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Welfare in the 21st century: Increasing development, reducing inequality, the impact of climate change, and the cost of climate policies

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ABSTRACT

Climate change is real and its impacts are mostly negative, but common portrayals of devastation are unfounded. Scenarios set out under the UN Climate Panel (IPCC) show human welfare will likely increase to 450% of today's welfare over the 21st century. Climate damages will reduce this welfare increase to 434%.

Arguments for devastation typically claim that extreme weather (like droughts, floods, wildfires, and hurricanes) is already worsening because of climate change. This is mostly misleading and inconsistent with the IPCC literature. For instance, the IPCC finds no trend for global hurricane frequency and has low confidence in attribution of changes to human activity, while the US has not seen an increase in landfalling hurricanes since 1900. Global death risk from extreme weather has declined 99% over 100 years and global costs have declined 26% over the last 28 years.

Arguments for devastation typically ignore adaptation, which will reduce vulnerability dramatically. While climate research suggests that fewer but stronger future hurricanes will increase damages, this effect will be countered by richer and more resilient societies. Global cost of hurricanes will likely decline from 0.04% of GDP today to 0.02% in 2100.

Climate-economic research shows that the total cost from untreated climate change is negative but moderate, likely equivalent to a 3.6% reduction in total GDP.

Climate *policies* also have costs that often vastly outweigh their climate benefits. The Paris Agreement, if fully implemented, will cost $819–$1,890 billion per year in 2030, yet will reduce emissions by just 1% of what is needed to limit average global temperature rise to 1.5°C. Each dollar spent on Paris will likely produce climate benefits worth 11¢.

Long-term impacts of climate policy can cost even more. The IPCC's two best future scenarios are the "sustainable" SSP1 and the "fossil-fuel driven" SSP5. Current climate-focused attitudes suggest we aim for the "sustainable" world, but the higher economic growth in SSP5 actually leads to much greater welfare for humanity. After adjusting for climate damages, SSP5 will on average leave grandchildren of today's poor $48,000 better off every year. It will reduce poverty by 26 million each year until 2050, inequality will be lower, and more than 80 million premature deaths will be avoided.

Using carbon taxes, an optimal realistic climate policy can aggressively reduce emissions and reduce the global temperature increase from 4.1°C in 2100 to 3.75°C. This will cost $18 trillion, but deliver climate benefits worth twice that. The popular 2°C target, in contrast, is unrealistic and would leave the world more than $250 trillion worse off.

The most effective climate policy is increasing investment in green R&D to make future decarbonization much cheaper. This can deliver $11 of climate benefits for each dollar spent.

More effective climate policies can help the world do better. The current climate discourse leads to wasteful climate policies, diverting attention and funds from more effective ways to improve the world.

This article will outline how to establish a rational climate policy in the context of many other, competing global issues.

It takes its starting point from the standard climate models as described by the UN Climate Panel, the IPCC, in its latest, fifth assessment (IPCC 2013a) and impact models (IPCC 2014a) along with its special 1.5°C report (IPCC 2018), showing that climate change is real and man-made, and CO_2 and other greenhouse gasses lead to higher global temperatures, which on average cause a net detriment to humanity.

Global warming[1] has become a top priority across the world with almost every nation committing to a target of limiting global temperature rise at or just above 1.5°C. This is partly because climate impacts have been presented repeatedly as catastrophic, leading many people to believe that unmitigated climate change is likely to lead to devastated lives, collapsing societies, and even human extinction.

These claims of devastation are almost entirely unwarranted and can lead to wasteful climate policies in which resources are allocated and decisions made driven by fear and panic. In order to identify rational climate policies, it is first necessary to address these misplaced concerns about devastating impacts from climate change.

I will do this with data from the most respected sources. Given the divisive nature of the climate debate, my first choice where available will be data from the UN Climate Panel, the IPCC, which is respected by all parties. I will use global data where available and I will mostly use US data when I refer to a specific country, partly because of the much

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[1] or climate change; it will be used interchangeably in this article

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greater availability of long-term data for the US, and partly because of its uniquely highlighted profile in the global climate conversation.

The first chapter of this article will explore the backdrop to the climate conversation. It will show that the likely future is not one of devastation. Instead, the IPCC's own scenarios show it is likely that human welfare will continue to make dramatic increases throughout the 21st century. Welfare will be described throughout the article mostly using GDP per capita because, despite criticism, this measurement correlates highly with almost all desirable variables, including higher life satisfaction, better health, longer life, less child death, higher education, less malnutrition, less poverty, more access to water, sanitation, and electricity, along with better environmental performance.

Further, inequality in the 21st century is expected to decline precipitously to levels not experienced in the 20th or even 19th century. Each person will have access to much more energy, which is crucial to deliver opportunities and lift people out of poverty, and since services will get even more effective, the experienced increase in opportunities will be even greater.

This backdrop of dramatic and inclusive welfare growth is challenged in Chapters 2 and 3 by the specter of global warming, leading to worse lives and lower welfare.

In Chapter 2, I will first detail how it is possible for most people to *believe* things are getting worse, whereas the data shows this mostly to be untrue. The first factor is the Expanding Bull's-Eye Effect, which points out increasing population and more wealth lead to higher damages from natural disasters. A hurricane or flood hitting a sparsely populated Florida in 1900 would have done little damage. A similar strength hurricane or flood hitting a densely populated, wealthy Florida in 2020 leads to much higher costs. The cause is not climate change, but social change.

The second factor is that it is common in the climate change literature for projected impacts from climate change to disregard adaptation. If sea levels rise some 70 cm until 2100 and no nation adapts and maintains dikes at today's heights, the world will suffer catastrophic floodings possibly costing more than a hundred trillion dollars a year. It is entirely implausible that nations will not adapt and heighten dikes and other defenses as sea levels rise and incomes more than triple. Using more realistic assumptions of adaptation, impacts typically go from catastrophic to small or even declining.

Next, I look at four areas where escalating climate impacts are popularly portrayed: droughts, floods, wildfires, and hurricanes. I explore the claims that they already impact us negatively because of global warming, and that future warming will make them even worse. These are shown to be mostly incorrect and unsubstantiated in the actual descriptions in the IPCC reports and peer-reviewed literature.

Finally, I will present two general indicators that demonstrate increased resilience: that the number and risk of climate-related deaths have dropped by more than 95%, and that the fractional cost of climate impacts is *not* increasing, but actually decreasing.

In Chapter 3 I will present the generalized costs of climate impacts that are estimated in so-called Integrated Assessment Models (IAM). These show that realistically, the costs of unmitigated climate impacts are in the order of 3.6% of GDP by 2100 — a problem, but not a devastation. I will then address worries that the IAM costs miss challenges including catastrophes, ocean acidification, and biodiversity loss. Many aspects are already included, and a sizable 0.73 percentage points is added for omitted costs. Taking account of the actual estimates of these potentially left-out costs shows that it is likely that they are fully included within this buffer. I finally show that even with sizable climate cost estimates, the vast, expected baseline increase in welfare will in no way be compromised. While the overall welfare increase is about 600–1,000%, the decrease is one or two orders of magnitude lower.

This background now gives us a baseline from which we can evaluate climate policies, estimating their costs and benefits. Chapter 4 evaluates the costs and benefits of the most important current climate policy, the Paris Agreement. It is found that Paris will deliver very little CO_2 or temperature reduction at a cost of $1 trillion–$2 trillion per year. While these reductions will have benefits, it is likely that the costs will vastly outweigh the benefits, with every $1 of cost achieving 11¢ of climate benefit.

Chapter 5 allows us to consider the generally optimal climate policy. This emphasizes that climate policy consists of *two* costs: climate costs and climate policy costs. Each impacts welfare, so we need to minimize the total cost and hence minimize the total reduction in global welfare. This is achieved using Nordhaus' DICE model, showing that with realistic assumptions, smartly designed if less effectively implemented climate policies can save us $18 trillion, or 0.4% of all future global GDP.

However, the more important finding is that we need to avoid policies that would attempt to achieve reductions of 2°C or 1.5°C. This would be a devastating policy for the world, eradicating at least $250 trillion in welfare, or 5.4% of all future global GDP.

Chapter 6 puts the climate problem in perspective. While global warming definitely is a challenge, it is a rather small issue compared to most other human challenges, both measured in welfare and in number of dead. It shows that most people rank issues like health, education, and nutrition much higher, and that most of the world's most effective policies can do much more than what even effective climate change policies can do.

The conclusion outlines the need for policymakers to weigh approaches to make sure we tackle the negative impacts of climate change without ending up incurring more costs by engaging in excessively expensive climate policies. It affirms that we should not remain passive in the face of global warming, but we should also avoid overly ambitious and costly climate policies, and must ensure that the world remains on a growth path that will continue to deliver significant welfare gains, especially for the world's poorest.

1. Baseline for welfare, inequality, and energy, 1800–2100

As a field of study, climate change gives us an immense opportunity to access long-term forecasts and use these as ways to help inform not only climate policy but global policy in general. In this first section, I will outline the impacts on welfare, inequality, and energy access over the past two centuries and the rest of this century.

1.1. GDP is a good measure for welfare

This paper is primarily concerned with maximizing human welfare, thus requiring a relevant indicator.

The standard human welfare indicator used is GDP per person. This has long been criticized for being overly simplistic and misleading. Robert Kennedy famously pointed out that GDP “counts air pollution and cigarette advertising and ambulances to clear our highways of carnage. It counts special locks for our doors and the jails for the people who break them” (Robert 1968). Yet, it “does not allow for the health of our children, the quality of their education, or the joy of their play.” He concluded, GDP “measures everything in short, except that which makes life worthwhile.”

An updated critique from the OECD's High Level Group on the Measurement of Economic Performance and Social Progress underscores the point that GDP was not designed to provide a proxy for both economic and general welfare (Stiglitz et al., 2018). Instead, a broader dashboard of indicators is suggested, being “small enough to be easily comprehensible, but large enough to summarize what we care about.”

The problem is that most suggestions for the replacement of GDP as a measure include a dizzying array of indicators, from the UN's 169 SDG targets (UN 2015) to the 50 well-being indicators in OECD's own *How is life* (OECD 2017).

Moreover, while it would be convenient if *one* indicator could indeed capture everything, GDP is remarkably good at capturing many of the issues we care most about. This is unsurprising, since higher GDP

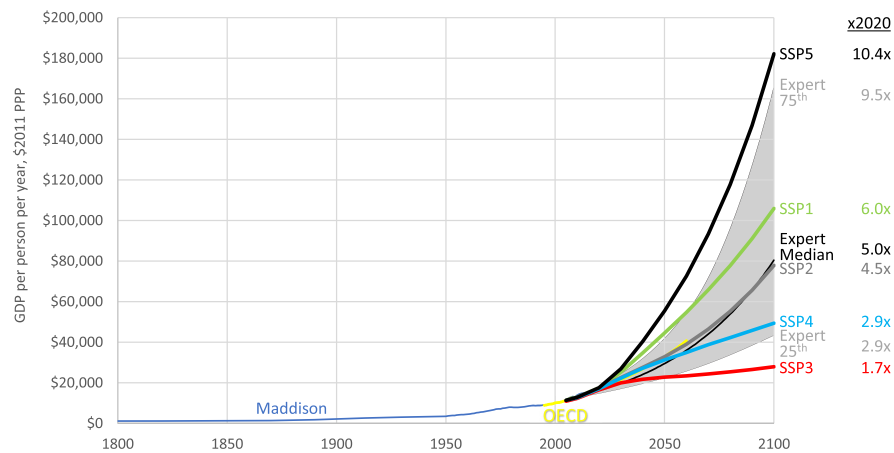

Fig. 1. Global GDP per capita, 1800–2100 in $2011 PPP. Historic data from Maddison (Maddison 2006; Bolt et al., 2018). Forecasting from OECD 2060-predictions (OECD 2018), expert elicitation forecast for 2100 (Christensen et al., 2018) with median and 25th and 75th quartile predictions, and UN Climate Panel Shared Socio-economic Pathways (SSPs) for 2100 (IIASA 2018; Riahi et al., 2017). The two highest-income SSPs are "Sustainability" SSP1 and "Fossil fueled development" SSP5. Far right shows multiple of 2020 per capita income for 2100.

gives us the resources to tackle many problems. GDP per person correlates very highly with health indicators such as life expectancy and (negatively) with under-5 mortality (Sharma 2018), as well as with education (Habermeier 2007), unsurprisingly making it highly correlated to the UN's Human Development Index (Rosling 2012).

Growth in GDP per capita was also a major part of lifting more than a billion people out of poverty (Page and Pande 2018; Dollar et al., 2016). Higher GDP per capita has reduced malnutrition dramatically over the past three decades (Goedecke et al., 2018) and has delivered better nourished children in India (Ghosh 2018).

Higher GDP per person enables the poor to stop using polluting wood and dung for heating and cooking (McLean et al., 2019), and gives better access to infrastructure services like water, sanitation, electricity, and telephony (Steckel et al., 2017). There is even a strong correlation between GDP per person and national environmental performance on a wide range of parameters (EPI 2018, Fig. 3-1).

Perhaps most importantly, GDP per person is very good at capturing perhaps the central estimate for human welfare: namely, subjective well-being. In a test of six other beyond-GDP indices (Human Development Index, Inequality-Adjusted Human Development Index, OECD Better Life Index, Index of Social Progress, the Well-Being Index and the Social Development Index), it turns out that GNI per capita does better at predicting subjective well-being than five of the other indices (Delhey and Kroll 2013). As these authors conclude, this suggests that "economic activities and the affluence they create actually do make life worthwhile for a huge majority of people."

Despite its criticisms, because GDP per person correlates highly with subjective well-being as well as life expectancy, child survival, escape from poverty and malnutrition, access to infrastructure, and better environmental performance, I will in this article use it as the main indicator for human welfare.

1.2. Baseline welfare for the future

While most forecasts for GDP go out a few years or maybe a few decades, the need for climate data to forecast emissions and hence the economic activity for the entire 21st century means that we have scenarios showing us the likely development of human welfare for the next eight decades.

A survey of experts shows that the expected median annual per capita increase is 2.59% for the period 2010–50 and 2.03% for the full 2010–2100 (Christensen et al., 2018). This means that the GDP per

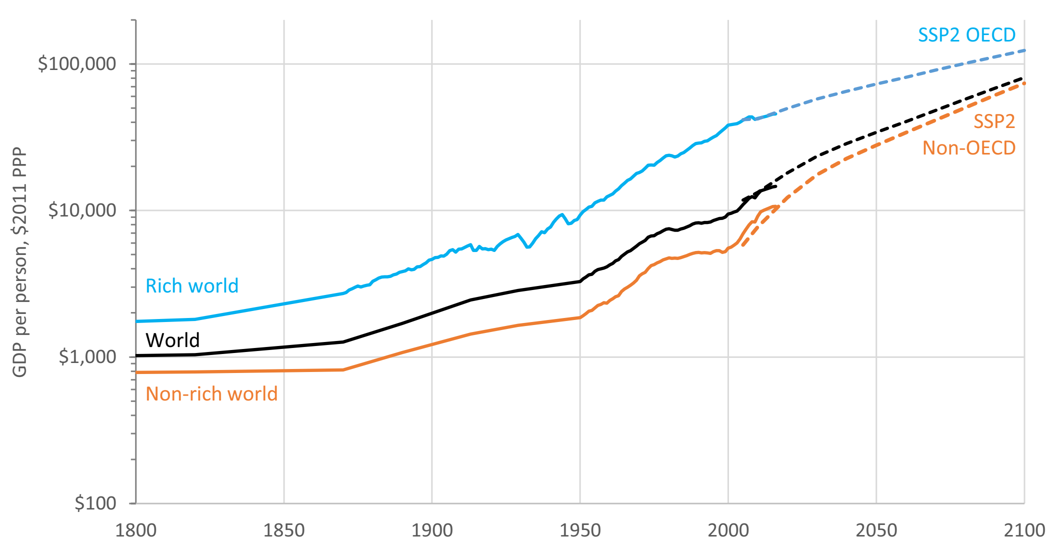

Fig. 2. GPD per capita for rich, non-rich, and world, 1800–2100 in $2011 PPP. 1800–2016 is from Maddison (Maddison 2006; Bolt et al., 2018), using Western Europe and Western Offshoots (the United States, Canada, Australia, and New Zealand) as rich world, and extracting rest from weighted world average. Notice that especially the non-rich world is only roughly correct far back in time. SSP2 "Middle-of-the-road" scenario shows OECD, non-OECD, and world GPD per capita (IIASA 2018; Riahi et al., 2017).

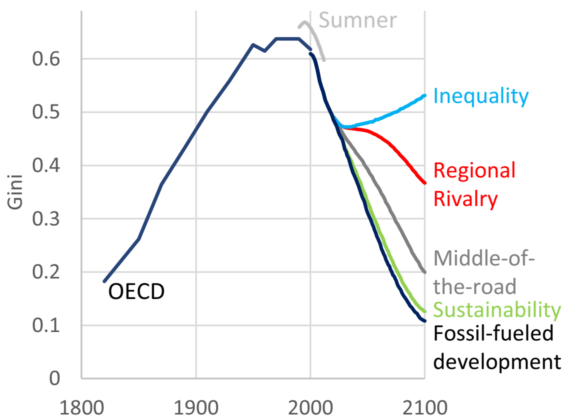

Fig. 3. Global between-country inequality 1820–2100 in $2005 PPP. Data from 1820–2000 is from Maddison, here from (Zanden et al. 2014, 208). The original data is in $1990PPP, but series adjusted to common data point from 2002 in both $2005 PPP and $1990 PPP (Milanovic 2011, 500). Data from 1990–2012 from (Sumner 2019). The five scenarios from 2000–2100, here from (Riahi et al., 2017 Fig 2D). The same article series carries another, somewhat different between-country inequality estimation, showing an implausible 0.85 in 1980 (Dellink et al., 2017, 210).

capita in 2100 will be 610% of the 2010 GDP per capita. The study also shows a tightening of inequality because lower-income countries will grow faster: high-income countries will see a median per capita growth of a lower 1.46% (368% as rich by 2100) whereas low-income countries will see a median growth of 2.53% (948% as rich by 2100).

A similar effort, based on exploring a number of narratives, comes from the UN's so-called Shared Socioeconomic Pathways (Riahi et al., 2017, compared to previous SRES 2007, Grübler et al., 2007). They describe five plausible major global development paths, including development in income, energy use, and emissions, as briefly described in Table 1. Compared to 2010, they see GDP per capita in 2100 at levels from 227% to 1,426%. According to (Christensen et al., 2018) the SSPs have a downward tendency in that they don't represent the upper quartile of the uncertainty distribution of GDP per capita by 2100. In fact, there is a 10% chance that incomes per capita by 2100 would be higher than 2,150% of the figure in 2010.

Fig. 1 shows how the 2100 prediction for GDP per capita of expert survey matches up well with the "middle-of-the-road" SSP2 and all scenarios show substantial income increases. Of the two climate scenarios with highest income growth, the first is the "Sustainability — taking the Green Road" SSP1, which finds the world shifting onto a sustainable path, emphasizing more inclusive development that respects perceived environmental boundaries (Riahi et al., 2017). The second is the "Fossil fueled development" SSP5, in which the world places increasing faith in competitive markets, innovation, and participatory societies to produce rapid technological progress and development of human capital as the path to sustainable development (other studies find similar income increases, e.g., Viguié et al., 2014).

1.3. *Future welfare distributed more equally*

The distribution of welfare became ever more important in the past decade (Piketty 2017; Barnett et al., 2017). The forecasts and scenarios from Fig. 1 foresee a declining inequality as the rest of the world catches up with the current "rich world." As mentioned above, (Christensen et al., 2018) the low-income countries grow their GDP per capita almost three times faster than the high-income countries. OECD's long-term forecast expects non-OECD countries to grow their per capita GDP by 2060 to 992% of their 1995 income compared to OECD increases of 278% or a growth increase more than three times faster (OECD 2018).

In Fig. 2 we see how the rich world took off (Deaton 2015), increasing GDP per person by 25 times from 1820 to 2016, whereas the non-rich world increased a smaller 13.5 times. This increased inequality globally. But for the next 80 years, SSP2 envisions an increase of 2.5 times for the OECD, but six times for the non-OECD, reducing inequality.

Fig. 3 specifically shows global between-country inequality from 1820 to 2100 with the five SSP scenarios. It uses the Gini coefficient, which is a measure of income inequality ranging from 0 (full equality) to 1 (complete inequality). Inequality can be measured in three different ways (Bourguignon 2015; Bourguignon and Morrisson 2002; Milanovic, 2011, 2013, 2016; Milanovic and Lakner 2015). First, it can be measured *within* a single country, estimating the inequality of all its citizens from richest to poorest. Second, it can be measured *between* countries, assuming all citizens from each country have that country's average income, estimating the inequality from rich Americans to poor Indians. Third, it can be measured across nearly 8 billion individuals irrespective of their citizenship, from the richest Indian and American billionaire to the poorest Indian and American. Since we have much better data for nations, and only good future estimates for nations, Fig. 3 here shows the development in between-nation inequality.

In the early part of the 1800s, about 70% of the global inequality across all individuals in the world came from inequality within each country — what mattered was which "class" you belonged to, not which country you came from (Milanovic 2011). The inequality

Table 1
Overview of UN's 5 Shared Socioeconomic Pathways, from (Riahi et al., 2017).

Name	Description	Narrative
SSP1	**Sustainability–taking the Green Road**	The world shifts toward a more sustainable path. Management of the global commons slowly improves, educational and health investments accelerate. Consumption is oriented toward low material growth and lower resource and energy intensity.
SSP2	**Middle of the road**	The world follows a path in which social, economic, and technological trends do not shift markedly from historical patterns
SSP3	**Regional rivalry**	A resurgent nationalism, and regional conflicts, push countries to increasingly focus on domestic or regional issues. Investments in education and technological development decline. Economic development is slow, consumption is material-intensive, and inequalities persist or worsen over time. A low international priority for addressing environmental concerns leads to strong environmental degradation in some regions.
SSP4	**Inequality—a road divided**	Highly unequal investments in human capital lead to increasing inequalities and stratification both across and within countries. Social cohesion degrades and conflict and unrest become increasingly common. Environmental policies focus on local issues around middle- and high-income areas.
SSP5	**Fossil-fueled development—taking the highway**	This world places increasing faith in competitive markets, innovation, and participatory societies to produce rapid technological progress. There are strong investments in health, education, and institutions to enhance human and social capital. At the same time, the push for economic and social development is coupled with the exploitation of abundant fossil fuel resources and the adoption of resource and energy intensive lifestyles around the world. Local environmental problems like air pollution are successfully managed.

between countries was fairly low, as most countries were equally poor. That is why Fig. 3 shows a low between-country inequality in the early 1800s.

As the industrialized world developed and pulled away, inequality between countries increased spectacularly. In the second half of the 20th century, both global inequality and between-country inequality reached unprecedented highs. About 80% of the global inequality now came from between-country inequality. While “class” still made a smaller difference in your global ranking of income, your citizenship or location made all the difference on whether you would be rich or poor. In Fig. 3, the between-country inequality maxed out around the 1950s to 1980s.

Since then, developing country per person growth rates have increased dramatically, perhaps most importantly in China, while developed country growth rates have slowed. Since the 1980s, global inequality has been declining, and between-country inequality has been declining since 1995 (Sumner 2019). All five SSPs indicate that between-country inequality will never reach the levels from the late 20th century. Even the most pessimistic SSP4 “inequality,” will by the end of the century reach levels equivalent to the early part of last century. The other scenarios will see even greater reductions in between-country inequality to levels in the 1800s, with the middle-of-the-road SSP2 reaching the between-country inequality of 1820, and SSP1 and SSP5 even dropping below.

Thus, the likely welfare impact over the 21st century is to reverse the inequality that has inexorably increased over the past two centuries in two ways. First, it is likely that global inequality will decline faster and possibly more than it increased over the past two centuries. Second, the dramatic decline in between-country inequality will mean a decline in the importance of citizenship or location for inequality and a return to the importance of within-country inequality and “class.”

1.4. Baseline energy use

There is a clear and strong correlation between energy and GDP[2] along with its provision of goods and services, although the causal direction is still debated (Menegaki 2014; Hajko et al., 2018; Kalimeris et al., 2014). We can think of energy as access to manpower or servants, each with the same work power as a healthy adult male. Smil finds that an average man can provide 100 W of work (with an average woman at 60 W) (Smil 2017). Used 24–7 over a full year, that is equivalent to 876 kWh. Today, readily available energy gives the average person in the OECD access to 60 full-time servants, while in the poorer world, it is equivalent to 14 servants. In this way, energy is an equalizer giving everyone, from poorest to richest, access to do much more than what is possible with one's own body.

