 2050. After 2050, the projects become more uncertain due to uncertainty surrounding the rate at which both the Greenland and Antarctic ice caps can be expected to melt.[21] Median projections range from 40-80cm in a low emissions scenario to 70-150cm for a high emissions scenario. Updated estimates of satellite-based altimetry have recently tripled the estimates of vulnerability to coastal flooding. These estimates suggest that some 650m people live on land below the projected annual flood levels for 2100 and up to 340m for 2050.

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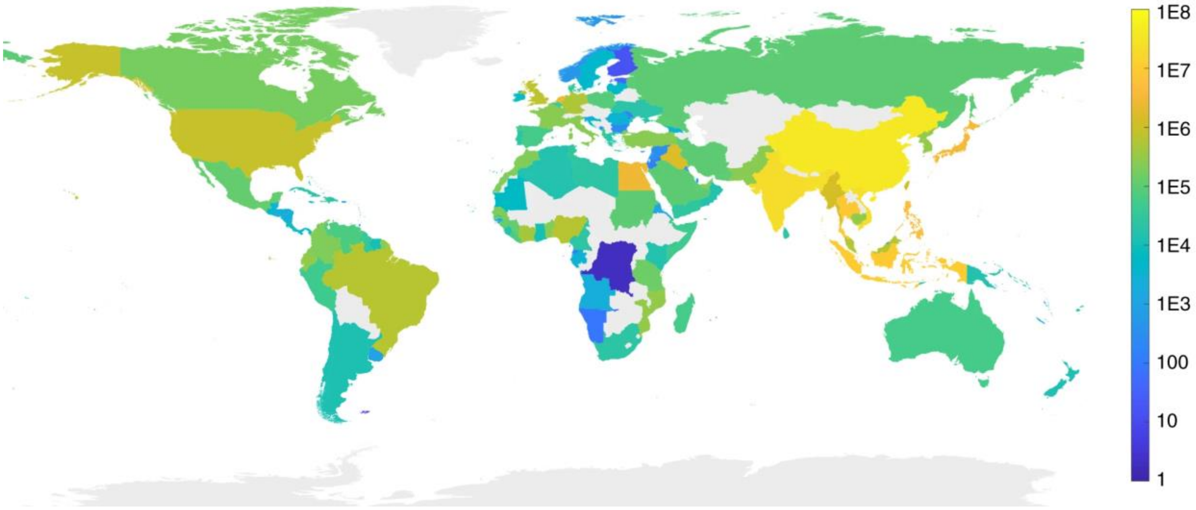
[20] Storlazzi et. al. (2018)

[21] Kopp et. al. (2017)

Number of people on land exposed to coastal flooding by 2050 under RCP 4.5



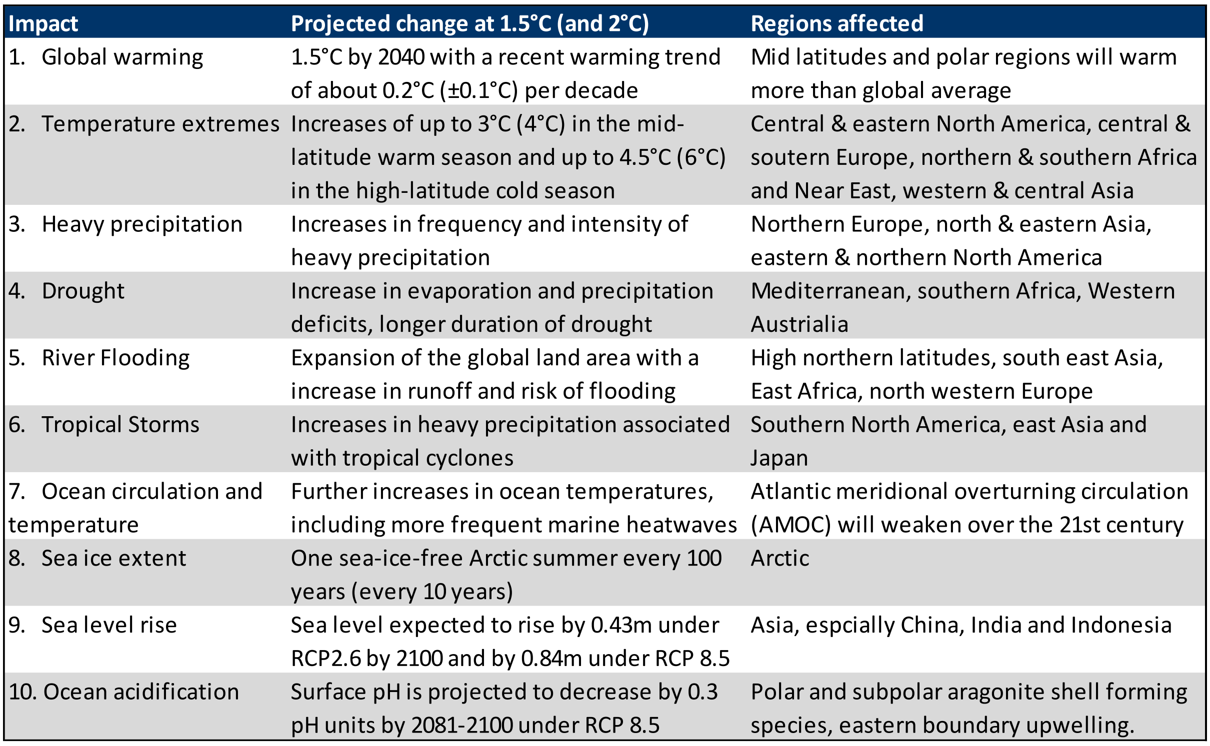
Source: Kulp and Strauss (2019)

One of the reasons why there is so much uncertainty about the extent of future sea level rises is the uncertainties surrounding the rate of melting of the major ice caps. There is also evidence that significant instabilities exist for both the Greenland and Antarctic ice sheets, which could result in multi-meter rises in sea level on timescales of less than a century. There is medium confidence that these instabilities could be triggered at the sort of temperature increases we are likely to experience in the next 20-30 years. A look at paleoclimate information suggests that prior interglacial (warm) periods were only about 1°C warmer than today, but sea levels were 4-6m higher.

