J.P.Morgan

Economic Research
January 14, 2020

Special Report

Risky business: the climate and the macroeconomy

- **Climate change is a slow-moving process, but it is no less dangerous for that. It is likely to be one of the key defining features of the coming decades. The longer action is delayed the more costly it will be to deal with the issues. Moreover, a delayed policy response opens us up to potentially catastrophic outcomes, which might be impossible to reverse.**

- **This report examines climate change in three sections: the mechanics of climate change; the impact of climate change; and the response to climate change.**

- **The mechanics of climate change considers the journey from human activity to CO_2 emissions, from CO_2 emissions to atmospheric CO_2 concentrations, from atmospheric CO_2 concentrations to the global temperature and from the global temperature to the global climate. The climate system is complex, non-linear and dynamic. There is considerable inertia in the system so that emissions in the coming decades will continue to affect the climate for centuries to come in a way that is likely to be irreversible. Uncertainty is endemic, not just about modal effects but also about the shape of the probability distributions, especially how fat the tails are.**

- **The impact of climate change is broad based covering GDP, the capital stock, health, mortality, water stress, famine, displacement, migration, political stress, conflict, biodiversity and species survival. Uncertainty is endemic here as well, trying to evaluate the impact of a climate that the earth hasn't seen for many millions of years. Empirical estimates based on the variability of the climate in recent decades likely massively underestimate the effects.**

- **The response to climate change should be motivated not only by central estimates of outcomes but also by the likelihood of extreme events (from the tails of the probability distribution). We cannot rule out catastrophic outcomes where human life as we know it is threatened.**

- **To contain the change in the climate, global net emissions need to reach zero by the second half of this century. Although much is happening at the micro level, it is hard to envisage enough change taking place at the macro level without a global carbon tax.**

- **But, this is not going to happen anytime soon. Developed economies, who are responsible for most of the cumulative emissions, worry about competitiveness and jobs. Meanwhile, Emerging and Developing economies, who are responsible for much less of the cumulative emissions, still see carbon intensive activity as a way of raising living standards. It is a global problem but no global solution is in sight.**

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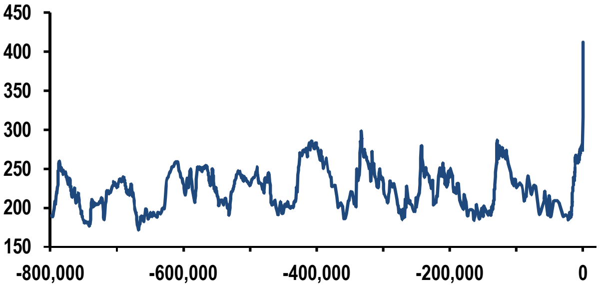
Introduction

In the 800,000 years prior to the industrial revolution, the atmospheric concentration of CO_2 oscillated in a range from 170ppm (parts per million) to 300ppm. This ebb and flow in CO_2 emissions was mainly driven by volcanic activity and ocean fissures. Since the industrial revolution, CO_2 concentrations have climbed dramatically to the current level of around 410ppm (Figure 1).[1] This increase in CO_2 concentrations reflects the burning of fossil fuels for electricity generation and transportation, industrialization, and changes in agriculture and land use (deforestation).

Figure 1: Atmospheric concentration of carbon dioxide

Parts per million (ppm)

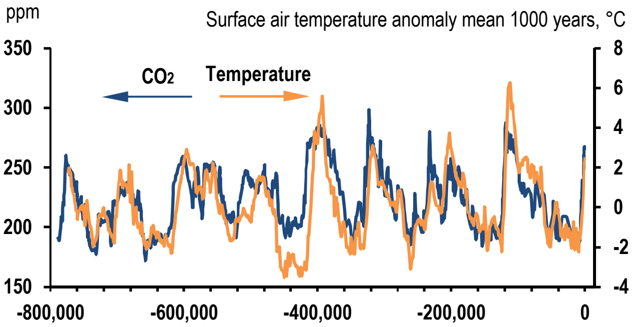


Source: See footnote 1, J.P. Morgan Years before 1950, 0 = 1950

There has been a relatively close relationship between CO_2 concentrations and temperature over the last 800,000 years (Figure 2).[2] These long run estimates of CO_2 concentrations and temperature are based on ice core data from Antarctica so they are not estimates of global conditions. But the impression is very strong. Over the last 800,000 years, through to the middle of the 19th century, as CO_2 concentrations oscillated in a 170ppm to 300ppm range, the Antarctic temperature oscillated in a range from -3.5°C to +6.3°C (relative to the average temperature over the last 1000 years).

More recent data indicate that the increase in the global average surface temperature since pre-industrial times has been around 1°C (Figure 3).[3] This has been associated with a rise in CO_2 concentrations from 280ppm to around 410ppm. However, given the long lags between emissions and temperature, the global temperature will keep rising in the coming decades even if CO_2 concentrations are stabilized at current levels.

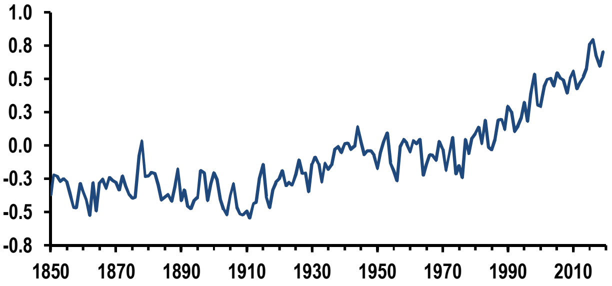
Figure 2: CO_2 concentration and temperature over 800,000 years



Source: See footnote 2, J.P. Morgan Years before 8000 BC, 0 = 8000 BC

Figure 3: Global mean temperature anomalies

°C difference relative to 1961-1990 average



Source: Footnote 3, J.P. Morgan

Increases in the global average surface temperature affect the earth's climate system. This system is complex, non-linear and dynamic. It is helpful to think of the climate as the probability distribution of weather outcomes.[4] Each day's weather comes from this distribution. In fact, the climate system covers more than what we normally think of as the weather—temperature, precipitation, wind, cloudiness and storms. It also covers complex features such as snow and ice cover, the sea level, atmospheric and ocean circulation patterns (such as the Gulf Stream and the El Niño Southern Oscillation). All of these interact in complex, non-linear and dynamic ways. Of particular importance are positive feedback mechanisms

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[1] Lüthi et al, High-resolution carbon dioxide concentration record 650,000-800,000 years before present. *Nature*, Vol. 453, pp. 379-382, 15 May 2008.; Petit et al, Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica, *Nature* 399: 429-436.; C. D. Keeling et al, Exchanges of atmospheric CO2 and 13CO2 with the terrestrial biosphere and oceans from 1978 to 2000. I. Global aspects, SIO Reference Series, No. 01-06, Scripps Institution of Oceanography, San Diego, 88 pages, 2001.

[2] Lüthi et al, High-resolution carbon dioxide concentration record 650,000-800,000 years before present. *Nature*, Vol. 453, pp. 379-382, 15 May 2008; Friedrich, T. et al., Nonlinear climate sensitivity and its implications for future greenhouse warming, Science Advances, Vol. 2, 2016

[3] Morice, C. P., J. J. Kennedy, N. A. Rayner, and P. D. Jones, Quantifying uncertainties in global and regional temperature change using an ensemble of observational estimates: The HadCRUT4 dataset, 2012

[4] Auffhammer, M., Quantifying economic damages from climate change. JEP, Fall 2018

which create amplification in response to initial shocks. Due to this complexity, climate models, even if they are huge, don't fully capture everything that is going on.

If we think of the climate as a probability distribution covering weather and these other aspects, climate change refers to a shift in the moments of this probability distribution. And what matters is not simply the mean and variance, but also the skewness and kurtosis. Skewness and kurtosis determine the fatness of the tails—the likelihood of low-probability, extreme events.

The Paris agreement on climate change, adopted in December 2015, has a central objective of limiting the rise in the global temperature "to well below 2°C above pre-industrial times, and to pursue efforts to limit the temperature increase even further to 1.5°C." This objective is to be met by the end of the century. Given that the rise in atmospheric CO_2 has already increased the global temperature by around 1°C relative to pre-industrial times, and there is a lagged effect still to come, these Paris objectives look challenging, especially with the US decision to leave the Paris Accord (Table 1, RCP8.5 is a BAU pathway).

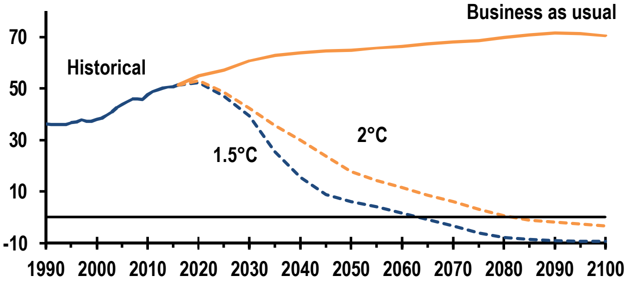
Global greenhouse gas (GHG)[5] emissions in 2017 were around 52GtCO₂eq (gigatonnes of CO_2 equivalent). If no new policies are enacted relative to what was legislated as of the end of 2017, emissions would rise to 60GtCO₂eq by 2030 and 70GtCO₂eq by the end of the century (Figure 4, Business-as-usual (BAU) scenario). This would likely mean a global temperature increase of around 3.5°C at the end of the century relative to pre-industrial times. To achieve the Paris objective of limiting the temperature increase to below 2°C (with a 67% likelihood), global GHG emissions would have to fall to 42GtCO₂eq by 2030 and to minus 4GtCO₂eq by the end of the century. To achieve the Paris objective of limiting the temperature increase to 1.5°C (with a 50% likelihood), global emissions would need to decline to 39GtCO₂eq by 2030 and minus 10GtCO₂eq by the end of the century[6].