Since 1800, the average energy available for an average human has increased 3.5 times, and will likely almost double by the end of this century, as shown in Fig. 4.

Globally in 1800, traditional biomass (mostly wood) was almost the only energy source for cooking and heating. Coal slowly substituted part of the wood throughout the 1800s, partly because wood became scarce and costly, but per person energy only increased 18% from 1800 to 1900. Even after World War II in 1945, the average energy per person had only increased by half from its value in 1800. Over the next three and a half decades, energy availability doubled by 1980, slowed by the first and second oil crisis, and has only increased slightly since. While the middle-of-the-road scenario envisions an almost-doubling by 2100, the sustainable scenario (along with the SSP3 and 4) sees only a 30% increase, and the fossil-fuel dominated scenario expects 325% of the average person's 2017 energy.

Notice that the benefits of energy have grown much faster, because of an increasing efficiency in using energy to deliver services. This is partly because processes have become more efficient—around 1800, steam engines only converted 6% of total energy into usable energy, whereas modern combined-cycle gas turbines can reach 60% efficiency (Smil 2017). But much more so, it is because technological progress has enabled far greater production of benefits from smaller energy inputs — the classical example is light, which has seen a dramatic efficiency increase from open fires and whale oil lamps to light bulbs, CFL, and LED lights (Nordhaus 1997).

Almost identical to the global average, energy per person in England and Wales increased 3.7 times from 1800 to 2010 (Warde 2007, 72). However, the consumption of energy services increased many times more, because technological breakthroughs allowed more benefits from each kWh (Fouquet 2014). The average person enjoyed 18 times more effective domestic heating in 2010 than in 1800. Likewise, the average person benefited from 170 times more transport services, traveling almost 18,000 kms each year as opposed to just 105 km in 1800. Freight transport increased even more at 231 times, covering more distance with higher weights. Light increased an astonishing 21,000 times, from available light equivalent to one candle 20 min a day in 1800 to the equivalent of 268 candles always shining (underscoring that increased efficiency need not imply reduced consumption, Franceschini and Pansera 2015).

Fig. 4 also shows how the energy system has transitioned a number of times, from being dominated by wood, to greater reliance on coal, then to oil and then gas (Fouquet 2010; Fouquet and Pearson 2012; Smil 2017). The energy transition is often portrayed as a shift from one source (Zhang et al., 2016) toward the next source, but as Fig. 4 shows, this is almost entirely wrong (Newell and Raimi 2018). If anything, when oil was added to coal, coal didn't decrease, and when natural gas increased, neither oil nor coal decreased. Humanity seems to simply add more and more energy from all the available sources. Wood is perhaps the only exception, as it has declined per person, not the least because it is less flexible to use, leads to indoor air pollution, and hence is mostly associated with poverty.

Vaclav Smil notes that most people think the 19th century was dominated by coal, the 20th century by oil, and the 21st century will belong to renewable energy (Smil 2014). In fact, the 19th century got 85% of its energy from wood, while coal at 34% provided the most energy in the 20th century (with oil and wood almost equal at 28% and 23%, respectively).

Moreover, it seems dubious whether renewables will dominate the 21st century. When measuring renewables in percent of global energy, almost all energy was renewable in 1800, as seen in Fig. 5. Over the next 170 years, it declined to about 13–14%, where it remained for half a century up till today—in 2018 it was almost 14%. Of this 14%, 70% came from biomass and 18% from hydro, with wind, geothermal, and solar PV supplying 5%, 4% and 2%.

To look at the future of the share of renewables, the IEAs Stated Policy scenario assumes that all countries will implement all their stated plans and ambitions, including what they have promised in the Paris Agreement. This seems rather optimistic, as a study of the promises finds that of the 197 signatories, only 17 countries—such as Algeria and Samoa—have set national policies or laws that will actually live up to their promises for the Paris agreement (Nachmany and Mangan 2018). Even with this assumption, the IEA finds that renewables will reach 20% by 2040. The more realistic Current Policies scenario finds renewables will reach 17%.

Fig. 5 also shows the five SSPs, of which only the “sustainable” SSP1 ends up with 45% renewables in 2100, with the other four scenarios reaching between 14–23%. By 2050, it seems likely that the share of renewables will still be lower than its share in 1950.

Individuals in the rich world enjoy energy availability of more than 50,000 kWhs, and Fig. 6 shows that four of the five SSP scenarios expect an average 40% increase over the century. The only outlier is the “sustainable” SSP1, which expects a reduction in energy consumption by one-third.

[2] https://bit.ly/2Xqo9BS

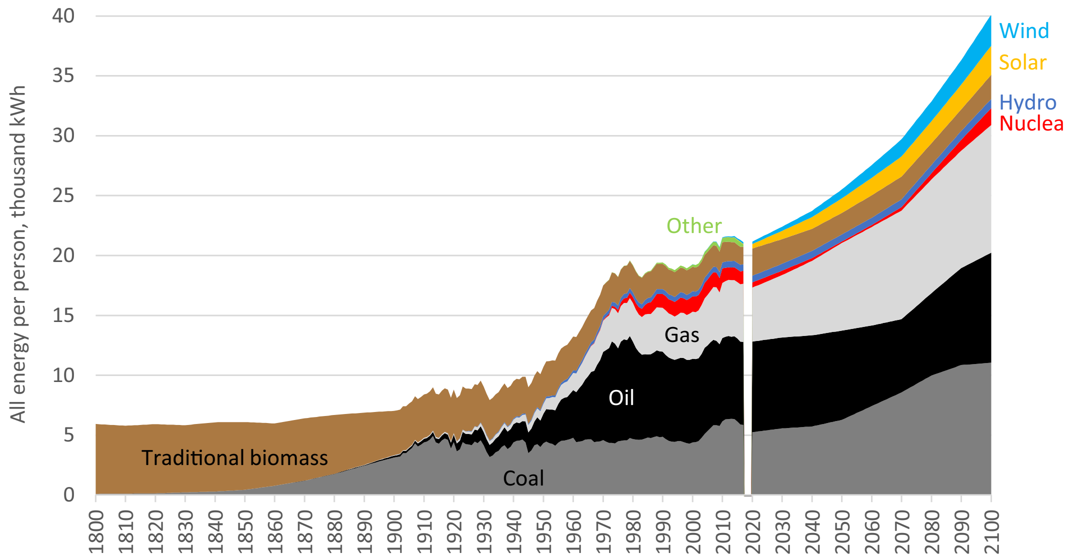

Fig. 4. All energy (not just electricity) per person in the world, 1800–2100, TPES (total primary energy supply) measured in kWh, denoting natural gas with “gas.” Historical data 1800–2017, SSP2 middle-of-the-road scenario for 2020–2100. 1800–1900 plus traditional biomass data up to 2017 from (Vaclav Smil 2017, 240–41); see also (Fouquet 2009). 1900–1979 from (Benichou 2014; Etemad and Luciani 1991), 1971–2017 from (IEA 2018, 2019a), 2020–2100 SSP2 including population from (IIASA 2018; Riahi et al., 2017), global population 1800–2017 from (HYDE 2019; Roser and Ortiz-Ospina 2019). “Other” includes liquid biofuels, geothermal, solar thermal, modern biofuels, and waste. There are some minor discrepancies from the historical data to scenario data: SSP2 nuclear is inexplicably halved, SSP2 biomass seems to include all modern biofuels and possibly waste, and SSP2 solar is somewhat larger than IEA solar.

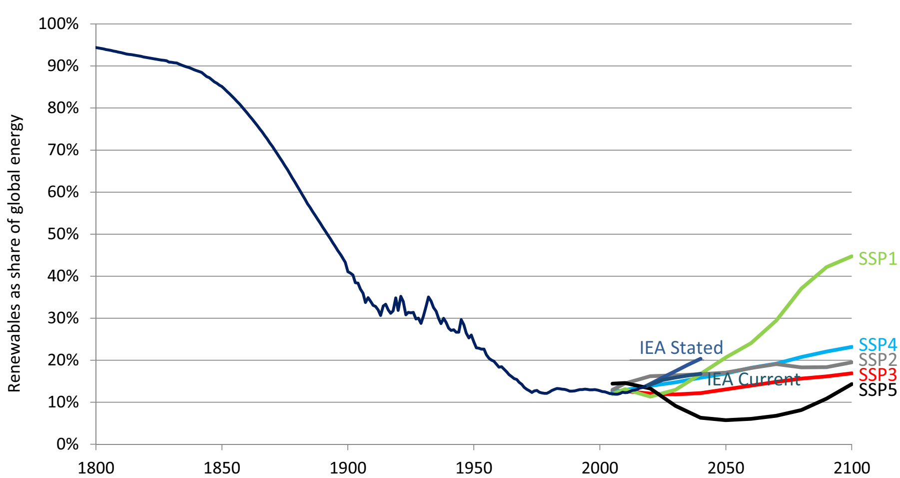

Fig. 5. Renewable energy (biomass, hydro, solar PV, solar CSP, solar thermal, wind, geothermal, and others) in percent of total energy 1800–2100; TPES (total primary energy supply). 1800–1900 (Fouquet 2009), 1900–1979 (Benichou 2014; Etemad and Luciani 1991), 1971–2018 from (IEA 2019a; Miguel 2019b), 2018–40 from (Miguel IEA 2019b) Stated Policies and Current Policies. 2020–2100 for all marker SSPs (IIASA 2018; Riahi et al., 2017).

A person in the non-OECD area had just a quarter of the energy available to an OECD individual in 2005. For all scenarios, energy increases, but three show only very modest increases. For the “regional rivalry” SSP3 and the “inequality” SSP4, this is mostly a consequence of income growth slowing (leading to an income in 2100 worth 220% and 340% of 2019 incomes). For the “sustainable” SSP1, this is built in, with the expectation that “consumption is oriented toward low material growth and lower resource and energy intensity.” Only in the “fossil fuel” SSP5 will an individual in the non-OECD see his or her energy access by 2100 surpass that of the rich world's in 2005.

1.5. Summary: much higher welfare, energy access, and less inequality

We have shown how energy has become more plentiful, allowing each person to do more and often with less. Fouquet (2014) summarizes this achievement: “Over the last two hundred years, industrialized societies have been freed from their dependence on land and wood for heating, humans and horses for power and transport, and sunlight and moonlight for illumination.” Simultaneously, the average person has experienced a dramatic increase in welfare measured in GDP per person, and is likely to become even better off by the end of the century. This matters not only for money but as a proxy for higher life satisfaction. And while the industrialization of the West also increased inequality, especially between-nations, many developing nations are now growing faster and both between-nations and individual inequality has started declining. It is likely that between-nation inequality will be at or below the inequality of 1820.

Besides these fundamentally positive trends, we also expect to see increasing life expectancy, higher literacy, and better nutrition, to a large part caused by these higher incomes, increase in energy access, and reduction in inequality.

2. Global warming's specific impact on current and future welfare

Since global warming has a long-term net negative impact, it will eventually reduce the expected future welfare gains. This section will

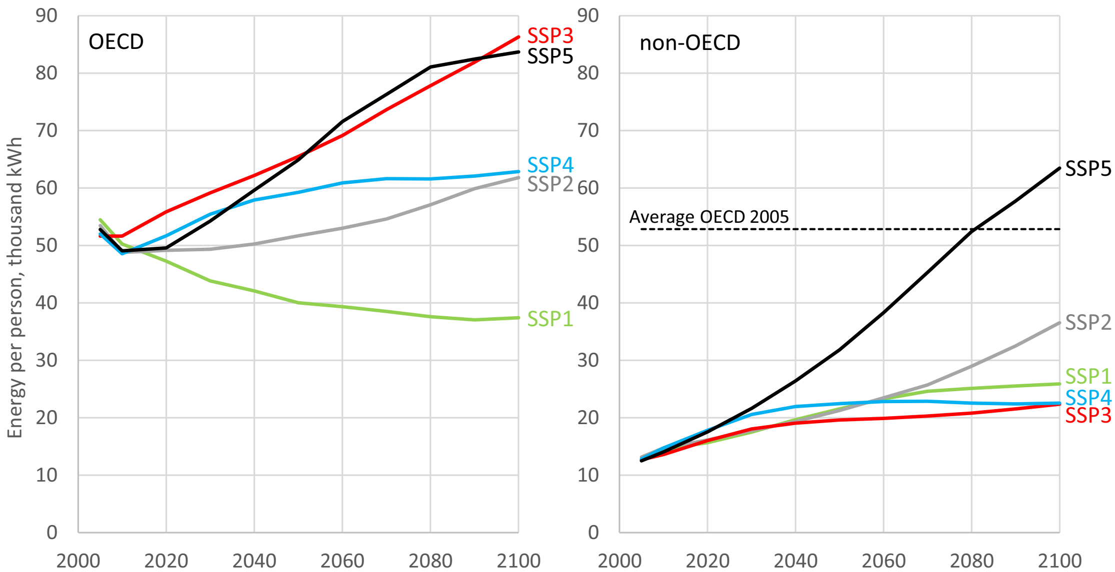

Fig. 6. Energy per person, 2005–2100 for OECD and non-OECD, in thousand kWhs for all SSPs (IIASA 2018; Riahi et al., 2017).

investigate the impact today and into the future, and end up with a representation of welfare reduction in terms of percent of GDP per person.

Many climate campaigners suggest that climate impacts are enormous and might even negate or reverse the expected future welfare increases (e.g., Breyer et al., 2017). In this section we will demonstrate that such statements are incorrect for a number of crucial issues (like coastal flooding or hurricanes), and in the next section we will demonstrate the same point generally (using the climate damage function from integrated assessment models).

However, it is worth first exploring *why* so many people are led to believe that climate impacts are and will be much greater than what realistic models actually show. Specifically, many fearful explanations of global warming miss two crucial points. First, all kinds of disasters are likely to become bigger as there are more people and more wealth in the path of danger. This is called the Expanding Bull's-Eye Effect. This means that increasing damages should be normalized to a standard population before any additional increase can be ascribed to global warming. Second, most negative effects of global warming will be diminished by adaptation, and omitting explicit adaptation leads to assessments of future climate damage that are, sometimes wildly, exaggerated.

2.1. Expanding bull's-eye: bigger catastrophes even without climate

With any new flood, wildfire, or hurricane, news media pictures of immense impact and suffering are frequently offered as an example of how climate is making disasters more frequent and worse. What is often missing in this analysis is how society has changed to cause any one disaster having a much worse *impact*. This is called the Expanding Bull's-Eye Effect (see Fig. 7), as we over time see an increasing number of people with more valuable assets exposed to these disasters (Strader and Ashley 2015; Ashley et al., 2014):

> The expanding bull's-eye can be thought of as an archery target, where inner rings are made up of people and their possessions, and arrows symbolize hazard events. Unlike real archery, the expanding bull's-eye target rings enlarge over time. This amplification results in a greater likelihood of arrows hitting an inner ring on the target. Accordingly, as population continues to grow and expand, the chance that a hazard impacts developed land, resulting in a disaster, increases.

This means that one cannot merely demonstrate bigger catastrophes and claim these are caused by a worsening climate, without first correcting for the increased damage that would be expected from more people and more wealth. I will address and correct as far as possible for the Expanding Bull's-Eye Effect below.

2.2. Adaptation: less damage from future catastrophes of coastal flooding

Many argue that the climate costs of future problems from climate change will be immense. What often underpins such claims is the fact that adaptation to the problems is neglected, leading to climate costs being vastly exaggerated compared to the more realistic costs of a world where adaptation takes place (e.g., Fleischer et al., 2011).

Take studies of a very obvious cost of climate change, coastal flooding, caused by sea level rise. When presented to the public, the future costs are often shown as being in the tens of trillions of dollars per year or above. In the alarmist book, *The Uninhabitable Earth*, coastal flooding impacts are summarized this way:

> *If no significant action is taken to curb emissions, one estimate of global damages is as high as $100 trillion per year by 2100. That is more than global GDP today. Most estimates are a bit lower: $14 trillion a year, still almost a fifth of present-day GDP.* (Wallace-Wells 2019, 61)

Yet, because it ignores adaptation, this description exaggerates the problem by up to two thousand times. The misleading narrative is, unfortunately, often encouraged by research that routinely neglects adaptation or treats it as a casual add-on.

Many studies do routinely find that without adaptation, flooding costs can run into the trillions of dollars per year by the end of the century. Such findings, of course, also turn into lots of citations and headlines.

To do so, some studies (e.g., Vousdoukas et al., 2017) simply estimate (correctly) that sea levels will increase because of climate change over the 21st century, and count (correctly) how many people and wealth in those areas will be flooded without additional flood protection (extremely dubious).

Others, such as Jevrejeva et al., 2018, do almost all of the modeling without adaptation and only briefly mention impacts with adaptation in the "Discussion" section at the end. However, the headline-worthy costs come from modeling without adaptation, and hence that cost is more

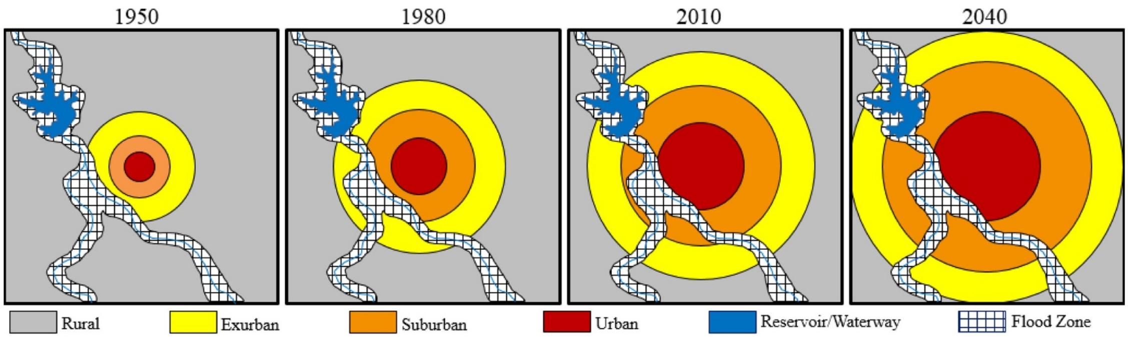

Fig. 7. The Expanding Bull's-Eye effect: A hypothetical flood impacting a city that is growing will cause moderate damage in 1950 and much more damage in 2040, because of many more people and wealth exposed to the flooding. From (Ashley et al., 2014); see also http://chubasco.niu.edu/ebe.htm.

likely to gain attention. Indeed, the journal's own news release for Jevrejeva *only* mentions the headline-grabbing cost of flooding from no adaptation, reaching $14 trillion annually by 2100.[3] Predictably, this figure of $14 trillion found its way into the media across the world including *Newsweek, Axios, Science Daily, New Scientist,* and *India Today*. None mentions the fact that even an extremely stingy adaptation would reduce costs by 88% (similar to the tenfold reduction found in Diaz 2016), and any realistic adaptation would reduce it much, much more.

To achieve the $14 trillion result, Jevrejeva et al., 2018 must assume that no country will ever increase the heights of its dikes, although sea levels rise over the century and countries become much, much richer and able to afford much more protection. While this may be simpler to model as a pure academic exercise, it is unhelpful as a model to inform the public. Indeed, the article *explicitly* acknowledges that its central assumption is unrealistic: “While the present analysis has focused upon the potential costs of flooding in the absence of additional adaptation from the existing baseline, it is clear that *all coastal nations have, and will continue to adapt* by varying degrees to sea level rise” (Jevrejeva et al., 2018, 8, italics added). The article even continues that “standards of protection are likely to improve particularly with economic growth,” making the baseline assumption even more indefensible.

In reality, studies clearly show that for most of humanity, coastal protection makes simple, economic sense (Lincke and Hinkel 2018; Nicholls 2018; Hinkel et al., 2014). About 13% of the global coastline, or 92,500 km, will be protected no matter the amount of sea level rise, discount rate, and wealth, and this coastline accounts for 90% of global coastal floodplain population and for 96% of assets (Lincke and Hinkel 2018).

In one of the most highly cited papers on coastal flooding, Hinkel et al., 2014 shows the impact on flooding from high and low temperature rises across all five SSPs, with and without adaptation. The results are substantially similar across all combinations, and Fig. 8 shows the flooding impact of high warming on the fossil-fuel developed SSP5 scenario.

In 2000, the model finds that globally 3.4 million people are flooded each year from coastal flooding. The number of flooded is an average across a wide range of modeling assumptions, with different digital elevation models, population datasets, four different climate models, and three land-ice scenarios of sea level rise from ice sheets and glaciers — the lowest combinations show 1.5 million flooded, the highest, 5.3 million flooded. All of the points below remain substantially unaltered, if we were to pick the highest (or lowest) estimates instead.

The model finds an annual damage cost in 2000 of $11 billion on top of the dike maintenance cost of $13 billion. The total $24 billion cost is equivalent to 0.05% of global GDP.

If there is no adaptation and all dikes are just maintained at their 2000 height, a high sea level rise of about 75 cm by the end of the century will make flooding progressively much more likely and much more severe, flooding many more people, much more infrastructure, and incurring much higher costs. Since the dikes are not raised, the annual costs in 2100 will remain much the same at $24 billion. However, the damages are catastrophic, with an average year seeing 187 million people flooded, costing an average of $55 trillion or 5.3% of global GDP. The high end could even see 350 million people flooded each year at a cost of $112 trillion annually—almost 11% of global GDP.

As the authors put it, “Damages of this magnitude are very unlikely to be tolerated by society and adaptation will be widespread.”

Adaptation will increase with sea level rise. As societies see greater threats, they will increase the dikes to reduce these threats (Lincke and Hinkel 2018). But the evidence also clearly shows that adaptation will increase with higher incomes. At the same level of threat, richer countries can afford to demand higher dikes and more protection. In the SSP5 world, where each person will be ten times richer than we are today, safety standards will increase markedly. (In the peripheral discussion of adaptation in Jevrejeva et al., 2018 they find a much lower cost reduction from adaptation because the paper almost only models adaptation to higher sea levels, unreasonably expecting that a much richer world will spend almost nothing extra to be much safer.)

Hinkel et al., 2014 models both sea level-driven and income-driven adaptation and finds that at a moderately higher cost of $48 billion in annual dike costs, flooding even with a much higher sea level will have been reduced dramatically—on average, 15,000 people will be flooded in this very rich world (with a maximum of 0.3 million).[4] This is in line with the current evidence, where deaths from storm surges have been declining even as sea levels have risen (Bouwer and Jonkman 2018). Damage costs will be similarly modest at $38 billion. In total, the cost of coastal flooding will impose an impact on society of 0.008% of global GDP.

So, stepping back, warming and increasing sea levels will definitely increase inflation-adjusted coastal flooding costs from $24 billion to $86 billion. Yet, a much richer world spending threefold more on protection, will mostly see this as progress: it will experience a 99.6% decrease in flood victims while spending a much smaller fraction of its income, down from 0.05% to 0.008% of global GDP.

[3] https://iopublishing.org/news/rising-sea-levels-cost-world-14-trillion-year-2100/

[4] A new study suggests that the number of people vulnerable to sea level rise could be three times higher than previously estimated (Kulp and Strauss 2019). It is hard to tell if this will dramatically drive up protection costs, since the increase comes from identifying bad measurements of e.g. tree-tops as ground level. Many of these bad measurements are likely “islands” within areas below sea level that would likely have been protected in the current, extended protection. But even if this new information were to increase dike costs three times, the total cost in the example of 3x$48 billion would still lead to *lower* overall damages of 0.03% of GDP.