10. Ocean chemistry

The oceans have absorbed about 30% of anthropogenic CO_2, resulting in ocean acidification and changes in carbonate chemistry that are unprecedented in the last 65 million years. This is particularly problematic since many planktons at the bottom of the food chain are constructed upon a carbonate skeleton which is dissolved in more acidic water. Hence SR1.5 warns that there are risks to the survival, growth, development and abundance of a broad range of marine organisms ranging from algae to fish. This has the potential to have a significant impact on aquaculture and fisheries. Small-scale fisheries in tropical regions are expected to experience growing risks because of significant habitat loss, with substantial losses expected for coastal livelihoods and associated industries.

The effects of global warming



Impact	Projected change at 1.5°C (and 2°C)	Regions affected
1. Global warming	1.5°C by 2040 with a recent warming trend of about 0.2°C (±0.1°C) per decade	Mid latitudes and polar regions will warm more than global average
2. Temperature extremes	Increases of up to 3°C (4°C) in the mid-latitude warm season and up to 4.5°C (6°C) in the high-latitude cold season	Central & eastern North America, central & soutern Europe, northern & southern Africa and Near East, western & central Asia
3. Heavy precipitation	Increases in frequency and intensity of heavy precipitation	Northern Europe, north & eastern Asia, eastern & northern North America
4. Drought	Increase in evaporation and precipitation deficits, longer duration of drought	Mediterranean, southern Africa, Western Austrialia
5. River Flooding	Expansion of the global land area with a increase in runoff and risk of flooding	High northern latitudes, south east Asia, East Africa, north western Europe
6. Tropical Storms	Increases in heavy precipitation associated with tropical cyclones	Southern North America, east Asia and Japan
7. Ocean circulation and temperature	Further increases in ocean temperatures, including more frequent marine heatwaves	Atlantic meridional overturning circulation (AMOC) will weaken over the 21st century
8. Sea ice extent	One sea-ice-free Arctic summer every 100 years (every 10 years)	Arctic
9. Sea level rise	Sea level expected to rise by 0.43m under RCP2.6 by 2100 and by 0.84m under RCP 8.5	Asia, espcially China, India and Indonesia
10. Ocean acidification	Surface pH is projected to decrease by 0.3 pH units by 2081-2100 under RCP 8.5	Polar and subpolar aragonite shell forming species, eastern boundary upwelling.

Source: Special Report on Global Warming of 1.5°C; Special Report on the Ocean and Cryosphere in a Changing Climate

Climate tipping points

It is useful to briefly highlight the importance of potential non-linearities in the climate system and the role the feedback as these may significantly increase the current amount of warming projected this century. James Hasen (2009) eloquently explains that climate or Earth system feedbacks are the guts of the climate change problem; while climate forcing drives climate change, feedbacks determine the magnitude of the climate change. And while in principle feedbacks can be either positive or negative, Hansen argued that the most startling advances in recent understanding of climate change is that the dominant slow feedbacks are mostly positive, they are not nearly as slow as we once believed. The most obvious example of a climate feedback is the melting of Arctic Sea ice. Snow and ice have a high reflectivity or ‘albedo’, while land and oceans absorb most of the sunlight; if the snow and ice melt, earth absorbs more sunlight which is a positive feedback, amplifying climate change and rising temperatures still further.

The snag is that because these feedbacks are difficult to model accurately and were believed to be relatively slow acting, they are therefore mostly absent from the IPPC projections. However, thawing tundra or permafrost may be the single most important amplifying climate feedback and yet none of the IPCC’s climate models include the CO2 or methane emissions from warming tundra as a feedback. This is especially worrying because the melting of permafrost is obviously temperature dependant. The hotter the Earth gets, the stronger these feedbacks will become. There is therefore a very good chance the current crop of simulations used to produce AR5 underestimate future warming (Romm 2018) and it will be interesting to see if temperature projections are revised higher when the 6th Assessment Report is published in 2021.

The projections in SROCC suggest that a quarter of remaining permafrost could melt by 2100 under RCP 2.6, while two thirds of the existing permafrost could melt under RCP8.5. The RCP 8.5 scenario leads to the cumulative release of tens to hundreds of gigatons of carbon (GtC) and methane with the potential to significantly exacerbate global warming.

Climate Sensitivity

One of the most quoted metrics in the global warming literature is the idea of equilibrium climate sensitivity – how much warming were to occur if CO^2 levels in the atmosphere were to double from their pre-industrial levels to 550 ppm. We know from scientific measures that doubling CO2 levels would increase the climate forcing by 4 Watts per m^2. The tricky question is how much warming this increase in forcing will produce. Here paleoclimate information provides relatively precise evaluation of how sensitive the climate is to changes in climate forcing. The beauty of using paleoclimate data is that all the physical mechanisms that exist in the real world are explicitly included; there are no parts of the Earth’s climate system that are left out because they are too complicated to model.