Table 1: IPCC Representative Concentration Pathways (RCPs)

	CO_2 concentration ppm	Temperature °C	Sea level m
RCP 2.6	420	1.0 (0.3-1.7)	0.4
RCP 4.5	650	1.8 (1.1-2.6)	0.5
RCP 6	850	2.2 (1.4-3.1)	0.5
RCP 8.5	1370	3.7 (2.6-4.8)	0.6

Source: IPCC

Figure 4: Global greenhouse gas emissions
GtCO2-eq



Source: See footnote 6, J.P. Morgan

CO_2 emissions dominate overall GHG emissions, accounting for almost 70% of total emissions. CO_2 emissions—generated by power production, industry, transport, agriculture and deforestation—are currently on an unsustainable trajectory (Table 2). If no steps are taken to change the path of emissions, the global temperature will rise, rainfall patterns will change creating both droughts and floods, wildfires will become more frequent and more intense, sea levels will rise, heat-related morbidity and mortality will increase, oceans will become more acidic, and storms and cyclones will become more frequent and more intense (Figures 5[7] and 6[8]). And as these changes occur, life will become more difficult for humans and other species on the planet.

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[5] Analysis of climate change either focuses on all greenhouse gases (GHG) measured in CO_2 equivalents or just carbon dioxide. In this note we focus mainly on CO_2. Other GHG include methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons and sulphur hexafluoride.

[6] Keramida, K., Tchung-Ming, S., Diaz-Vazquez, A.R., Weitzel, M., Rey Los Santos, L., Wojtowicz, K., Schade, B., Saveyn, B., Soria-Ramirez, A., Global Energy and Climate Outlook 2018: Sectoral mitigation options towards a low-emissions economy, European Commission, 2018

[7] Siddall, M., Rohling, E.J., Almogi-Labin, a., Hemleben, C., Meischner, D., Schmelzer, I., Smeed, D.A., Sea-level fluctuations during the last glacial cycle, Nature, Vol. 423, pp. 853-858, 2003. Petit J.R., Jouzel J., Raynaud D., Barkov N.I., Delmotte M., Kotlyakov V.M., Legrand M., Lipenkov V., Lorius C., Pépin L., Ritz C., Saltzman E., Stievenard M., Climate and Atmospheric History of the Past 420,000 years from the Vostok Ice Core, Antarctica, Nature, 399, pp.429-436, 1999.

[8] Extreme events include geophysical, meteorological, hydrological and climatological events that "have caused at least one fatality and/or produced normalised losses ≥US$ 110k, 300k, 1m or 3m (depending on the assigned World Bank income group of the affected country)," Munich Re, 2019

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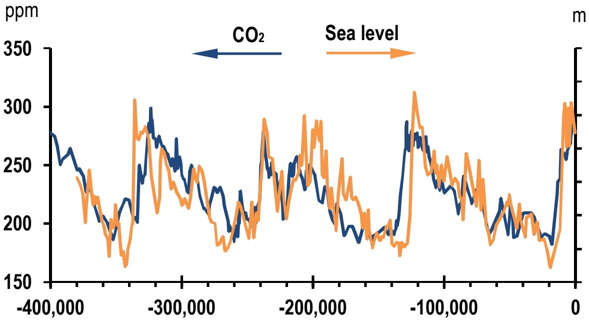
Table 2: Global greenhouse gas emissions to meet Paris 2°C objective

$GtCO_2eq$ (gigatonnes of CO_2 equivalent)

	2010	2020	2030	2050
Total GHG emissions	47.5	53.0	42.2	17.9
CO_2 emissions from fuel combustion	30.7	35.4	29.7	12.1
Power generation/district heating	11.6	13.5	9.4	2.0
Industry	6.1	6.4	6.0	2.3
Buildings	2.9	2.9	2.4	1.4
Agriculture	0.4	0.5	0.4	0.2
Transport	7.1	8.6	7.9	4.0
Other	2.6	3.6	3.6	2.2
CCS (CO_2 captured)	0.0	0.0	0.0	1.2

Source: Tchung-Ming, S., Diaz-Vazquez, A. R., Keramidas, K., Global Energy and Climate Outlook 2018:GHG and energy balances 2018 GHG and energy balances – Supplementary material to "Global Energy and Climate Outlook 2018: Sectoral mitigation options towards a low-emissions economy." EUR 29573 EN, Publications Office of the European Union, Luxembourg, 2018, J.P. Morgan

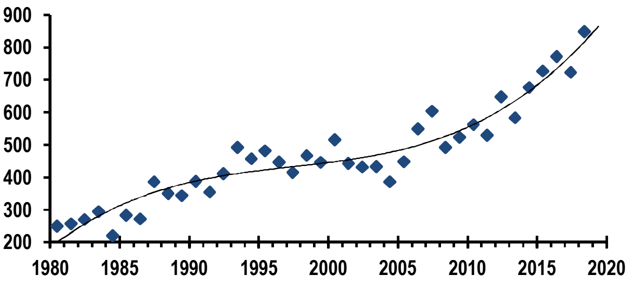
Figure 5: CO_2 and sea level over the past 400,000 years



Source: See footnote 7, J.P. Morgan

Figure 6: Worldwide extreme weather events

Number of events per year



Source: NatCatService, Munich Re; J.P. Morgan; See footnote 8

Although the direction of travel is clear, the challenge is to determine the pace of the change and the extent of the damage that climate change will inflict. Only then can decisions be made about appropriate changes, either to adapt to climate change or to mitigate to reduce emissions. Unfortunately, decision making is hard because uncertainty pervades the world of climate change, in four key ways.

First, there is uncertainty about the path of emissions. Population and economic growth are key drivers of emissions. Uncertainty about population growth is due to wide ranges for fertility and longevity (see here). Uncertainty about growth in GDP per capita is due to wide ranges for productivity growth (driven by technical change, institutions and structural policies). Uncertainty about the path of emissions also relates to the role of technology in improving both the energy efficiency of economic activity and the CO_2 intensity of energy production (principally electricity).

Second, there is uncertainty about the impact of CO_2 concentrations on the global temperature. The key issue here is the value of the Equilibrium Climate Sensitivity (ECS), which predicts the change in the global average surface temperature for each doubling of CO_2 concentrations in the atmosphere. There is huge uncertainty about the mean of this probability distribution and the shape of the distribution around the mean. Of particular importance is the fatness of the tails.

Third, there is uncertainty about the broader impact of rising temperatures on other aspects of the climate, e.g. the frequency and intensity of extreme weather events and the rise in the sea level.

And fourth, there is uncertainty about how the change in the climate affects GDP and other important issues such as heat-related mortality and morbidity, famine, water stress, migration, conflict, species survival and biodiversity.

Clearly humans and other animals have adapted to live in pretty diverse parts of the world with very different climates. The issue now is the pace and magnitude of the upcoming change in the climate. Due to the impact of human activity, atmospheric CO_2 concentrations are increasing at a faster pace than ever seen before and the climate is responding accordingly. Although precise predictions are not possible, it is clear that the earth is on an unsustainable trajectory. Something will have to change at some point if the human race is going to survive.

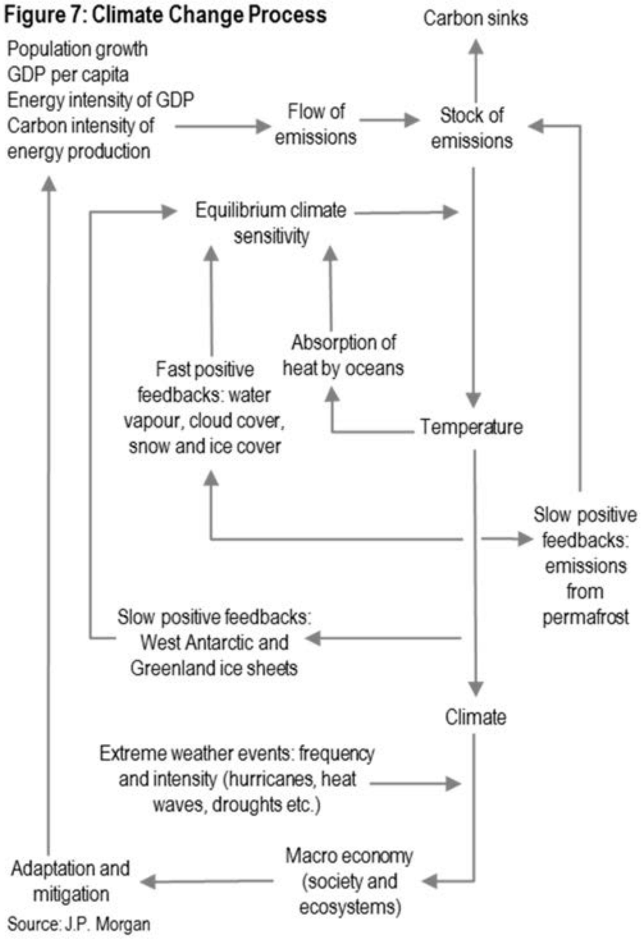
Figure 7 illustrates how human activity influences the climate, and then how the climate influences human activity. This special report follows the main threads of this exhibit, in three main sections:

Section 1: the mechanics of climate change;

Section 2: the impact of climate change;

Section 3: the response to climate change.