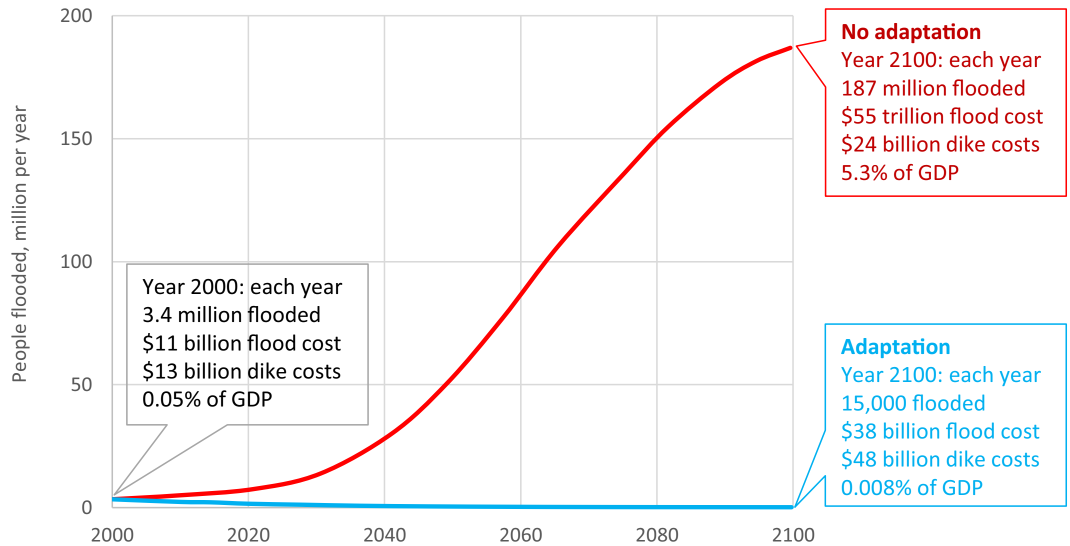

Fig. 8. Million people flooded by coastal flooding from 2000–2100, using the fossil-fuel driven SSP5 scenario with the RCP8.5 climate scenario, essentially giving a high temperature increase and a sea level rise of 64 to 86 cm. The red line indicates no additional adaptation (dikes remain at the height of 2000). The blue line indicates adaptation, meaning investing in rising dikes both because of increasing sea levels and because of increasing incomes. Dike costs include both capital and additional maintenance cost. Percent is total cost of flood and dike costs. All costs in 2005 US$, from (Hinkel et al., 2014, S4, S5 and S6). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

As one recent book on climate adaptation points out, such adaptation costs "are lower than conventional instinct suggests" (Nicholls 2018, 24), but are in agreement with the general literature (e.g., Hallegatte et al., 2013). However, we should still remain vigilant: today, US coastal cities have much higher expected damage costs than European coastal cities because they have much lower protection standards, so more investment is needed. Likewise, rapidly growing regions in developing countries will likely have a growing adaptation deficit, because coastal development takes priority to investments in adaptation.

Nonetheless, the main point is clear. With realistic adaptation, climate change will make coastal flooding more expensive in absolute terms, but smaller in relative terms. It will cost perhaps $86 billion annually by the end of the century, with a high sea level rise and a high level of protection. It will also dramatically reduce the number of people flooded and the fractional cost of flooding to entire GDP.

Hinkel et al., 2014 summarize their findings by saying "flood damages by the end of this century are much more sensitive to the applied protection strategy than to variations in climate and socioeconomic scenarios"—what mostly matters is whether we adapt or not, not whether sea levels rise a lot or whether we get a little or a lot richer.

Yet, when most members of the public hear about these studies through the news media or popular non-fiction books, they learn of the unrealistic scenarios with no adaptation and trillions of dollars of costs. The quote from *The Uninhabitable Earth* above (Wallace-Wells 2019, 61), declaring that without drastic CO_2 cuts the costs of flood damage will reach $14 trillion or possibly even $100 trillion per year in 2100, entirely relies on the two studies described here.

The reference to a cost of $14 trillion per year is from Jevrejeva et al., 2018, who clearly said that adaptation will happen, and that even with an unrealistically weak adaptation, costs will be much lower.

The reference to the $100 billion is the news release for the Hinkel et al., 2014 study, emphasizing the entirely implausible high end of the entirely inconceivable no-adaptation scenario, which the authors explicitly say won't happen.

Decision-makers and the public will be led astray by reliance on information from news releases and newspaper articles that ignore adaptation. Many readers of Wallace-Wells will believe the actual costs of climate-amplified coastal flooding are more than two thousand times what the realistic impacts will actually be. They will believe the future holds a huge loss in welfare (from a cost of 0.05% to 5.3% of GDP) instead of the slight *increase* in welfare that we are likely to see (because of a cost reduction from 0.05% to 0.008% of GDP).

2.3. Drought

It is instructive to look at a few, concrete impacts of the most visible issues that are associated with the portrayal of climate change devastation. President Obama repeatedly emphasized climate change means that we both are seeing and will see "more extreme droughts, floods, wildfires, and hurricanes" (Obama 2013). The UN Secretary-General similarly claims that "climate disruption is happening now, and it is happening to all of us. … Every week brings new climate-related devastation. Floods. Drought. Heat waves. Wildfires. Superstorms" (Guterres 2019). In a recent survey, it was found that such extreme events are what make most people change their minds on climate (EPI and AP-NORC 2019).

Yet, the data doesn't support or only marginally supports such claims. Moreover, there are almost invariably more effective policies to reduce net impacts.

For drought, the IPCC concludes "there is low confidence in attributing changes in drought over global land areas since the mid-20th century to human influence" (IPCC 2013a, 871). Moreover, it concludes "there is low confidence in a global-scale observed trend in drought" with drought having "likely increased in the Mediterranean and West Africa and likely decreased in central North America and northwest Australia since 1950" (IPCC 2013a, 50). The IPCC repudiated previous findings from 2007, saying our "conclusions regarding global increasing trends in droughts since the 1970s are no longer supported" (IPCC 2013a, 44). This was because new data showed no increased global drought (Sheffield et al., 2012; van der Schrier et al. 2013), and one study even showed a persistent decline since 1982 (Hao et al., 2014), while the number of consecutive dry days has been declining for the last 90 years (Donat et al., 2013, 2112). The new IPCC 1.5°C report concurs, but adds that there is medium confidence that greenhouse gas warming has contributed to increased drying in the Mediterranean region (IPCC 2018, 196).

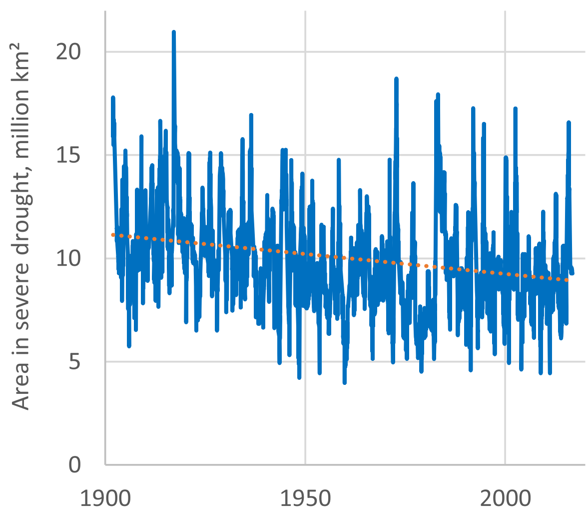

Fig. 9. Global area in severe meteorological drought, 1901–2017 measured by Standardized Precipitation Index (SPI) being less than −1.5 over 6 months, (Watts et al., 2018). Linear best fit, not significant.

The World Meteorological Organization has through the Lincoln Declaration on Drought Indices recommended that "the Standardized Precipitation Index (SPI) be used to characterize the meteorological droughts around the world" (Hayes et al., 2010). Fig. 9 shows the global area under severe meteorological drought for 1901–2017, showing no increase over the last 116 years.

The US Fourth National Climate Assessment reaffirmed the IPCC finding and stated unequivocally that "drought has decreased over much of the continental United States in association with long-term increases in precipitation" (USGCRP 2017, 49–50, 231). Both IPCC and USGCRP find that there is currently no attribution possible for drought (IPCC 2013a, 913; USGCRP 2017, 236). Thus, it is incorrect to say that currently we are seeing the climate impact of drought, either globally or in the US.

However, the IPCC suggests with medium confidence that with extreme emission scenarios (RCP8.5), it is likely that drought risk could increase in currently dry regions towards the end of the century (IPCC 2013a, 1032). Similarly, the USGCRP finds that "under higher scenarios and assuming no change to current water-resources management, chronic, long-duration hydrological drought is increasingly possible by the end of this century" (USGCRP 2017, 240). Thus, it is possible to argue that climate change can make drought worse, but it is important to point out that this is only with high-end scenarios and towards the end of the century. Moreover, the USGCRP makes it clear that this potential worsening requires an assumption of no change to water-management. In reality, such change is not only likely but also much more efficient. A recent study for California showed that during droughts, reservoir operation can reduce the drought deficit by about 50%, whereas extensive water usage (mostly irrigation) can almost double drought duration and deficit (He et al., 2017)—both actions that can be more readily changed than CO_2 levels.

2.4. Flooding

The IPCC cannot say whether flooding on a global level is increasing or even if the flooding is increasing or decreasing: "There continues to be a lack of evidence and thus low confidence regarding the sign of trend in the magnitude and/or frequency of floods on a global scale over the instrumental record" (IPCC 2013a, 112, 214). The USGCRP summarizes the IPCC to say they "did not attribute changes in flooding to anthropogenic influence nor report detectable changes in flooding magnitude, duration, or frequency" (USGCRP 2017, 240). Flooding in the US has increased for some areas (the upper Mississippi River valley) and decreased for others (Northwest). However, "formal attribution approaches have not established a significant connection of increased riverine flooding to human-induced climate change" (USGCRP 2017, 231). The new IPCC 1.5°C report finds that "streamflow trends since 1950 are not statistically significant in most of the world's largest rivers" and that more streamflows are decreasing than increasing (IPCC 2018, 201)

For the future, USGCRP argues that given we know heavy precipitation will be increasing, it seems likely that this could "contribute to increases in local flooding in some catchments or regions" (USGCRP 2017, 242, Keigo 2018, 146). However, they also acknowledge that we don't even know *when* we will be able to detect any impact from climate on flooding (USGCRP 2017, 231). The IPCC similarly concludes that global warming would lead to an expansion of the area with significant increases in runoff, which can increase flood hazards (IPCC 2018, 203), but also emphasizes that "trends in floods are strongly influenced by changes in river management" (IPCC 2013a, 214).

Again, it is simply unwarranted to posit current flooding as an example of impacts from climate change. Even in the future, this is much more strongly influenced by other human impacts like river management and extensive building on floodplains than climate change. A recent study points out that "despite widespread claims by the climate community that if precipitation extremes increase, floods must also," it actually seems like "flood magnitudes are decreasing" (Sharma et al., 2018).

In this respect, flooding is definitely an example of the Expanding Bull's-Eye Effect. While we don't have global analyses, we can look to US data to show the impact of correcting for the Expanding Bull's-Eye Effect.

In an analysis of vulnerability in Atlanta from 1990–2010, the authors find that the number of exposed housing units on the 100-year floodplain has increased by about 58% in just 20 years (Ferguson and Ashley 2017), although outside the regulatory 100-year flood zone growth was slightly higher at 71%. This means that with the same amount of flooding and all other things equal, Atlanta in 2010 would on average see 58% more housing units flooded than in 1990. We need to also consider that each house has become bigger and more valuable, meaning losses would be even higher.

If we look at the US inflation-adjusted flood costs from 1903–2018 in Fig. 10, it is apparent that costs are now 370% of what they were in 1903, from an expected cost of $3.5 billion in 1903 to $12.9 billion in 2018. This could be used to suggest that flooding is getting worse and climate might be responsible.

However, we must first adjust for the many more buildings being built on the floodplains. On a US scale, housing units have doubled from 68 million in 1970 to 137 million in 2017 (Census 2011, 2018a). Moreover, they have become about 50% larger since 1973 (Klotzbach et al., 2018, 1371), and the average price of almost $400,000 today is 280% of its inflation-adjusted cost in 1970 (BEA 2019b; Census 2018b). If the number of houses on floodplains have increased similarly in numbers and value, it would be reasonable to expect an increase in total costs of 280% x 200% or 560%. Given that the Atlanta study showed that houses on the 100-year floodplain only grew at 80%, it would perhaps be more realistic to expect an increase of 280% x 200% x80% or 448%.

Unfortunately, we don't have continent-wide estimates of houses in floodplains so one simple way to adjust the flood costs is to divide the impact by total US GDP. This grew slower, with 2017 GDP at 317% of the 1970 GDP, so this is a conservative correction. Yet, the right-hand side of Fig. 10 shows a very different picture, with costs in 1903 at 0.48% of GDP, dropping almost an order of magnitude to 0.055% by 2018.

Importantly, by itself this does not show whether flood events are fewer or vulnerabilities have declined, but it does show that flooding is

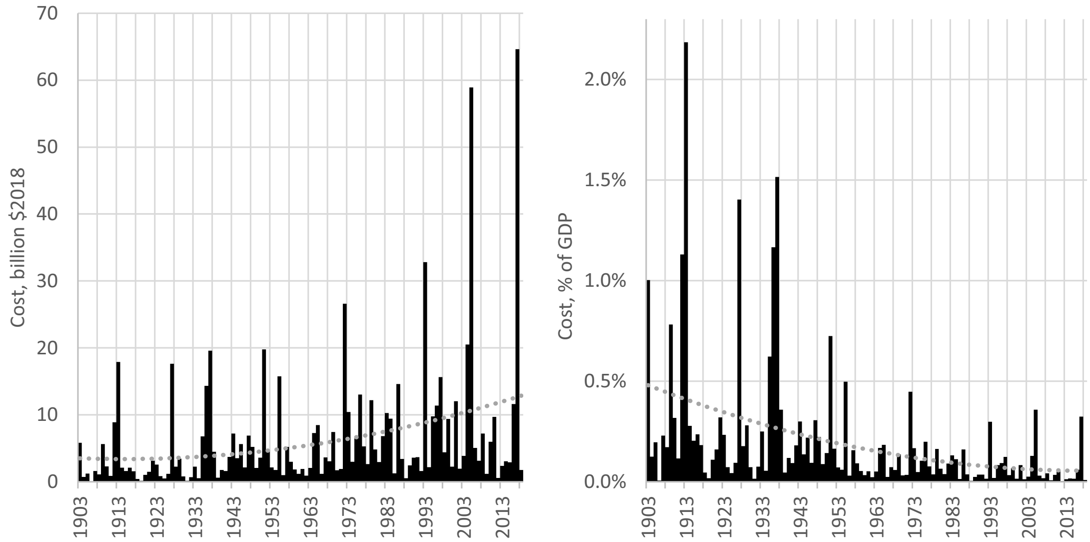

Fig. 10. Flood costs for the US, 1903–2018 in $2018 and in percent of GDP. Loss data from National Weather Services (NWS 2015), which discontinued its data from 2015. 2015–18 is from individual year reports, which do not seem entirely consistent with previous years (Statista 2018). GDP from (BEA 2019a; Smits et al., 2009), and when relevant adjusted for inflation by (BEA 2019b). Best estimate with 2nd order polynomial least square.

not getting out-of-hand but rather constitutes an ever-smaller problem for the American economy.

2.5. Wildfire

A recent academic paper on wildfire summarizes:

> *many consider wildfire as an accelerating problem, with widely held perceptions both in the media and scientific papers of increasing fire occurrence, severity and resulting losses. However, important exceptions aside, the quantitative evidence available does not support these perceived overall trends*. (Doerr and Santín 2016)

By examining sedimentary charcoal records spanning six continents, we find that global burning has declined sharply since 1870 (Marlon et al., 2008). To a large extent this is because of the so-called pyric transition, where humans stopped burning wood at home and started burning fossil fuels in power plants and cars (NAS 2017, 13). This means that today, fire has all but vanished from houses. As one fire-expert points out, it is "possible to live years in a modern house without ever seeing the fires that once, almost by definition, made a house a home" (Pyne 2001, 161). By boxing in fire in engines and power stations, we have been able to reduce its presence in the rest of the world.

There is plenty of evidence for this reduction in fire (Arora and Melton 2018; Li et al., 2018; Yang et al., 2014), with satellites showing a 25% reduction in burnt area just over the past 18 years (Andela et al., 2017). As is evident in Fig. 11, the primary factor in global burnt area reduction over the past 110 years is humans: when they start living and planting crops they want to avoid fire (Knorr et al., 2014), and do so with fire suppression and forest management.

While deforestation has reduced the amount of forests, it is likely that fires in forests have declined even in percentage of the remaining forest areas across the past century. A recent simulation shows that the burnt area for crops and pasture has increased globally since 1900, but burnt area in secondary and especially primary land (disturbed but recovering and undisturbed land) has declined more, reducing annual burnt area by a third (Ward et al., 2018, 135). If the fraction of burning in forest and non-forest primary and secondary lands has stayed constant, this means that even forests are now experiencing less burnt area, given that forested areas have declined less at 15% (Hurtt et al., 2011, 137–138).

For nations, we have the longest forest fire data series from the US. The US National Climate Assessment's main conclusion on wildfire is that "incidence of large forest fires in the western United States and Alaska has increased since the early 1980s" and that these are projected to increase further with higher temperatures (USGCRP 2018, 231). While the factual part of this quote is correct and the projection likely correct, it needs to be seen in context. Yang et al., 2014, 259–260) finds that fire suppression in the US and elsewhere has about halved burnt area in the northern extra-tropics, and only in the last decades has it picked up a couple of percent.

If we look at the entire US wildfire data set in Fig. 12, as documented by the US Forest Service, we see that while there has been an increase from 3 million acres burnt in the 1980s to 7 million in this decade, it is dwarfed by the 39 million annual acres burnt in the 1930s and likely even higher burn rates before that.[5] Thus, if anything, while

[5] Some have tried to contend that this early burn data should not be used, because they may be less fact-checked (Hausfather 2018). Spokesperson for the National Interagency Fire Center, Randy Eardley, insists

"I wouldn't put any stock in those numbers. … Back then we didn't have a reliable reporting system; for all I know those came from a variety of different sources that often double-counted figures. When you look at some of those years that add up to 60 or 70 million acres burned a lot of those acres have to be double counted two or three times."

Of course, arguing without data that these figures "for all he knows" *might* have been double or triple counted is a poor argument. Nowhere in the data do they add up to 60 or 70 million acres (1930 is the highest at 52.3 million acres). These data have been gathered by the US Forest Service *Forest Fire Statistics* since 1930 (USFS 1931), and are accessible for each year. The whole data series has been gathered in the US Historical statistics of the United States (Census 1975). The majority of the burnt area comes from unprotected areas, and the data comes from participating states reporting to the USFS.

In (USFS 1931), it is possible to see that the burnt areas for 1930 comes predominantly from Florida (18 million acres), Georgia, and South Carolina (about 5 million acres each), Mississippi (7 million acres), and Arkensas (almost 5 million acres). This fits with the view of Florida, according to a college fire textbook: "in the early 20th century, the saying was, 'Florida burned twice a year'. Ranchers burnt late in the dry season, just before the rains, and often they burnt again at the end of the dry season to encourage a second growth of forage. This is no doubt an exaggeration, but one with a hefty kernel of truth. In the early 20th century, the state forester announced that 115% of the state had burnt over the past year" (Scott et al., 2014, 226–27).

These early data have also been used in a wide range of credible publications

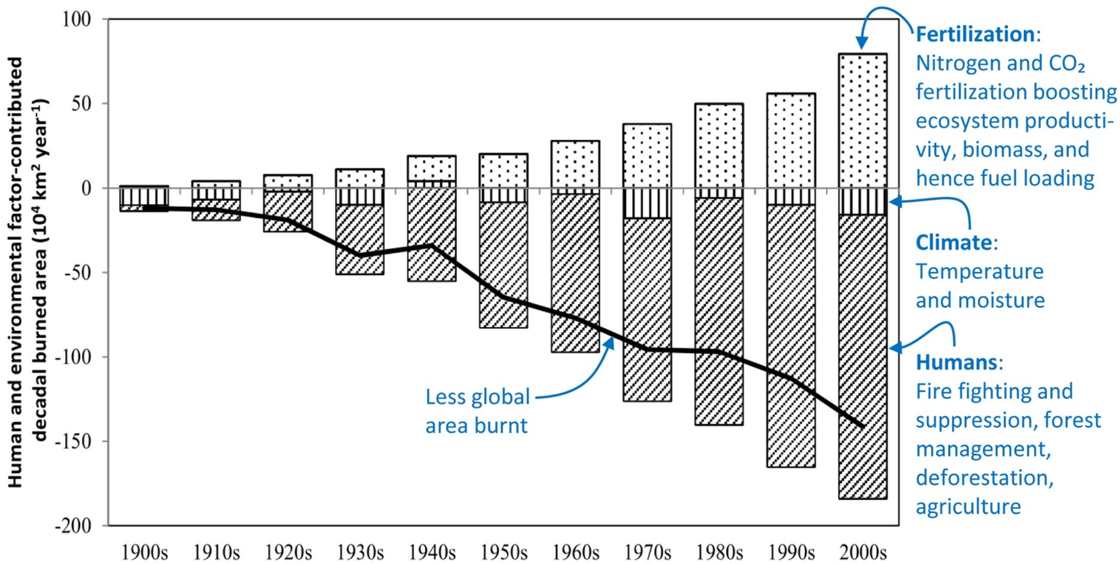

Fig. 11. Changed burnt area from 1901–2007, based on model runs with and without humans, climate, CO_2 and nitrogen deposits. This graph identifies how humans and climate are reducing burnt area, whereas fertilization with nitrogen and CO_2 increases the burnt area. In total, burn area has declined more than 1.4 million km^2, from almost 5 million in the 1900s to just above 3.5 million km^2 in the 2000s, (Yang et al., 2014).

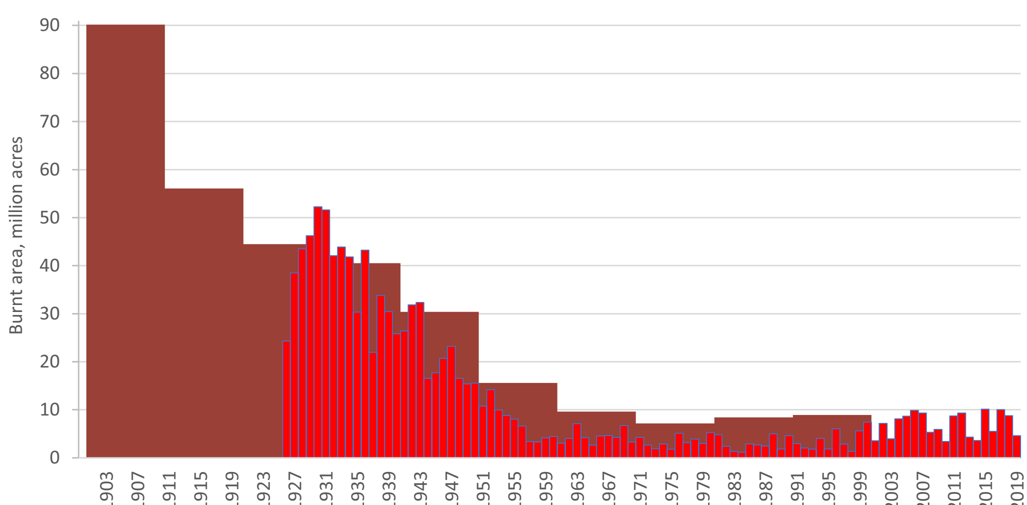

Fig. 12. Wildfire burnt area in the US 1926–2018, and estimated decadal burnt area 1900–2000. Annual data from (Census 1975, L48-55; NIFC 2019), decadal data from (Mouillot and Field 2005, 404–5). (Reynolds and Pierson 1941, Table 4) indicates that fire consumed even more of the US forests in the 19th century; see also (Marlon et al., 2012).

climate change might be increasing burn risks, it does so from a very modest level, compared to historical data.

As in other areas we have discussed, the conversation on wildfire often leaves out the human component. A study showed the relative effects on fire and found that when humans are around, they override the effect of climate (Syphard et al., 2017). Specifically, they found only human variables were significant for fire, such as "distance to road," "distance to developed," "population," and "proportion developed," whereas "precipitation" and "temperature" were very insignificant and explained nothing.

The expanding bull's-eye effect is clear in Fig. 13, which shows an increased number of people and their possessions being placed in fire's way. In 2010, the US had 124 million housing units, 700% of the number in 1940 (Strader 2018, 549). For the Western US, 22 million homes in 2010 were 1,250% of the number in 1940.

But what matters for risk increase is the number of houses built where fire happens. Since most of the risk is in the West, the entire US only saw about 6 million houses or 5% of its increase going into these risk zones. But *within* the Western US, about a third of all new homes were built in medium-to-very high fire risk zones.

(footnote continued)
(Hill 1999, 15; Keeley and Syphard 2017; McKelvey and Busse 1996, 1120; Pyne 2004, 201; Littell et al. 2009, 1005). Perhaps most telling, these numbers were entirely embraced by the US government at the time, here from a national publication by the assistant to the chief of the US Forest Service, starting: "The American record of land misuse is almost unparalleled. Forest lands, which constitute almost one-third the area of the continental United States, offer a striking example. Today a little more than two-thirds of them—and three-fourths of the most valuable, or commercial forest lands—are in private ownership. On these lands in recent years fires *have burned about 40,000,000 acres annually*—an area greater than that of Connecticut, Massachusetts, New Hampshire, Virginia, Maryland, and West Virginia combined" (italics added, Hammatt 1936, 1).

