Economic Impacts

The Economic Consequences of the Climate Crisis

Leonie Wenz and Friderike Kuik

In order to avert catastrophic climate change, the international community committed to the Paris Agreement, with the goal to limit "the increase in the global average temperature to well below 2 °C above pre-industrial levels" and pursue efforts "to limit the temperature increase to 1.5 °C above pre-industrial levels." (United Nations, 2015). In an optimistic case the recent emission reduction commitments of individual countries would be roughly enough to meet the 2 °C-goal of the Paris Agreement. But the emission reduction measures that are currently already implemented still fall short of these voluntary commitments: According to the United Nations Emissions Gap Report 2021, we are currently heading for a warming of about 2.7 degrees (UNEP and INEP DTU Partnership, 2021).

In this chapter, we shed light on the economic damages that might be expected in a world in which temperatures are 3 degrees higher than in pre-industrial times. Based on the current state of science, we present and discuss various transmission channels from climate change to the economy (see also section "Climate Change Affects All Sectors of the Economy") and outline possible consequences for the economy as a whole (see also section "The Costs of Climate Change"). A guiding question for these discussions is how future damages can credibly be estimated. The past years have given a glimpse of the high humanitarian and economic costs that

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The views expressed herein are those of the author and do not necessarily reflect those of the European Central Bank.

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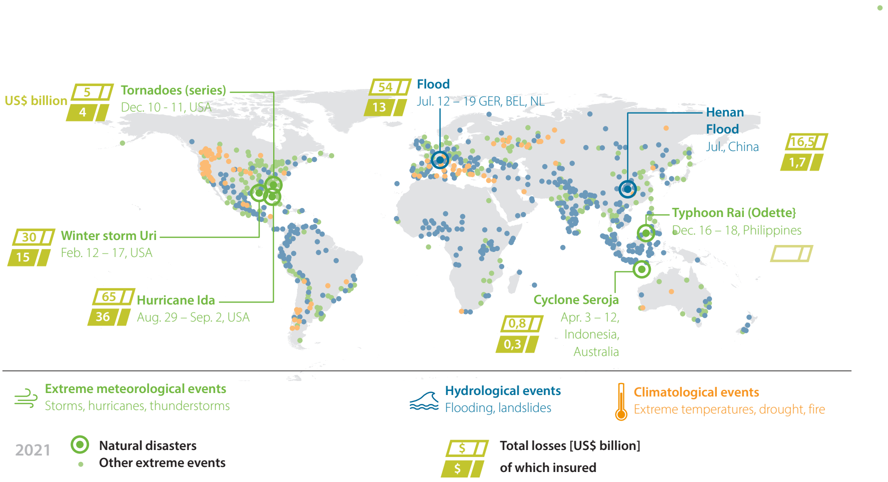

Fig. 1 Overview of some of the most expensive natural catastrophes in 2021. The figure only includes catastrophes related to weather or climate extremes, not earthquakes or volcanic eruptions. (Data from Munich Re, 2023)

climate change can cause. Figure 1 gives an illustration of some of the most severe events in 2021—the series of extreme weather events has continued since then.

From Degrees Dollars: How to Measure the Cost of Climate Change?

Weather extremes—which are becoming more frequent and more intense due to climate change—do not only lead to high human costs but also cost us a lot of money and harm the economy. But what exactly is the cost of climate change—what are plausible economic damages in a world in which warming reaches 3 degrees? Is it even possible to provide a credible estimate, and why do we need such precise cost estimates?

The biophysical effects of climate change, such as rising temperatures, changing precipitation patterns, melting glaciers, rising sea levels, increasing weather extremes, and ocean acidification are well understood for the most part and can, thanks to sophisticated computer models, be estimated with increasing precision.

These climate impacts can affect the economy in many ways, either directly or indirectly through different channels and—in many cases complex—interactions. Some impacts are easily expressed in monetary terms, others, such as losses in biodiversity or human lives, are difficult or impossible to put a price tag on. Yet other effects are difficult to foresee and assess, such as those that can occur when dangerous tipping points are crossed. Ultimately, the Earth's climate system as well as our economy are highly complex: when strongly disturbed—as is the case with a changing climate—we may be facing effects that are so far not anticipated.

Cost-Benefit Arguments Or: What's the Price Tag?

If it is complex to assess the damages from climate change, and fraught with uncertainty, why should we even bother to express them in dollars or euros? Shouldn't it be sufficient to understand the biophysical effects of climate change, to come to the conclusion that the global community of states must urgently act to stop the emission of greenhouse gases?

In fact, cost arguments do play an important role in public and political discourse. However, it is the costs of financing the energy and climate transition that seem rather concrete, whereas perceptions of the costs induced by climate change damages often still remain rather vague.

This prevents a fair and robust comparison of the costs of protecting our climate against the benefits, where the latter consist in averted climate damages and adaptation expenses. Such a comparison can be conducted formally via cost-benefit analyses or rather informally via public perception. A key figure in this context is the so-called "*social cost of carbon*"—a figure that, roughly speaking, expresses the social cost (in US dollars) of emitting one additional metric ton of CO_2. To estimate this metric, we need a good understanding of which climate damages are likely and how much they would cost. This is also important for efficiently planning adaptation measures as well as for climate justice considerations.

Integrated Models

In a cost-benefit analysis, 2018 Nobel laureate William Nordhaus calculated that a temperature target of "+3.5 °C" would be optimal from a purely economic point of view, because it would minimize the sum of the monetary costs of climate protection and climate damages (Nordhaus, 2018; Hänsel et al., 2020). For his calculations, Nordhaus used the DICE model he had been developing since the 1990s, a so-called *Integrated Assessment Model* (IAM) (Nordhaus & Boyer, 2000).

IAMs map the interactions between the economic, energy and climate systems in a simplified way to estimate the costs and benefits of climate policy (Stern, 2007). Other well-known IAMs are, for example, the PAGE model on which the *Stern Report*[1] from 2006 is based on the FUND model. In these models, cost estimates for specific climate impacts are based on one or more damage functions, which

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[1] The British economics professor and former chief economist of the World Bank Nicholas Stern published a comprehensive report on the economic effects of climate change in 2006, which he had prepared on behalf of the British government.

are informed by empirical estimates. In addition to IAMs, other types of structural or semi-structural models are increasingly being used to estimate the economic impacts of climate change (Gallic & Vermandel, 2020).[2]

Nordhaus' calculations and model have given rise to discussion and criticism since first presented. One aspect criticized is that too little weight was given to climate damages occurring on longer horizons, based on the assumption that future generation would be better offer, which would, for example, facilitate adaptation (discounting) (Azar & Sterner, 1996; Stern, 2007). IAMs have also been criticized for not representing potentially catastrophic climate impacts (Weitzman, 2009; Pindyck, 2013). The most important criticism, however, is related to damage functions, which—for a long time—were only based on a few empirical studies, many of them dating back to the 1990s (Greenstone, 2016; Howard & Sterner, 2017; Auffhammer, 2018).