Hansen (2009) argued that we can evaluate climate sensitivity by comparing the last glacial period 20,000 years ago with the recent interglacial period, the late Holocene. In both periods the Earth was in energy balance within a small fraction of a Watt as sea level was stable in both periods, including that the major ice sheets were not melting or growing. Global average temperatures are 5°C hotter in the Holocene than in the last ice age. By measuring the composition of air trapped in polar ice, we know that climate forcing due to greenhouse gases was about 3 Watts per m2, while changes in the Earth’s Albedo contributed a further 3.5 Watts per m2. Adding these together gives a climate sensitivity of 0.75°C per Watt per m2- and implies 3°C of warming for the 4 Watt per m2 associated with the forcing from a doubling carbon dioxide. The is roughly comparable with RCP4.5 which envisages CO2e emissions levelling off at 580ppm.

3. QUANTIFING ECONOMIC DAMAGE

Climatic factors directly affect a number of economic outcomes, most obviously agricultural output, as well as critical economic resources, such as water and human health. But climate shifts can also impact indirectly on a wider range of economic activities, including manufacturing, energy production, transport and services such as tourism. Inflationary pressures might arise from a decline in the supply of goods or from productivity shocks caused by weather-related events such as droughts, floods, storms and sea level rises. These events could result in large financial losses, while investment aimed at necessary adaptation may lead to a significant global increase in the demand for loanable funds – which may in turn put upward pressure on the neutral interest rate. The macroeconomic implications of climate change will differ across countries, with more advanced economies typically more able to finance the necessary adaptations, and less developed countries likely to suffer more directly the economic costs of climate-related risks[22].

Estimating the economic cost of greenhouse gas emissions is challenging for a number of reasons. While emissions are local (or national), the effects are global and vary across both time and space. Secondly, today's emissions will continue to have an impact for several centuries, raising difficult questions about how we should value the future and what is an appropriate response to uncertainty. If one considers the social cost of carbon to be the discounted present value of damage from one ton of CO_2 emissions (or equivalent), then the choice of discount rate is hugely significant. Equally problematic, this number is not a constant, as the cost of damages increases over time and may be highly non-linear as economic damages increase with temperature.

3.1 THE SOCIAL COST OF CARBON

The catch-all, summary statistic used in policy analysis and investment appraisals to measure the economic damage from climate change is the social cost of carbon, expressed as the dollar value of the total damages from emitting one ton of carbon dioxide into the atmosphere. Calculations of the social cost of carbon are typically obtained from what are known as integrated assessment models (IAMs)[23]. These models integrate a standard economic model (like the Global Economic Model) with a simple climate model to derive estimates of the impact of emissions on climate variables like temperature, rainfall and sea level. These climate outcomes are then related to a set of damage functions that calculate the economic damages at a regional and global level. The discounted difference between the baseline projection and one with higher emissions is the economic (or social) cost of carbon.

Given the complexities of modelling both the Earth's climate system and the global economy, this calculation is understandably subject to a high degree of

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[22] See for example IMF (2017).

[23] The three most well-known of which are: DICE (Dynamic Integrated Climate-Economy) model maintained by William Nordhaus; FUND (Climate Framework for Uncertainty, Negotiation and Distribution) by David Anthoff and Richard Toll, and the PAGE (Policy Analysis of the Greenhouse Effect) model by Chris Hope.

uncertainty and the IAMs continue to attract a high level of criticism[24]. The difficulty in coming up with an accurate estimate of the social costs of carbon primarily stems from a combination of four factors:

- Uncertainty over the appropriate discount rate.
- The challenge of calculating a truly 'global' cost that includes the impact of all externalities on all sectors across the whole planet (as opposed to a national or industry specific estimate).
- The fact that the damage function should allow for and measure the full costs of adaptation.
- The need to value things that are notoriously difficult to value like ecosystem services and human life.

The current US administration, for example, considers only domestic damages in the estimate of the social cost of carbon it uses for investment appraisals.[25] This amounts to an estimate of between $1 (for a 7% discount rate) and $7 (for a 3% discount rate) for the estimated externality of one ton of carbon emitted in 2020. In contrast, the Interagency Working Group set up by President Obama (and since disbanded) came up with an estimate of $42 per ton (using a 3% discount rate) after 50,000 simulations on the above-mentioned integrated assessment models.

Auffhammer (2018) argues that the damage functions used in integrated assessment models are significantly out of date. He quotes a study by Moore et.al. (2017), which updated the damage function in the FUND model by incorporating the most recent empirical estimates of the impact of global warming on agriculture and found a doubling of the social cost of carbon by updating that sector alone. In a similar vein, none of the studies used to construct the damage function in the PAGE model are from after 2010. Greenstone (2016) argues that this ignores more than 100 empirical studies published since 2010 which use more up-to-date economic techniques and data.

3.2 DIRECT ESTIMATES OF THE COST OF CLIMATE CHANGE

Perhaps the most obvious approach to estimating the costs of climate change is direct measurement, using estimates of the cost (damage) inflicted by weather-related disasters. The National Oceanic and Atmosphere Administration (NOAA), for example, tracks and evaluates weather and climate related disasters in the US. It puts the estimated cost of weather and climate related disasters in the US in 2017 at $306bn, which amounts to 1.6% of GDP, with tropical cyclones being by far the most damaging.[26] Obviously, that figure is stochastic, with the current five-year moving average (which is still heavily inflated by 2017) running at a more modest $100bn per year.