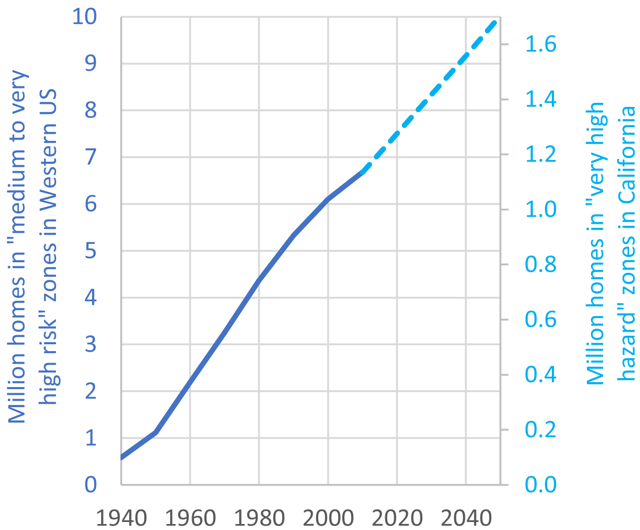

Fig. 13. Million homes in high wildfire risk zones from 1940–2050. Data from 1940–2010 is from (Strader 2018, 557) and covers homes in medium to very high fire risk zones in the entire Western US. Data for 2010–2050 comes from (Mann et al., 2014, 447) and is a BAU growth projection of homes in California within very high fire hazard severity zone. Notice the different scales for Western US on the left and California on the right. The risk zones are not comparable; fire risk is actual fire risk, since that risk is much higher around Idaho, the worst in California is only "medium." California zones are based on wildfire hazard severity zone by the California Fire and Resource Assessment Program.

Thus, in 2010, the number of houses at risk in the West is 1,150% of what it was in 1940. Even if the fire risk remains the same, we are likely to see many more structures destroyed by fire.

Another study shows the likely risk increase in a subset of the Western US, namely California, up to 2050 (Mann et al., 2014). Using physical hazard zones based on factors like vegetation density and slope severity, they project under Business-As-Usual the number of houses in the highest fire hazard zone, and find the number will likely increase by 50% to 1.7 million homes in 2050.

As Fig. 13 suggests, the two studies probably show about the same trend for California and for the Western US. That means that in 2050, the number of houses at risk of fire will be 1,700% of what it was in 1940, entirely because of more houses built in high-risk zones.

I am not aware of any US estimates for fire costs, adjusted for risk increases, but several studies of bushfire (wildfire) in Australia have done exactly that (Crompton et al., 2010; McAneney et al., 2019). They find that while bushfires since 1925 have destroyed more houses and killed more people, this is because of more people and more houses in vulnerable areas. When the number of houses damaged is adjusted for the number of houses at risk, the trend in houses damaged is (insignificantly) decreasing (Crompton et al., 2010, 305). Similarly, normalized damage costs from bushfires declined (insignificantly) from 1966 to 2016 (McAneney et al., 2019, 17)

Future wildfire is estimated to increase with global warming. Globally, compared to the year 2000, a worst-case, high warming trend will increase global burned area by 8% in 2050 and 33% in 2100 (using RCP8.5 and changes in managed lands (Kloster and Lasslop 2017, 64). In California compared to 1961–1990, global warming by itself will increase median burned area by 15–20% in the middle of the century, and 40% towards the end of the century (Bryant and Westerling 2014; Fig. 2). But the 15–20% climate-driven increase for California from 1976–2050 is rather small compared to the almost 300% increase in number of houses in the highest hazard zone over the same period (Fig. 13). This shows that the planning decisions on where to place future growth of houses is much more important than the climate impact. That is also the conclusion of a study on future wildfire risk in California: "the effects of growth scenarios tend to dominate those of climate scenarios" (Bryant and Westerling 2014).

Wildfire has declined dramatically, both globally and for the US, over the past century. While it is likely global warming will increase wildfire somewhat in the future, the much larger impact will come from planning decisions of whether to allow much more housing in high-risk areas.

2.6. Hurricanes

Hurricanes, or tropical cyclones, are the costliest catastrophes in the world. The cost of US landfalling hurricanes alone constitute two-thirds of the entire global catastrophe losses since 1980 according to global reinsurer Munich *Re* (Weinkle et al., 2018). Hurricanes Katrina, Sandy, Harvey, Irma, and Florence have all been used as examples of how global warming is making extreme weather worse—perhaps most pithily in the Bloomberg *Businessweek* cover of Hurricane Sandy with a picture of a blackout New York and letters in font size 300: "It's Global Warming, Stupid" (Barrett 2012).

Yet, this is not what the peer-reviewed literature says. The IPCC concludes that we cannot confidently attribute hurricanes to human influence: "There is low confidence in attribution of changes in tropical cyclone activity to human influence" (IPCC 2013a, 871). Indeed, globally, hurricanes are not getting more frequent: "current data sets indicate no significant observed trends in global tropical cyclone frequency over the past century" (IPCC 2013a, 216). However, they do find that "frequency and intensity of storms in the North Atlantic have increased" but because of particulate air pollution (IPCC 2013a, 50, 7). We cannot blame this storm increase in the Atlantic on climate: "the cause of this increase is debated and there is low confidence in attribution of changes in tropical cyclone activity to human influence" (IPCC 2013a, 113).

The US National Climate Assessment agrees that hurricane activity in the Atlantic has increased, but attribution is not currently possible (USGCRP 2017, 259, 258).

The latest paper confirms this: "currently we cannot attribute changes in North Atlantic hurricane intensity to human-related forcings" (Trenary et al., 2019). The Geophysical Fluid Dynamics Laboratory at NASA similarly tells us that not only is attribution not yet attainable, but we can't know for at least a couple of decades (GFDL/NASA 2019). They tellingly conclude: "the historical Atlantic hurricane frequency record does not provide compelling evidence for a substantial greenhouse warming-induced long-term increase."

Moreover, as Fig. 14 shows, the number of continental US landfalling hurricanes shows no trend in frequency or intensity — in fact, the trend is slightly (statistically insignificant) *declining* for both all and major (category 3 and up) hurricanes (Klotzbach et al., 2018).

So while Bloomberg and many news media sources confidently claim that hurricanes are being exacerbated by global warming, it would be more helpful to look at the bull's-eye, which is definitely expanding.

As Fig. 15 shows, the US population since 1900 has more than quadrupled. But moving to the coastline has clearly been much more alluring. The population of all the coastal counties from Texas to Virginia on the Gulf and Atlantic coast has seen population increase from less than 2 million to more than 31 million in 2020, 1,640% of the 1900 population. There are now many more people living in Dade and Broward counties in South Florida than the entire coastal populations from Texas to Virginia in 1940. Incredibly, Florida's 35 coastal counties have increased a phenomenal 67.7 times, from less than a quarter-million to over 16 million in 2020.

Clearly, when a hurricane hit in the past, it would only affect a much smaller number of people—if a hurricane ripped through Dade and Broward today, it would in some way be the equivalent to a

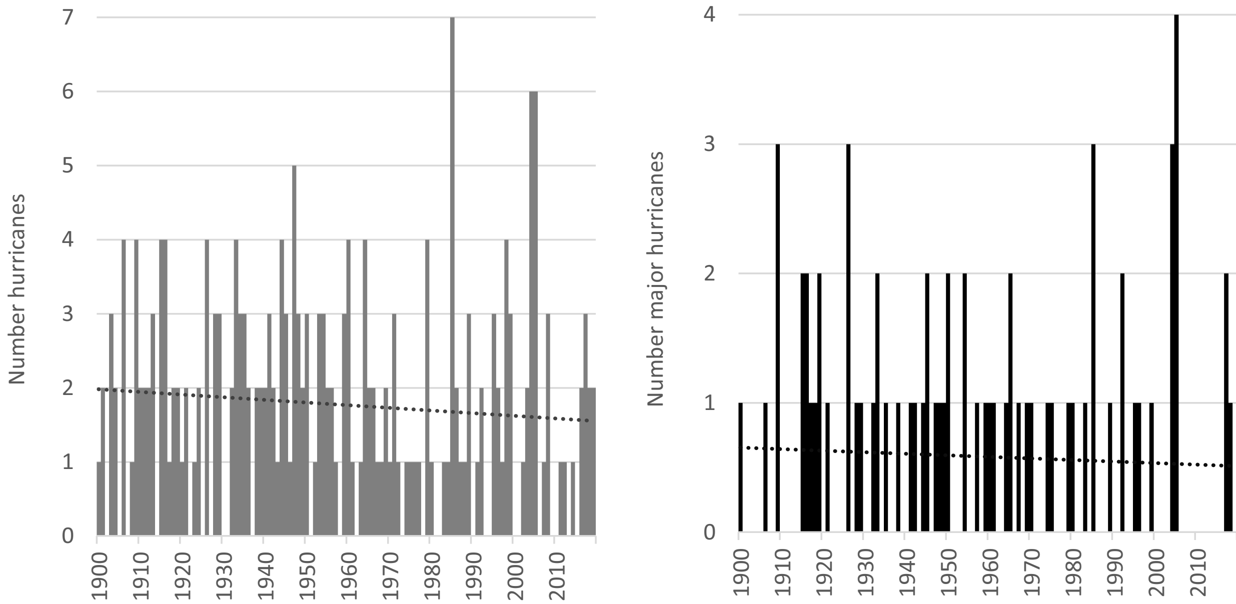

Fig. 14. Number of continental United States landfalling hurricanes 1900–2019. Left, all hurricanes, right, major hurricanes (category 3 and above), with (insignificant) regression lines, (Klotzbach et al., 2018), with 2018–19 from personal communication with authors.

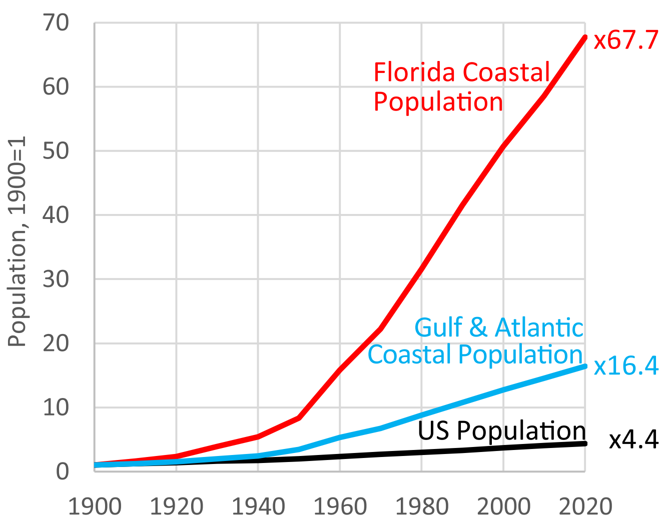

Fig. 15. Population index (1900 = 1) 1900–2020 for the US, the 123 coastal counties on the Gulf and Atlantic coast until and including Virginia, and the 35 coastal counties in Florida. Data 1900–2010 from (Census 1992, 2010, 2012), and 2020 data for the US from the 2017 population prediction (Census 2017) and using linear extrapolation for each county in the two other data sets.

hurricane ripping through the entire Gulf and Atlantic coast in 1940.

Housing units on the coast have similarly seen a spectacular increase (Freeman and Ashley 2017). In 1940, there were 4.4 million units within 50 kms of the coast all the way from Texas to Maine. In 2000, the 26.6 million units were 600% of the 1940 number. And almost everyone wants to live close to the coast—the first 50 kms have twice as many houses as the next 150 kms inland.

That many more people live in the paths of hurricanes with many more (and more expensive) houses goes a long way to explain why the cost of hurricanes keeps going up as seen on the left in Fig. 16. This data is often used to suggest that global warming is making hurricanes worse and more damaging.

But correcting for the many more people and more expensive houses tells a very different story. Consider the Great Miami Hurricane of 1926, which tore through downtown Miami. Because only about 100,000 people lived there at the time, with less costly houses, the inflation-adjusted damage ran to $1.3 billion. However, modeling the cost of the very same hurricane tearing down the same path today would make it the costliest US catastrophe ever, with damage worth $254 billion. Modeling all 212 US continental hurricane landfalls as if they landed in today's setting of people and infrastructure corrects for the expanding bull's-eye and shows that there is no significant increase in hurricane-adjusted costs: this can be seen on the right in Fig. 16. Similar results are found for Australia (McAneney et al., 2019) and China (Chen et al., 2018).

Looking to the future, the IPCC finds that the best, but weak, evidence suggests that hurricanes will become fewer but more intense, as does USGCRP and GFDL (GFDL/NASA 2019; IPCC 2018, 178; Keigo USGCRP 2018, 257). This will lead to more costly hurricanes. But as population keeps growing and the number of houses 50 km from the coast could more than double this century, these changes will increase damages much more, swamping the climate signal. In one recent model (Gettelman et al., 2018), the researchers first take out social change, so society stays as it is today, and explore what will then happen with hurricane damages from much increased sea temperatures that could take place in 2070–90. They find that total global damages from hurricanes will increase from $67 billion to $97 billion, a 45% increase. However, the impact is much worse if we keep temperatures as they are today but let society grow richer, with more people and goods in harm's way. This will cause hurricane damage to grow much faster to about 300% of today's cost.

Simulating stronger adaptation as societies grow richer and expressing the costs in percent of GDP makes this point even clearer. Today, hurricanes cost about 0.04% of global GDP (Bakkensen and Mendelsohn 2016; Mendelsohn et al., 2012). Over the century, society will keep getting richer and able to afford to spend more resources on resilience and adaptation. If we assume hurricanes stay as today (no climate change), global hurricane damages in 2100 will make up a much lower cost share of 0.01% of GDP. However, if we expect stronger but fewer hurricanes, along the lines of IPCC's projections, the global

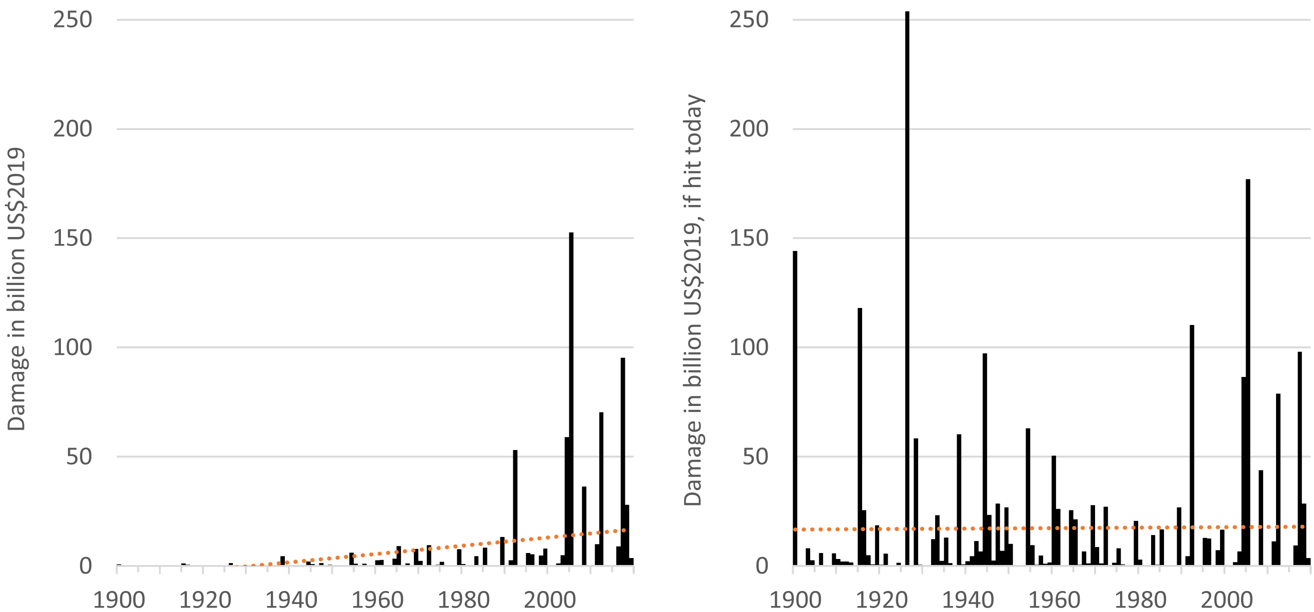

Fig. 16. Left side, cost of all landfalling hurricanes in the continental US from 1900–2019 in $2019. Right side, same hurricanes, cost if they had hit the US as it looks today (Pielke and L.andsea, 1998, 199; Klotzbach et al., 2018; Weinkle et al., 2018, 2005), with 2018–19 from personal communication with Pielke. Dotted line is linear best fit.

cost share will increase to 0.02% of GDP. Taking a step back, climate change will make future hurricanes more damaging (0.02% instead of 0.01%), but because the world is getting much richer, hurricanes will have a *lower* cost share in 2100 than they do today (0.02%, not 0.04%).

Thus, decision-makers should consider how to best reduce hurricane damage: through climate policy that reduces future temperature rises, or through social policies that reduce vulnerability through adaptation or lifting people out of poverty. As we will see later, even very strong climate policy will cost a lot but only have a little temperature impact in many decades. Therefore, it turns out that social policies are typically much more effective—for some interventions, a dollar spent on reducing vulnerability can help 52 times more than one spent on climate policy (Pielke 2007).

2.7. Becoming more resilient: wealth and human ingenuity

When looking to the future, it is easy to foresee problems but harder to envisage solutions. We started this section looking at coastal flooding with and without adaptation (Section 2.2). As sea levels rise, it is easy to think more people and structures will be flooded. The reality is that humanity is ingenious. Richer people will have more options to be resilient, protecting land, valuables, and people, resulting in fewer people flooded and a lower damage fraction of GDP.

We will see this globally documented below, resulting in fewer climate-related deaths and a lower weather-related fraction of GDP costs. But here, it is worth noticing how this resilience is already playing out in a myriad of local and global settings.

Globally, over the past 30 years, rising sea levels have *not* resulted in more land underwater. Adding up all the coastal land lost and reclaimed, it turns out that the total coastal area has increased by more than 13,000 km^2 (Donchyts et al., 2016). This is perhaps most visibly the world's largest coast reclamation of the 80 km^2 of Palm Island and adjacent islands along the coast of Dubai, but across the world, many countries have shaped and extended their coastlines by land reclamation. Bangladesh, despite popular understanding, has net added about 480 km^2 of land in the face of sea level rise.

Locally, we see this adaptation most clearly where catastrophes have made sea level rise much faster. The small Ubay island at the center of the Philippines has never been more than a sand bank, at high risk of flooding (Esteban et al., 2019). After a 7.2 magnitude earthquake in 2013, it experienced land subsidence probably in excess of 1 m, so that it is now completely submerged during the highest tides of the year.

Despite attempts to relocate the impoverished community to the mainland, residents have remained, adopting century-old adaptation strategies of elevating the floors of their houses using coral stones, or placing their houses on stilts. At the same time, they elevate their belongings using especially adapted furniture, and use elevated pathways that traverse the island, so they are still mobile during high tides, collecting rainwater in water tanks. They have also adapted their evacuation strategies from being evacuated only in strong typhoons to evacuating to the mainland in weaker storms. One meter of sea level rise leaves communities on low-lying islands worse off, but even if they are very poor, they can adapt and essentially ward off most of the negative impacts.

Resilient adaptation is even achievable for richer but still developing nations. Indonesia's capital Jakarta, home to more than 12 million people, has for decades seen land subsidence from groundwater extraction and the load of buildings and constructions compressing the soil (Abidin et al., 2011). Since 1925, the coastal half of the city has subsided by 2–4 m (Andreas et al., 2018; Fig. 2). Coastal GPS indicate subsidence rates of about 10 cm per year (Abidin et al., 2011, 1765). The huge coastal development area of Pantai Mutiara has subsided by 1.8 m in the last 19 years, now having a mean elevation of 31 cm below sea level (Park et al., 2016).

Yet, Jakarta has largely tackled this through building dikes and elevating port wharfs, along with elevating new construction areas, while reclaiming land with new luxury projects (Esteban et al., 2019). (Of course, ending groundwater extraction would by far be the most effective way to stop Jakarta from sinking further.)

Stepping back, Jakarta is dealing with a relative sea level rise of 1.8 m in just a few decades, much more than worst-case global projections for the next eight decades. It is doing so with ingenuity and technological capability supported by more financial resources.

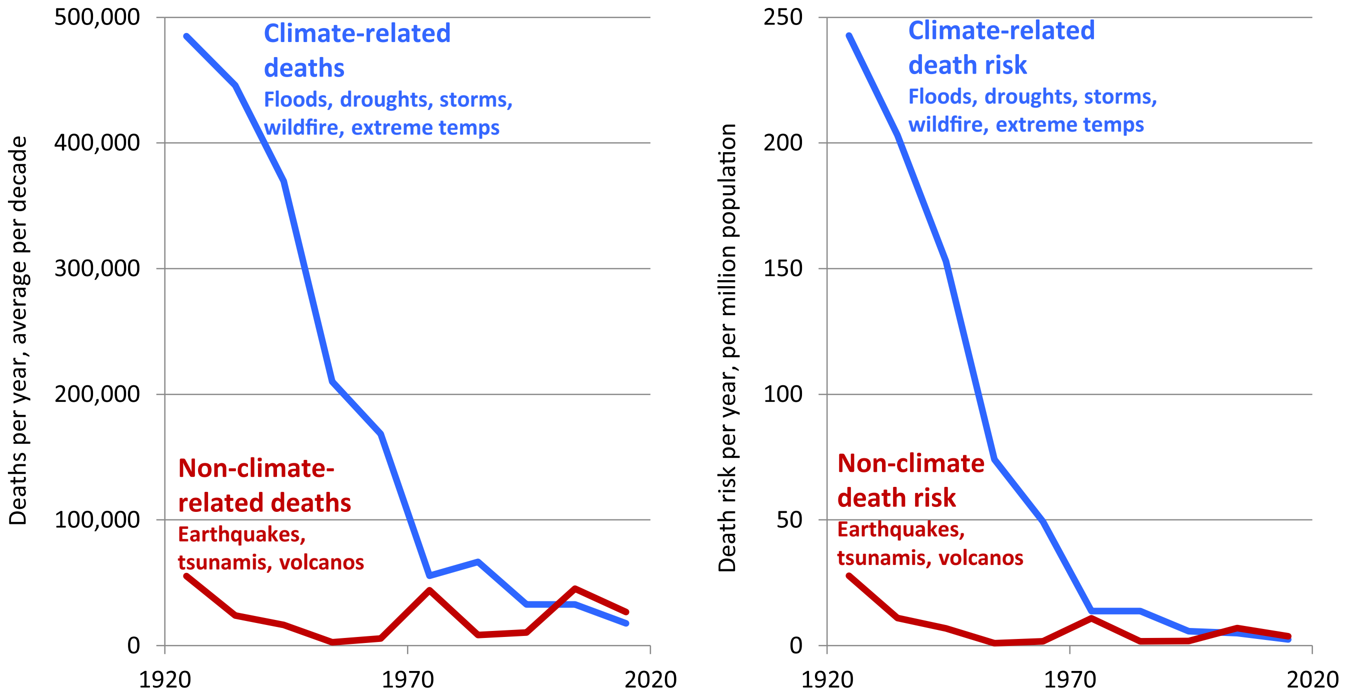

Fig. 17. Climate and non-climate-related deaths and death risks from disasters 1920–2018, averaged over decades. Data comes from EM-DAT (2019), using floods, droughts, storms, wildfire, and extreme temperatures for climate-related deaths, and earthquakes, tsunamis, and volcanos for non-climate-related deaths. Average per decade 1920–29, 1930–39 up to 2010–2018, with data plotted at midpoint (1924.5, 1934.5, with last incomplete decade at 2014). For instance, the 2004 tsunami, which killed 227,000 people, shows up as 22,700 people each year for 2000–2009. However, the tsunami "only" contributed about half of all deaths from non-climate-related deaths in the 2000s at 454,000, making the annual non-climate-related deaths for the 2000s 45,400. Population data from (OurWorldInData 2019).[7]

A case from a rich country comes from the 2011 Tohoku earthquake and tsunami, which not only devastated Japan but also caused a substantial sinking, lowering the northeastern part of Japan by 78 cm (Esteban et al., 2019). This caused much of the coastline to be barely above sea level and large parts to be flooded at high tides. The Japanese government responded with a massive program of public works, raising some areas by up to 8 m and whole cities by 3 m, ensuring that no ground was lost to the sea (Esteban et al., 2015; Esteban et al., 2019). Of course, rich world wealth makes such an effort possible, but the fact that 200 km of coastline can be raised in a matter of years shows that it is possible and feasible to see adaptation to lower effective sea level rises happen over a century.