Since then, our knowledge of socio-economic climate damages has improved significantly(Carleton & Hsiang, 2016). In the last 10 to 15 years, there has been a vast amount of new empirical studies. Various scientific teams have integrated these recent empirical findings into Nordhaus' DICE model or other IAMs—and, based on this new knowledge, now conclude that the Paris Agreement is optimal also from an economic point of view, as the economic costs of additional warming would be much higher than the costs required to meet the goals of the Paris Agreement (Glanemann et al., 2020; Hänsel et al., 2020; Ueckerdt et al., 2019).

Empirical Models: Learning from the Past to Predict the Future

The rapid expansion of empirical literature on the climate-economy relationship that we have seen in the last 10 to 15 years benefitted from several different developments. First, the amount of available data and new data sources continues to grow, such as climate data collected by satellites, but also data on social and economic indicators as obtained from social media, nighttime light measurements, or GPS trackers. Second, increased computing capacities make it possible to process and analyze these data. Finally, methods for deriving robust conclusions from data have also continuously evolved and improved. These methods come primarily from statistics and econometrics and are increasingly being complemented with machine learning algorithms.

The core idea of these empirical approaches is to explore the impact of past climatic conditions and weather extremes on economically relevant factors, as a basis to derive estimates of future damages (Dell et al., 2014; Hsiang, 2016; Kolstad & Moore, 2020). For example, one might look at how extreme temperatures have

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[2] Here, for example, the development of structural macroeconomic models should be mentioned, such as so-called dynamic stochastic general equilibrium models (DSGE models). Compared to IAMs, these models focus on a more detailed description of the macroeconomic adjustment after the occurrence of climate impacts.

historically affected labor productivity in order to estimate future productivity losses from rising temperatures. This can be done both for individual economically relevant sectors and variables such as labor productivity, agriculture, or electricity demand (bottom-up; see also section "Climate Change Affects All Sectors of the Economy") and directly at the macroeconomic level with respect to impacts on economic output (top-down; see also section "The Costs of Climate Change").

Roughly speaking, two methodological approaches can be distinguished, with more and more hybrid variants emerging. One approach compares countries or regions with different climatic conditions, to explore the influence of the prevalent conditions on economically relevant factors (cross-sectional analysis). An obvious problem with this approach is that there are many other economically relevant differences among countries. Some of these can be controlled for by also measuring them and including them in the statistical model. Others are not directly observable or correlate with both climate and the economic variable under consideration and thus distort the actual effect that climate has on the economy.

Another approach is to compare a country or region with itself at different points in time (time series analysis), i.e., to examine whether economic performance was lower in an especially hot or especially wet year than in a year with average or moderate weather. The advantage of this approach is that all factors that are specific to a country or region and that have not changed over the observation period can be eliminated from the calculation. If the analysis can be carried out for several countries at the same time (panel analysis), all factors that are specific to a particular year and might have influenced economic performance in that year can also be accounted for. These might be global economic shocks, such as financial crises or a pandemic, or climate phenomena such as El Niño. Controlling for these country- and year-specific "fixed effects" then enables very robust conclusions to be drawn about plausibly causal relationships (Kolstad & Moore, 2020; Auffhammer, 2018).

The disadvantage of this approach is that the effects of short-term weather shocks may only be partly informative about damages induced by long-term climatic changes (Kolstad & Moore, 2020); this is especially problematic with regard to extreme weather events of previously unknown strength, frequency and simultaneity as well as the crossing of dangerous tipping points. In a similar vein, adaptation measures that may not yet have been observable in the past, but seem plausible for the future, are not accounted for.

Risk and Adaptation

In addition to climate change damages or the *social cost of carbon*, some studies focus on a risk-based approach, i.e., assessing the risk of a sector, region, or country of being affected by climate change (IPCC, 2022a, b). This risk depends on the biophysical effects of climate change itself *(hazard)*, but also on how much one is *exposed* to it *(exposure)*, and on how vulnerable one is to damage *(vulnerability)*. For example, a region's risk of economic damage from forest fires may be higher if the area at risk of fire is close to settlements, cities, or industrial plants. Another example is flooding: a region is at a higher risk of economic damage from flooding if populated areas, infrastructure, or industrial facilities are located in the flood zone.

The vulnerability and hence the economic damage caused by climate change can theoretically be reduced through adaptation measures such as (as in the last example) flood protection. Other examples of such measures are increased coastal protection, better water management, an expanded extreme weather warning network, or infrastructure adapted to climate change (Feyen et al., 2020).

Adaptation measures, however, entail costs of their own—financial resources that must be mobilized and that, in the absence of climate change, could have been invested in other, more productive ways. Furthermore, there is a limit to the possibility to adapt: with increasingly severe climate change, adaptation will not be sufficient to avert all economic damages. Already now, according to estimates by the Intergovernmental Panel on Climate Change (IPCC), some weather and climate extremes have led to irreversible damage (IPCC, 2022a, b).

If adaptation measures are insufficient or impossible, people will have to use another one of the above-mentioned three levers: their exposure. This can mean, for example, resettlement or migration—with economic effects that are very difficult to assess. Climate and weather extremes are already leading to increased migration (IPCC, 2022a, b). Conversely, an increase in exposure—for example, expansion of settlements or industrial areas in a region threatened by climate impacts—can entail increased risk. This phenomenon has likely contributed to rising costs from extreme events in recent decades.

Climate Change Affects All Sectors of the Economy

Many biophysical climate impacts have a direct and immediate effect on the economy. For example, extreme weather events such as tropical cyclones or floods can destroy houses, factories, or important infrastructure and can disrupt transportation routes. Dying coral reefs affect the tourism and fishing industries, forest fires harm the forestry business, and droughts destroy harvests, thereby raising food prices.

Besides these direct effects, there may be other, less obvious, indirect, or interacting effects. In fact, the ways in which climate change affects the economy are numerous and may be complex and interconnected. For a classification and quantification of climate change damages, an overview of different transmission channels is helpful. For example, the main risks from climate change in Europe, according to the IPCC (Kovats et al., 2014), include:

- Extreme heat, impacting health and well-being as well as ecosystems;
- Extreme heat and drought, impacting agricultural yields;
- Water scarcity, impacting various areas of economic and daily life;
- Flooding near rivers or coasts, impacting people, the economy, and infrastructure.