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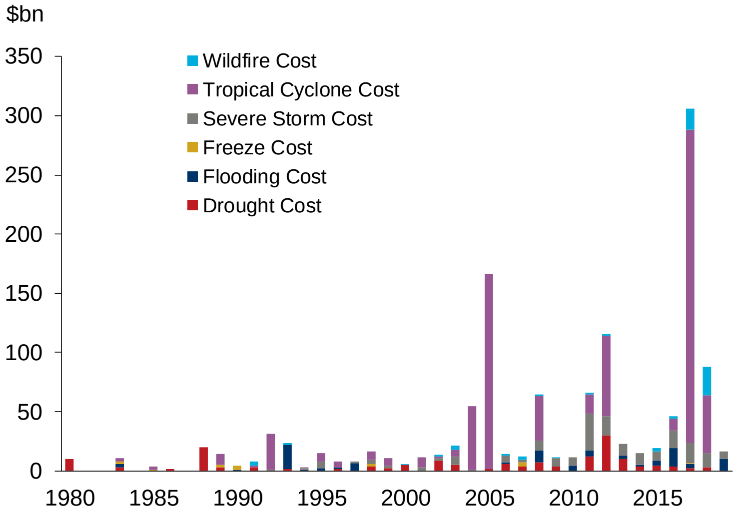
[24] See for example Anderson and Jewell (2019).

[25] Auffhammer (2018) p. 36.

[26] Source: NOAA National Centre for Environmental Information (NCEI) U.S. Billion-Dollar Weather and Climate Disasters (2019). https://www.ncdc.noaa.gov/billions/

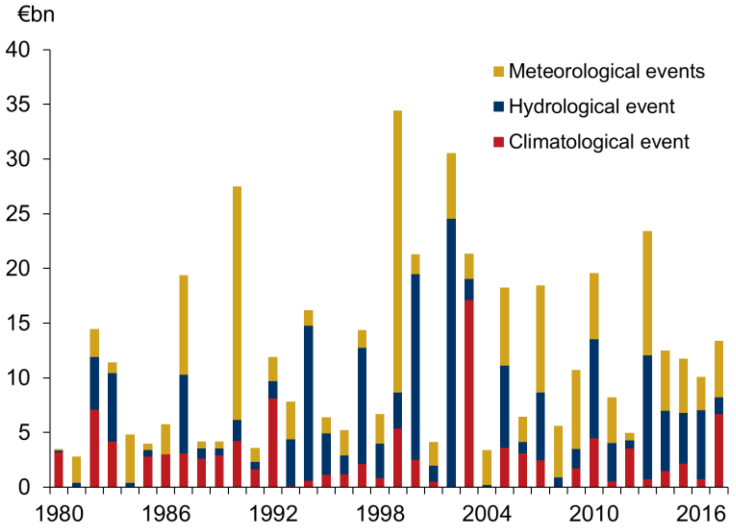
Cost of Weather and Climate Disasters in US



Source: Oxford Economics/NOAA

In Europe, similar data are collated by the European Environment Agency, which tracks data on the economic damages caused by extreme climate events for the 33 countries in the European Economic Area. Without the huge damages caused by hurricanes, the European figures are an order of magnitude lower; between 1980 and 2017, combined losses from climate-related events[27] amounted to €453bn (in 2017 prices), an average of €12bn per year (i.e. less than 0.1% of GDP per year). To put the US and European figures into context, a recent paper by Burke and Tanutama (2019) estimates that since the year 2000, global warming has already cost both the US and the EU at least $4 trillion in lost output (and tropical countries are more than 5% poorer than they would have been without this warming.)

Damage caused by climate events in the EEA



Source : Oxford Economics/European Environment Agency

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[27] Meteorological events: storms; Hydrological events: floods; Climatological events: heatwaves, droughts & forest fires.

In a similar vein, Munich Re estimates total global losses from natural disasters in 2017 at $345bn, falling to $178bn in 2018,[28] while Swiss Re puts the 2017 figure at $337bn. The United Nations Global Assessment Report on Disaster Risk Reduction (UNISDR 2015) concludes that economic losses from disasters such as earthquakes, tsunamis, cyclones and flooding are now reaching an average of $250bn to $300bn each year, with future expected annual losses estimated to be $314bn in the built environment alone. Annual losses on this scale represent just over 0.4% of world GDP.

From an economic point of view, it is important to appreciate that this damage is not simply subtracted from GDP. Indeed, to the extent that the capital and housing stock is damaged by extreme weather events and has to be rebuilt, it is highly likely that these damages will provide a boost to GDP in the short run. However, in so far as these damages represent accelerated depreciation or replacement investment, they are in effect resources that are not being used productively to increase the existing capital stock and hence boost future productive capacity in the long run.

3.3 RICARDIAN CROSS-SECTIONAL REGRESSIONS

The alternative to direct loss estimates is to take an econometric approach. Mendelsohn, Nordhaus and Shaw (1994), for example, were the first to employ a cross-sectional regression to estimate the impact of changing temperatures on agriculture. If land markets function perfectly, then land values should reflect the profits that a given parcel of land can generate. Land values can then be decomposed into a number of different components, one of which may be long averages of temperature or rainfall. Over the years, this kind of cross-sectional approach has been applied to numerous sectors and countries. However, it is not without its limitations, with the resulting estimates potentially subject to omitted variable bias.