2.8. Becoming more resilient: fewer deaths

When establishing the seriousness of the impact of a catastrophe, maybe the single most important human measure is the death toll or, more technically, the excess death rate (Ó Gráda 2010, 86–87). Unlike most other measures like "people affected" it is not subject to shifts in social constructs. Nonetheless, evidence shows that demographic calculations typically lead to lower estimations of excess deaths than those provided by journalists and other contemporary observers (WPF 2019). Reaching back in history, more of the estimates are provided by observers rather than based on academic study, which possibly gives earlier data an upward bias. On the other hand, it is also likely that going back in time, the historical record leaves out more catastrophes, and that earlier events are also less likely to be recognized or recorded as catastrophes, conceivably causing a downward bias (Hasell and Roser 2017).

The leading database for all catastrophes is the International Disaster Database, commonly known as the Emergency Events Database (EM-DAT 2019). From 1900 to 2019 it lists 38.6 million deaths from disasters. About 39% are labeled biological (viruses and bacteria) and what they call "complex" but is almost entirely the politically enforced 1932 starvation in the Soviet Union (the Holomodor). The other 23.4 million deaths fall into four main categories: 50% droughts, 30% floods, 11% earthquakes, and 6% storms, with 3% from all other causes (such as avalanches, heat waves, mudslides, etc.).

Take these disaster deaths and split them into deaths that could either be affected by climate (that is, weather disasters that could be affected by the changing climate) and not affected by climate, and take the averages of deaths across decades (given the high year-on-year variance) and we get the graphs shown in Fig. 17.

In the right panel, we see the annual death risk for a single person from both climate-related and non-climate-related deaths has declined, indicating a lower social vulnerability. However, climate-related risks have declined much more: over the past century, the non-climate risk has declined by 85% but the climate risk has declined by an astounding 99%. Had a person lived her entire 70-year life at the climate-related risk in the 1920s, she would have had 1.7% chance of dying from a climate-related catastrophe.[6] Living at the risk of the 2010s, the life risk for dying of climate-related disasters was 0.018%.

In total numbers, the decline is smaller (as the global population has quadrupled), but still impressive at reducing global deaths from climate-related disaster from almost half a million people each year to less than 20,000 per year in the 2010s—a reduction of 96%. For non-climate-related deaths, the reduction is about 50% from the 1920s to the

[6] One minus the binomial of every year not dying for 70 years, with death risk of 243 of a million (0.0243%), or 99.97575ˆ70 = 98.3%, or death risk of 1.7%.

[7] Data showed in figure starts from 1920, since there seems to be many more disasters missing in the 1910s than in other decades. Comparing deaths from droughts from EM-DAT with the famine list in (Hasell and Roser 2017), they match up about 1:3. However, the 1910s have EM-DAT only describe one-eighths of the numbers found by Hasell and Roser, for instance leaving out the 1917-19 Persia drought/famine, which (WPF 2019) puts at 455,000 dead, but seems to be more likely estimated at around 2 million (https://en.wikipedia.org/wiki/Persian_famine_of_1917%E2%80%931919).

2010s, but the trendline is almost flat.

It is to be expected that it is much harder to avoid death from non-climate-related disasters, since these are mostly earthquakes that are hard to predict. Hence, only better building standards can help. However, the large reduction in climate-related deaths from disasters shows a dramatic increase in climate resilience, likely mostly brought about by higher living standards, a reduction in poverty, improvement in warning systems, and an increase in global trade, making especially droughts less likely to turn into widespread famines.

The same declining trend for climate-related mortality rates is found across individual hazards from flood, flash flood, and coastal flood, over heat and cold deaths to drought and wind damage (Formetta and Feyen 2019). A 10-year moving average from 1980 to 2016 shows a 6.5-fold reduction in the mortality rate (ranging from a twofold reduction in floods to a 16-fold reduction in flash floods).

We often forget how much of the world was devastated by famines in previous centuries. Although famine outside of wartime disappeared from the developed world after the mid-nineteenth century (Ó Gráda 2010, 8), large famines continued in poorer countries, with the late 1870s killing more than 7 million in India and 9.5–13 million in China (Ó Gráda 2010, 21). Even the 1928–30 drought was described by the Committee of the China Famine Relief Fund as "one of the most wide-spread and severe famines in many decades," spreading inland to the upper reaches of the Yellow River, Inner Mongolia, Gansu, and Shaanxi, where "three successive harvest...failed to materialize," leaving more than 50 million people in total '"severely affected" (Fuller 2015, 157–58). In total, the Famine Trends Dataset estimates 5.5–10 million dead (WPF 2019), with EM-DAT conservatively counting 3 million deaths.

Fig. 17 shows that we are now much less vulnerable to climate impacts than at any time in the last 100 years. It is possible that climate change has made impacts worse over the last century (although the discussion on floods, droughts, wildfire, and hurricanes suggests this is not the case), but resiliency from higher living standards has entirely swamped any potential climate impact.

2.9. Becoming more resilient: impact costs

The second-most important impact measure after deaths is the total cost. In the US, one such measurement of costs from climate impacts is the heavily promoted "Billion-Dollar Weather and Climate Disasters" (NCEI 2019). This time series shows how the number of disasters costing an inflation-adjusted billion dollars or more has increased from about three in the early 1980s to about 15 in the late 2010s, and is commonly referenced to show how increasing temperatures cause more climate damage. In early 2019, a *Washington Post* article was distributed across the US with the telling headline: "More billion-dollar US disasters as world warms" (Dennis and Mooney 2019). In strong language, the journalists outline how the "number of billion-dollar weather disasters in the United States has more than doubled in recent years, as devastating hurricanes and ferocious wildfires that experts suspect are fueled in part by climate change have ravaged swaths of the country," citing an "alarming trend" which is "fueled, at least in part, by the warming climate."

In an economic commentary, Zagorsky, 2017 critiques the NCEI billion-dollar disaster statistic:

> *Even with the inflation adjustment, a key reason we have more costly disasters is simply that the economy is much bigger today than it was in the 1980s.*
>
> *When the economy was smaller, disasters caused less economic damage. There were fewer homes, factories, and office buildings to destroy, so it was harder for a natural disaster to cause a billion dollars' of damage.*
>
> *Since 1980, the U.S. economy has more than doubled. … In other words, a storm happening today will cause more damage than an identical one occurring decades earlier simply because there is more to destroy.*

He suggests a simple adjustment, setting a threshold each year that is equivalent to the fraction of the entire GDP of an inflation-adjusted billion-dollar destruction in 1980. That means that a billion-dollar disaster in 1980 would have caused $2.3 billion in costs in 2010, in a 2.3-times-bigger US economy. Thus, we should only count the number of disasters with a disaster cost higher than $2.3 billion This reduces the number of 1980-billion-dollar disasters in recent years dramatically.

While Zagorsky does not present any statistical test, it is easy to replicate his data, and his adjustment shows that the highly significant increase in billion-dollar disasters disappears. From a linear regression showing a highly significant extra billion-dollar disaster every four years, and an R^2 of 0.54, we get an insignificant, slight upwards slope of one billion-dollar disaster more every 25 years, and an R^2 of 0.06.

Moreover, as shown above with the increasing bull's-eye effect, GDP is sometimes likely to provide an insufficient adjustment, and at times this will be spectacularly insufficient. While the average GDP per person in the US increased 8.5 times from 1900 to 2016[8] and population increased 4.25 times, we would expect about 36 times as much damage (8.5 × 4.25) from more people and more expensive stuff. However, when Florida's coastal population increased more than 64 times, we should expect 544 times more damage from hurricanes in Florida. Using GDP will under-adjust by 15 times.

Thus, for the US, it is a better option to use the existing and specific data available with the relevant adjustments, which we saw above shows no significant signs of adjusted increase for hurricanes, floods, and droughts.

However, GDP adjustment is the only option for effectively comparing disaster costs across the world (Pielke 2019). Moreover, it is also how all the UN member nations have decided to measure progress on making cities and human settlements safe and resilient in Goal 11.5: "decrease the direct economic losses relative to global gross domestic product caused by disaster" (SDGs 2015), and in its indicators for reducing vulnerability to climate-related extreme events (IAEG-SDGs 2019, 1.5.2).

Since data before mid-1990s are not complete (Pielke 2019, 2), we start the analysis in 1990, although that may bias the analysis towards showing escalating disasters over time. However, the analysis, shown in Fig. 18, clearly demonstrates that global weather-related costs over the past 28 years have not increased. It has most likely declined from 0.26% of global GDP in 1990 to 0.19% in 2018. The other global disaster estimate, from Aon Benfield, is only available from 2000–18 (AonBenfield 2019). While it is generally a third higher than Munich *Re*, the data is closely matched (R^2 = 0.90) and if backcasting with Munich *Re* data to recover the data from 1990–99, it has an only slightly faster decline, from 0.34% to 0.27%.

The same declining trend for climate-related loss in percent of exposed GDP is found across individual hazards using Munich *Re* data. A 10-year moving average from 1980 to 2016 shows a 4.5-fold reduction averaged across all hazards mortality rate (Formetta and Feyen 2019, Table B2).

Thus, on the resiliency indicator as agreed by all nations in the SDGs, the cost of weather-related disasters relative to global GDP has not increased, and likely decreased. Again, this does not indicate that there are no relative increases in weather disasters (although the above discussions on droughts, floods, wildfires, and hurricanes also showed little or no increase globally), but only that resiliency has outpaced any such increase.

3. Global warming's total impact on current and future welfare

There is a literature going back almost 30 years trying to estimate the total costs of impacts of climate change (Cline 1992;

[8] https://ourworldindata.org/grapher/maddison-data-gdp-per-capita-in-2011us-single-benchmark?time=1900..2016&country=USA

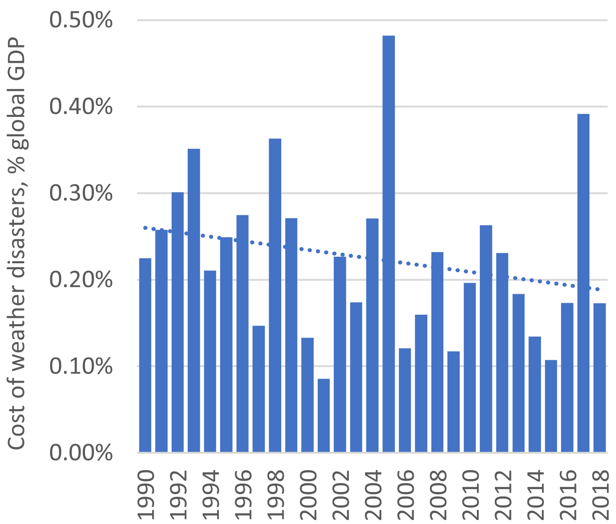

Fig. 18. Global weather-related disaster cost share of global GDP 1990–2018. Costs from 1990–2017 from Munich *Re* in (Pielke 2019), 2018 costs from (MunichRe 2019), global GDP from (Worldbank 2019), using the latest World Bank Global Economic Prospects GDP from January 2019 to estimate global GDP for 2017 and 2018. Linear best estimate, decline is not statistically significant.

Nordhaus 1991; Nordhaus and Moffat 2017; Tol 2009). These estimates typically try to capture the most important and highest cost impacts, such as agriculture, sea-level rise, energy, and forestry. Some, such as the FUND model, also include cost impacts from water resources, tropical storms, extratropical storms, biodiversity, cardiovascular and respiratory diseases, vector-borne diseases (such as malaria), diarrhea, and migration. Others, such as PAGE model, attempts to include costs of potential discontinuities, such as the Greenland ice sheet melting rapidly (Diaz and Moore 2017).

3.1. The climate damage functions from integrated assessment

The UN Climate Panel did a survey of all the relevant studies estimating the net costs of global warming at different global temperatures (IPCC 2014a, 690), and Fig. 19 shows the updated version. It indicates that now (with about 1°C global temperature increase), it is not even certain if the net global impact is positive or negative, but it is certainly not a large negative. The impact of 1.5°C is likely slightly negative — the latest IPCC report found that the cost of 1.5°C was 0.28% of global GPD (IPCC 2018, 256; Watson and Quere 2018, 23).

Nordhaus and Moffat (2017) examine a number of different ways to parametrize the data, settling on the median quadratic weighted regression, showed in Fig. 19. It estimates the cost of 4°C (which is likely what we will see at the end of the century without any additional climate policies) at 2.9% GDP loss. They point out that while most studies include key sectors, none include all sectors, with especially many non-market impacts missing, including losses from biodiversity, ocean acidification, and melting permafrost. While it stands to reason that the most costly sectors would have been modeled, the estimates are likely to be underestimates of the true damages. To adjust for that, Nordhaus and Moffat add 25% in damages, which while consistent with estimates from other studies (Nordhaus and Sztorc 2013, 11) is still somewhat of a judgment call, since it is essentially estimating what hasn't been analyzed. However, this means the best estimate for the damage of 4°C is a reduction of GDP of 3.64%. For comparison, the 1.5°C IPCC report finds the cost of unmitigated warming by 2100 to be 2.6% of GDP (at a slightly lower 3.66°C)(IPCC 2018, 256)

3.2. Agreement across integrated assessment models

The models that attempt to estimate the climate impacts and monetize their impacts are known as integrated assessment models (IAMs, e.g. IPCC 2014b, 422ff). There are at about 20 IAMs (Weyant 2017) but many are more detailed process IAMs, and we will here focus on the three most well-known and used costs and benefits IAMs, which have also been used by the US government to estimate the Social Cost of Carbon (IWG 2016), namely DICE (Nordhaus and Sztorc 2013), FUND (Tol and Anthoff 2014), and PAGE (Hope 2011).

Because IAMs can estimate the impact costs from unmitigated

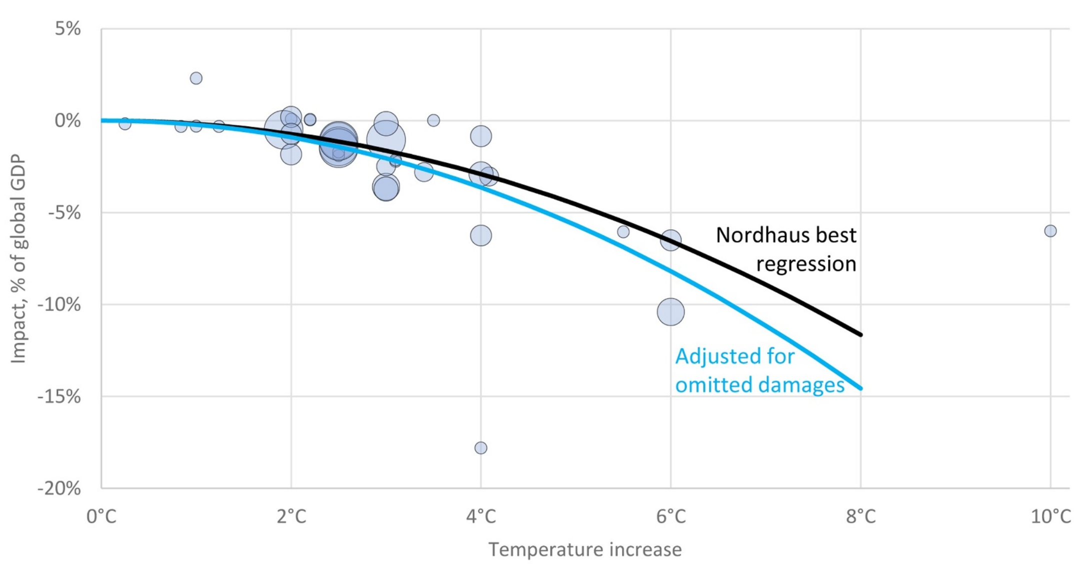

Fig. 19. Total impact from temperature increase measured in percent of global GDP, based on 38 published estimates in the literature (Nordhaus and Moffat 2017), which is an update of (IPCC 2014a, 690, SM10-4). Size of circles shows the weight of the individual studies (larger circles for latest estimates, using independent and appropriate methods, smaller circles for earlier estimates, secondhand studies or less appropriate methods). Best regression is estimated using median quadratic weighted regression (quantile regression). To reflect unquantified costs, the adjusted best regression has added 25 percent of the monetized damages to reflect these non-monetized impacts (Nordhaus and Sztorc 2013, 11).

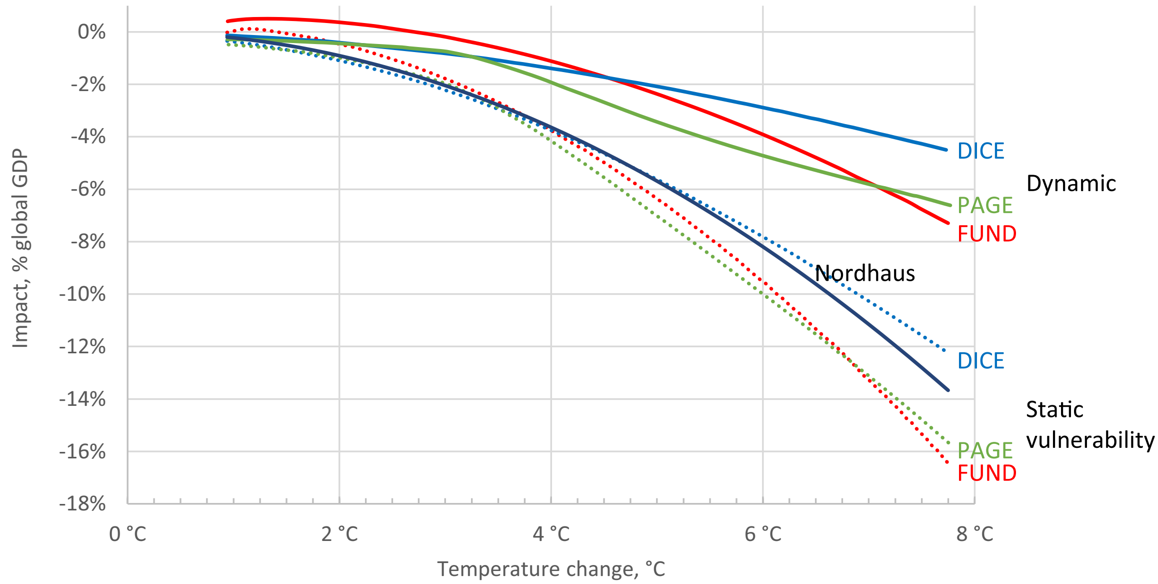

Fig. 20. Impact from temperature change for three IAMs, measured in percent of global GDP, for both dynamic (solid) and static (dotted) vulnerability (Diaz and Moore 2017, Fig. 2c). FUND originally includes dynamic vulnerability, whereas the solid DICE and PAGE are estimated. DICE and PAGE originally include static vulnerability, and the dotted FUND is estimated. The black curve denoted "Nordhaus" is the best estimate including omitted damages from Fig. 19.

climate and the policy costs from climate mitigation, they can help identify the optimal climate policy, which we will look at below. But their damage module can also help identify the global costs for different temperatures. It is often pointed out that while DICE and PAGE estimate similar levels of total damages, FUND projects much lower impacts, with global net benefits at lower levels of warming. However, this turns out to mostly rest on the fact that FUND models dynamic vulnerability, expecting richer populations to be less affected by most challenges (Diaz and Moore 2017; Tol 2002). For instance, the load of vector-borne diseases like malaria might increase as temperature increases, but when a population becomes sufficiently rich, it can afford an effective health care that essentially eradicates malaria.

In Fig. 20, we can see that the three IAMs, when they all include dynamic vulnerability, have about the same cost structure. Similarly, leaving out dynamic vulnerability for all three IAMs (the versions in dotted lines) indicate higher costs but are still fairly similar. Notice that PAGE explicitly includes catastrophic impacts after 3°C, which further emphasizes that these cost estimates are reasonable estimates of the full impact of temperature increases including potential catastrophes. Moreover, PAGE leaves out adaptation, which would again lower the cost estimates slightly.

In the following we will use the blue cost estimate from Nordhaus including omitted damages in Fig. 19, based on the literature review of available cost estimates, which is also marked as solid black in Fig. 20. This is, if anything, an overestimate as it both leaves out dynamic vulnerability and some adaptation, both of which would lead to lower estimates of costs.

3.3. Catastrophes, biodiversity, ocean acidification missing from the GDP costs?

While the costs in Figs. 19 and 20 are expressed in percent of GDP, this does not mean they are all monetary costs. Some, like changes in heating and cooling costs or hurricane damages, are clearly monetary costs. But others, such as cost of wetlands loss and biodiversity loss in FUND, are not. They are constructed to be understood as equivalent to an experienced welfare loss — that is, when we talk about a specific climate impact resulting in a 0.1% loss of GDP, it means the impact will have the same disutility as an income reduction of 0.1% of GDP.

Yet, a common objection to the Nordhaus' cost curve is that many important costs such as catastrophes, biodiversity loss, and ocean acidification have been left out (Diaz and Moore 2017; Weyant 2017). This objection is rather weak, for three reasons.

First, many of these problems are actually assessed in some or all the IAMs. For instance, all three models include some estimate of catastrophic impacts. PAGE includes an explicit estimate for the costs of increased risks of tipping points, such as the Greenland ice sheet disintegration and a disruption of the monsoon or of the thermohaline circulation. It is modeled as an increasing probability, starting at 3°C, of a 15% GDP loss. For 4°C it reaches a cost of 0.71% GDP. DICE includes catastrophic impacts in its net damage based on Nordhaus' survey of catastrophic outcomes (Nordhaus 1994). FUND similarly includes the costs of catastrophic outcome through tails of its parameter distributions.

Second, many of these omitted impacts are rather small. Nordhaus recently estimated the cost of one such catastrophe: the Greenland Ice Sheet entirely disintegrating over the next two thousand years (Nordhaus 2019). It shows that although the costs can mount to hundreds of trillions of dollars by the third millennium, by 2100 it will have a trivial impact. It will, through higher sea level rise, have a cost of $91 billion or 0.012% of GDP (and even by the year 3000 the cost incurred is rather modest at 1.3% of GDP).

Likewise, FUND includes a modeled cost of biodiversity loss of 0.21% GDP by 4°C (Diaz and Moore 2017). Compare this to the current annual global domestic spend on biodiversity at $20 billion (UNEP 2014, 435) or 0.027% of GDP, and the spend on all biodiversity and ecosystem services including development aid and agricultural subsidies at $52 billion (Parker et al., 2012, 29) or 0.077% of GDP. Despite UNEP calling for increasing investments to $150 billion–$440 billion per year (0.18–0.51%) for biodiversity, the spend has stayed almost constant at 0.027% (UNEP 2014, 435), indicating that the current revealed willingness to pay for securing biodiversity is not much higher than the present 0.027%.

The cost of acidification is not included in either model, and it has so far only been estimated in one study (Colt and Knapp 2016), which finds what a complete ocean acidification would imply, with 2000 ppm

CO_2 and average ocean pH of 7.5 by the year 2200. They model a complete collapse of commercial marine capture fisheries, a complete collapse of recreational and subsistence marine capture fish harvests, and a complete loss of tourism and recreation from coral reefs. This would not spell the end of fish consumption, because even very high acidification would have minimal impact on aquaculture, which is already now controlling all or most inputs, such as buffered water. And aquaculture is already producing two-thirds of the total, global, first-sale value of fish (FAO 2018, 2). Yet, the loss of ocean fisheries, recreational and subsistence fisheries, and all coral reef tourism and recreation is not trivial. The researchers estimate the worst-case cost of this complete collapse at $301 billion. Estimating the growth rate of the 22nd century as similar to the middle-of-the-road SSP2, this translates into global GDP by 2200 at $4,040 trillion, meaning that the worst-case cost of a complete marine fisheries and coral reef tourism collapse in 2200 is equivalent to a loss of 0.0075% of GDP.

Third, the 25% damage addition from the black to the blue line in Fig. 19 was exactly intended to include extra, uncounted costs. For the Nordhaus estimate at 4.1°C it leads to a cost increase from 3.06% GDP loss to a GDP loss of 3.82%. This means an estimate of unmodeled losses worth 0.77 percentage points. Compare this to the cost of current biodiversity of 0.027% of GDP, to the collapse of the Greenland Ice Sheet worth 0.012% of GDP, or the cost of a complete marine fisheries and coral reef tourism collapse at a cost of 0.0075% of GDP. This indicates that the 0.77 percentage point has space for very many left-out costs — indeed, it could accommodate a hundred different impacts, each as negative as the worst-case complete loss of marine fisheries and coral reef tourism collapse in 2200.

In conclusion, not only are catastrophes and biodiversity not absent from the impact models, but the additional 0.77 percentage points from unmodeled costs can accommodate these and many other such costs, meaning that this cost estimate is likely not underestimated.