Figure 7: Climate Change Process



Source: J.P. Morgan

Section 1: The mechanics of climate change

In this section we consider the impact of human activity on the climate: from human activity to CO_2 emissions; from CO_2 emissions to CO_2 concentrations; from CO_2 concentrations to the global temperature; and from the global temperature to the global climate.

From human activity to CO_2 emissions

The first step in the journey of climate change is the impact of human activity on CO_2 emissions.

To understand the evolution of emissions, it is helpful to look at the Kaya identity (Table 3). This looks at four key drivers of emissions of CO_2: population growth (P), growth of GDP per capita (GDP/P), the energy intensity of the economy (E/GDP), and the emissions intensity of energy production (GHG/E). The Kaya identity is:

$$GHG=P*(GDP/P)*(E/GDP)*(GHG/E)$$

Table 3: The evolution of global GHG emissions 1990-2050

$GtCO_2$-eq to achieve 2°C Paris scenario

Starting date	**1990**	**2015**
GHG emissions at start	35.5	49.2
Contributions over next 25/35 years		
Population growth	13.7	7.5
Growth in GDP/capita	20.2	25.9
Energy intensity of GDP	-15.3	-35.9
Carbon intensity of energy	-4.9	-29.7
Ending date	**2015**	**2050**
GHG emissions at end	49.2	17.0

Source: European Commission, Global Energy and Climate Outlook 2018, J.P. Morgan

The impact of population growth and growth in GDP per capita are straightforward: with an unchanged energy structure they will exert upward pressure on emissions. The energy intensity of GDP depends on the sectoral structure of the economy; on the energy efficiency of buildings, transport, and industry; and on changes in land use (agriculture and forestry). Finally, the emissions intensity of energy production depends on the shift from carbon-producing energy sources (coal, gas and oil) to non-carbon sources (including nuclear and renewables).

The world's population is currently around 7.7 billion and according to UN estimates it will reach 9.7bn in 2050 and 10.9bn in 2100, due to the interaction between declining fertility and increasing longevity[9]. The pressure on emissions from the population will continue to increase in the coming decades, but at a slower pace than in recent decades as the growth in the global population slows. From 1980 to 2015, the global population increased by 66%. Between 2015 and 2050 it is expected to increase by 32%. The slowdown in population growth in the coming decades reflects an assumed further decline in the global fertility rates (children per adult female), from 3.9 in 1980 to 2.5 in 2019, to an assumed 2.2 in 2050 and an assumed 1.9 in 2100. Meanwhile, life expectancy at birth has increased from 60.3 years in 1980, to 72.0 years in 2019, and is expected to reach around 76.8 years in 2050 and 81.7 years in 2100.

Generating a long-run forecast of the growth in GDP per capita at a global level is very challenging due to huge uncertainties about productivity growth (driven by technological progress, physical capital, human capital and structural reform) and the extent to which the population participates in the labor force (influenced by longevity and pension systems). After growing at a 2.8% pace in the decade through 2007 and

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[9] United Nations, Department of Economic and Social Affairs, Population Division, World Population Prospects 2019: Highlights (ST/ESA/SER.A/423), 2019

at a 2.4% pace in the decade after 2008, the OECD projects that global GDP per capita will increase by 2.3% a year from 2020 to 2050.[10] This is close to the estimate by Christensen et al,[11] who forecast an average increase in global GDP per capita of 2.1% per year in the period 2010-2100. They also highlight the considerable uncertainty around this estimate, with a standard deviation of 1.1%-pts. If the distribution is normal, with 68% of the distribution within one standard deviation of the mean, then there is a 16% likelihood that the growth of global GDP per capita will be below 1% and a 16% likelihood that it will be above 3.2%. A low global growth rate through 2100 would ease pressure on emissions, while a high growth rate would add pressure, unless offset by greater climate mitigation policy and technological change.

Table 4: Decomposition of GHG emissions to meet 2°C target

Annual changes

	Energy intensity of GDP	Emissions intensity of energy production
1990-2015	-0.612	-0.196
2015-2050	-1.026	-0.849
% change	68	332

Source: European Commission, Global energy and climate change, 2018, J.P. Morgan

Given these developments in population and GDP per capita, future emissions will depend on the energy intensity of GDP and the emissions intensity of energy production. Both of these drivers of emissions have declined in recent decades, but to achieve the Paris objective of limiting the temperature increase to less than 2°C, the pace of decline has to pick up significantly. Table 4 shows the declines in the energy intensity of GDP and the emissions intensity of energy production over the period 1990 to 2015. To meet the Paris 2°C objective, the annual pace of decline of the energy intensity of GDP has to almost double while the annual pace of decline of emissions intensity of energy production has to increase almost fourfold, according to the EC calculations.

From CO_2 emissions to CO_2 concentrations

The next step in the journey of climate change is the impact of cumulative CO_2 emissions on CO_2 concentrations in the atmosphere. It is the stock of CO_2 in the atmosphere that impacts the global temperature, rather than the flow of CO_2 emissions. Changes in atmospheric CO_2 concentrations depend on the net effect of emissions from power generation, industry, transport and changes in land use, on the one hand, and absorption of CO_2 by natural carbon sinks (trees and other plants, the soil and the oceans), on the other hand. The Global Carbon Project estimates how these carbon sinks have evolved over recent decades (Table 5). But there is huge uncertainty about how this carbon cycle works and how it will evolve. Indeed, there is a concern that elevated atmospheric CO_2 concentrations will decrease the absorptive power of these natural carbon sinks, as they either get saturated or diminish in size (deforestation) (Figure 8).[12]

Table 5: Global carbon emissions and carbon sinks

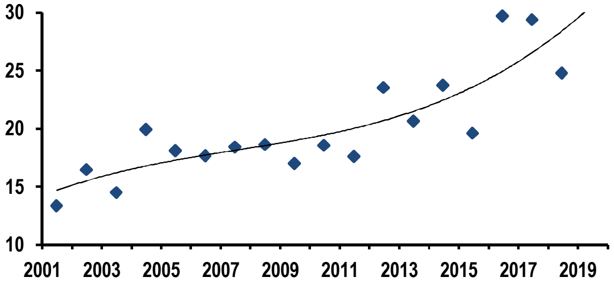
$GtCO_2$, annual averages

	CO_2 emissions	Land use change emissions	Ocean sink	Land sink
1960-1969	11.29	5.38	3.74	4.39
1970-1979	17.12	4.30	4.87	7.57
1980-1989	19.95	4.39	6.31	6.60
1990-1999	22.99	4.96	7.20	8.68
2000-2009	28.41	4.69	7.76	9.92
2010-2017	35.04	5.42	9.10	11.50

Source: Boden, T. A., Marland, G., and Andres, R. J.: Global, Regional, and National Fossil-Fuel CO2 Emissions, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., U.S.A., doi 10.3334/CDIAC/00001_V2017, 2017; available at: http://cdiac.ess-dive.lbl.gov/trends/emis/overview_2014.html, average of two bookkeeping models: Houghton, R. A. and Nassikas, A. A.: Global and regional fluxes of carbon from land use and land cover change 1850-2015, Global Biogeochemical Cycles, 31, 456-472, 2017; Hansis, E., Davis, S. J., and Pongratz, J.: Relevance of methodological choices for accounting of land use change carbon fluxes, Global Biogeochemical Cycles, 29, 1230-1246, 2015, Le Quéré et al. 2018b, J.P. Morgan

Figure 8: Global tree cover loss

Million hectares/yr



Source: See footnote 12, J.P. Morgan

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[10] OECD, "Long-term baseline projections, No. 103," OECD Economic Outlook: Statistics and Projections (database), https://doi.org/10.1787/68465614-en (accessed on 30 December 2019), 2019.

[11] Christensen, P., Gillingham, K., Nordhaus, W., Uncertainty in forecasts of long-run economic growth, PNAS, Vol. 115, 2018

[12] Hansen, M. C., P. V. Potapov, R. Moore, M. Hancher, S. A. Turubanova, A. Tyukavina, D. Thau, S. V. Stehman, S. J. Goetz, T. R. Loveland, A. Kommareddy, A. Egorov, L. Chini, C. O. Justice, and J. R. G. Townshend. 2013. "High-Resolution Global Maps of 21st-Century Forest Cover Change." Science 342 (15 November): 850–53.
"Loss" indicates the removal or mortality of tree cover and can be due to factors such as mechanical harvesting, fire, disease, or storm damage, it does not equate deforestation (Global Forest Watch, 2019); Canopy cover threshold of more than or equal to 30% has been used.