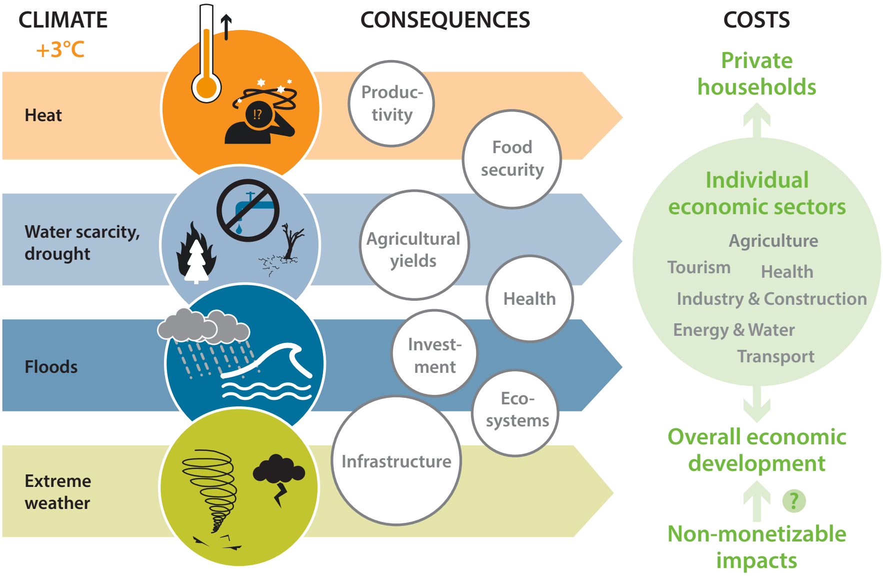

Fig. 2 The diagram shows examples of transmission channels through which biophysical climate impacts can cause economic damages. The categorization of biophysical impacts is illustrative, the individual categories overlap and are not mutually exclusive. The transmission channels are complex and interlinked, and the effects may mutually influence one another (Wenz & Kuik)

In the following we present examples of transmission channels that are related to some of these risks (Fig. 2). It should be noted that most of our examples concern Europe—yet the world's poorer countries are generally likely to be more strongly affected and will have fewer means to adapt, with severe consequences for their food security and human health (Stern, 2007). For example, the IPCC concludes in its Sixth Assessment Report that climate change contributes to humanitarian crises in especially vulnerable areas and that extreme weather events have a greater impact on economic growth in developing than in industrialized countries (IPCC, 2022a, b). The examples we give stem from a variety of studies, some of which are based on different warming scenarios. Therefore, some of the examples do not refer to a global mean temperature increase of 3 degrees, but to an even more pessimistic scenario, leading to warming of more than 4 degrees by the end of the twenty-first century.[3]

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[3] In order to facilitate the comparability of studies and results, the scientific community has agreed on a common set of scenarios that describe different emission pathways and the respective increases in global mean temperature by the end of the twenty-first century. Since the IPCC's Fifth Assessment Report 2013/14, these have been the so-called *Representative Concentration Pathways* (RCPs) (van Vuuren et al., 2011) which were supplemented by socio-economic narratives (Shared Socioeconomic Pathways; SSPs) with the Sixth Assessment Report 2021/22. Some of the examples mentioned here are based on the RCP 8.5 scenario. This corresponds to an increase in global mean temperature of about 4.4 degrees by the end of the century (2081–2100) compared to pre-

Main Transmission Channels

Too Much Water Many transmission channels are associated with changes in the availability of water—either due to extreme precipitation and flooding, or due to the absence of rain. For example, a higher number of rainy days or days with extreme precipitation within a year were found to reduce economic output—especially in richer industrialized countries such as Germany, Japan or the US (Kotz et al., 2022). The services and manufacturing sectors are especially affected, where effects might materialize through damage to infrastructure, the interruption of transportation routes and supply chains, planning uncertainties or health effects. Extreme precipitation is increasing almost everywhere in the world due to climate change (Min et al., 2011). For example, in a world that is 2 degrees warmer, the probability of an extreme rainfall event, which currently occurs once in 20 years, increases by 45% in northern Europe and by 37% in central Europe (Kharin et al., 2018).

Moreover, with a warming of just 1.5 degrees, there is already a more than 40% higher chance of extremely high water levels in the Rhine or the Indian Ganges, to name some examples (Paltan et al., 2018). In a world that is 3 degrees warmer, river floods in Europe might lead to damages amounting to €40 billion (Feyen et al., 2020)—about as much as the costs caused by the 2021 flood disaster in Western Germany, the Netherlands and Belgium, but recurring every year. The cost of coastal flooding might even reach €238 billion per year in Europe—significantly exceeding, year after year, the cost of Hurricane Katrina, the most expensive natural disaster in US history to date (NOAA, 2021). Other estimates suggest that in a 4 degree warmer world, economic losses from river flooding in Germany would increase more than ten-fold—and by as much as 3214% in Bangladesh (Alfieri et al., 2017). In the examples mentioned, the total costs may be considerably reduced with adequate adaptation measures.

Too Little Water More than two thirds of global freshwater resources are used for irrigation and food production (in some countries of the Global South even up to 95%), one fifth for industry and energy, and only about 12% directly by households (Zhongming et al., 2021). Water scarcity in a world that is 3 degrees warmer thus affects food security in particular, but also industry and the energy sector. In a world that is 3 to 4 degrees warmer, the proportion of the earth affected by extreme drought could increase from 3% at the beginning of the millennium to 30% by the end of the twenty-first century (Burke et al., 2006). In southern Europe, droughts that statistically occurred once every 100 years at the beginning of the millennium might recur roughly every 10 years (Lehner et al., 2001). The European Commission estimates that droughts in a 3 degree warmer world would cost Europe €45 million per year, compared to €9 million per year today (Feyen et al., 2020). The same study estimates

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industrial times (1850–1900). Other examples mentioned assume less pessimistic scenarios or explicitly estimate the effect at that point in time at which, according to climate models, a warming of 3 degrees is likely to be reached.

that 13 million more people in Europe would live in regions at risk of water scarcity. Changing weather conditions (especially drought) would also lead to a significantly higher risk of forest fires. This risk would still be highest in Southern Europe—but by no means limited to this region: across Europe, a further 15 million people could be exposed to a similarly high risk of forest fires. In a 3 degrees warmer world, the area potentially affected by forest fires might almost double in a normal Mediterranean summer (Turco et al., 2018).