3.4. Unrealistic alternative loss models

In the last years there has been an alternative approach to the mainstream climate cost estimates that have generated dramatically higher costs (Pretis et al., 2018) (Burke et al., 2015; Burke *et al.* 2018; Hsiang et al., 2017).

Here, let us concentrate on Burke et al. (2015) and its clone (Burke et al. 2018), which both produce a global estimate. The first paper contributes global estimates of the damage impact from global warming, showing that impacts for SSP5 in 2100 likely will reduce global GDP by 23%, which is “many times larger than leading models indicate.” This result stems exclusively from estimating how national growth rates depend on the average national temperature. They find that cold countries grow less fast when temperatures drop for a single year, and grow faster when temperatures are slightly higher in one year. The obverse is true for hot countries, where cold shocks increase growth rates, and heat shocks decrease growth rates. They find the inflection point at 13°C. If these trends hold for the rest of the warming century, they find that cold countries will grow faster and hot countries slower than they would otherwise have done. In 2010, the majority of the world's GDP was created in countries below 14°C (the US is at 13.6°C). But most of the population is in countries above 14°C, and the expansion over the 21st century in both GDP and population will mostly take place in countries over 14°C. So, in 2100 with the SSP5 and a population-weighted temperature rise of 4.3°C (from RCP8.5), more than eight times more GDP will be produced in countries with an average temperature above 14°C. Thus, if the growth rate increases for the countries below 13°C but decreases for countries above 13°C, the slowdown will be large and cumulative over the 21st century.

These results crucially rely on an absence of adaptation over the 21st century. In their description of the data, they claim that “results using data from 1960 to 1989 and 1990–2010 are nearly identical (Fig. 2c)” and that “substantial observed warming over the period apparently did not induce notable adaptation.” Yet, the growth relationship for the two time periods as shown in their Fig. 2c actually changes from an optimum of 12.3°C to an optimum of 14°C, a change of 1.7°C, whereas the average temperature between the two time periods changed just 0.39°C (HadCRUT4 2019). So, surprisingly, based on their own evidence, the world *more* than adapted to the temperature increase of 0.39°C.

So, instead of extrapolating without adaptation and finding a 23% reduction, one could more reasonably argue that on their own data, nations actually adapt and even adapt beyond the temperature increase. If the same model is run with this assumption, by 2100, the 4.3°C will have moved the optimum to 31.5°C ($=13+4.3 \times 1.7/0.39$). This would cause the model to show that global warming would *increase* by almost 1,100% rather than decrease by 23%.

Both these formulations are deeply suspicious. Burke et al. (2015) shows absurd GDP results, with Iceland becoming 30 times richer than today, and Mongolia 200 times richer than today, becoming four times richer per person than the US.

A new study (Letta and Tol 2019) shows that the extrapolation for reduction in GDP growth is empirically unfounded for rich countries, meaning the total impact of the Burke et al. (2015) argument cannot be 23% but maximally 3%.

Another paper, cross validating Burke et al. (2015) and similar papers, (Newell et al., 2018) shows that these are incredibly vulnerable to mis-specification. A slight change in the GDP-maximizing temperature can change whether GDP of a few major economies would benefit from or be harmed by projected warming.

Indeed, they find that simply adding a cubic temperature term to Burke et al. (2015) reduces the GDP impact by half to 11%. Removing their country-specific time trends makes the model predict an *increase* in GDP of 12%, as does using region-year fixed effects (+10%).

Across all the model estimates (Newell et al., 2018) finds the GDP impacts range from −48% to +157%, and the weighted, average effect is actually a *positive* 13.5%. They find that estimating the GDP damage as a level effect rather than as a growth effect is much more robust and is very likely to imply 1–2% GDP loss by 2100.

While the IPCC (IPCC 2018, 256) references (Burke et al., 2018) for a cost estimate of 1.5°C and 2°C, they also reference (Watson and Quere 2018) for the costs of 1.5°C, 2°C and 3.66°C (no policy), which finds costs of 0.28%, 0.46%, and 2.62% of GDP, which is very close to the black Nordhaus line in Fig. 20 (not surprising, since the costs were modeled in PAGE).

In conclusion, apart from being simply implausible (with Mongolia becoming the second-richest people in 2100), this alternative approach to cost estimates is ill-founded and vulnerable to mis-specification. It emphasizes why the well-established, decade-long research behind the cost estimates of Figs. 19 and 20 are the more likely cost estimates to be used.

3.5. Global warming is a real cost, but welfare will still be much higher in 2100

When compared to the dramatic increases in projected income across the century in the SSPs as shown in Fig. 1, the climate costs are rather small. The projected temperature in 2100 for the SSPs range from 3.24°C in the sustainable SSP1 scenario to 4.86°C in the fossil fuel-driven SSP5. This means that the negative climate impact in 2100 for SSP1 will be 2.5% of GDP, whereas SSP5 will see a negative 5.7% impact. It means that instead of per person GDP in 2100 being six times larger than its 2020 value, it will be 5.9 times its 2020 value after deducting the climate damage. The fossil fuel-driven scenario will see a larger reduction, from 10.4 times its 2020 value to 9.8 times. This is depicted in the upper-left part of Fig. 21. Not shown, the middle-of-the-road SSP2 scenario expects the per-person GDP in 2100 to be 4.5 times its 2020 GDP. With climate damages deducted, the 2100 GDP per person would be a smaller 4.3 times its 2020 value.

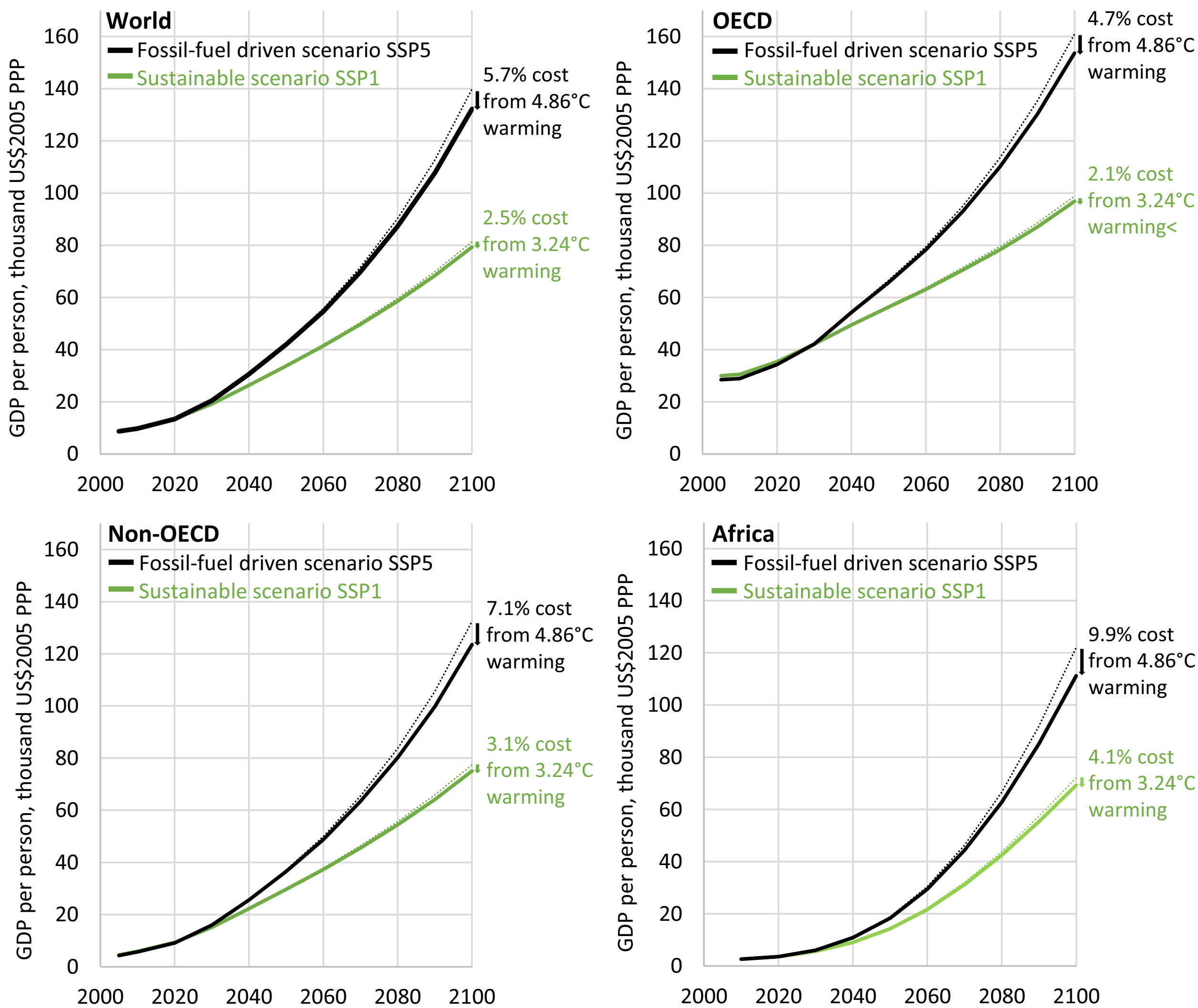

Fig. 21. GDP per person, 2005–2100 for World, OECD, non-OECD, and Africa, without climate damage, and with climate damage deducted, for the coolest scenario, the sustainable SSP1 reaching 3.24°C by 2100, and the hottest scenario, the fossil-fuel driven SSP5, reaching 4.86°C by 2100 (IIASA 2018; Nordhaus 2010; Nordhaus, 2013; Riahi et al., 2017).

It is also well-known that the climate impact will harm poorer countries more than richer countries, partly because poorer countries are more exposed, partly because they tend to be in already hotter places, and partly because being poor means less adaptive capacity (Tol 2019). One regional model, RICE, estimates damage impacts for 12 groupings of countries, including the US, the EU, Japan, China, Africa and Latin America (Nordhaus 2010, 2013). Using this model, we can show the income per person across the century and subtract the climate damage to show the actual welfare across different scenarios.

In Fig. 21 we can see the negative climate impact on incomes across the world and for the two extreme temperature scenarios, the SSP1 and SSP5. It is clear that poorer countries lose more—with Africa losing the most. In 2100, Africa will lose 4.1% to global warming with the SSP1, and it will lose much more in the hotter, fossil fuel-driven world of SSP5, with a welfare reduction of 9.9% in 2100. Yet, it is also clear that it matters much more *which* scenario the world will follow. While Africans will lose much less to climate change in SSP1, they will still be *much* better off in SSP5, being 30 times richer in 2100 than in 2020, even after accounting for climate damages, compared to “just” 19 times better off in SSP1.

The SSP5 world will eradicate poverty faster and better than even the SSP1 world (Rao et al., 2019). On average, the world will see 26 million more poor every year until mid-century in an SSP1 world compared to the SSP5 world. Both scenarios will still do much better than the middle-of-the-road SSP2, which will see 146 million more poor than the SSP5, and they vastly outperform the regional SSP3 and inequal SSP4, which on average will see more than 400 million more poor each year.

With almost similar population, the SSP5 world will be almost twice as rich at an annual GDP of $1,034 trillion versus $563 trillion in the SSP1 world. This obviously matters directly since higher incomes allows individuals to access more education and access goods and services. But one measure stands out. A rich literature shows that being richer also means being healthier. Both society and individuals can afford to buy more risk reduction and health benefits, from purchasing seat belts, air bags, and bicycle helmets over better medical care and nutritious food, to ensuring better opportunities for offspring (Broughel and Viscusi 2017; Hahn et al., 2000; Keeney 1990; Lutter and Morrall 1994; Lutter et al., 1999). The literature estimates the impact of higher incomes resulting in lower death rates.

Of course, as societies get richer, the cheap opportunities for health improvement will decline and the cost of achieving every avoided premature death will increase. Nonetheless, the incredible difference in total GDP between SSP1 and SSP5 has a dramatic impact on the number

Table 2
Cost of Paris promises in billion US$, based on reduced GDP growth in multi-model estimates from EMF24, EMF28, AME and CLIMACAP-LAMP, as discussed in text, and with a proportional cost estimate for the remaining 20% for the rest of world. The first column shows the most effective policy, conducted with a single increasing carbon tax across the entire policy area. The most likely policy column assumes costs to double, as EU climate policies have shown.

Cost of Paris Billion $ per year	Most effective policy	Most likely policy
USA	**154**	**308**
EU	**322**	**644**
China	**200**	**400**
Mexico	**80**	**160**
Rest of world	**189**	**378**
Global cost	**945**	**1890**

of avoided premature deaths.

We here use an estimated value of statistical life across the world transferred according to (Robinson et al., 2019, using 160 times GDP per cap, and unitary elasticity) and 10% as the marginal propensity to spend on health (Broughel and Viscusi 2017). We will use the GDP per person for SSP1 and SSP5, but assume that both scenarios have a population like SSP5, to avoid population artefacts.

In SSP1, with an average global income of $81,000 in 2100, slightly higher than today's US GDP, the value of statistical life will also be slightly higher at $13 million. If we were to move from SSP1 to the richer SSP5, each person would gain $58,000 in 2100. Although if just 10% is spent on health, and the value of statistical life is higher, this still means that globally an extra $43 trillion would be used for health spending. This would translate into an extra 3.3 million premature deaths avoided, or 4% of global deaths. This is a lower estimate.

Using the middle estimate of willingness-to-spend from (Lutter and Morrall 1994, 55), which is likely an overestimate, means avoiding almost 10 million premature deaths.

Even with the lower estimate of 3.3 million avoided deaths by 2100, moving across the century with SSP5 instead of SSP1 will avoid more than 80 million premature deaths this century.

4. Climate cost-benefit: the case of the Paris agreement

4.1. Costs of the Paris agreement

There is no official estimate of the cost of the Paris Agreement. Instead, I will here use existing, peer-reviewed published cost estimates on similar trajectories to make an estimate.

Europe's climate promises are probably the best documented in peer-reviewed literature, but this literature also clearly shows that the studies typically lag political decisions by some years. Thus, we have good estimates for previous decisions but fewer for those considered under the Paris Agreement.

Previous studies of economics of climate and energy have clearly shown two things. First and perhaps not surprisingly, in the rare cases where official cost estimates are made, these are often significantly underestimated. The EU estimated that the total cost of its 2020 policies could be as little as an annual 0.4% GDP loss (€64 billion per year) (Capros et al., 2008, 48). The peer-reviewed cost was 1.3% (€209 billion annually), or more than three times larger (Tol 2012). Similarly, the Mexican government assumed its climate policies would cost $6–33 billion annually by 2050 (Veysey et al., 2016). The peer-reviewed literature, supported by the US EPA and the EU, shows that this is “far lower than any of the cost metrics reported by the CLIMACAP-LAMP models.” Indeed, they find the cost in 2050 to be between 14 and 79 times higher, at about $475 billion annually (Veysey et al., 2016).

Second, politicians rarely pick the most efficient climate policies that cut CO_2 at the lowest cost. This typically doubles the cost. The EU could have reduced its emissions by switching to gas and improving efficiency for a cost of 1% of GDP (Bohringer et al., 2009). However, inefficient solar subsidies and biofuels are often more alluring, which is why the actual EU cost more than doubled to 2.2% of GDP. As the researchers say: “The inefficiencies in policy lead to a cost that is 100–125% too high.”

In the following, I will tally the costs for the US, EU, Mexico, and China, which make up about 80% of the total promised reductions.

Under the Trump presidency, the US has announced a decision to leave the Paris Agreement. However, this will only take effect in late 2020, after the next presidential election, so for now the US is still a signatory.

In its Nationally Determined Contribution (NDC) to the UNFCCC (USNDC 2016) the US promised that it would reduce its overall greenhouse gas emissions (GHG) 26–28% below the 2005-level by 2025. The US is very clear in its submission that this is a one-point promise in 2025: “The US target is for a single year: 2025.”

There is no official estimate for this promise. We can turn to the Stanford Energy Modeling Forum for the US, the so-called EMF 24 (Fawcett et al., 2014). The program has run more than a hundred scenarios estimating all greenhouse gas emissions and the GDP cost. Estimating the lost GDP cost with a regression across all these data points suggests that cutting 26% in 2025 results in a GDP loss of about $154 billion annually, and 28% incurs an annual GDP loss of $172 billion.

The EU promises in its NDC to cut its emissions by 40% below 1990-levels in 2030 (EUNDC 2016). While there are no official estimates of the cost, the latest peer-reviewed Stanford Energy Modeling Forum for the EU, the so-called EMF 28, estimates costs from a number of different reductions (Knopf et al., 2013). The closest policy attempts to reduce emissions by 80% in 2050, which leads to an average reduction in 2030 of 41%. That reduction across the models that estimate GDP loss is equivalent to reducing EU's GDP by 1.6% GDP in 2030 – or €287 billion ($322 billion) in 2010-euros.

China has promised to reduce its energy intensity to at least 60% below 2005 (China NDC 2016), equivalent to reducing its emissions by at least 1.9 Gt CO_2 each year. In the international research project the Asia Modeling Exercise (Calvin et al., 2012a, 2012b), nine energy-economic models estimate what different efficient reduction policies will attain in emission reductions and GDP reductions. Using the AME data, it is likely that China can reduce 1.9Gt CO_2 for about $200 billion in annual GDP loss.

Mexico has enacted the strongest climate legislation of any developing country. It has conditionally promised to reduce its emissions by 40% below what it would otherwise have emitted by 2030 (Mexico NDC 2016). The CLIMACAP-LAMP project has estimated costs throughout Latin America and the peer-reviewed analysis for Mexico (Veysey et al., 2016) finds that the Mexican cost in 2030 is about 4.5% of GDP or about $80 billion annually.

The total cost of US, EU, China, and Mexico adds up to $739 billion (or $757 billion if the US goes for 28%). Given that the reductions from US, EU, China, and Mexico sum to about 80% of all reductions, it is reasonable to assume that the $756 billion constitutes 80% of the total cost, making the global cost about $945 billion.

Table 2 shows the estimate of $945 billion in annual lost GDP by 2030 if all nations enact the most efficient climate policy (an increasing carbon tax which is uniform across sectors and, for the EU, across countries). This is close to the (Akimoto et al. 2017, 201) least-cost estimate of 0.38% of GDP, which at SSP5 would be $819 billion in 2018 US$. Interestingly, if the Paris pledges were instead implemented with global least-cost measures (that is, many of the EU emission reduction promises would take place in lower-cost places like India and China), then the cost could be less than half at $345 billion (0.16%).

However, given that the Paris Agreement is focused on national promises, it is implausible that global least-cost measures will be implemented. Moreover, previous experience shows that even *national* effective climate policies are very unlikely to be implemented, and this makes the total cost more likely to at least double (as found, e.g., by (Bohringer et al., 2009)).

Thus, it is likely that the global cost of Paris will reach at least \$1 trillion annually by 2030, and the cost with realistically less-efficient policies could very likely get close to \$2 trillion annually. With more realistic assumptions using second-best analysis, explicitly including inertia and myopic behavior in a general equilibrium modeling framework, the costs of Paris by 2030 could reach 4.25% or \$5.4 trillion annually (costs likely smaller, since paper estimates price compared to no climate policy from 2001, Li et al., 2017; Figs. 4 and 6).

Just comparing to the \$2 trillion cost, it is about 100 times the \$20 billion the world annually spends on biodiversity (UNEP 2014, 435) or the \$19 billion the world annually spends on HIV (UNAIDS 2019, 174). The Paris Agreement will *every year* cost about 2–5 times the *total* cost of the world's previously most expensive global treaty—the Versailles treaty (and its implementation of the 1921 London Schedule of Payments) of World War I. Reparations cost Germany 132 billion German Marks or about \$400 billion in present-day dollars (Gomes 2010, 47). The annual cost of the Paris Agreement is at par with the entire expenditure for the world's military (\$1.8 trillion/year in 2018, (SIPRI 2019).

4.2. Benefits of the Paris agreement

There are two main ways to estimate the impact of Paris. One looks at its impacts on CO_2 emissions, the other on its impact on global temperature by 2100.

The UNFCCC, which organized the Paris Agreement, estimates the total impact of all promises to be a reduction of "2.8 (0.2–5.5) Gt CO_2e in 2025 and 3.6 (0.0–7.5) Gt CO_2e in 2030" with the central figure showing the median outcome and the 20–80% range (UNFCCC 2015, 10). Aggregated from 2016–2030, assuming linearity from 2015–25 and 2026–30, the UNFCCC median reduction from the Paris Agreement is 31.8 Gt CO_2e and the high-end estimate is 63.8 Gt CO_2e. There is broad agreement on this size: (JRC 2015) finding a conditional and unconditional reduction of 6 Gt CO_2e by 2030, linearly equivalent to 48 Gt CO_2e over the period, (Akimoto et al. 2017) finding a reduction of 6.4 Gt CO_2e in 2030, linearly equivalent to 51.2 Gt CO_2e.

The Stanford Energy Modeling Forum global business-as-usual scenario shows a cumulative emissions 2016–2100 of 6970 Gt CO_2e (Kriegler et al., 2014), very similar to the UNEP BAU cumulative emissions of 7142 Gt CO_2e (UNEP 2015, xix). This means that the Paris Agreement median reduction is equal to about 0.45% of global BAU emissions from 2016–2100, or at the upper end equal to 0.9%.

There is an approximate linear relationship between cumulative CO_2 emissions and global temperature response (Stocker et al., 2013, 27), with the transient climate response to cumulative carbon emissions likely in the range of 0.2°C to 0.7°C per 1000 Gt CO_2 (0.8°C-2.5°C per 1000 GtC, Stocker et al., 2013, 16–17), and 0.45°C being perhaps the most realistic (Kriegler et al., 2018, 3; Matthews et al., 2012, 4369). That means that the Paris Agreement promises from 2016–30, which will cut maximally 63.8 Gt CO_2e, will reduce global temperatures about 0.029°C and certainly less than 0.045°C (similar to Lomborg 2016).

However, many models show dramatically bigger temperature impacts from Paris (Hausfather 2017). An overview of nine models shows that eight of them find Paris will reduce temperatures by more than 0.8°C. Let's look at the most publicly referenced, from the so-called Climate Action Tracker, showing a large reduction of 1.5°C.[9]

If we look at Fig. 22, we see how the history of emissions increased rapidly in the first 15 years of this century, from 39 to 51Gt CO_2e. Using the UNEP business-as-usual, we differentially show the high-end reduction of the Paris Agreement totaling 64 Gt CO_2e from UNFCCC (2015). If we run this reduction from 2016–30, with a reasonably fast return to BAU after 2030, using the rapid MAGICC climate model (Meinshausen et al., 2011), we get a temperature reduction of 0.04°C (Lomborg 2016).

Implementing the Paris agreement is costly, reducing annual GDP by \$1 trillion–\$2 trillion by 2030. Thus, it is unlikely that nations will volunteer to adhere to its requirements after it expires in 2030. (Of course, it is entirely possible that many nations will come together later and make new promises for the period after 2030, but it seems a stretch to argue that is still the impact of the original promises made in Paris in 2015.)

Yet, for purposes of comparison, let us assume that nations would continue adhering to their high-end promises for 2030 for the next seven decades, in total cutting 540 Gt CO_2e, however implausible, as it is equivalent to accepting an undiscounted \$70trillion+ in extra costs. The difference in temperature by 2100 is 0.17°C (Lomborg 2016). Compare this to the IPCC linearity, which suggests that the temperature reduction from 540Gt would be in the order of 0.24°C. (Since much of the reduction is late in the century, part of the temperature reduction will only show in the next century.)

But here we see the reason that Climate Action Tracker gets a much higher temperature reduction. The tracker estimates a much, much higher reduction after 2030. Indeed, compared to the actual Paris Agreement of maximally 64Gt, CAT expects 50 times more reductions to follow after 2030. Based on CAT's own estimates, 3270 Gt CO_2e will reduce temperatures from 4.2°C in 2100 to 2.7°C or a reduction of 1.5°C.[10] This fits well with the IPCC linearity estimate of a 1.47°C reduction.

While one can legitimately argue that the impact of a concrete promise can bleed into future actions, it seems tenuous to claim that the relatively tiny 64Gt Paris promises will somehow magically implicitly encapsulate seven decades of reductions 50 times their size. It would be similar to an overweight dieter promising to eat a single salad and then suggesting this constitutes success for a decades-long future diet and a rock-hard beach body. Indeed, if the same approach were used for the 1992 Rio promises, where the rich world promised to cut its greenhouse gas emissions by 2000 to 1990-levels (UNFCCC 1992, 4.2.a-b), we should say that both the Kyoto Protocol and the Paris Agreement and all subsequent treaties were "caused" by the Rio promises. This would clearly be wrong, as the entire rich world (Annex I) only fulfilled its promise because of the Soviet collapse. The OECD broke its Rio promises with emissions 5% *higher* in 2000, only to belatedly fulfill its promise in 2009 because of the effects of the global recession.[11]

It seems eight of the nine studies referenced in (Hausfather 2017), like Climate Action Tracker, assume much higher post-2030 reductions than the actual Paris Agreement promises. Many of the actual results are hard to replicate—e.g., (JRC 2015) do not even show emissions to 2100, but simply state that the BAU will result in 3.8–4.7°C (averaged by Hausfather to 4.4°C), whereas the analysis finds that Paris agreement *and* "prolonged effort after 2030 result in curbing emissions" will result in about 3°C.