The UN Intergovernmental Panel on Climate Change (IPCC) maps cumulative CO_2 emissions from 2011-2100 onto atmospheric CO_2 concentrations in 2100 (Table 6).[13] A business-as-usual policy would see atmospheric CO_2 concentrations in 2100 of 645-780ppm. This compares with the pre-industrial average of around 280ppm, and the current level of around 410ppm. If CO_2 concentrations reach this level there is no likelihood of meeting the Paris objectives.

Table 6: From cumulative CO_2 emissions to temperature increases

Cumulative CO_2 emissions 2011 - 2100 $GtCO_2$	CO_2 concentrations in 2100 ppm	Temperature in 2100 relative to 1850 - 1900 °C*	Probability of exceeding 2°C gain in temperature %
630 - 1180	390 - 435	1.6 (1.0 - 2.8)	25
960 - 1550	425 - 460	1.9 (1.2 - 3.3)	47
1720 - 2240	425 - 520	2.2 (1.4 - 3.6)	69
1870 - 2440	500 - 545	2.5 (1.5 - 4.2)	84
2570 - 3340	565 - 615	2.8 (1.8 - 4.5)	92
3620 - 4990	645 - 780	3.4 (2.1 - 5.8)	99
5350 - 7010	810 - 975	4.5 (2.8 - 7.8)	100

Source: IPCC (see footnote) *10th to 90th percentile in parentheses

From CO_2 concentrations to temperature

The next step is the impact of atmospheric CO_2 concentrations on temperature. This is referred to as the Equilibrium Climate Sensitivity (ECS), which is defined as the impact on the global average surface temperature of a sustained doubling of CO_2 concentrations in the atmosphere, relative to pre-industrial times, once the climate system has reached a new equilibrium. The ECS is estimated from complex climate models and from the paleoclimate record.

The IPCC's most recent estimate of the ECS is a range from 1.5°C to 4.5°C. Interestingly, this range has changed very little over recent decades despite a considerable research effort. A doubling of CO_2 concentrations would involve a rise from the pre-industrial average of around 280ppm to 560ppm. With CO_2 concentrations already around 410ppm, a doubling from pre-industrial times will likely occur by around 2070 in the absence of a significant change in policy.

It is possible to argue that the impact of ongoing emissions on the climate will be modest. It is also possible to argue that it will be catastrophic. If the ECS is at the bottom of the IPCC's range there would be little need for a dramatic policy of climate mitigation. If a doubling of CO_2 concentrations led to a temperature increase of 1.5°C, then it would be reasonable to begin mitigation efforts modestly and build up gradually over time. But, it seems very unlikely that the ECS is as low as 1.5°C. There has been a 46% increase in CO_2 concentrations since pre-industrial times, which has been accompanied by an increase in the global average surface temperature of close to 1°C. Given that it takes time for CO_2 concentrations to have their full effect on global temperature, this suggests an ECS well above the lower end of the IPCC's range.

In contrast, an ECS in the top half of the IPCC's range would be of much greater concern. Gauging the consequences of a temperature increase of 3–4.5°C is very difficult. The earth has not seen an average temperature 3°C above pre-industrial times for around four million years and has not seen an average temperature 4.5°C above pre-industrial times for at least ten million years. But if CO_2 concentrations reach 700 ppm, which is quite likely under a BAU policy and would be 2.5 times higher than the pre-industrial average, and if the ECS is 4.5, the top end of the IPCC's range, the ultimate increase in the global temperature would be around 11°C. This would create huge challenges for the survival of the human race.

The uncertainty over the ECS relates to how the climate system will change as the Earth warms. There are two key sources of uncertainty around the ECS: fast positive feedback mechanisms, which work over a period of decades, and slow positive feedback mechanisms, which work over periods of hundreds or thousands of years. These mechanisms either increase the stock of CO_2 in the atmosphere or amplify the impact of CO_2 concentrations on the global temperature.

Fast positive feedback mechanisms refer to how a warming atmosphere increases water vapor and clouds, and reduces snow and sea ice, which will change the impact of CO_2 concentrations on the global temperature. Water vapor is a GHG so as the atmosphere warms the impact of CO_2 emissions on the climate will increase. With snow and sea ice there is an albedo effect. As snow and sea ice melts, less sunlight is reflected due to the darker nature of the land and sea. Thus, warming-induced reduction in snow and sea-ice cover will also increase the climate's sensitivity to a given CO_2 concentration: an increase in the ECS. Tan et al.[14] argue that a significant amount of uncertainty about the ECS is due to the behavior of clouds. They argue that climate models fail to fully account for shifts in the composition of mixed-phase clouds (those consisting of ice crystals and supercooled liquid droplets). As the temperature rises, mixed-phase clouds reflect less sunlight back into space. These fast positive feedback mechanisms will unfold over the coming decades, but

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[13] IPCC, AR5 Climate Change 2014: Mitigation of Climate Change, chapter 6, 2014

[14] Tan, I., Storelvmo, T., Zelinka, M. D., Observational constraints on mixed-phase clouds imply higher climate sensitivity, Science, Vol. 352, 2016

the precise impact on the ECS is uncertain. According to Tan et al., the ECS could be in a range of 5°C to 5.3°C, significantly higher than the IPCC estimate.

In addition to the fast positive feedback mechanisms, uncertainty about the ECS over a longer horizon is created by slow positive feedback mechanisms, which operate over a period of centuries or even thousands of years. Slow positive feedback mechanisms include changes to atmospheric circulations, ice sheet cover and the behavior of the oceans, vegetation and soil carbon sinks. They are slow because it takes a long time for atmospheric conditions to change and for ice sheets to melt. The concern about the slow positive feedback mechanisms is that they may have tipping points which occur much earlier, which create irreversible and possibly accelerated developments.

Table 7: Positive climate feedback mechanisms

Type of feedback	Mechanism
Fast feedbacks	
Water vapor	Traps heat in the atmosphere
Clouds	High clouds trap heat in the atmosphere
Arctic sea ice	Less reflection of sunlight and more heat absorption
Glaciers	Less reflection of sunlight and more heat absorption
Slow feedbacks	
Greenland and Antarctic ice sheets	Less reflection of sunlight and ocean circulation
Atlantic meridional overturning circulation	Major reduction in strength
El Nino Southern oscillation	Increase in amplitude
North Atlantic ocean convection	Major reduction in strength
Permafrost	Release CO_2 and methane
Reduced carbon sinks	Release CO_2
Amazon rainforest dieback	Release CO_2
Boreal forest dieback	Release CO_2

Source: Kopps, Shwom, Wagner and Yuan, Tipping elements and climate-economic shocks: Pathways toward integrated assessment, Earth's Future, 2016; NASA; Met Office; J.P. Morgan

Importantly, tipping points are either about passing a point of no return, where a reduction in CO_2 concentrations would fail to return the climate to the original state, or about a pick up in the momentum of change, for example the speed at which ice sheets melt. They are not about cliff-edge abrupt changes where the behavior of the climate dramatically shifts in a short period of time.

Broadly speaking, there are two types of tipping points for slow positive feedback mechanisms.

First, those tipping points that increase CO_2 emissions in the atmosphere. Around half of anthropomorphic CO_2 emissions get absorbed by vegetation, soil and the oceans (carbon sinks). The concern is that the ability of these sinks to absorb emissions declines as the temperature rises. This would increase the impact of anthropomorphic emissions on the climate. There are also processes that release more CO_2 into the atmosphere. For example, as the frozen tundra in Canada and Russia melts it will release CO_2 and methane into the atmosphere. Another example is the risk of die-back in the Amazon and Boreal forests, which would also increase CO_2 in the atmosphere. Again, both of these will increase the impact of anthropomorphic emissions on the climate.

And second, those tipping points that change the way the ocean and atmospheric circulation systems work and amplify climate change relative to CO_2 concentrations. Examples here include, changes to the Indian monsoon, the melting of the Greenland and West Antarctic ice sheets, changes to the Atlantic Meridional Overturning circulation and the El Niño Southern Oscillation.

There is huge uncertainty about when these tipping points might occur. Even if the full impact of the slow positive feedback mechanisms may take a long period to be felt, the tipping point could occur much sooner. In considering where the dangerous threshold might be, Steffen et al.[15] suggest 2°C “because of the risk that a 2°C warming could activate important tipping elements, raising the temperature further to activate other tipping elements in a domino-like cascade that could take the Earth System to even higher temperatures”.