When Schlenker, Hanemann and Fisher (2005) re-estimated the original Mendelsohn, Nordhaus and Shaw (1994) analysis with the inclusion of irrigation, the estimated impact of climate change went from being slightly beneficial to robustly negative.[29] This approach also implicitly assumes costless adaptation to climate change, when in reality the inclusion of new costs (like irrigation) that where not encountered before is exactly what we are trying to gauge. Equally, the fundamental issue about future climate change is that it is likely to be outside the previous historical experience and agents may already be basing their decisions on the basis of expectations of future climate change. Severen, Costello and Deschenes (2016), for example, argue that failing to incorporate these expectations leads to a significant underestimation of the projected impacts of climate change.

Despite these limitations, this cross-sectional approach forms the basis of damage functions embedded in the main integrated assessment models (IAMs). Nordhaus and Moffat (2017), for example, update the earlier cross-sectional estimates of climate damages reviewed in Tol (2009 & 2014) and fit an aggregate damage function to the resulting scatter plot of estimates. Having

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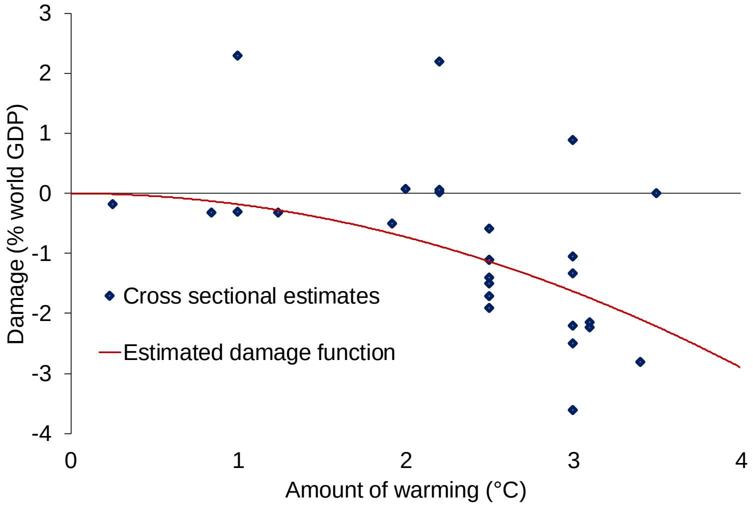
[28] Source: Munich Re NatCat Service. https://natcatservice.munichre.com/

[29] Auffhammer (2018)

dropped 'outliers', their preferred damage function takes the form $D = -0.18T^2$ where D is the percentage loss in the level of world GDP and T is the increase in global warming.[30] After making an additional judgmental adjustment of 25%, their estimated impact is -2% of GDP at 3°C of warming, rising to -8% of GDP at 6°C. The studies used in the paper and the fitted damage function are shown in the figure below:

Impact of global warming on world GDP



Source: Oxford Economics / Nordhaus and Moffat (2017)

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[30] The economic impact of climate change assessed in the cross-sectional literature is usually measured in terms of the welfare equivalent loss in income. Invoking the circular flow of money in the economy, here we equate income to expenditure to GDP.

Table 2: Estimates of the economic impact of global warming

Reference and year published		Warming ° C	Damage % GDP
Nordhaus (a)	1994	3	-1.33
Nordhaus (b)	1994	3	-3.6
Nordhaus (b)	1994	6	-10.4
Fankhauser	1995	2.5	-1.4
Tol	1995	2.5	-1.9
Nordhaus and Yang	1996	2.5	-1.7
Pambeck and Hope	1996	2.2	2.2
Mendelsohn, Schlesinger and Williams	2000	2.2	0.03
Mendelsohn, Schlesinger and Williams	2000	2.2	0.07
Mendelsohn, Morrison, Schlesinger and Andronova	2000	2	0.08
Mendelsohn, Morrison, Schlesinger and Andronova	2000	3.5	0.01
Nordhaus and Boyer	2000	2.5	-1.5
Tol	2002	1	2.3
Maddison	2003	3.1	-2.22
Rehdanz and Maddison	2005	1.24	-0.32
Rehdanz and Maddison	2005	0.84	-0.32
Hope	2006	2.5	-0.58
Nordhaus	2006	3	0.9
Nordhaus	2006	3	-1.05
Nordhaus	2008	3	-2.49
Maddison and Rehdanz	2011	4	-17.8
Bosello et. al.	2012	1.92	-0.5
Roson and van der Mesbrugghe	2012	3.1	-2.14
Roson and van der Mesbrugghe	2012	5.5	-6.05
Nordhaus	2013	3	-2.2
Cline	1992	2.5	-1.1
Cline	1992	10	-6
Nordhaus	2010	3.4	-2.8
Dellink	2012	2.5	-1.1
Kemfert	2012	0.25	-0.17
Hambel	2012	1	-0.3
Average of the above	2003	2.9	-2.0
Dell, Jones and Olken	2012	1	-1.3
Burke, Hsiang and Miguel	2015	4	-23
Burke et. al.	2018	2.75	-20
Burke et. al.	2018	4	-30
Avevedo et. al.	2018	4	-9
Kahn et. al	2019	4	-7.2
Average of the recent time series panel estimates since 2012	2019	3.3	-15.1

Source: Nordhaus and Moffat (2017), extended and updated by Oxford Economics

Attempts to build up estimates of the effects of global warming by aggregating across a number of channels have seen renewed interest recently. A team at Moody's Analytics[31] has extended the earlier work of Robson and Sartori (2016) on the World Bank GTAP database and considered the impact of global warming on six factors: sea level, human health, labour productivity, agriculture, tourism and energy demand. They find two groups of countries are most severely affected: those in particularly hot climates (Malaysia, Algeria, the Philippines and Thailand), which suffer from a marked decline in tourism, and the major oil producers in the Middle East, which experience a short decline in oil exports. Weighting the aggregates by GDP suggests a 0.75% decline in global GDP for the roughly 2°C of warming expected by 2050 in RCP 8.5.