Heat In a world that is 3 degrees warmer, about half the population of the EU and the UK could be exposed to an intense heatwave every year—an event that without climate change statistically occurs only every 50 years (Feyen et al., 2020). This could cause up to 90,000 additional deaths each year. Heat waves are deadly and expensive weather extremes: the damage heatwaves already cause each year is estimated at around $100 billion for the United States alone (Atlantic Council, 2021). High temperatures affect our well-being, social interactions, and productivity. For example, researchers found that higher temperatures increase the risk of mental health problems, suicides, and individual and group conflicts (Hsiang et al., 2013; Obradovich et al., 2018; Helman & Zaitchik, 2020). They also found that the tone in social networks becomes harsher and that schoolchildren perform worse in warm classrooms (Stechemesser et al., 2021, 2022; Graff et al., 2018). Temperatures above about 25 °C reduce the productivity of workers, an effect that is especially relevant for industries, such as construction or agriculture, which require a lot of outdoor work (Ramsey, 1995; Hsiang, 2010; Dunne et al., 2013; Szewczyk et al., 2021). For the European heat waves of 2003, 2010, and 2015, one study puts the losses in the ten most affected countries at $59 to $90 per worker in agriculture and $41 to $72 per worker in the construction sector (Orlov et al., 2019). For China, another study estimates that heat-related productivity losses resulted in costs of $126 billion in 2017 (Wenjia et al., 2021). Heat stress also causes a variety of health complaints, ranging from skin rashes to muscle cramps and insomnia to heat-related strokes. In addition to the suffering of the people affected, it also causes costs for the general public, for example through increased hospitalization and absenteeism from work (Semenza et al., 1999; Gronlund et al., 2014; Phung et al., 2016; Obradovich et al., 2017; Sherbakov et al., 2018).

Storms, Unstable Weather and More The impact channels described above are not exhaustive but provide a first insight into the multitude of economically relevant damages and costs that materialize in a warming world. In addition, there are the costs of tropical cyclones, such as those that hit North and Central America as well as East and Southeast Asia in 2021 and caused immense damage there (Fig. 1). As warming progresses, such storms could also form at higher latitudes and thus affect millions more people (Studeholme, 2021). But even weather that is "just" more unstable can have a negative economic impact—for example through health effects and agricultural losses, or because it means planning uncertainty for decision-makers and thus paralyses investments (Wheeler et al., 2000; Shi et al., 2015).

Complex Interactions

In a closely interconnected economic world, the effects of climate and weather extremes may not remain local but can propagate along global supply and value chains as well as via price signals—even across national borders (MacKenzie et al., 2012; Wenz & Levermann, 2016; Wenz & Willner, 2022). For example, severe flooding in the Thai capital Bangkok in 2011 resulted in a shortage of hard drives in Europe (Haraguchi & Lall, 2014). In 2021, the timber industry in North America was affected by forest fires, a beetle infestation, and sawmill closures due to the pandemic, so that more timber was imported from Germany. Subsequently, timber became expensive and scarce in Germany (Denkler, 2021). As a result of such "cascading effects", the actual damage from weather extremes can be greater than what is observed only locally—especially if several events occur simultaneously in different regions (Kuhla et al., 2021). For example, not only direct damages from river floods are expected to increase (a global increase of 15% to around US $600 billion within the next 20 years), but also indirect effects could arise along the supply chains (leading to damage of another US $200 billion) (Willner et al., 2018). Such effects are especially critical if they lead to supply shortages, for example of medicines or food (Bren d'Amour et al., 2016).

Interaction effects with other crises such as the Covid-19 pandemic are also relevant, for example if combating them ties up important resources: The IPCC emphasized that the interplay of different climatic and non-climatic risks can lead to risk cascades across sectors and regions (IPCC, 2022a, b). At the same time, adaptation to climate change can also have an impact on other sectors relevant to climate change. One example is the installation of power-hungry air-conditioning systems to prevent heat stress. In emerging economies such as India, Indonesia, and Vietnam, a recent study foresees rising electricity demand due to increasing heat (Rode et al., 2021).[4] Another study shows that rising temperatures will also change electricity in Europe: demand will shift from Northern to Southern countries, and the annual peak load will shift from winter to summer—shifts that might pose major challenges to the existing infrastructure (Wenz et al., 2017).

Only a few studies estimate economic damages that might occur if individual tipping points[5] in the climate system are exceeded. What complicates such assessment is that the effects of tipping points are felt on different, sometimes very long time scales. The discounting already mentioned (see also section "Empirical

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[4] However, many regions of the world could still be too poor at the end of the twenty-first century for their electricity demand to increase drastically due to rising temperatures. Moreover, the additional demand for electricity in emerging economies may be offset globally by reduced heating in countries with colder climates (Rode et al., 2021).

[5] If tipping points are exceeded, large, accelerating and often irreversible changes occur in the climate system which can have serious consequences. It is assumed that some tipping points will already be exceeded with an average warming of 1 to 2 degrees (Lenton et al., 2019). In a world that is three degrees warmer, the risk of additional damage from exceeded tipping points would be substantial.

Models: Learning from the Past to Predict the Future") therefore plays an important role here. A recently published overview study integrates several estimates of economic impacts from the crossing of different tipping points (Dietz et al., 2021), concluding that tipping points increase the Social Cost of Carbon by about 25% (compared to an estimate of economic climate impacts without taking tipping points into account). The study also indicates a probability of about 10% that the integration of tipping points in damage estimates more than doubles the costs.

A Price Tag for Everything?

As already mentioned, some damages can directly be expressed in monetary terms, whereas others are difficult to monetize but still very relevant for the economy and society. This includes, for example, the loss of labor due to migration, illness, or death, or the lost recreational function of burnt forest areas. In addition to the purely economic costs, many climate events cause high humanitarian and social costs, which in turn can have direct and indirect effects on the economy. These include the fact that people may develop mental problems such as depression or anxiety and post-traumatic stress disorders as a result of extreme weather events (Munro et al., 2017; Schwartz et al., 2017), which have to be treated, with corresponding negative effects on their productivity. In addition, things that do not easily carry a price tag may also have value for us, such as the preservation of biodiversity.

An important question is whether and how such damages should be incorporated into estimates of the costs of climate change. Economists have developed various techniques for assigning a monetary value to non-market damages. So-called willingness-to-pay approaches, for example, aim to measure what we are willing to pay to avoid certain damages or to maintain certain features and functions like, for example, ecosystem services. Some studies follow a recommendation of the US Environmental Protection Agency (EPA) and value a statistical human life at $7.4 million (EPA, 2010). This value is controversial: There are voices that argue in favor of greater differentiation, reflecting, for example, that older people contribute less to economic growth (EPA, 2010; Hsiang et al., 2017). Others highlight significant ethical problems—especially if the value is set differently for developed and less developed countries—and recommend that such damages should not be expressed in monetary terms but presented separately (Stern, 2007).