Some analysis suggests that the ECS is much higher than the IPCC estimate. In a reconstruction of the climate of the last 784,000 years, Friedrich et al[16] estimate an average ECS of 3.2°C, almost identical to the mid-point of the IPCC range. But, they find that the ECS is very sensitive to the background climate state. Thus, during glacial periods they estimate an ECS of 1.8°C, while for interglacial periods they estimate an ECS of 4.9°C. Since we are currently in an interglacial period, this ECS estimate is considerably higher than the mid-point of the IPCC range. Using their model and the IPCC Representative Concentration Pathway (RCP) scenario 8.5—broadly a business-as-usual emissions outlook—they estimate a global surface temperature increase from 1880 to 2100 of 5.9°C (with a likely range of 4.8°C to 7.4°C). This is

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[15] Steffen, W., Rockstrom, J., Richardson, K., Lenton, T. M., Folke, C., Liverman, D., Summerhayes, C. P., Barnosky, A. D., Cornell, S. E., Crucifix, M., Donges, J. F., Fetzer, I., Lade, S. L., Scheffer, M., Winkelmann, R., Joachim Schellnhuber, H., Trajectories of the Earth System in the Anthropocene, PNAS, 2018

[16] Friedrich, T., Timmermann, A., Tigchelaar, M., Elison Timm, O., Ganopolski, A., Nonlinear climate sensitivity and its implications for future greenhouse warming, Sci. Adv., 2016

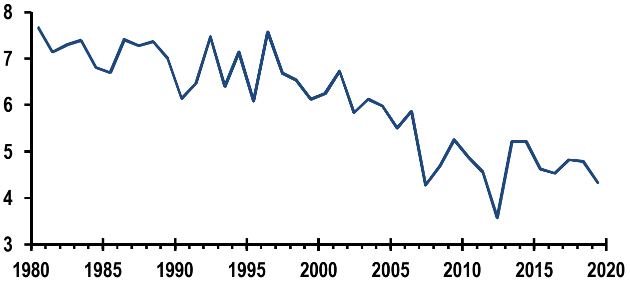
more than 2°C higher than the IPCC's central estimate of the impact of this RCP scenario.

Over the long term the ECS is almost certainly higher than the IPCC's estimate, even leaving aside Friedrich et al.'s work. Using the paleoclimate record, Hansen et al[17] argue that the IPCC estimate of the ECS does not fully account for slow positive feedback mechanisms, which may take centuries or millennia to fully unfold. It is estimated that if slow feedback mechanisms are fully included, the ECS rises to 6°C, double the IPCC estimate.

While Hansen et al.'s estimate of the ECS may take hundreds or thousands of years to be fully realized, Friedrich et al. argue that a higher ECS may have an impact much sooner, by the end of this century. Hansen et al.'s work also recognizes this possibility. They argue that the changes already seen in the Greenland and Antarctic ice sheets are occurring at a faster pace than existing climate models would have predicted, possibly due to the unprecedentedly rapid rise in CO_2 concentrations, so the slow feedback mechanisms may be operating more quickly than seen in the paleoclimate record (Figure 9).

Figure 9: Arctic sea ice

Average September extent, million square km



Source: NASA, J.P. Morgan; Arctic sea ice reaches its minimum each September (NASA)

Thus far, we have focused on the IPCC's central estimate for the ECS. But, the whole probability distribution matters as well. When the IPCC states that the ECS is likely between 1.5–4.5°C, it means that 66% of the probability distribution is in this range. This means that one third of the probability distribution is outside that range, mostly to the upside (Table 8).

Table 8: The IPCC's pdf for Equilibrium Climate Sensitivity

< 1°C	1.5-4.5°C	> 6°C
Extremely unlikely	Likely	Very unlikely
< 5% probability	> 66% probability	< 10% probability

Source: IPCC, J.P. Morgan

There is now a broad discussion of how uncertainty about the shape of the ECS probability distribution should influence the policy debate. For example, Weitzman[18] highlights the importance of the shape of the probability distribution, especially the fatness of the tails. In a simple climate model, he illustrates how the shape of the probability distribution for the ECS influences the likelihood of extreme outcomes. He estimates the effect of an atmospheric CO_2 concentration of 600ppm on the level of the global temperature. If the distribution for the ECS is normal, there is a 4% likelihood that the temperature increase would exceed 6°C and a 10^{-8}% likelihood that the temperature increase would exceed 12°C. In contrast, if the distribution is Pareto, which has fatter tails, Weitzman calculates that there is an 8% likelihood that the temperature increase would exceed 6°C and a 1.1% likelihood that the temperature increase would exceed 12°C. Given that a 12°C temperature increase would create huge challenges for the survival of the human race, Weitzman argues that "the primary reason for keeping GHG levels down is to insure against high temperature catastrophic climate risks."

From temperature to climate

Much of the debate about climate change is framed around the temperature increase relative to pre-industrial norms. But the climate is about much more than the temperature. A rise in the temperature will trigger changes in the climate: shifts in patterns and amounts of precipitation (including monsoons), decreases in ice coverage, changes in wind patterns (for example, El Niño), changes in humidity, the greater likelihood and severity of extreme weather events (droughts, storms, hurricanes, cyclones), and changes in flooding and sea levels. There is huge uncertainty about all of this due to the complex nature of the climate system.

Consider the issue of the impact on the climate of the melting of the Greenland and West Antarctic ice sheets.

Nordhaus analyses the economic impact of a potential disintegration of the Greenland ice sheet.[19] This is clearly a huge issue because a complete melting of the Greenland ice sheet

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[17] Hansen, J., M. Sato, P. Kharecha, D. Beerling, R. Berner, V. Masson-Delmotte, Pagani, M., Raymo, M., Royer, D.L., and Zachos, J.C., Target atmospheric CO_2: Where should humanity aim?, Open Atmos. Sci. J., 2008

[18] Weitzman, GHG Targets as Insurance Against Catastrophic Climate Damages, 2012

[19] Nordhaus, W., Economics of the disintegration of the Greenland ice sheet, PNAS, vol. 116, 2019

would raise the sea level by around 7 meters, as well as change other aspects of the climate. Although a full melting might take 500-1000 years, irreversible non-linear tipping points could occur much sooner. Nordhaus argues that because the dynamic of disintegration is slow moving, a moderate discount rate puts the damages at close to zero in net present value terms. However, uncertainty about the non-linear interactions between the Greenland ice sheet and other dimensions of the climate system creates doubt about how precise Nordhaus can be.

Other scientists are more concerned. Focusing on both the Greenland and West Antarctic ice sheets, Hansen et al[20] argue that even a warming of 2°C relative to pre-industrial times could be dangerous and lead to a "non-linearly growing sea level rise, reaching several meters over a timescale of 50-150 years." In an extensive study of the complex and dynamic climate system, they find that various slow feedback mechanisms in atmospheric and ocean circulation systems make ice sheets vulnerable to accelerating disintegration.

Hansen et al. also argue that non-linear ice sheet dynamics shorten the lag between increases in temperature and increases in sea level to only decades rather than centuries or millennia. This has huge implications if correct. If, for example, the sea level rose by 2 meters by 2100, this would displace hundreds of millions of people and create huge challenges for cities such as London, New York, Shanghai, Calcutta, Jakarta and Tokyo (Table 9). But the issue for coastal regions is not just the average sea level rise but also extreme weather events such as storms and cyclones. Hansen et al.'s analysis also suggests an increase in severe weather events alongside the rise in sea levels. Their message is that we have a climate emergency which should mean a rapid reduction of CO_2 emissions.

Table 9: Effects of sea level rise

Sea level rise, m	Land loss, km^2	% of global land area	Net population displaced	% of global population
0.5	877,000	0.6%	72,000,000	0.9%
2	1,789,000	1.2%	187,000,000	2.4%

Source: Nicholls et al., Sea-level rise and its possible impacts given a 'beyond 4°C world' in the twenty-first century, Phil. Trans. R. Soc. A, 2011, J.P. Morgan

Uncertainty caused by the shape of the ECS probability distribution, and especially the fatness of the upper tail, is one good reason for climate mitigation policies. Another good reason is the inertia in the climate system. Emissions of CO_2 today will continue to affect the climate not just in the 21st century but for hundreds, if not thousands, of years afterwards.

Looking at past experiences of the earth's climate, a sustained rise in CO_2 concentrations to 1000ppm or more would ultimately make the earth uninhabitable to human life as we know it now. In the Eocene and Late Cretaceous periods—35 to 90 million years ago—CO_2 concentrations in the atmosphere were similar to where we will reach in 2100 with a business-as-usual approach. But back in the Eocene and Late Cretaceous periods, temperatures were around 5-8°C warmer than pre-industrial times and the sea level was 60-170 meters higher than today (Table 10).

Table 10: Past historical experiences

Epoch	Years before present	Atmospheric CO_2 ppm	Global surface temperature Relative to pre-industrial times, °C	Sea level rise Meters
Current	0	410	1.0	N/A
Mid Holocene	6500	260	0.75	N/A
Eemian period	125000	290	1.25	6-9
Mid Pliocene	4 million	425	2-3.5	10-22
Mid Miocene	16 million	400	4.5	10-60
Eocene	35-55 million	680-1260	5-8	60-140
Late Cretaceous	90 million	1000	6.5	170

Source: Hayhoe, K., et al., Climate models, scenarios, and projections. In: Climate Science Special Report: Fourth National Climate Assessment, Volume 1, U.S. Global Change Research Program, 2017; Van Sickel, W., et al., Late Cretaceous and Cenozoic sea-level estimates: backstripping analysis of borehole data, onshore New Jersey, Basin Research, 2004; Steffan et al, Trajectories of the Earth System in the Anthropocene, PNAS, 2018; J.P. Morgan

Section 2: The impact of climate change

It seems clear that a business-as-usual approach to climate mitigation would lead to a significantly higher temperature and a significantly more adverse climate. To gauge what action to take in the face of climate change, it is helpful to know the economic and welfare consequences of different pathways for the climate. In this section we look at the estimates of climate change on GDP, and on other aspects of the human condition and on the earth's ecosystem.