Hausfather (2017) claims 1.2°C reduction on average for the eight models, which by the IPCC linearity would mean a rough equivalence of cutting 2,640 Gt CO_2e. Since the actual Paris Agreement promised at the high end 63.8Gt CO_2e, the assumed reductions post-Paris are more

[9] Hausfather writes 1.6°C, based on a high average of CATs BAUs (4.1-4.7°C, with 4.4°C as average), and a low average of outcome (2.7-3.0°C with 2.8°C as average). CAT clearly indicates that part of the emission reduction from 2016-30 comes from previous policy promises, but in Hausfather's article and in general, this is attributed to the Paris Agreement.

[10] The BAU runs close to the lower bound of CATs BAU interval, which they find gives 4.1-4.7°C. That makes 4.2°C the more likely outcome. We use the lower end for Paris, which is associated with 2.7°C.

[11] GHG total without LULUCF, in kt CO_2 equivalent, from https://di.unfccc.int/time_series

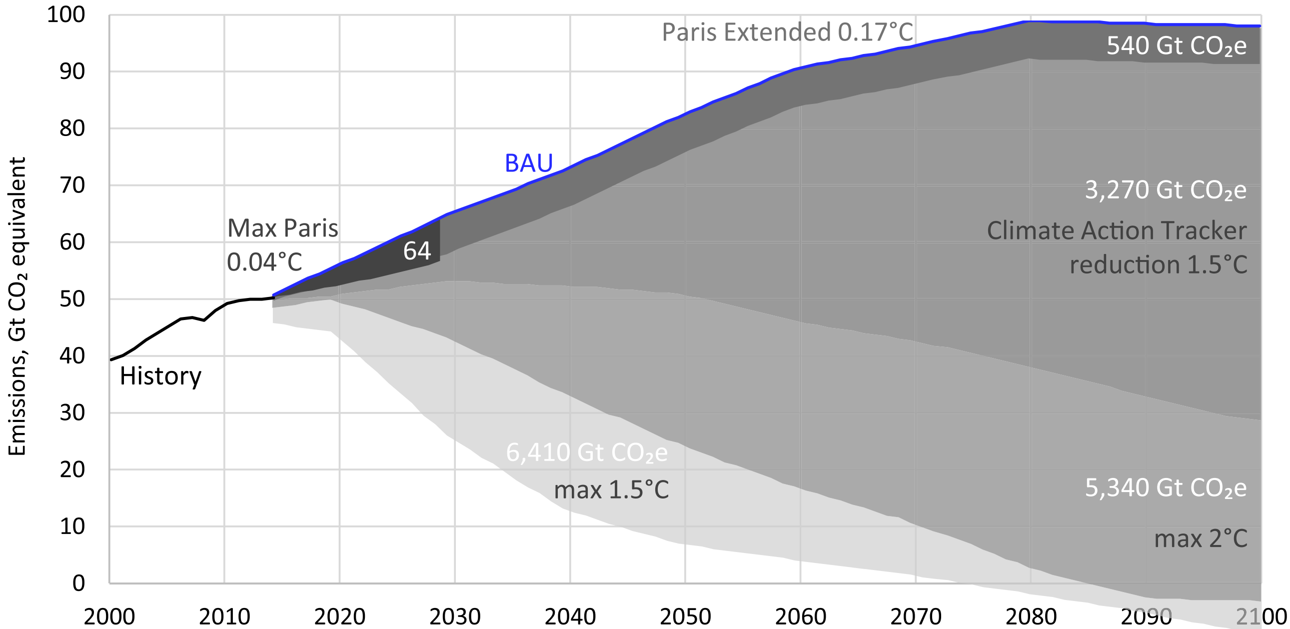

Fig. 22. Paris Agreement, CO_2e emissions and reductions. Actual Paris Agreement of 64Gt, Extended Paris cutting 540Gt, Climate Action Tracker cutting 3,270Gt, and IMAGE max 2°C pathway cutting 5,340Gt and max 1.5°C pathway cutting 6,410Gt (CAT 2018; IIASA 2018; Lomborg 2016; UNEP 2015). All emissions have been harmonized with the BAU from UNEP, which means increasing emissions a bit for (UNFCCC 2015) and placing it in the lower fifth of the BAU for (CAT 2018).

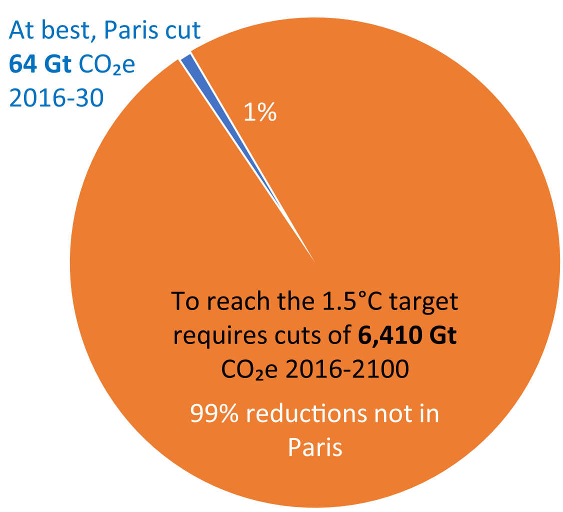

Fig. 23. Median aggregate emission cut estimate from Paris Agreement 2016–30 is 31.8 Gt CO_2e, and high-end estimate is 63.8 Gt CO_2e (UNFCCC 2015, 10). To reach a low or no overshoot 1.5°C we need to cut 6410 Gt CO_2e (IMAGE, SSP1 1.9, IIASA 2018).

than 40 times higher than what the actual agreement promises.

Moreover, while Hausfather (2017) claims that MIT should suggest that the Paris agreement reduces temperatures by 0.8°C, the actual MIT finding was that "the COP21 [Paris] contribution to avoided warming … is about 0.2°C less warming by the end of the century" (MIT 2015, 2), right in line with the Paris extended scenario of 0.17°C in Fig. 22.

Given the elasticity of claiming temperature reductions from the Paris Agreement, perhaps it is easier to simply agree that Paris at most entails promises to cut emissions by an extra 63.8Gt CO_2e by 2030. This cut is under 1% of what is necessary to cut to get to 1.5°C, which is a reduction of 6,410 Gt CO_2e, as shown in Fig. 23.

And while many studies would already have us popping the champagne corks because of a multitude of imagined follow-on successful carbon reduction treaties across the century owing to the Paris Agreement, the first 63.8 Gt CO_2e itself does not seem all that likely to materialize. One study shows all major industrialized countries are failing to meet the pledges they made in Paris (Victor et al., 2017), with the US only on track to deliver 6.5 percentage points of its promised 26–28% reduction in 2025, the EU only legislating for 19 percentage points of its 40% reduction promises in 2030, and Japan only on track to meet 12 percentage points of its promised 26% in 2030.

Another study shows that while Paris has 197 signatories, including 157 making emission reduction promises, the majority of the promises are not encased in national laws, and almost all are not sufficiently legally binding to actually deliver the promises. In fact, only 17 countries have made national law that is consistent with their promises—these tend to be low-emitting countries including Guatemala, Papua New Guinea, Samoa, and Tonga (Nachmany and Mangan 2018).

So, it is likely that the Paris Agreement will in fact deliver less than 1% of the emission cuts needed to keep temperature rises below 1.5°C.

4.3. Cost-benefit of Paris

A straightforward way to compare the costs and benefits of the Paris Agreement is to compare the average cost of cutting a metric ton of CO_2 with the social cost of carbon (SCC) or the equivalent benefit of an avoided ton of carbon, similar to the analysis in (Tol 2012).

As the annual cost of Paris in 2030 lies between $800 billion and $2 trillion, as discussed above, and it will deliver carbon cuts of maximally 7.5Gt CO_2e (UNFCCC 2015, 10), each ton reduced will cost on average $109–252.

The SCC based on the average of DICE, FUND, and PAGE with their own discount rates is about $16/ton in 2030 (discount rate of about 4.5% until mid-century, compared to IWG 5%, Gillingham et al., 2018, 817; IWG 2016, 4). An average across a wider range of damage functions (including Weitzman 2011) shows that for 2030 the SCC per ton at 1.5% pure time preference is $15, $29, $65, $28, and $20 across SSP1-5 (Yang et al., 2018, 229), with an overall average of $31.4/ton.

We see the results in Table 3, which shows for each of the three Paris cost estimates and each of the six SCC estimates for 2030 how the cost of cutting a ton of CO_2 is in the hundreds of dollars, and the

Table 3
Benefit-cost ratio for different estimates of the cost of Paris from Table 2 and (Keigo Akimoto et al. 2017, 201), benefits from (IWG 2016; Yang et al., 2018) as discussed in text. Ratios range from 0.06 to 0.60, indicating that a dollar spent on Paris can achieve somewhere from 6¢ to 60¢ of climate benefits (avoided damage). The average is 25¢ of social benefits per dollar spent when policies are optimal (row 1 and 2), and 11¢ of social benefits with more likely policies (row 3).

Benefit-cost ratioof Paris Agreement			**Benefit** of one ton CO_2 avoided in 2030 Social cost of carbon in 2030						
			IWG	SSP1	SSP2	SSP3	SSP4	SSP5	Average SSPs
Cost Paris 2030		$/ton	16	15	29	65	28	20	31.4
$819 billion per year	Optimal	109	0.15	0.14	0.27	0.60	0.26	0.18	0.26
$945 billion per year	Optimal	126	0.13	0.12	0.23	0.52	0.22	0.16	0.23
$1890 billion per year	Realistic	252	0.06	0.06	0.12	0.26	0.11	0.08	0.11

benefits are in the tens of dollars. Not a single instance of the analysis has benefits higher than costs. For the optimal policies, which will deliver the promised emission cuts at the lowest costs, each dollar of social cost delivers on average 25¢ of social benefits (in long-run avoided climate damage). For the realistic scenario, where ineffective, partially overlapping policies will require higher spending for the same carbon cuts, each dollar will generate just 11¢ of climate benefits (avoided costs).

In short, under a wide range of optimistic or realistic cost estimates and under all the main estimates for benefits of cutting a ton of CO_2, the Paris Agreement is not worth its costs. It will likely deliver just 11¢ of climate benefits for each dollar spent.

If, as is likely, the world does not deliver fully on the Paris Agreement, costs will be lower, but so will benefits. Although the marginal costs might be slightly lower, it is exceedingly unlikely that they will be 3–9 times lower, which would be necessary to push the very low benefit-cost ratios above unity.

At any reasonable estimate of costs, benefits, and implementation, the Paris Agreement is unlikely to be a beneficial investment for the world.

5. Cost-benefit analysis for climate policy

Unabated climate change has ever-increasing costs, as we have seen in Fig. 19. The public climate conversation focuses on these costs.

However, the crucial point for an informed global climate conversation is that the costs of climate damage are only *one* of *two* important costs. Climate change has a real cost. But climate *policy* also has a real cost, and one that escalates as promises and targets ratchet up. From a welfare and a cost-benefit analysis point of view, the important issue is to find the point where the costs of climate *plus* the costs of climate policy are lowest.[12] This approach has been the career-long focus for William Nordhaus, who in 2018 was awarded the Nobel Prize in economics for this thinking.

5.1. The most effective climate policy with perfect implementation

An obvious first observation tells us that we should find the climate policies that are the most effective—that deliver the most CO_2 cuts for the price—since that will reduce the costs without reducing the benefits. In principle, no one in the climate debate would question this. For most economists, the most effective policy is a uniform, global carbon tax, rising through time along with the SCC. This regulatory policy is what Nordhaus models.

The outcomes of Nordhaus' model are shown in Fig. 24, estimated as discounted costs over 500 years. With no additional climate policy, the model estimates rising CO_2 emissions across the century, only leveling off towards the end of the century and declining into the 22nd century. This will lead to temperatures rising to 4.1°C by 2100. (Temperatures will continue increasing and first peak at 7.2°C in the 24th century. The

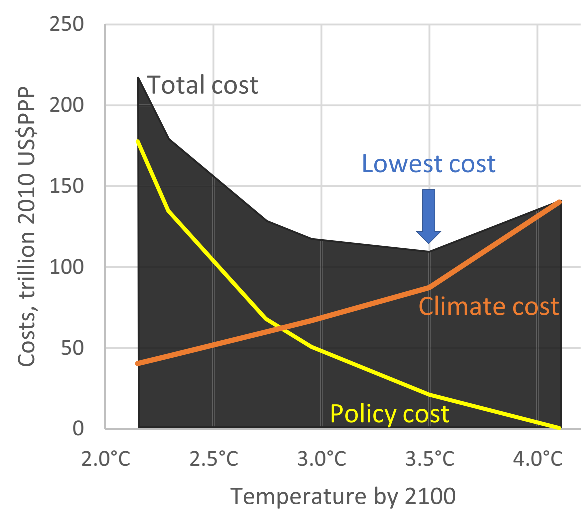

Fig. 24. Total, discounted climate costs and policy costs for different temperature outcomes by 2100, along with the total cost (the sum of climate and policy cost). All use base (4.1°C) discount rates for comparability. DICE-2016R2 from 2017 (Nordhaus 2018a) run on GAMS,. The results for 4.1°C, 3.5°C and 2.3°C are near-identical to the runs in (Nordhaus 2018b).

resulting discounted costs are included to 2510, but we use the temperature in 2100 for the *x*-axis.) The policy cost is calibrated from a large number of recent IAMs and declines exponentially as technology makes low- or zero-carbon energy ever cheaper.

The discount rate is set at the empirical rate of approximately 4.4%, and slowly declining. The damages are evaluated approximately at the blue line in Fig. 19. The full, discounted damage costs across the five centuries is $140 trillion, as shown by the orange line at 4.1°C. The discounted policy cost is almost nonexistent at $354 billion, and only different from zero because the existing climate policies from before 2013 remain.

Each other point on the *x*-axis of Fig. 24 shows a world which sets a global CO_2 tax for each time period throughout the five centuries that maximizes the discounted global welfare subject to a temperature constraint.[13] As the temperature by 2100 is reduced, the climate damages go down. However, making the climate more benign has an increasingly steep policy price.

Take for instance 3°C. This describes a world that maximizes its discounted welfare with a temperature constraint such that it reaches 3°C by 2100. This temperature constraint turns out to be 3.25°C, which is reached around 2160. The total climate cost is $67 trillion, which is

[12] Another approach is to find where the benefit-cost ratio is highest.

[13] Actually, the stretch between 4.1°C and 3.5°C is impossible to reach with the current formulation of DICE, since a limit above 4.05°C (which is denoted "3.5°C by 2100" in graph) does not constrain the maximization of welfare, and the actual temperature rise again just finds the 3.5°C by 2100 pathway.

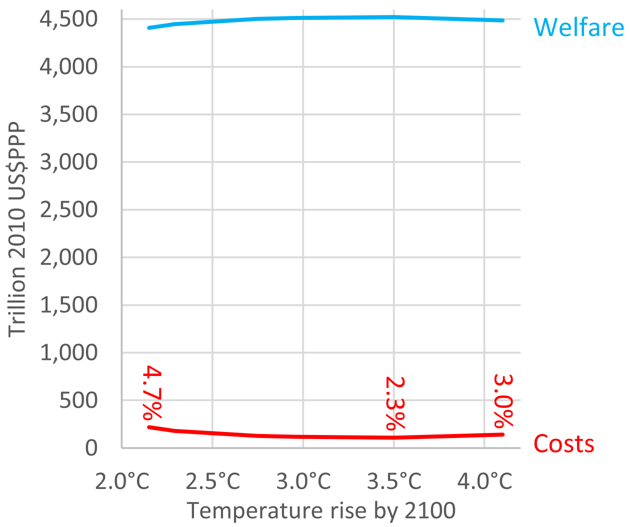

Fig. 25. Total discounted costs for climate and climate policy, and total discounted welfare across five centuries for different climate outcomes. Percent is of total GDP, which is consumption (welfare) and climate and climate policy costs. DICE-2016R2 from 2017 (Nordhaus 2018a) run on GAMS.

much cheaper than the 4.1°C climate costs. On the other hand, the policy costs of $51 trillion are much larger.

In total, achieving 3°C in 2100 has a cost of $117 trillion. This is cheaper than the $140 trillion total cost from the no-climate policy 4.1°C scenario.

However, maximizing the discounted welfare regardless of temperature is the point where the costs of climate and policy are lowest. In Nordhaus' model, this happens at 3.5°C in 2100, where discounted climate costs of $87 trillion and policy costs of $21 trillion lead to an absolute minimum cost of $108 trillion.

In a welfare-economic sense, this is the optimal climate world where the discounted cost of climate has been balanced against the discounted cost of climate policy such that the discounted total welfare is maximized. Although 3.5°C sounds like a rather small reduction in temperatures, this is because temperatures react slowly even to large changes in emissions. A 3.5°C, the world will be dramatically altered by climate policy: in just 50 years, it will *halve* global emissions compared to business-as-usual and see carbon taxes of $150, equivalent to 36¢ on a liter of gasoline ($1.35 per gallon).

What becomes clear as we go further towards low temperatures is that climate costs decrease but policy costs escalate rapidly. Indeed, Nordhaus' model cannot ramp up the global CO_2 tax fast enough to deliver a 1.5°C or even a 2°C world. As he points out: "A limit of 2°C appears to be infeasible with reasonably accessible technologies even with very ambitious abatement strategies" (Nordhaus 2018b, 334).

But even a world that delivers a temperature rise of 2.15°C by 2100 (peaking at 2.35°C in 2160) is not all that attractive. While it has the lowest discounted climate cost of just $40 trillion, the necessary policy costs to achieve such a low-carbon world are at an all-time high of $170 trillion, reaching a total cost of $218 trillion.

Looking at the whole picture, as shown in Fig. 25, climate policy should be about minimizing the loss of welfare from climate *and* climate policy. Without any climate policy, the welfare loss is 3% of GDP. With careful climate policy and a globally coordinated, rationally rising CO_2 tax across all countries and centuries, it is possible to achieve a reduction in welfare loss of 0.7 percentage points to 2.3%, reaching 3.5°C in 2100. A moderate climate policy can definitely make a net benefit for society.

But what is also clear from Fig. 25 is that we should be cautious not to go too far towards strong climate policies, which could be much more detrimental to global welfare. The costs could reach 4.7% of GDP if we attempt to keep temperature rises to 2.15°C in 2100, which is still *less* ambitious than the popular argument enshrined in the Paris Agreement for keeping temperature rises under 2°C and possibly below 1.5°C. While it is important to note that climate economics show moderate climate policies to be net beneficial, it is at least as important to warn against the much more serious harm that overly strong climate policies can inflict.

5.2. The most effective climate policy with imperfect implementation

While much has been said and discussed about the realism of the damage function (which with dynamic vulnerability would be significantly lower as we saw in Fig. 20), the modeling of climate policy cost is almost invariably done on an expectation of optimality. That is, climate polices are modeled as if all actors carefully coordinate their policies across borders and time with a single CO_2 tax to achieve the optimal outcome.

In the real world, of course, a global carbon tax is not carefully coordinated across all borders and across coming centuries. Plausibly, there could be thousands of different CO_2 taxes in the world—different across nations and different within each nation for a myriad of energy and tax regimes. The OECD has catalogued about 25 different CO_2 taxes for each nation (OECD 2013), and in a newer account increased this to 35 areas (OECD 2015, 141ff). Even if many of the effective CO_2 taxes are zero, it is likely 192 countries have more than several thousand different CO_2 taxes.

Moreover, these taxes emphatically do not move in a coordinated fashion over decades and centuries, but are rather decided by political opportunism and setbacks.

Thus, it beggars belief to model the cost of the climate policy as the optimal path, expecting a uniform, steadily increasing, global carbon tax carefully coordinated among China, India, the US, the EU, and everyone else across decades and centuries.

We know that even closely coordinated climate policies like the EU 20–20 policy, arguably run under a single policy unit, become more than twice as costly as the optimal policy (Bohringer et al., 2009). Similarly, one of the most popular climate policies in the US, the Renewables Portfolio Standards, is typically about twice as costly as the optimal policy (Young and Bistline 2018). Moreover, negotiations over climate responsibility are also inefficient — the distribution of carbon cuts across the Paris Agreement made reductions more than twice as expensive as they should have been at least-cost implementation (Akimoto et al. 2017).

Thus, it is reasonable to expect that the real-world outcome of any policy from Nordhaus' DICE model becomes *at least* twice as expensive as modeled. If anything, the evidence for a doubling of costs is *both* for implementation and for planning, suggesting the actual inefficiency could be four times as big. Moreover, as these examples are for limited and disjointed policy endeavors, it is plausible that global, long-term climate policy would be even more ineffective.

Running the same DICE optimization but conservatively using twice as high policy costs delivers an instructive corrective to the emphasis on the benefits of smart climate policy. There is still an opportunity to reduce total costs from the no-policy scenario. Because realistic climate policy costs increase twice as fast, the optimum is now at 3.75°C. It means a smaller reduction in total costs from $140 trillion at 4.1°C to $122 trillion at the optimal 3.75°C point.

However, with realistic policy costs more ambitious, climate policies like 3°C by 2100 have a discounted climate and climate policy cost of $166 trillion, higher than a no-policy 4.1°C world.

The "dip" in the total cost curve in Fig. 26 has become much shallower, and as we go toward more ambitious climate policies, the increase in total cost has become much steeper.

If we make attempts towards a 2°C target, we can still only reach 2.15°C by 2100, but the policy costs will now dramatically outweigh the

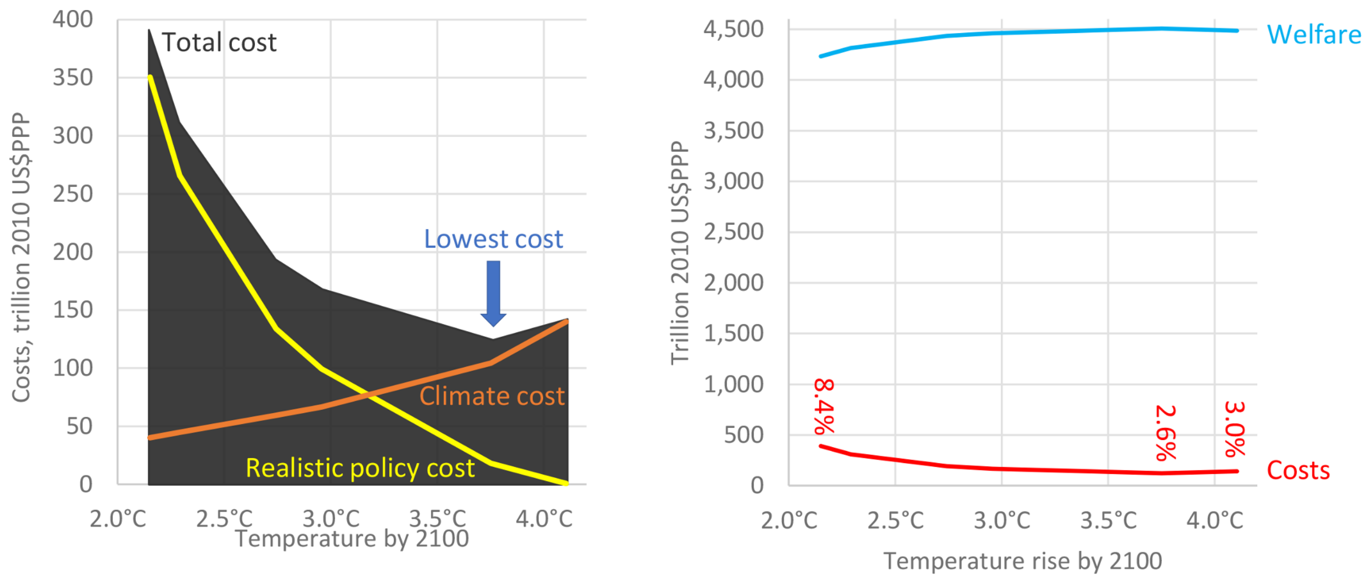

Fig. 26. Incorporating realistic costs, discounted climate and policy costs to the left, discounted total costs and welfare to the right, as in Fig. 24 and Fig. 25. The percentage costs are not double of Fig. 25 because the climate cost remain the same.

reduction in climate costs, giving a total cost of $390 trillion, almost three times the original problem (4.1°C at $140 trillion).