The Cost of Climate Change

As outlined above, climate change will have massive effects on many sectors and areas of life that are economically highly relevant. But what will be the effect on the economy as a whole? A 2021 Reuters survey of climate economists shows a wide range of estimates (Fig. 3). On average, the experts estimated that under a

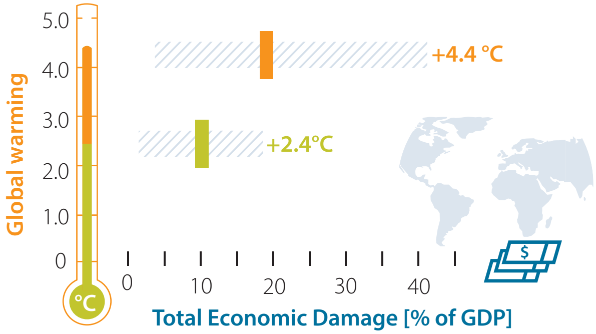

Fig. 3 Total economic damage for different levels of warming. Shown are median (orange), minimum and maximum, based on the assessments of 13 experts. (Data from Reuters, 2021)

pessimistic scenario of unchecked climate change—implying about 2.4 degrees of warming by 2050 and 4.4 degrees by 2100—global economic output (Gross Domestic Product, GDP) would be reduced by about 10% by the middle of the twenty-first century and by about 18% by the end. In Stern's 2006 Review, the damage caused by 3 degrees warming was estimated at 5% to 20% of global GDP, whereby the lower end of the estimate does not take into account damage to health, ecosystems, etc. Due to the wide range of estimates and the difficulty of comparing the underlying methods, the IPCC's Sixth Assessment Report does not include any concrete figures in its summary, but concludes that the damage could be higher than previously assumed (IPCC, 2022a, b).

The cost range can be explained by, amongst others, the diversity of approaches to estimating the macroeconomic damage, which was already discussed in this chapter. Different underlying assumptions also play an important role. In the following three sections, we discuss some of the factors and sources of uncertainty that contribute to the wide range of damage estimates.

From Micro to Macro

One obvious way of estimating the total cost of climate change is to consider the net effect of all individual effects. This is the approach taken by a comprehensive 2017 study for the US. The study focuses on six different sectors and—building on previous research findings– estimates and monetizes the expected damage in each sector and then adds them up (Hsiang et al., 2017). Specifically, the interdisciplinary research team looked at agriculture, crime, storm surges, energy, mortality and labor. They identified the greatest damages due to higher mortality, followed by damages in the agriculture sector, to labor, and in the energy sector. With global warming of 3 degrees, the total direct damage by the end of this century is estimated at about 1.5% to 2% of US gross domestic product, with the costs distributed very unevenly across the US and disproportionately burdening regions in the already poorer South. A report by the Deloitte Economics Institute published in 2021 uses a similar approach to estimate the costs of a 3-degree warmer world for Germany. The damage channels considered there include heat stress, damage to capital stock, loss of agricultural land and agricultural yields, declining tourism revenues, and human health impacts. Based on this, the report concludes that the damage to the German economy could amount to €730 billion over the next 50 years. Such figures would, according to the report, lead to the loss of almost half a million jobs.

Such bottom-up approaches have the advantage that, in addition to estimating the total costs, they also provide a good understanding of processes—for example, how much the individual damages contribute to the total costs. Such insights can play an important role in prioritizing adaptation measures. A shortcoming of bottom-up approaches is that one has to be confident that all mechanisms through which climate change can cause significant economic damage are sufficiently well-known and considered. Furthermore, aggregation may not always be straight-forward due to concerns of double-counting and possible interaction effects between different sectors (Dell et al., 2012).

Climate Change Impacts on Economic Growth

Another possibility is to directly assess the effects of climate change on macroeconomic growth. In this case, changes in economic output observed in the past years are statistically compared against changes in local weather, while accounting for confounding effects. The thus identified effect of changes in temperature and precipitation on the economy is then used to derive possible economic losses under future warming.

Various studies have found a clear non-linear relationship between average annual temperature and productivity (Dell et al., 2012; Burke et al., 2015; Pretis et al., 2018; Kalkuhl & Wenz, 2020; Kahn et al., 2021). If the temperature in a country or region rises from one year to the next, this usually harms the local economy.

An evaluation of climate and economic data of the last 40 years from more than 1500 regions worldwide has shown that an increase in the annual mean temperature of about 1 degree leads to economic losses of 1 to 2% (Kalkuhl & Wenz, 2020). The warmer the region, the greater the losses—though in some regions that were previously very cold, an increase in the mean annual temperature can even be beneficial from an economic point of view. With this approach it also becomes clear that climate change will affect different regions differently. The Earth is warming at different rates regionally, and individual regions' vulneability to damages also varies.

If we take this observed relationship between temperature and economic output as a starting point for future damage, the following picture emerges: If the Earth were to warm by about 4.4 degrees by the end of the century compared to pre-industrial times (corresponding to the RCP 8.5 scenario described in section "Climate Change Affects All Sectors of the Economy"), this would reduce global GDP by about 14%. In tropical, poorer regions, losses would be even higher,

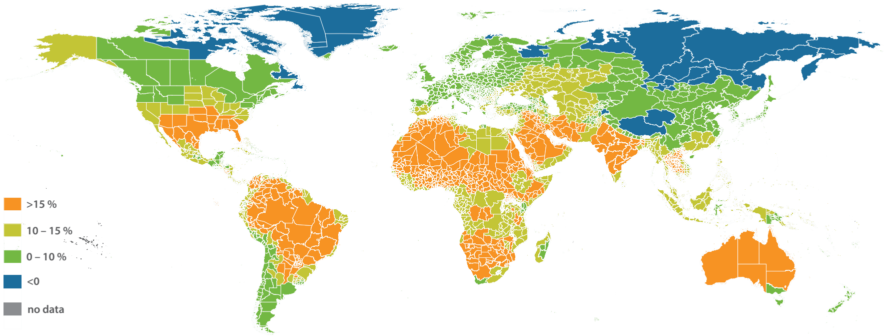

Fig. 4 Regional income losses in the year 2100. Estimates assume a pessimistic scenario (about 4.4 degrees warming compared to pre-industrial times) (Kalkuhl & Wenz, 2020)

possibly over 20%. In the comparatively cooler German regions, they would be about 5% (see Fig. 4). This is comparable to the 5% decline in German output in 2020 in the wake of the Covid-19 pandemic or the impact of the financial crisis of 2008/09 (5.7%) (Tagesschau, 2021).

There is, however, one very important difference to previous economic crises such as the financial crisis or the Covid-19 pandemic: these previous crises were of limited duration. This enables governments to mitigate negative economic and social impacts, for example with government aid and economic stimulus programs. Climate change, however, will not simply recede again, but will be permanent in the best case, or become ever more severe as long as emissions are not reduced—the resulting decline in economic productivity may therefore also be permanent.