Estimates of climate change on GDP

The channels through which climate change will affect GDP are very broad because climate change is itself very broad. Most macro assessments focus on the impact of changes in

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[20] Hansen, J., Sato, M., Hearty, P., Ruedy, R., Kelley, M., Masson-Delmotte, V., Russell, G., Tselioudis, G., Cao, J., Rignot, E., Velicogna, I., Tormey, B., Donovan, B., Kandiano, E., von Schuckmann, K., Kharecha, P., Legrande, A. N., Bauer, M., Lo, K.W., Ice melt, sea level rise and superstorms: evidence from paleoclimate data, climate modeling, and modern observations that 2°C global warming could be dangerous, Atmospheric Chemistry and Physics, Vol. 16, pp. 3761-3812, 2016

temperature on crop yields, labor supply and labor productivity.

In a summary of all the macroeconomic assessments he can find, Tol[21] lays out the impact on the level of GDP of various increases in global temperature, relative to pre-industrial times, in cross-sectional, panel models and Impact Assessment Models (Table 11[22]). A number of things are striking here.

First, given the importance of the issue, there are very few estimates, 26 in all.

Second, current policies would result in a global temperature increase of around 3.5°C at the end of the century, relative to pre-industrial times, yet only two of the estimates examine the impact of temperature increases significantly above 3°C.

Third, given that these are estimates of the impact on the level of GDP in 2100 they are incredibly small. At the moment, global GDP is around US$100tn. At a growth rate of 2% a year, global GDP would reach around US$500tn at the end of the century. A loss of even 7%, the highest estimate in the table, would still leave the level of GDP in 2100 over four and a half times higher than today.

And fourth, these are counterfactual losses rather than actual losses. Nobody would have an income in 2100 lower than today in absolute terms, but rather lower than it would have been in the absence of climate change.

Table 11: Impact of climate change on GDP

Global mean surface temperature increase °C	No. of estimates	Impact % on level of GDP	
		Average of estimates	Range of estimates
≤ 2	4	0.3	-0.5 to 2.3
2.5	11	-1.3	-3.0 to 0.1
3.0	9	-2.2	-5.1 to -0.9
5.4	1	-6.1	-6.1
6.0	1	-6.7	-6.7

Source: See footnote 21, J.P. Morgan; Columns 3 and 4 are the % impact on the level of GDP in 2100 relative to a scenario of no climate change.

More recent work on the damage of climate change on GDP has focused on growth effects, especially the likelihood that climate change will impact labor supply growth (heat-related mortality and morbidity) and productivity growth (heat-related morbidity and heat stress) as well as the level of output. To the extent that climate change lowers growth rates, the negative impact of climate change will be greater, especially over long horizons. However, the impression given by Tol's analysis is not changed by much.

A recent econometric study[23] considers the impact of temperature and precipitation changes on labor productivity growth. This study combines time series data from 1960-2014 with cross-country data from 174 countries. It looks at the impact on labor productivity of deviations in climate (temperature and precipitation) from their historical averages. Their analysis suggests that an increase in the global average surface temperature of around 3.5°C above pre-industrial levels—broadly a business-as-usual (BAU) environment in line with the IPCC RCP 8.5 scenario—would reduce global GDP per capita by 7.2% by 2100.

The authors provide estimates of the impact of BAU on all 174 countries in their sample, where some countries will experience temperature increases well above the mean. Eighteen countries have an income shock in 2100 of more than 10% (including the US) and two have an income shock of more than 15%. But assuming that GDP per capita keeps growing over the next 80 years, even a 15% shock to the level of income looks small. If we assume current income is $100, then 2% growth over the next 80 years would deliver an income of around $500 in 2100. Instead of an income of $500 in 2100, a 15% shock to the level of income would deliver an income of $425. That would still be over four times higher than today's income. These calculations illustrate that the income losses from BAU climate policy are counterfactual rather than actual. In no estimate is the level of income in 2100 lower than it is today.

Other research has come up with larger effects. Burke et al[24] have estimated a model that shows sharp declines in labor supply, labor productivity, and crop yields beyond certain temperature thresholds. Their analysis suggests that an increase in average temperature of around 3.5°C, relative to pre-industrial times, would reduce the level of global GDP by around 23% in 2100. This is much larger than the estimates in the table above, but it is still a counterfactual loss. If we assume current income is $100, then 2% growth over the next 80 years would deliver an income of $500 in 2100. A

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[21] Tol, R., The economic impacts of climate change, Review of Environmental Economics and Policy, 2018

[22] The final two columns show the impact of climate change on the level of GDP in 2100 relative to the situation of no climate change

[23] Kahn, Mohaddes, N.C. Ng, Pesaran, Raissi and Yang, Long-term macroeconomic effects of climate change: a cross-country analysis, NBER working paper, 2019

[24] Burke, M., Hsiang, S. M., Miguel, E., Global non-linear effect of temperature on economic production, 2015

23% loss would still leave income in 2100 standing at $385, considerably higher than today's level.

Wealth effects and the discount rate

The true economic losses from failing to mitigate climate change are much greater than suggested by these income losses. If an income effect persists through time, then it is important to consider the present value of the income losses, which represents the impact on wealth rather than income. This is not generally considered by economists studying climate change. But, it is important. Of course, the discount rate is critical in evaluating the net present value of a permanent loss to the level of GDP, and in the climate change literature there is an intense debate about what discount rate to assume.

The Stern report[25] in 2007 argued for a discount rate close to 1%, while at the time Nordhaus[26] argued for a discount rate closer to 6%. To see the impact of the discount rate, the net present value of a permanent 7% shock to income with a 1% discount rate is almost seven times the annual level of GDP (Table 12). This means that in the absence of climate mitigation policies, the global economy's wealth would be lower than it would otherwise have been by an amount equal to seven times annual GDP. The shock to wealth declines as the discount rate rises. At a 4% discount rate, a 7% permanent income shock reduces wealth by 175% of annual GDP relative to what would otherwise have happened. At a 6% discount rate, the net present value of the income losses would be 117% of annual GDP.

Table 12: Net present value of income shock
% of annual GDP

	Discount rate			
Income shock	1%	2%	4%	6%
-1%	99	50	25	17
-3%	298	150	75	50
-5%	497	250	125	83
-7%	695	350	175	117
-10%	993	500	250	167
-15%	1490	750	375	250

Source: J.P. Morgan

Even though a proper assessment of the significance of these climate-driven GDP shocks needs to include the impact on wealth (the net present value of income), these are still counterfactual losses of wealth. Wealth is not lower in absolute terms, but rather it is lower than it would otherwise have been in the absence of climate change. Given that wealth is likely to grow over the coming 80 years, even sizable losses in wealth still leave future generations wealthier in 2100 than the current generation.

Economic impacts are too small

Most likely, these estimates of the income and wealth effects of unmitigated climate change are far too small. Econometric models are based on historical data of variations in temperature and precipitation seen over recent decades. But, we have not seen enough variability in the data to make these models reliable. A BAU climate policy would likely push the earth to a place that we haven't seen for many millions of years. Experience over recent decades is not a useful guide to that kind of future.

Moreover, economists have struggled to quantify the impact of other aspects of climate change beyond temperature and precipitation, such as extreme weather events, droughts, heatwaves, floods and sea level increases. These broader aspects of climate change would not only impact GDP and welfare directly, but would also have indirect effects via morbidity, mortality, famine, water stress, conflict and migration. There will also be damage to buildings and infrastructure and possibly the premature scrapping of some of the capital stock as policy and technology change. Moreover, there are plenty of non-linearities in both the climate system and the macro economy which could make the economic consequences of BAU much more severe.

The economics of climate change is also in the tails of the probability distribution, and in the risk of disastrous outcomes. Uncertainty about the shape of the fat tail of the ECS probability distribution function can have a huge impact on estimates of economic damages. Economic models struggle to deal with an ECS from the fat upper tail. For example, Calel et al.[27] note that IAMs (Integrated Assessment Models) can suggest that a 10°C temperature rise would depress global GDP in 2100 by only 17%, while a 20°C temperature increase would depress global GDP in 2100 by only 50%. Given that a temperature increase of 10°C would make life on earth extremely challenging, while a temperature increase of 20°C would almost certainly make the earth uninhabitable, these estimates show that economic models struggle to deal with low probability events that could prove catastrophic.

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[25] Stern, N., The Economics of Climate Change, 2007

[26] Nordhaus, W., A Review of the Stern Review on the Economics of Climate Change, JEL, 2007

[27] Calel, R., Stainforth, A. D., Dietz, S., Tall tales and fat tails: the science and economics of extreme warming, Climate Change, 132 (1). pp. 127-14, 2015

The impact of climate change beyond GDP

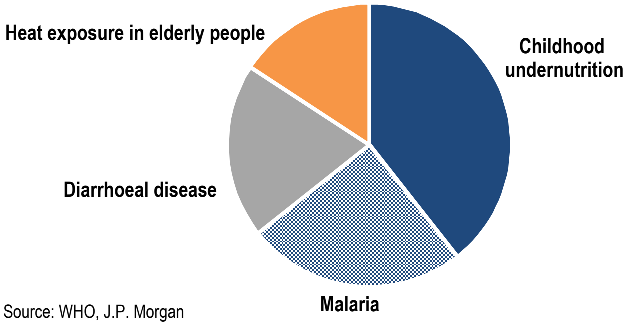
Some economists have tried to quantify the impact of climate change beyond GDP. Hsiang et al.[28] estimate the effect in the US of temperature and rainfall on agriculture, mortality, crime, labor, coastal impacts and energy demand. They do not include the impact of climate change on morbidity or labor productivity. Aggregating across sectors using willingness-to-pay or accounting data, they estimate that for the US as a whole, the shock to the level of GDP (as a % of GDP) for 1.5°C of warming is +0.1 to -1.7% of GDP, while for 4°C of warming the shock to the level of GDP is -1.5 to -5.6% of GDP. This reflects reduced agricultural yields, increased mortality, increased crime, reduced labor supply, increased electricity demand and amplified coastal impacts due to more hurricanes and sea level increases. Given that these losses are relative to a counterfactual baseline, we would stress that these effects are small relative to a level of income that could be five times higher in 2100. Indeed, they are not that different to the more narrowly based estimates highlighted above. These estimates alone do not sound particularly alarming, but quantifying the impact of climate change only in dollar terms overlooks the potential severity of the human and environmental costs.