These estimates still seem relatively modest and it is noticeable that nearly all the studies quoted suggest that the impact of warming even up to as much as 3°C will only be a few percentage points of world GDP and may even be positive in a few countries. Intuitively, this hardly seems tenable in view of the recent IPCC Special Reports. While analytically tractable, the choice of transmission channels is invariably limited, and the econometric evidence seems heavily constrained by historical experience. In a recent review of IAMs, when discussing the calibration of aggregate damage functions, Pindyck (2013) pessimistically concluded:

"the choice of values for these parameters is essentially guesswork. The usual approach is to select values such that [damages] for T in the range of 2°C to 4°C is consistent with common wisdom regarding the damages that are likely to occur for small to moderate increases in temperature…..The bottom line here is that the damage functions used in most IAMs are completely made up, with no theoretical or empirical foundation."

3.4 REDUCED-FORM TIME-SERIES PANEL ESTIMATES

In response to the problems with the cross-sectional approach, the last 10 years have seen a growing literature using longitudinal panel data. There are now a number of reduced-form time-series panel estimates of GDP growth across countries as a function of annual temperature variations. Dell, Jones and Olken (2012), for example, look at the effects of annual temperature and precipitation changes on 125 countries from 1950-2003. They find that in poorer countries, a 1°C temperature increase reduces GDP by about 1.3 percentage points.

One obvious problem with this approach is that countries can, over time, adapt to higher temperatures, and estimates that do not take this adaptation into account may overstate the economic impact. On the other hand, in so far as the costs of adaptation may be significant – for example, the building of extensive flood defences − these time-series estimates may still be an underestimate. To counter this criticism, the paper also examines the impact of temperature as a distributed lag and finds that the impact persists over time. This suggests that higher temperatures may reduce the growth rate of poor countries, and not simply the level of output; it also suggests that poor

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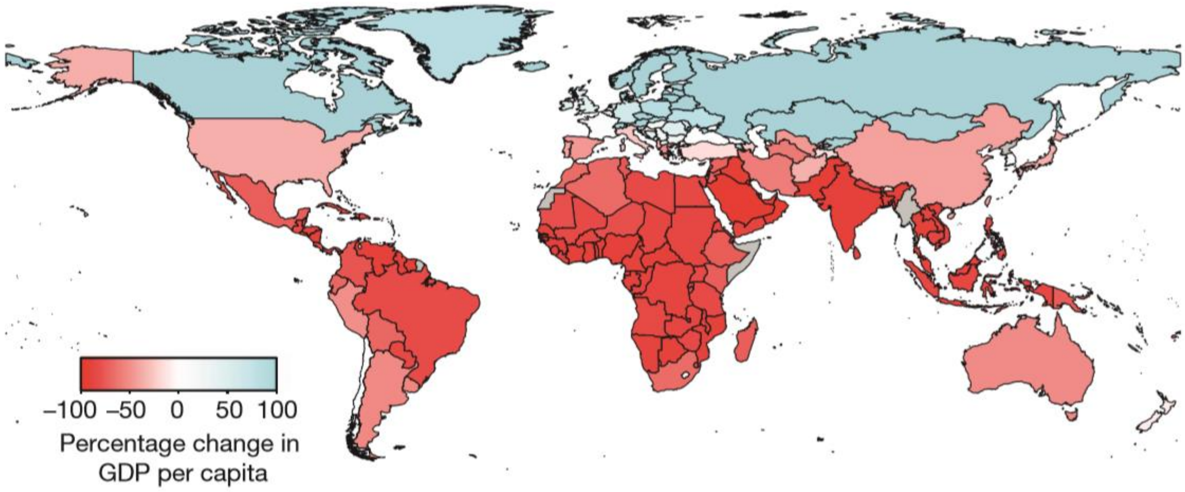
[31] Lafakis et. al. (2019).

countries do not tend to adapt over time in ways that would reduce the impact of higher temperatures.

In what is probably the benchmark study of this new literature, Burke, Hsiang and Miguel (2015) pursue a similar panel data strategy looking at data from 166 countries over the period 1960-2010. They find that productivity (GDP per capita) is a concave function of temperature, with productivity peaking at an annual average temperature of 13°C and declining strongly at higher temperatures. This result, they argue, is globally generalisable, unchanged since 1960, and apparent for agricultural and non-agricultural activity in both rich and poor countries. Cold (and typically rich) countries' productivity increases as temperature increases up to an annual average temperature of 13°C. Productivity then declines gradually with further warming and this decline increases at higher temperatures. If future adaptation is the same as observed in the historical data, then unmitigated global warming is expected to reduce global GDP per capita by 23% by 2100, under RCP 8.5. Again, the authors use additional lags to estimate long-run impacts of climate change and when these are included with differentiated rich and poor country responses, projected global losses are 2.2 times larger than in the benchmark approach.

Projected effect of temperature changes: Country-level estimates by 2100 under RCP 8.5



Source: Burke, Hsiang and Miguel (2015)

In contrast, using a more disaggregated dataset of 11,000 districts across 37 countries, Burke and Tanutama (2019) find that local level growth in GDP responds non-linearly to temperature across all regions, with 'peak' productivity effects occurring earlier, at 10°C. This suggests that the impacts of a given temperature exposure do not vary meaningfully between rich and poor regions (but exposure to damaging temperatures is more common in poor regions).