In an attempt to ameliorate climate change, we might end up avoiding part of the climate costs but saddling the world with climate policies that are so expensive the total costs almost triple. That is a bad deal.

This can also be seen in the right pane of Fig. 26, showing damages can be realistically reduced from 3% of GDP to 2.6%, delivering $18 trillion of total benefits. Again, with careful climate policy, even accepting that it will be more expensive because it will be disjointed, disorganized, and globally uncoordinated, it is possible to achieve an improvement over a no-policy outcome. Cutting a smaller part of the CO_2 emissions will help the world warm slightly less with only a modest policy cost. Such a realistic, moderate climate policy can definitely make a net benefit for society.

However, the steep rise of the total costs with more ambitious climate policies shows it is crucial to avoid such policies that would be much more detrimental to global welfare. The realistic costs could climb to 8.4% of GDP if we attempt to reach 2.15°C in 2100, while still being less ambitious than the Paris Agreement.

When looking at the total welfare at the top in the right pane of Fig. 26, it is a worthwhile goal to move to a world where global welfare is improved slightly. But it is much more crucial to avoid a world where ambitious climate policies end up leaving us much poorer, regardless of intentions.

6. Climate policy's place in making a better world

Global warming is very clearly seen as the most important environmental problem in the world today, ahead of air pollution and water pollution (IPSOS 2019a). Yet, there is a curious disconnect between this perception and the actual size of the different environmental problems. The simplest (and hardest to manipulate) way to show the size of the different environmental problems is to look at the number of human deaths from different environmental issues.

6.1. Priorities of environmental concerns

Fig. 27 makes it clear that almost all environmentally caused deaths come from outdoor and indoor air pollution plus ozone; unsafe water and sanitation plus handwashing; and lead and radon. Global warming makes up less than 2% of global environmental deaths, and 0.26% of all global deaths (UNDESA 2017).

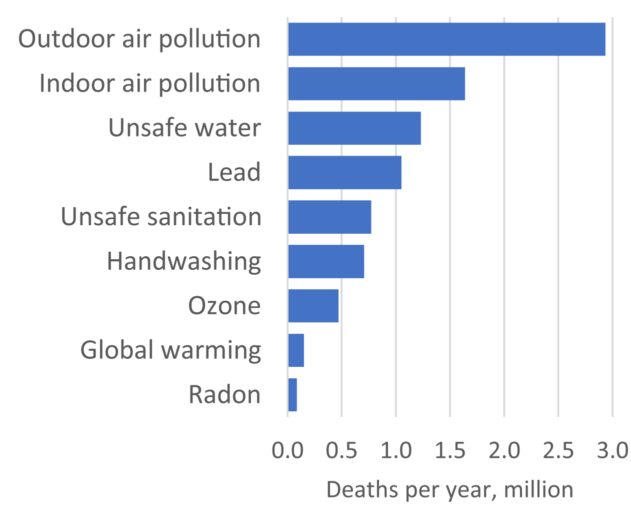

Fig. 27. Deaths from environmental issues in 2017, from Global Burden of Disease (IHME 2019; Stanaway et al., 2018), occupational risks like "occupational asbestos" omitted. While future GBD might include global warming deaths, they are not modeled in the current edition. Instead, estimate from World Health Organization (WHO 2019).

A recent study estimated how much global problems had cost the world across a wide range of issues, measured in percentage of global GDP (Lomborg 2013). All analyses estimated the cost of *not* solving the problem — so the cost of malnutrition is estimated by establishing how much richer the world would have been every year if everyone were well fed, and hence more productive and less sick. Likewise for health (how much richer the world would be without easily curable diseases) and for education (if much of the world had not been illiterate for generations). For comparability, only part of a problem was investigated (the problem of illiteracy is only part of the educational challenge), so these are definitely underestimates. Yet, the overview in Fig. 28 shows how the world has moved dramatically towards smaller problems. It also puts in perspective the challenge of climate change: Yes, it is a problem, but not the end of the world.

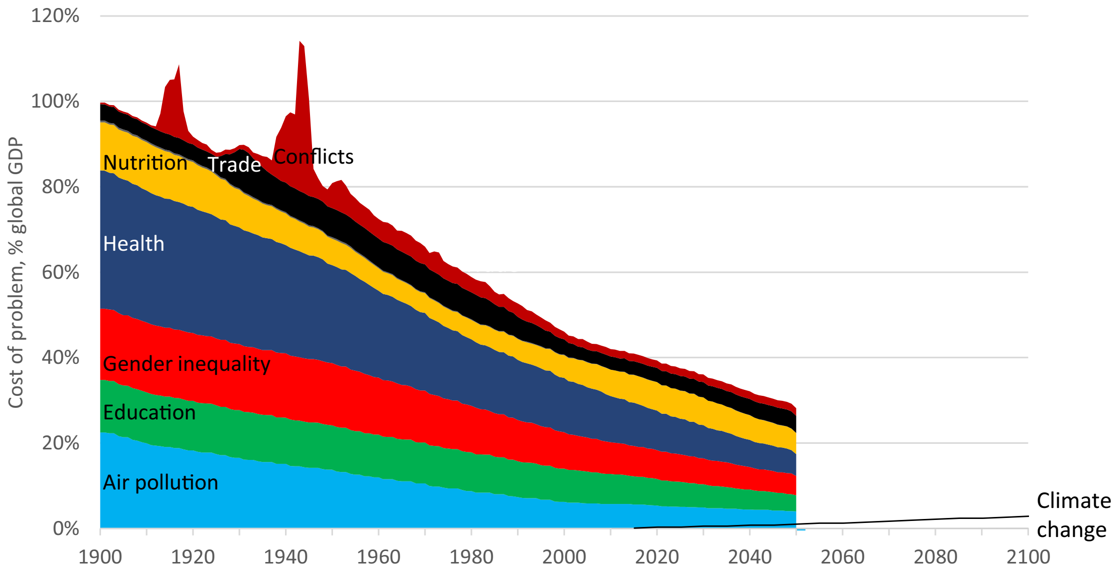

Fig. 28. How much richer would the world have been had we solved certain issues, 1900–2050 (Lomborg 2013). The estimate for each problem shows how much richer the world could have been had this problem been addressed (so can add to more than 100%). For reference, how much richer the world would be if we didn't have global warming (the cost in percent of global GDP of Nordhaus optimal 3.5°C scenario, 2015–2100).

Global warming has historically ranked rather low in global surveys on importance when considered alongside all challenges. However, with the recent strong focus on climate, it has risen dramatically in importance over the past years. In the EU, "the environment, climate change and energy issues" is now the fourth most important issue of 13, up from 11 of 13 in 2014 (EU 2014, 13; Miguel 2019, 23).

One global, monthly updated survey of global concerns is the IPSOS *What worries the World* survey of 28 countries (IPSOS 2016; Miguel 2019b). For most countries the samples are representative of the broader population, although some of the large developing countries like Brazil, China, India, Malaysia, Mexico, Russia, and South Africa are more likely representative of an affluent, connected subset of the population. The main question asks what three topics the respondent finds most worrying. Global warming used to come in low at 15 of 17; now it is in the middle at 9 of 17.

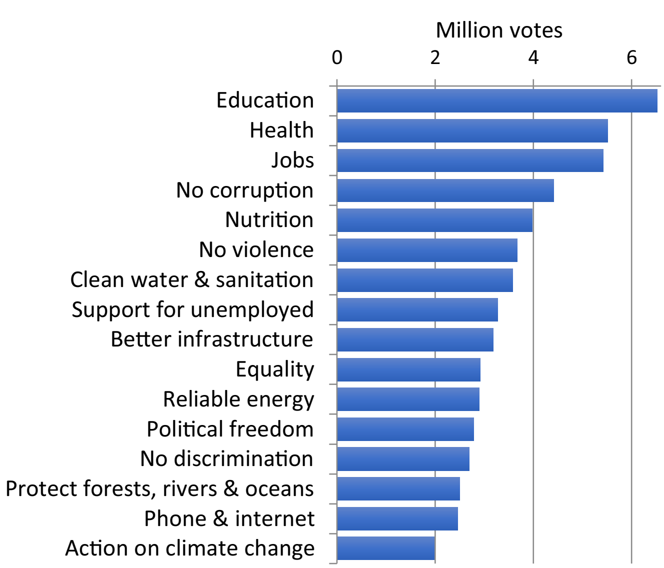

Fig. 29. Global top priorities, organized by the UN, votes of 9.7 million people across the world (MyWorld 2015).

For the US, climate has consistently been at or near the bottom of priorities — in early 2019 it placed 17th of 18 public priorities (Pew 2019) and 11th of 12 priorities for the 2018 midterm elections (Gallup 2018). In the IPSOS poll from July 2019, climate ranked much higher, 6th of 17 (IPSOS 2019b).

For Africa, Afrobarometer asks about the most important problems, but climate change is not among them (Afrobarometer 2018, 6). In an attempt to estimate the importance of climate and other SDGs to Africans using proxies, climate action is found to "barely register" at 3% of citizens' priorities (Afrobarometer 2018, 10).

In the run-up to deciding the global targets that ended up being called the Sustainable Development Goals, the UN undertook a global survey of priorities, eventually covering almost 10 million people, as seen in Fig. 29. While it is only semi-representative, it is the only broad, global survey of its kind that tries to directly capture the priorities of the world. It asked people to prioritize 16 important issues, and the top-ranked items were very clear: education, health, jobs, an end to corruption, and nutrition. "Action taken on climate change" came in 16th of 16.

Clearly, humanity can tackle more problems at the same time. Yet, we clearly do not tackle all problems in their entirety at once. So, it is important to find out where resources can do the most good first. Cost-benefit analysis can be a powerful tool to help indicate which policies can do the most good.

As we found above, the benefit-cost ratio of the Paris Agreement is likely to be 0.11—indicating that Paris is a poor way to help, as it only provides 11¢ of social benefits for every dollar spent.

Compared to a no-policy scenario, Nordhaus' optimal policy with efficient policies provides $52 trillion in benefits (avoided climate damages) from an investment of $21 trillion in climate policies (resources that could have been used elsewhere). That means the benefit-cost ratio (BCR) is 2.5, delivering $2.50 of social benefits for every dollar spent. This is a fairly good deal.

Attempting to keep temperature rises under 3°C will cost a much higher $50 trillion, but given that it will avoid $73 trillion in climate damages it is still an acceptable policy, delivering $1.46 of benefits for every dollar spent (a BCR of 1.46).

Getting close to a 2°C cap, on the other hand, costs $177 trillion for a $100 trillion in climate benefits, delivering only 56¢ back on the dollar.

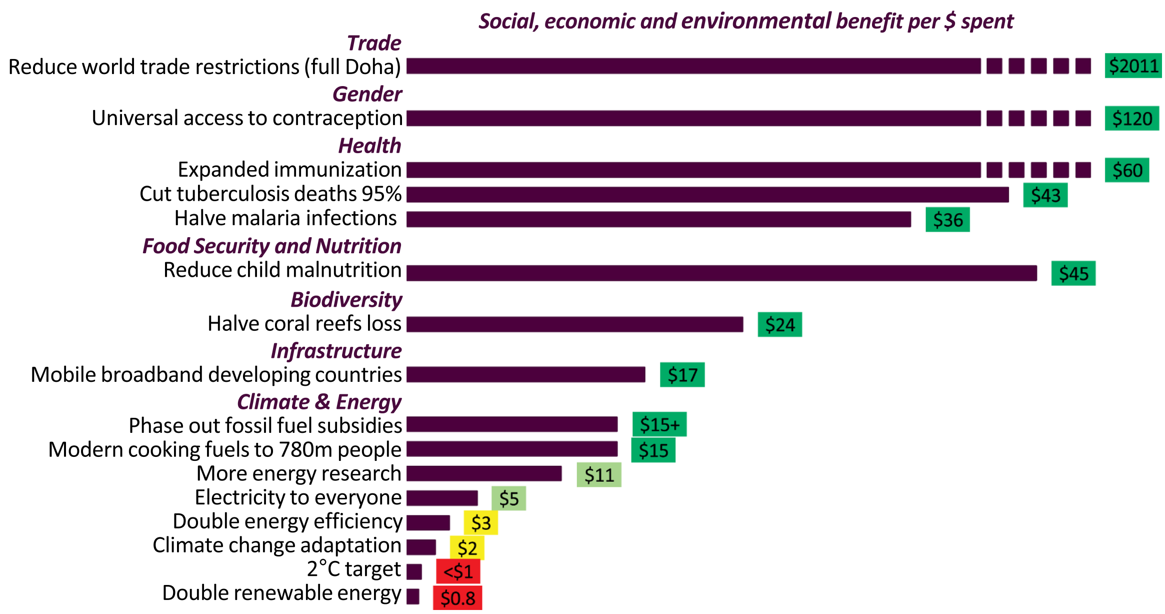

Fig. 30. Selected overview of more than 75 cost-benefit analyses of interventions for the UNs Sustainable Development Goals (Lomborg 2018). The length of the line shows the benefit-cost ratio, so longer lines are better. Dark green indicates "phenomenal" targets, achieving more than $15 of social benefits for every dollar spent. Light green are "good" targets with a BCR between $5 and $15, yellow delivers benefits between $1 and $5, with red denoting "poor" targets that do less good than the resources spent. All data available at post2015consensus.com. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

With a more realistic policy being twice as expensive, the BCR for the optimal 3.75°C is slightly lower at 2, with $17 trillion in policy costs delivering $36 trillion in benefits. But now, even 3°C is a bad deal with almost $100 trillion in policy costs to achieve $73 trillion in climate benefits. The BCR for 2.15°C drops to 0.28.

6.2. *The world's many priorities according to the UN sustainable development goals*

The first cost-benefit analysis of the UN Sustainable Development Goals (SDGs) provides an overview of many of the best (and not-so-good) policy interventions, as encapsulated by the SDGs' targets. Fig. 30 shows a small subset of these interventions.

What is clear is that some interventions within the climate and energy space are good or great investments, whereas others are less so. Doubling renewable energy will deliver considerable benefits worth about $450 billion per year, but unfortunately this will come at a cost of about $550 billion annually, making it a rather poor target. The 2°C cap is poor, as we have seen in the Nordhaus analysis above.

Adaptation is a fair investment, often returning a couple of dollars back on every dollar spent. While our discussion above would make many believe that it returns more, the marginal benefits are rather low because most adaptation is already being extensively implemented since it is privately profitable.

The best climate policy turns out to not be the BCR 2.5 of Nordhaus, but investment in green energy R&D. If we could innovate the price of green energy down below the cost of fossil fuels, it would avert the damages of climate change entirely and without additional costs (Lomborg 2010). As Akimoto et al. points out, it is unrealistic to expect that very high carbon prices will be politically accepted. Instead, "emissions are reduced drastically only with successful development of both low cost innovative technologies and social innovations" (Keigo 2017, 203). It is estimated each dollar spent of green energy R&D could deliver $11 of social benefits.

But there are many investments enshrined in the SDGs that would do *much* more good. Mobile broadbands in developing countries increase growth rates, making every dollar pay off 17 times. Halve coral reef loss not only improves biodiversity but also boost fisheries and tourism, meaning each dollar spent returns $24 of social benefits.

Reducing early childhood malnutrition means that children develop their brains better, learn more in school, and become much more productive adults. Each dollar spent will improve welfare by $45.

Many targets within health are very powerful investments—expanding immunization to even more diseases will cost about $1 billion, but save about a million lives each year. A dollar spent delivers $60 of social benefits.

Access to contraception costs $3.6 billion per year, but allows better spacing of children, improving investment in each child, reducing both deaths among mothers and their children. With fewer children per year, it also leaves more capital to each child, making the child and the adult more productive (the demographic dividend). In total, a dollar spent on contraception can deliver an amazing $120 of social benefits.

Finally, freer trade as envisioned in a successful Doha round can slightly boost global growth. Although it is only a tiny bit of an increase each year, because it cumulates and each country's growth helps all others, it will generate massive benefits over just 15 years. Each person in the developing world will, on average, get about $1,000 higher incomes each year. A dollar spent here could generate thousands of dollars in social returns.

6.3. *Summary: climate compared to other important issues*

We have seen that, when measured on the important measure of human deaths, climate change is far from the most important environmental challenge facing humanity, proving less deadly than outdoor air pollution, indoor air pollution, unsafe water, lack of sanitation, lack of handwashing, or deaths from lead or from radon. Furthermore, analysis of the cost of global problems shows both that the world has moved dramatically towards smaller problems, and puts the challenge of climate change into context alongside other, larger problems.

We have also seen that while global warming is becoming a higher priority to many developed countries, for the world it is still not high and for the poorest likely very low.

Furthermore, cost-benefit analysis of the UN Sustainable

Development Goals (SDGs) shows that several climate-related investments are ineffective: doubling renewable energy will deliver considerable benefits worth about $450 billion per year, but unfortunately this will come at a cost of about $550 billion annually, making it a rather poor target. The 2°C cap is poor, as we have also seen in the Nordhaus analysis. Adaptation is a fair investment, often returning a couple of dollars back on every dollar spent. The best climate policy in this analysis is investment in green energy R&D. If we could innovate the price of green energy down below the cost of fossil fuels, it would avert the damages of climate change entirely and without additional costs.

We have also seen that outside the area of climate change, there are many investments enshrined in the SDGs that would do *much* more good than these climate policies. These include rolling out mobile broadband in developing countries; halving coral reef loss; reducing early childhood malnutrition; expanding immunization to cover more diseases; improving access to contraception; and developing freer trade.

7. Conclusion

As municipalities, counties, and even countries declare a "climate emergency," it is apparent that global warming is often being presented as an existential challenge requiring urgent and strong climate policies to avoid devastation.

This article has shown that these claims are misleading and often incorrectly describe the issue and its future. While climate change is real, human caused, and will have a mostly negative impact, it is important to remember that climate *policies* will likewise have a mostly negative impact. Thus, we must account for the effects of both to find the policies that will achieve the highest welfare gains.

7.1. Baseline welfare keeps increasing

This article first established how the baseline development for the world has improved dramatically and is likely to continue. Welfare has increased and will increase dramatically. While GDP per person is often criticized, it effectively captures some of the most important impacts for humans and the environment: longer life, less child deaths, better education, higher development, lower malnutrition, less poverty, more access to water, sanitation, and electricity, and better environmental performance. Most importantly, it strongly captures the most important welfare indicator, subjective well-being.

Welfare per capita has increased 16-fold from 1800 to today (Fig. 1), and it is likely to increase another 5–10 times by the end of the century. Likewise, the global income gap is closing (Fig. 2) and the world could by 2100 be less unequal than it has been in the last two hundred years (Fig. 3).

One of the main reasons we have become much better off is that we have access to much more energy. From 1800 until today, each person in the world has access to four times as much energy (Fig. 4). Because of efficiency gains, human benefits from energy have increased even more: Each person in Great Britain has obtained 18 times more domestic heating, 170 times more transport, and 21,000 times more light. This trend will continue towards 2100.

While many believe that renewables are slated to take over the world, this is unlikely to happen soon (Fig. 5). Indeed, by mid-century we will likely get less energy from renewables than we did in the last mid-century in 1950. By 2100, in the middle-of-the-road scenario, the world will still get 77% of its energy from fossil fuels.

That is why much of our progress in the 21st century will remain bound to fossil fuels (unless we innovate cheap green energy). Cutting back fossil fuels helps alleviate global warming but at the same time has real costs to human development. Thus, it is crucial to identify the size of the problem of global warming and the effectiveness of its solutions.

7.2. Climate impacts real but often vastly exaggerated

There are two major reasons why most people *believe* global warming is making things worse, whereas the data shows this mostly to be untrue. First, it is because of the so-called Expanding Bull's-Eye effect (Fig. 7). In just 20 years, the number of exposed houses on floodplains in Atlanta increased by 58% (while becoming more valuable). Not surprisingly, when a flood hits more houses that are each more valuable, damages will go up. But adjusted for wealth, US flooding costs have declined almost tenfold from 0.48% of GDP in 1903 to 0.057% in 2017 (Fig. 10)

Second, adaptation is often ignored and that leads to vastly exaggerated impacts. One good example is coastal flooding, where increasing sea levels might confer costs of up to $100 trillion+ per year, if we do not adapt (Fig. 8). However, if we do adapt, the cost of both flooding and adaptation in percent of GDP will *decline.*

Globally, climate-related deaths have declined 95% over the past century, while the global population has quadrupled (Fig. 17). When we look at all weather-related catastrophes across the globe, their share of global GDP has *not* increased, but rather decreased since 1990 (Fig. 18).

7.3. Costs and benefits: Paris agreement

The Paris Agreement will cost between $819 billion–$1,890 billion per year in 2030 (Table 2), most likely towards the upper end. The beneficial impact of the 2016–30 Paris Agreement will be rather small, at 1% of the cuts needed to achieve 1.5°C or an immeasurable 0.03–0.04°C temperature reduction by 2100.

The costs of the Paris Agreement are much larger than its benefits. For every dollar spent on Paris, we will likely avoid 11¢ cents of climate damage (Table 3).

7.4. Costs and benefits: optimal climate policy

Shedding unsubstantiated fears of global warming makes it easier to achieve a rational climate policy, securing the highest possible welfare. Climate decisions need to consider *two* costs: climate costs and climate policy costs. This paper uses Nordhaus' DICE model to find the climate policy that realistically will deliver the lowest combined welfare loss. This optimal policy will reach 3.75°C by 2100, still aggressively halving global emissions by 2100 compared to the no-policy scenario, saving about $18 trillion or 0.4% of GDP across the next five centuries (Fig. 26).

Aiming for much stronger climate policies will end up costing humanity much more than the benefits they provide. Trying to reach 2°C, which has become the least-ambitious target discussed internationally, could end up saddling humanity with more than $250 trillion in extra costs. The current level of climate ambition voiced by almost all policymakers and campaigners, while undoubtedly well-intentioned, will in total be hugely detrimental to the world, akin to cutting off one's arm to cure a wrist ache.

7.5. Climate policy in a world of many challenges

Yet, it is often argued that we need to proceed with strong climate policies to help the world and especially its poor. This is mostly bad advice. There are much more deadly environmental problems in the world (Fig. 27): indoor and outdoor air pollution kills almost 5 million people, while global warming kills perhaps 150,000. It is clear that global warming by any comparison is a small issue in a world still beset by problems of air pollution, lack of education, gender inequality, poor health, malnutrition, trade barriers, and international conflicts (Fig. 28). In the biggest UN-led global priority survey, global warming came in last, 16th of 16 priorities, with education, health, jobs, an end to corruption, and nutrition leading the field (Fig. 29).

There are many better ways to help than through traditional climate policies (Fig. 30). For climate, we should invest in green R&D and phase out fossil fuel subsidies. For the world's many other problems, we can do more good by halving coral reef loss, reducing child malnutrition, halving malaria infections, cutting tuberculosis deaths by 95%, expanding immunization, achieving universal access to contraception, and achieving freer trade. For a dollar spent, each of these policies would achieve hundreds or thousands of times more good than Paris.

7.6. The most important future choices

If we look at the future world outlook, we are likely to see a much richer humanity with much less poverty, more nutrition, better education, lower child mortality, longer lives, access to water, sanitation, and electricity, and better environmental performance. It will also be a world that will be less unequal and have much more access to energy.

We can see our choice of futures by looking at the five scenarios from IPCC. If we focus too much on global warming, we are likely to miss the by far most important investments in education and technological R&D to ensure we avoid the relatively poor scenarios of regional rivalry SSP3 or inequal SSP4. But even looking at the two richest scenarios from IPCC—the sustainable SSP1 and the fossil fuel-driven SSP5—an outsized focus on climate will make us choose less well. Aiming for the SSP1 is not bad. But the SSP5 world would be much better on almost all accounts. It would provide more energy, less poverty, less inequality, avoid more than 80 million premature deaths, and leave the average person in the developing world—after correcting for global warming—$48,000 better off each year by 2100. In total, choosing SSP1 in favor of SSP5 would leave the world half as rich, forgoing almost $500 trillion in extra annual welfare.

Global warming is real and long-term has a significant, negative impact on society. Thus, we should weigh policies to make sure we tackle the negative impacts without ending up incurring more costs by engaging in excessively expensive climate policies. We cannot and must not do nothing. But the evidence also manifestly alerts us to the danger that we end up with too ambitious and overly costly climate policies, and a general outlook that puts the world on a growth path that will deliver dramatically less welfare, especially for the world's poorest.

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