Climate change and health

The human cost of climate change will play out through worsening health outcomes. The World Health Organization (WHO) projects that over 2030-2050, climate change will cause around 250,000 additional deaths per year, with this being a conservative estimate, taking into account only a subset of possible channels (Figure 10).[29] The burden on human health will not be shared equally, with children, the elderly, and those in developing countries most vulnerable. In geographic terms, the WHO sees Sub-Saharan Africa being most affected in 2030 with the burden shifting to South Asia by 2050. Climate change will likely also have some localized positive effects on mortality and illness, due to fewer extreme cold days that would benefit some communities, but ultimately, the negative impact is projected to dwarf the positive.

Rising global temperature and more frequent episodes of extreme heat will affect human health through multiple channels. According to the WHO, warmer temperatures are linked to higher allergen levels, causing asthma, and also are associated with higher risk of mosquito-borne diseases including malaria and dengue. Moreover, heat stress, which can occur at temperatures above 35°C, is associated with respiratory and heart problems. Those working outdoors in sectors such as agriculture and construction are especially vulnerable to heat stress and decreased labor productivity is expected to become an increasing problem, particularly in South Asia and West Africa[30]. Episodes of extreme heat, which are expected to become more frequent, can be fatal, particularly for children and the elderly. Of the 250,000 extra deaths per year projected by the WHO, 38,000 are attributed to heat exposure in elderly people.

Figure 10: Additional annual deaths between 2030-2050 caused by climate change



Source: WHO, J.P. Morgan

In addition to rising temperature, variability in climate and precipitation patterns can also have detrimental health impact through the disruption of the production of staple crops, including rice, maize and wheat. Generally, warmer temperatures and fewer cold periods are expected to increase yields in cold geographies, but decrease yields in those that are already warm. However, climate change-induced droughts, excessive or unpredictable rainfall patterns and sea-level rise-induced land loss or salinization will almost certainly cause crop degradation. Rural communities in developing countries are most vulnerable—in part because of higher barriers to adaption—and crop failure will cause or exacerbate hunger and malnutrition.

Climate change also threatens water security, which is critical for food production, access to safe drinking water, adequate hygiene and the prevention of disease. Water stress, more generally, describes a high ratio of water withdrawal for human, agriculture, and industry usage, to water availability, and can be a result of a physical shortage or institutional or infrastructural failure. Currently, the Middle East and North Africa are the most water scarce regions globally, with over 60% of the population exposed to “high” or “very

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[28] Hsiang, S., et al., Estimating economic damages from climate change in the United States, Science 356, 1362-1369, 2017

[29] World Health Organization, Quantitative risk assessment of the effects of climate change on selected causes of death, 2030s and 2050s, 2014

[30] International Labour Organization, Working on a warmer planet: The impact of heat stress on labour productivity and decent work, 2019

high” degrees of water stress, compared to a 36% global average. The WHO predicts that by 2025 half the global population will live in areas afflicted by water stress. In addition to challenges posed by changing demographics and population growth, water stress can be exacerbated by climate change, as rainfall patterns become less predictable and more frequent flooding contaminates fresh water supplies.

Estimating the human health cost of climate change is fraught with challenges, hence the WHO estimates only focus on a subset of drivers, and notably do not account for the impact of natural disasters. It’s clear though that natural disasters, which will become more frequent with climate change, will also contribute to increased mortality and morbidity, destruction of shelter and disruption of medical supplies and services. And while developing countries are typically more vulnerable to such risks—due to already weaker infrastructure and less ability to adopt adaptation or mitigation technologies—natural disasters can have an impact on societies globally. Heat stress, water and food scarcity and natural disaster damage are consequences of climate change that bear a uniquely human cost, regardless of the impact on gross domestic product. They can also trigger second- and third-round effects, likely human migrations and conflict.

Climate change and migration pressure

Climate migration has long existed, but the pressing importance of it today relates to predictions that the effects of climate change will intensify this century. Migration is either internal (moving within a country) or external (cross-border), but of the one billion migrants globally at the moment, 75% are estimated to be internal. When migration is cross-border, migrants tend to stay within neighboring regions, where cultural, religious, or family ties are more easily maintained. Climate change is expected to increase the frequency and intensity of extreme weather events, pushing up internal migration as people relocate (in some cases temporarily) away from disaster zones. Rising sea levels are also a climate-related driver of internal migration and present a serious threat to inhabitants of low-lying coastal areas. In fact, rising sea levels pose an existential threat to some small island states.

The International Organization for Migration states that there are no reliable estimates of climate migration. And what’s more, most of the analysis focuses on internal migration. For example, the most extensive study of climate migration by the World Bank only focuses on internal migration.

The World Bank developed a model to project climate migration, which embeds slow-onset climate change into future population distributions for three emerging market regions: Sub-Saharan Africa, South Asia, and Latin America.[31] The model considers three scenarios. The “reference” scenario, poignantly also the most pessimistic scenario, assumes little to no climate policy, continued reliance on fossil fuels, and energy-intensive development. It is characterized by increasing greenhouse gas emissions, consistent with global warming of 2.5°C by 2050. It also assumes high population growth and growing inequality in low-income countries. The “more inclusive development” scenario assumes the same emissions profile, but with more moderate trends in population growth and inequality. The “climate friendly” scenario shares the same socioeconomic pathway as the “reference” case, but includes lower emissions, implying 0.3°C global warming by 2050. This scenario assumes rapid adoption of strong environmental policies and cleaner technology.

The headline findings of the report are the following: in the absence of policy action, climate change may result in the movement of 143 million people within their countries’ borders by 2050. Sub-Saharan Africa stands to be most affected, with internal climate migrants expected to account for 3.5% of the region’s population by 2050. The World Bank’s model is a step closer to grasping the magnitude of future climate migration, but since only three regions are covered, the estimates are a lower bound. Furthermore, the report exclusively models internal migration and excludes displacements due to extreme weather events (Table 13).

Table 13: Projection of internal climate migrants by 2050
Million people, unless otherwise stated

	"Reference" scenario		"More inclusive development" scenario		"Climate-friendly" scenario	
Total						
Number	117.5		85.1		51.1	
Min/Max	91.8	143.3	65.1	105.3	31.2	71.7
% population	1.8%	2.8%	1.3%	2.1%	0.6%	1.5%
Sub-Saharan Africa						
Number	71.1		53.3		28.3	
% population	3.5%		3.0%		1.4%	
South Asia						
Number	35.7		21.1		16.9	
% population	1.6%		0.9%		0.7%	
Latin America						
Number	10.6		10.5		5.8	
% population	1.6%		1.5%		0.9%	

Source: World Bank Groundswell Report (2018)

But internal migration is unlikely to be the only, or even the most important, consequence of climate change on popula-

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[31] Groundswell: Preparing for Internal Climate Migration”, The World Bank, 2018

tion movements. External migration is likely to increase as rising temperatures and unpredictable rainfall patterns affect agricultural production and water availability across whole regions. Unlike localized flooding or natural disaster damage, sustained warming and altered weather patterns are more likely to affect entire countries or regions, meaning internal or local migration is no longer an option. For example, the 1840s' Irish Famine was responsible for a vast external migration of Irish people to North America and England, since a mostly rural Ireland offered no industrial alternative to sustain a livelihood.

Climate change and conflict

In parts of the world where climate change intensifies competition for food, water and shelter, there is an increased risk of conflict. Research finds that above-average temperature and below-average rainfall are conditions positively associated with the initiation and duration of conflict.[32] However, the causality of violence is complex, and other factors, including socioeconomic standing, inequality, weak governance and past episodes of violence are all intertwined. Hence there are serious challenges in trying to predict when and where conflicts may arise in the face of a changing climate.

Nonetheless, the academic literature puts forward a number of channels through which climate change can induce conflict. While much of the research is based on context-specific case studies, it at least sheds light on how climate change might give rise to future conflicts. It also gives a broad sense of which communities are most vulnerable. Much of the research focuses on the effects in developing countries, and channels are likely to be felt more strongly in regions with a high dependency on agriculture as well as weak institutions or high corruption. A 2018 research paper by the Stockholm International Peace Research Institute, which focuses on climate conflict in South and South East Asia, categorizes the following pathways: deterioration of livelihoods, tactical consideration of armed groups, exploitation of social vulnerabilities and resources by elites, and displacement and migration.[33]

The first is perhaps the most obvious; in the context of water or food scarcity, or among communities where incomes from agriculture or fishing have collapsed, civil conflicts are more likely to erupt. Moreover, in this environment the opportunity cost of earning income though illegal activity or joining rebel groups is lower. Indeed, the paper finds that armed groups can exploit climate events to gain power. Such groups can become more violent during climate events in order to secure their own food needs, as well as utilizing periods of higher civilian popularity to expand recruitment.