In contrast to the quadratic functions in the IAMs, the estimated damage functions constructed are "roughly linear." This approximate linearity results from the fact that the broad distribution of initial country temperatures remains unchanged as temperatures are increased along different parts of a smooth response function, causing the average derivative of productivity to change little as countries warm. Hence, the intuition that global economic damages will be non-linear because micro-level responses are non-linear may not be correct.

Burke et. al (2018) estimate separate non-linear response functions for 165 countries over the years 1960-2010 using a fixed effects estimator. Their estimates suggest reduction in world GDP per capita of 15-25% by 2100 in the case of 2.5-3°C of warming, and reductions of more than 30% for 4°C of warming. Additionally, they find that the accrued global net present benefit of limiting warming to 1.5°C relative to 2°C would exceed $20 trillion (with a 3% discount rate).

Acevedo et. al (2018) extend the geographic and temporal coverage to more than 180 countries for the period 1950 to 2015, which forms the basis of Chapter 3 in 2017 IMF WEO. They find that the level of per capita income for a representative low-income country would be 9% lower by 2100 under RCP 8.5. Applying the same methodology to different independent variables, they also find that private investment would fall by 11% and public debt to GDP would rise by five percentage points in this scenario. At a sectoral level, they find that both agricultural and manufacturing output are affected by higher temperatures, while services sector output is relatively unaffected. Finally, from an econometric point of view, it is possible to argue that these panel estimates may be problematic since temperature, as an explanatory variable, is I(1) and is presumably only weakly exogenous with respect to GDP. These concerns are addressed in a new paper by Kahn et. al. (2019), which finds that world GDP per capita would be 7.2% lower by 2100 under RCP 8.5.

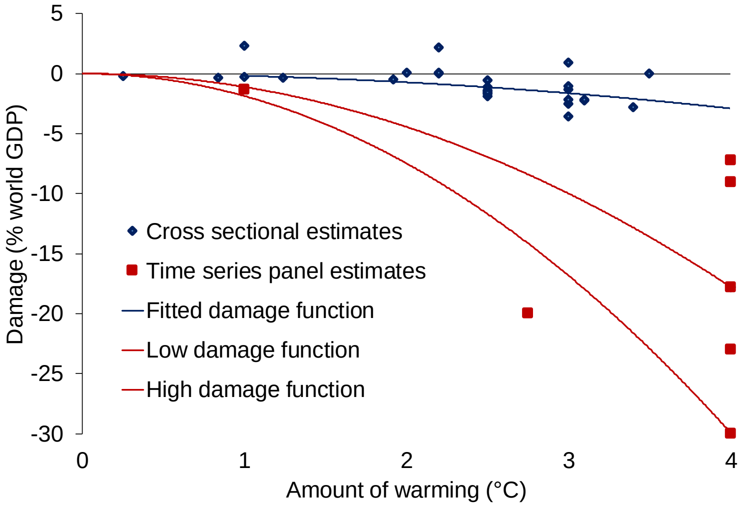
In contrast to these ‘top-down’ macro level approaches, the most recent literature has also seen a number of ‘bottom-up’ micro level analyses. In what is probably the most impressive study of the effects of climate change, Hsiang et. al (2017) employ a remarkably sophisticated (and computationally heavy) approach to estimating economic damages at county level for the United States. They look at the economic impact of higher temperatures and rainfall on six sectors, including agriculture, crime, coastal storms, energy demand, mortality and labour supply. Econometrically derived damage functions are constructed for each sector, which include an estimate of both market and non-market damages (costs).

Notionally, aggregated total damage is represented by a quadratic function that places the impact of the 4°C increase in GMST envisaged in RCP 8.5 at 1.5-5.6% of GDP. Approximating this damage function with a linear relationship suggests losses of about 1.2% of GDP per 1°C increase in GMST. It is perhaps interesting to note that the greatest direct cost of temperature increases in excess of 2.5°C comes from excess mortality, underscoring the weakness of papers that restrict the estimates of the cost of global warming to market-based estimates of GDP. The costs of coastal storm damage are also sizeable but do not scale with GMST, as the estimates of sea level rise are not explicitly calculated as a function of GMST.

Overall, the results of these modern panel estimates are up to an order of magnitude higher than the typical damage functions included in the main IAMs. Building on the estimates of Burke, Hsiang and Miguel (2015), Ricke et. al. (2018) estimate that the social cost of carbon may be as high as $430 per tonne, well outside the estimates typically used for investment appraisal discussed in Auffhammer (2018).

Focusing solely on the recent reduced-form estimates suggests a significantly steeper damage function. Notwithstanding the comments on the linear nature of the relationship discussed in Burke, Hsiang and Miguel (2015), the figure below shows two representative quadratic functions that might be considered as an illustrative range. Hence the 2°C of warming expected by 2050 in RCP 8.5 might incur costs of between 2.5% and 7.5% of global GDP. These effects are certainly big enough to be considered in economic forecasts for the first half of this century. Moreover, these are aggregate figures; some countries will experience damages significantly greater than this.

Impact of global warming on world GDP



Source: Oxford Economics

There are obviously huge uncertainties in these estimates. Extrapolating from estimates of the short-term weather shocks to persistent changes in climate for which there is no historical president remains a stretch. Certainly, this new literature does not appear to have been well received by the IAM community. Tol (2018) argues that it is an error to conflate annual estimates of temperature and rainfall with climate and argues that the time-series approach only estimates a short-run elasticity and hence “extrapolating the impact of weather shocks to the impacts of climate change is unlikely to lead to credible results.”