Even though the warming scenario used here is more pessimistic than the 3-degree scenario, it does provide a good indication of the massive challenges that await us in a 3 degrees warmer world. And yet, this estimate is a conservative one for various reasons. The 14% reduction in global GDP should be understood as a lower limit for the actual economic losses, because climate change is more than just a gradual increase in the annual mean temperature. The effects of extreme events and sea-level rise, as discussed earlier, are not included in such analyses. The same applies to non-monetary damages such as the loss of biodiversity or health impacts. Current studies also show that looking at annual averages falls short of gauging the actual damages. If, for example, temperatures fluctuate strongly around the monthly average or if there are more rainy days or days with extreme precipitation within a year, this causes additional harm to the economy (Kotz et al., 2021, 2022), resulting in higher economic losses (Waidelich et al., 2024). A recent study that also takes the effects from changes in rainfall and temperature variability into account, as well as the persistence of damages, projects a 19% income reduction on global average in 2050 compared to a world without climate change, irrespective of the emission scenario (Kotz et al., 2024).

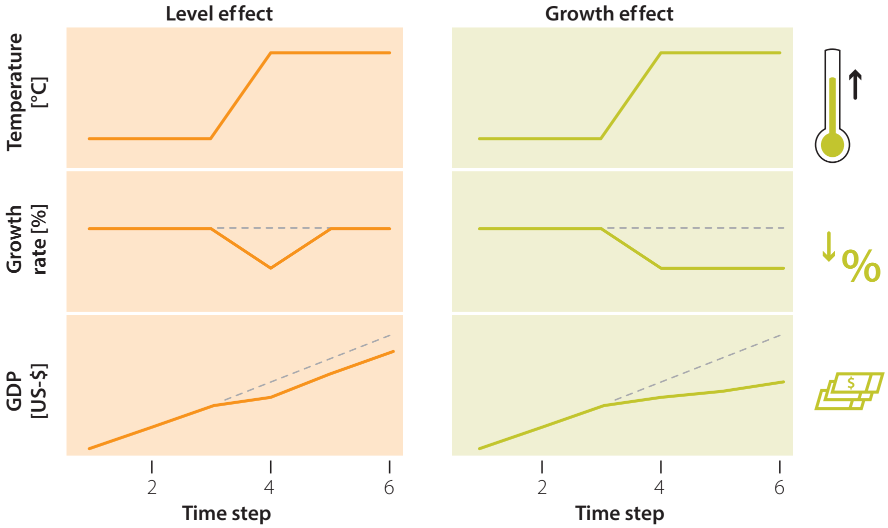

Fig. 5 Level and growth effects. The two columns illustrate how a permanent temperature increase would affect the growth rate of the economy and the gross domestic product—assuming level effects (left column) and growth effects (right column), respectively. In the case of growth effects, economic losses accumulate over time (Wenz & Kuik)

Level or Growth Effects—How Persistent Are the Economic Impacts of Climate Change?

A central question when estimating economic damages is whether the economy is only slowed down in the short term, or whether economic growth is permanently lowered by temperature changes and weather extremes (Fig. 5). Many damage estimates assume so-called level effects (Kalkuhl & Wenz, 2020). The assumption is that a permanent rise in temperature leads only initially to a reduction in economic growth which then returns to its original path. Consequently, economic output is permanently lowered by the same factor.

But there are also reasons to believe that weather extremes can more permanently reduce economic growth. Such long-term growth effects can occur when destroyed capital assets cannot be repaired or replaced for years, when people must give up their education as a result of weather extremes, or when investments cannot be made (Fankhauser et al., 2005; Moore & Diaz, 2015). A recent study shows that tropical cyclones and river flooding can reduce economic growth in affected countries for more than a decade (Krichene et al., 2021).

The right column in Fig. 5 illustrates growth effects for the temperature example. In this case, too, economic output decreases when temperature rises permanently. However, the losses increase with each year as they accumulate. A study from 2015 estimates that unmitigated climate change (scenario RCP 8.5) would reduce global

GDP in 2100 by about 23%, assuming such growth effects (Burke et al., 2015). In many countries of the global South, the losses would be as high as 100%.

A 2021 study demonstrates that the question of damage persistence is a key source of uncertainty in assessing the economic impacts of climate change (Kikstra et al., 2021). Based on an updated version of the PAGE model used in the Stern Review they find that economic output would be reduced by about 50% at the end of the century for a medium warming scenario, if assuming growth effects.[6] With level effects, the loss would "merely" be 6%. The authors consider an intermediate case likely, in which economic growth is slowed down for quite a while, i.e., the harm is partially, but not fully, persistent. In this scenario, the global GDP would be 37% lower, according to this analysis.

The question of level versus growth effects is thus by no means a purely technical one, but has major implications for the magnitude of damages and therefore for estimates of the costs of climate change and optimal climate policy. Accordingly, it is heavily debated in the scientific community and is the subject of active research, as it is statistically challenging to cleanly distinguish between the two effects (Bastien-Olvera et al., 2022; Kikstra et al., 2021; Newell et al., 2021; Kotz et al., 2024).

Climate Damages More Costly Than Climate Protection

The early 2020s have impressively illuminated several possible economic effects of extreme weather—a preview of a world in which global mean temperature could be 3 degrees higher than in pre-industrial times and in which weather extremes would be even more frequent and intense. In such a world, no region or economic sector would be spared from the effects of climate change.

Some costs arise through rather direct impact channels which can be estimated relatively well with conventional methods: the influence of rising temperatures and extreme heat on productivity and health, the effects of droughts and water shortages on agriculture and industry, the effects of heavy rainfall and flooding on buildings and infrastructure. By aggregating damages from these individual sectors or by assessing macroeconomic losses directly using data-intensive empirical approaches we can infer that the costs of a 3-degree warmer world could easily exceed 10% of global GDP. These costs are, moreover, very unevenly distributed globally with regions least responsible for historical climate change and with fewest means to adapt generally hit hardest.

Approaches to estimate these costs are associated with uncertainties: not all transmission channels and interactions can be captured, it is not certain how cost-effectively the world can adapt to a warmer climate, it is unclear how persistent the

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[6] The RCP 4.5 scenario, which corresponds to a warming of about 2.7 degrees at the end of the twenty-first century compared to pre-industrial times.

damages will be, and not all climate impacts can be expressed in monetary terms. Nonetheless, these approaches give a fairly reliable picture: the economic costs of climate change that is not ambitiously mitigated will be significant.

Of particular concern are complex interactions within and between the climate and economic systems. On the socio-economic side, these include crises, conflicts and migration as well as effects that trickle down complex supply chains. Uncertainties are further aggravated by the possibility of crossing tipping points in the climate system, by potential interaction effects among different climate impacts, or interacting climate-related and non-climate-driven risk factors.

As has become clear in this chapter, many aspects, assumptions, and uncertainties affect estimates of the costs of climate change. These factors also explain why there is a wide range of cost estimates and why it is likely that there is no upper bound to estimates of the economic costs from future climate change. However, one common message arises despite all uncertainties and different methodologies: it is much cheaper to protect our climate than to live with the economic consequences of a 3 degrees warmer world.

References

Alfieri, L., et al. (2017). Global projections of river flood risk in a warmer world. *Earth's Future, 5*(2), 171–182.

Atlantic Council. (2021). *Extreme heat: The economic and social consequences for the United States*.

Auffhammer, M. (2018). Quantifying economic damages from climate change. *Journal of Economic Perspectives, 32*(4), 33–52.

Azar, C., & Sterner, T. (1996). Discounting and distributional considerations in the context of global warming. *Ecological Economics, 19*(2), 169–184.

Bastien-Olvera, B. A., Granella, F., & Moore, F. C. (2022). Persistent effect of temperature on GDP identified from lower frequency temperature variability. *Environmental Research Letters, 17*(8), 084038.

Bren d'Amour, C., et al. (2016). Teleconnected food supply shocks. *Environmental Research Letters, 11*(3).

Burke, E. J., Brown, S. J., & Christidis, N. (2006). Modeling the recent evolution of global drought and projections for the twenty-first century with the Hadley Centre climate model. *Journal of Hydrometeorology, 7*(5), 1113–1125.

Burke, M., et al. (2015). Global non-linear effect of temperature oneconomic production. *Nature, 527*(7577), 235–239.

Carleton, T. A., & Hsiang, S. M. (2016). Social and economic impacts of climate. *Science, 353*(6304).

Dell, M., Jones, B. F., & Olken, B. A. (2012). Temperature shocks and economic growth: Evidence from the last half century. *American Economic Journal: Macroeconomics, 4*(3), 66–95.

Dell, M., Jones, B. F., & Olken, B. A. (2014). What do we learn from the weather? The new climate-economy literature. *Journal of Economic Literature, 52*(3), 740–798.

Denkler, T. (2021). *Kleines Tier, großer Effekt: Ein kanadischer Käfer lässt Holz in Deutschland knapp werden*. Sueddeutsche Zeitung.

Dietz, S., et al. (2021). Economic impacts of tipping points in the climate system. *Proceedings of the National Academy of Sciences, 118*(34).

Dunne, J. P., Stouffer, R. J., & John, J. G. (2013). Reductions in labour capacity from heat stress under climate warming. *Nature Climate Change, 3*(6), 563–566.

EPA, US Environmental Protection Agency. (2010). *Valuing mortality risk reductions for environmental policy: A white paper*.

Fankhauser, S., et al. (2005). On climate change and economic growth. *Resource and Energy Economics, 27*(1), 1–17.

Feyen, L., et al. (2020). *Climate change impacts and adaptation in Europe* (JRC PESETA IV Final Report).

Gallic, E., & Vermandel, G. (2020). Weather shocks. *European Economic Review, 124*.

Glanemann, N., Willner, S. N., & Levermann, A. (2020). Paris Climate Agreement passes the cost-benefit test. *Nature Communications, 11*(1), 110.

Graff, Z. J., Hsiang, S. M., & Neidel, M. (2018). Temperature and human capital in the short and long run. *Journal of the Association of Environmental and Resource Economists, 5*(1), 77–105.

Greenstone, M. (2016). *A new path forward for an empirical social cost of carbon*. Presentation to the National Academies of Sciences.

Gronlund, C. J., et al. (2014). Heat, heat waves, and hospital admissions among the elderly in the United States, 1992–2006. *Environmental Health Perspectives, 122*(11), 1187–1192.

Hänsel, M. C., et al. (2020). Climate economics support for the UN climate targets. *Nature Climate Change, 10*(8), 781–789.

Haraguchi, M., & Lall, U. (2014). Flood risks and impacts: A case study of Thailand's floods in 2011 and research questions for supply chain decision making. *International Journal of Disaster Risk Reduction, 14*(3), 256–272.

Helman, D., & Zaitchik, B. F. (2020). Temperature anomalies affect violent conflicts in African and Middle Eastern warm regions. *Global Environmental Change, 63*.

Howard, P. H., & Sterner, T. (2017). Few and not so far between: A meta-analysis of climate damage estimates. *Environmental and Resource Economics, 68*(1), 197–225.

Hsiang, S. M. (2010). Temperatures and cyclones strongly associated with economic production in the Caribbean and Central America. *Proceedings of the National Academy of Sciences, 107*(35), 15367–15372.

Hsiang, S. M. (2016). Climate econometrics. *Annual Review of Resource Economics, 8*, 43–75.

Hsiang, S. M., Burke, M., & Miguel, E. (2013). Quantifying the influence of climate on human conflict. *Science, 341*(6151).

Hsiang, S. M., et al. (2017). Estimating economic damage from climate change in the United States. *Science, 356*(6345), 1362–1369.

IPCC. (2022a). *Climate change 2022: Impacts, adaptation and vulnerability*. Working Group II Contribution to the IPCC Sixth Assessment Report, Cambridge.

IPCC. (2022b). *Summary for policy makers.*

Kahn, M. E., et al. (2021). Long-term macroeconomic effects of climate change: A cross-country analysis. *Energy Economics, 104*, 105624.

Kalkuhl, M., & Wenz, L. (2020). The impact of climate conditions on economic production. Evidence from a global panel of regions*, 103*, 102360.

Kharin, V. V., et al. (2018). Risks from climate extremes change differently from 1.5 C to 2.0 C depending on rarity. *Earth's Futures, 6*(5), 704–715.

Kikstra, J. S., et al. (2021). The social cost of carbon dioxide under climate-economy feedbacks and temperature variability. *Environmental Research Letters, 16*(9).

Kolstad, C. D., & Moore, F. C. (2020). Estimating the economic impacts of climate change using weather observations. *Review of Environmental Economics and Policy, 14*(1), 1–24.

Kotz, M., et al. (2021). Day-to-day temperature variability reduces economic growth. *Nature Climate Change*, 1–7.

Kotz, M., Levermann, A., & Wenz, L. (2022). The effect of rainfall changes on economic production. *Nature, 601*(7892), 223–227.

Kotz, M., Levermann, A., & Wenz, L. (2024). The economic commitment of climate change. *Nature, 628*(8008), 551–557.

Kovats, R., et al. (2014). Europe. In *Climate change 2014: Impacts, adaptation, and vulnerability. Part B: Regional aspects*. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Bednar-Friedl, B., et al. (2022). Europe. In *Climate change 2022: Impacts, adaptation, and vulnerability*. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.

Krichene, H., et al. (2021). Long-term impacts of tropical cyclones and fluvial floods on economic growth – Empirical evidence on transmission channels at different levels of development. *World Development, 144*, 105475.

Kuhla, K., et al. (2021). Ripple resonance amplifies economic welfare loss from weather extremes. *Environmental Research Letters, 16*(11).