To the extent that there may be scope for adaptation, these estimates may be an overestimate. But equally, these estimates will typically exclude the effects of extreme weather events if the severity or frequency of these events increases in the future, which seems likely. Certain expected events, such as rising sea levels or ocean acidification, have no recent historical precedent from which to draw inference, but will almost certainly have very significant economic consequences (and higher costs), which suggests that even these latest studies may still be underestimating the effects of global warming.

The panel studies also focus exclusively on measured market GDP and therefore do not incorporate several changes through which climate change will create non-market impacts, such as the loss of biodiversity (and associated ecosystem services) or the impact of higher human mortality. Finally, as reduced-form estimates, the panel approach is not able to separately identify the costs of adaptation. The need to build higher flood defences or invest in non-carbon infrastructure may boost GDP in the short run (especially in rich advanced economies) without necessarily adding to the productive capital stock and may therefore be to the detriment of long-run potential output.

4. CONCLUSION

In the absence of significant efforts to reduce greenhouse gas emissions, a high emissions scenario suggests that we will experience 1.5°C of warming (above pre-industrial levels) before 2040, with 2°C of warming likely to be experienced before 2055. These degrees of warming are likely to cause multiple changes in our planet's climate system, which will have observable and material economic effects in what is a comparatively short time horizon of 20 or 30 years. Putting a figure on the economic costs of global warming is conceptionally and computationally challenging. Aside from the direct estimates compiled by the insurance industry, this problem has typically been tackled in one of two ways: either one builds bottom-up estimates of the effects on specific sectors or one employs reduced-form panel estimates of the effects of 'weather' on aggregate macroeconomic outcomes.

Both approaches have drawbacks. At one level, the sectoral estimates are essentially arbitrary, often limiting themselves to a partial analysis of a handful of factors. While this approach does at least offer a way forward that is tractable, it is often not hard to identify factors that have been left out that might significantly increase the size of the estimates. Historically, this approach has tended to yield estimates that are relatively modest, suggesting that even 4°C of warming will only reduce global GDP by a few percentage points. Increasingly, this seems to be at odds with the effects of even comparatively modest degrees of global warming discussed in the IPCC's Special Report on Global Warming of 1.5°C.

In contrast, the recent reduced-form panel estimates of the effect of temperature rises on the whole economy's productivity appear to yield results that are almost an order of magnitude bigger, with the largest reductions in economic growth expected to be experienced by low and middle-income countries (in Africa, Southeast Asia, India, Brazil and Mexico). The most computationally detailed study to date (Hsiang et. al 2017) suggests that global warming of 1°C may already be costing the US 1.2% of GDP. For other countries more heavily impacted, the costs are likely to be even higher. Heuristically, the most recent literature surveyed here suggests that warming of 2°C may reduce the level of global GDP by anywhere between 2.5% and 7.5% compared to a baseline without any warming. These orders of magnitude are probably big enough to be included in long-run growth forecasts, projected over a 20 to 30-year time horizon. Moreover, it would not be surprising of the estimates of the economic effects of global warming continued to rise in the decades ahead.

Both approaches, however, are constrained by historical experience, which is problematic given that climate change is expected to take us to extremes for which there is no reliable available data. The challenge is to put a figure on the true costs of adaptation considering all the potential effects. Quite aside from an increased incidence of flooding and drought, some of the potential impacts of global warming, especially those associated with a loss of livelihoods and declining biodiversity, appear to be potentially catastrophic. Consider, for example, the potential impact of ocean acidification and the destruction of the entire marine food chain, which would obviously have significant human impacts. At the moment, the economic literature appears to be largely silent on the costs of such catastrophic events.

5. DATA SOURCES

5.1 GLOBAL MEAN SURFACE TEMPERATURE

There are three globally recognised measures of global mean surface temperatures (GMST):

The UK's Hadley Centre maintains the longest unbroken temperature record (HadCRUT4), with daily observations going back to 1772 and monthly observations going back to 1659. https://www.metoffice.gov.uk/hadobs/

NASA's Goddard Institute for Space Studies measures the temperature across 6,000 weather stations and then calculates the average across a much smaller number of grid squares (GISTEMP). NASA is able to supplement its weather station data with satellite observations for parts of the world where there are no stations − like the Arctic − which is not included in the Hadley Centre's HadCRUT4 series. https://data.giss.nasa.gov/gistemp/

The US National Oceanic and Atmosphere Administration (NOAA) uses a different technique again based on calculating the change in temperature from one year to the next. This technique is robust to missing years which enables the NOAA to use data from 7200 weather stations. https://www.climate.gov/maps-data/dataset/global-temperature-anomalies-graphing-tool

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OXFORD ECONOMICS

Global headquarters
Oxford Economics Ltd
Abbey House
121 St Aldates
Oxford, OX1 1HB
UK
Tel: +44 (0)1865 268900

London
4 Millbank
London, SW1P 3JA
UK
Tel: +44 (0)203 910 8000

New York
5 Hanover Square, 8th Floor
New York, NY 10004
USA
Tel: +1 (646) 786 1879

Singapore
6 Battery Road
#38-05
Singapore 049909
Tel: +65 6850 0110

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Email:
mailbox@oxfordeconomics.com

Website:
www.oxfordeconomics.com

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