Lehner, B., et al. (2001). *Model-based assessment of European water resources and hydrology in the face of global change*. Centre for Environmental Systems Resources. Universität Kassel.

Lenton, T. M., et al. (2019). *Climate tipping points – Too risky to bet against*. Nature Publishing Group.

MacKenzie, C. A., Santos, J. R., & Barker, K. (2012). Measuring changes in international production from a disruption: Case study of the Japanese earthquake and tsunami. *International Journal of Production Economics, 138*(2), 293–302.

Min, S.-K., et al. (2011). Human contribution to more-intense precipitation extremes. *Nature, 470*(7334), 378–381.

Moore, F. C., & Diaz, D. B. (2015). Temperature impacts on economic growth warrant stringent mitigation policy. *Nature Climate Change, 5*(2), 127–131.

Munich Re. (2023). NatCatSERVICE.

Munro, A., et al. (2017). Effect of evacuation and displacement on the association between flooding and mental health outcomes: A cross-sectional analysis of UK survey data. *The Lancet Planetary Health, 1*(4), e134–e141.

Newell, R. G., Prest, B. C., & Sexton, S. E. (2021). The GDP-temperature relationship: Implications for climate change damages. *Journal of Environmental Economics and Management, 108*.

NOAA Office for Coastal Management. (2021). *Hurricane costs*. https://coast.noaa.gov/states/fast-facts/hurricane-costs.html

Nordhaus, W. (2018). Projections and uncertainties about climate change in an era of minimal climate policies. *American Economic Journal: Economic Policy, 10*(3), 333–360.

Nordhaus, W. D., & Boyer, J. (2000). *Warming the world: Economic models of global warming*.

Obradovich, N., et al. (2017). Nighttime temperature and human sleep loss in a changing climate. *Science Advances, 3*(5), e1601555.

Obradovich, N., et al. (2018). Empirical evidence of mental health risks posed by climate change. *Proceedings of the National Academy of Sciences, 115*(43), 10953–10958.

Orlov, A., et al. (2019). Economic losses of heat-induced reductions in outdoor worker productivity: A case study of Europe. *Economics of Disasters and Climate Change, 3*(3), 191–211.

Paltan, H., et al. (2018). Global implications of 1.5 C and 2 C warmer worlds on extreme river flows. *Environmental Research Letters, 13*(9).

Phung, D., et al. (2016). Ambient temperature and risk of cardiovascular hospitalization: An updated systematic review and metaanalysis. *Science of the Total Environment, 550*, 1084–1102.

Pindyck, R. S. (2013). Climate change policy: What do the models tell us? *Journal of Economic Literature, 21*(3), 860–872.

Pretis, F., et al. (2018). Uncertain impacts on economic growth when stabilizing global temperatures at 1.5 C or 2 C warming. *Philosophical Transactions Royal Society A: Mathematical, Physical and Engineering Sciences, 376*(2119).

Ramsey, J. D. (1995). Task performance in heat: A review. *Ergonomics, 38*(1), 154–165.

Reuters. (2021). Climate inaction costlier than net zero transition: Reuters poll | Reuters.

Rode, A., et al. (2021). Estimating a social cost of carbon for global energy consumption. *Nature, 598*(7880), 308–314.

Schwartz, R. M., et al. (2017). Displacement and mental health after natural disasters. *The Lancet Planetary Health, 1*(8).

Semenza, J. C., et al. (1999). Excess hospital admissions during the July 1995 heat wave in Chicago. *American Journal of Preventive Medicine, 16*(4), 269–277.

Sherbakov, T., et al. (2018). Ambient temperature and added heat wave effects on hospitalizations in California from 1999 to 2009. *Environmental Research, 160*, 83–90.

Shi, L., et al. (2015). Impacts of temperature and its variability on mortality in New England. *Nature Climate Change, 5*(11), 988–991.

Stechemesser, A. H., et al. (2021). Strong increase of racist tweets outside of climate comfort zone in Europe. *Environmental Research Letters, 16*.

Stechemesser, A., Levermann, A., & Wenz, L. (2022). Temperature impacts on hate speech online: Evidence from 4 billion geolocated tweets from the USA. *The Lancet Planetary Health, 6*(9), e714–e725.

Stern, N. (2007). *The economics of climate change: The Stern review*.

Studeholme. (2021). Poleward expansion of tropical cyclone latitudes in warming climates. *Nature Geoscience, 15*(1).

Szewczyk, W., Mongelli, I., & Ciscar, J.-C. (2021). Heat stress, labour productivity and adaptation in Europe – A regional and occupational analysis. *Environmental Research Letters, 16*(10).

Tagesschau. (2021). *Wirtschaft bricht um fünf Prozent ein*.

Turco, M., et al. (2018). Exacerbated fires in Mediterranean Europe due to anthropogenic warming projected with non-stationary climate-fire models. *Nature Communications, 9*(1), 1–9.

Ueckerdt, F. et al. (2019). The economically optimal warming limit of the planet. *Earth System Dynamics 10*(4), 741–763.

UNEP and INEP DTU Partnership. (2021). *Emissions Gap Report 2021: The heat is on – A World of climate promises not yet delivered*.

United Nations. (2015). *Paris Agreement*. https://treaties.un.org/Pages/ViewDetails.aspx?src=TREATY&mtdsg_no=XXVII-7-d&chapter=27&clang=_en

van Vuuren, D., Edmonds, J., & Kainuma, M. (2011). The representative concentration pathways: An overview. *Climatic Change, 109*, 5–13.

Waidelich, P., et al. (2024). Climate damage projections beyond annual temperature. *Nature Climate Change*, 1–8.

Weitzman, M. L. (2009). On modeling and interpreting the economics of catastrophic climate change. *Review of Economics and Statistics, 91*(1), 1–19.

Wenjia, C., et al. (2021). The 2020 China report of the Lancet Countdown on health and climate change. *The Lancet, Public Health, 6*(1), e64–e81.

Wenz, L., & Levermann, A. (2016). Enhanced economic connectivity to foster heat stress–related losses. *Science Advances, 2*(6), e1501026.

Wenz, L., & Willner, S. N. (2022). 18. Climate impacts and global supply chains: An overview. *Handbook on Trade Policy and Climate Change, 290*.

Wenz, L., Levermann, A., & Auffhammer, M. (2017). North-South polarization of European electricity consumption under future warming. *Proceedings of the National Academy of Sciences*.

Wheeler, T. R., et al. (2000). Temperature variability and the yield of annual crops. *Agriculture, Ecosystems & Environment, 82*(1–3), 159–167.

Willner, S. N., Otto, C., & Levermann, A. (2018). Global economic response to river floods. *Nature Climate Change, 8*, 594–598.

Zhongming, Z., et al. (2021). *UN world water development report 2021* (Valuing Water).