It is not only rebel or terrorist groups that can take advantage of climate crises though. Research finds that community elites, such as landowners or corporations, might also use such events to gain influence, by securing aid distribution rights or unfairly claiming landownership during periods of migration. Migration itself can also give rise to conflict, as a result of cultural or religious tensions or through exacerbating the scarcity of natural resources.

Ecosystems and species survival

Beyond GDP accounting, one must also consider the impact of climate change on the natural world. Nature is the lifeblood of the planet and critical for human existence, providing food, energy and medicine and also playing a fundamental role in communities and cultures. Human activity has an outsized influence on the natural environment and scientists have documented significant declines and degradations to ecosystems and biodiversity. A landmark report, published by the United Nations in 2019, has found that the state of nature is deteriorating at a rate unprecedented in human history.[34] The extent and condition of ecosystems globally has found to have declined by 47% of their estimated natural baseline, and the report expects the decline to persist by at least 4% per decade. Moreover, the rate of extinction globally is estimated at tens to hundreds of times higher than the average over the last 10 million years. The rate of extinction is accelerating, with around one million species threatened with extinction, many within decades.

Climate change is among the primary drivers of a human-induced decline in the state of nature. The increased intensity and frequency of extreme weather events including droughts and floods as well as sea-level rise and ocean acidification (to name a few) exacerbate the already negative trends in the natural environment. Even without climate change, ecosystems and biodiversity face challenges from agricultural expansion, urbanization, exploitation and pollution. To give a sense of the scale of some of these issues, just 13% of the wetlands in 1700 remained by 2000, the global forest area is now estimated to be 68% of the pre-industrial level and

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[32] FAO, Food security and conflict: Empirical challenges and future opportunities for research and policy making on food security and conflict, 2018

[33] SIPRI, Climate change and violent conflict: Sparse evidence from South Asia and South East Asia, 2018

[34] IPBES, Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, Summary for Policymakers, 2019

around half the live cover on coral reefs has been lost since 1870. Many negative effects have accelerated in recent decades, which is hardly surprising since the value of food crop production has expanded 300% since 1970 and urban areas have more than doubled since 1992.

Climate change is expected to increasingly influence the natural world, and the UN bleakly warns that even moderate global warming of 1.5°C to 2°C will "profoundly shrink" the geographical areas where species are found. With 2°C global warming, research finds that 5% of species are at risk of climate-related extinction and this figure rises to 16% with 4.3°C of warming. The thresholds for coral reefs are much lower still, and 2°C warming is projected to reduce coral reefs to less than 1% of their former cover. If moderate levels of warming can have such devastating effects on the natural environment, it doesn't seem like an overreach to categorize the ecological situation as a state of crisis, requiring "transformative change" and international cooperation.

Section 3: The response to climate change

In this section we consider what needs to be done to either make it easier to live with climate change (adaptation) or to reduce the amount of climate change (mitigation).

CO_2 emissions as a global externality

Climate change reflects a global market failure in the sense that producers and consumers of CO_2 emissions do not pay for the climate damage that results. The standard economic answer to such an externality is a Pigovian tax: essentially a tax on CO_2 emissions. This would provide incentives to producers to shift production in a less CO_2 intensive direction, to consumers to shift consumption to less CO_2 intensive goods and services and to entrepreneurs to encourage innovation in low CO_2 technologies. It is best if the CO_2 tax is global to deal with the free rider problem.

In a recent study, the IMF estimated that in order to achieve the Paris 2°C objective, a global carbon tax should be introduced immediately and rise to \$75 a ton of CO_2 by 2030.[35] This would be a huge move given that the IMF estimates that the global average price on CO_2 emissions is currently around \$2 a ton, reflecting a number of regional and local carbon pricing schemes.

Given the current environment on international cooperation, and the positions on climate change taken by a number of world leaders, a global carbon tax is not going to happen anytime soon. Despite being signatories of the Paris agreement, and recognizing that there should be greater ambition in reducing emissions, a number of countries resisted agreement on a global carbon trading system at the recent UN summit in Madrid (COP25). A huge issue concerns equity across countries. Developed economies are reluctant to cut emissions, even though they have contributed the most to the stock of emissions over time, because this is seen as a threat to competitiveness and jobs. Emerging and developing economies who still see carbon intensity as a route to higher standards of living feel reluctant to curb emissions given that they have contributed so little to the climate problem (Table 14).

Table 14: Total CO_2 emissions from fossil fuels and cement production and gas flaring

$GtCO_2$ (% of global emissions)

	2016 emissions	2016 emissions per capita	Cumulative emissions 1960 - 2016	Cumulative emissions 1960 - 2016 per capita
Global	36.2 (100)	4.8	1248.4 (100)	241.7
China	10.2 (28.1)	7.2	190.6 (15.3)	174.0
US	5.3 (14.7)	16.4	278.2 (22.3)	1104.8
EU 28	3.5 (9.7)	6.9	228.8 (18.3)	488.5
India	2.4 (6.7)	1.8	43.5 (3.5)	50.8
Russia	1.6 (4.5)	11.3	98.1 (7.9)	703.7
Japan	1.2 (3.3)	9.5	55.8 (4.5)	471.3
Iran	0.7 (1.8)	8.2	15.1 (1.2)	299.3
Saudi Arabia	0.6 (1.8)	19.6	13.1 (1.0)	851.4
South Korea	0.6 (1.6)	11.7	15.1 (1.2)	370.0
Canada	0.6 (1.6)	15.5	25.3 (2.0)	938.1
Indonesia	0.5 (1.4)	1.9	11.2 (0.9)	64.6
Brazil	0.5 (1.3)	2.4	13.3 (1.1)	93.8
South Africa	0.5 (1.3)	8.3	17.1 (1.4)	481.6
Mexico	0.5 (1.3)	3.8	16.8 (1.3)	209.6

Source: Hannah Ritchie and Max Roser (2019) - "CO_2 and other Greenhouse Gas Emissions". Published online at OurWorldInData.org. UNFCCC and CDIAC. Tom Boden and Bob Andres (Oak Ridge National Laboratory); Gregg Marland (Appalachian State University). Tchung-Ming, S., Diaz-Vazquez, A. R., Keramidas, K., Global Energy and Climate Outlook 2018:GHG and energy balances 2018 GHG and energy balances – Supplementary material to "Global Energy and Climate Outlook 2018: Sectoral mitigation options towards a low-emissions economy". EUR 29573 EN, Publications Office of the European Union, Luxembourg, 2018, UN, J.P. Morgan

Without agreement at the global level, initiatives are taking place at a more local level. The EU and the UK have both made commitments to reduce net carbon emissions to zero by 2050, although it is not clear exactly how that will be achieved and how these plans will deal with the competitiveness problem. In theory, a country or region pursuing an ambitious emissions reduction objective could impose a carbon border tax, although this would be very controversial. Despite these problems, a number of countries and localities have carbon taxes or emissions trading regimes. These cover around 24% of global CO_2 emissions but at a low average price. In addition, technological change and public pressure are changing rapidly, leading to moves toward both adaptation and mitigation.

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[35] IMF, Fiscal Monitor: How to Mitigate Climate Change, Oct 2019

Adaptation and mitigation

Assessments of the economic consequences of climate change generally assume limited adaptation (adjusting to a more adverse climate) and mitigation (trying to stop a more adverse climate from developing). Adaptation—for example using more air conditioning units, building sea level defenses or using different crops—may limit the near-term impact of climate change on GDP, but at the risk of creating greater problems later, due to ongoing emissions.

The only way that climate change can be slowed, stopped or reversed is through mitigation strategies that impact emissions. One helpful way to think about mitigation is to return to the Kaya identity. This looks at the four key drivers of emissions of CO_2: population growth (P), growth of GDP per capita (GDP/P), the energy intensity of the economy (E/GDP), and the emissions intensity of energy production (GHG/E). The Kaya identity is:

$$GHG=P*(GDP/P)*(E/GDP)*(GHG/E)$$

Mitigation strategies involve changes in the energy intensity of GDP (E/GDP) and in the emissions intensity of energy production (GHG/E). E/GDP is influenced by the sectoral structure of the economy, on the energy efficiency in buildings, transport and industry, and on land use (agriculture and forestry). GHG/E is influenced by the mix of energy production (electricity) between carbon-producing sources of energy and non-carbon sources.

The energy intensity of GDP (E/GDP) has been declining in recent decades. Since 1990, it has broadly offset the increased pressure on emissions coming from population growth. In order to meet the Paris objective, the pace of decline in the energy intensity of GDP has to pick up in the coming decades by around 70% relative to what we have seen in recent decades.

Here it is relevant to consider broader GHG emissions rather than just CO_2 emissions. Agriculture, forestry and other land use (AFOLU) for example emits only modest amounts of CO_2 but emits a lot of other GHGs, especially methane (CH_4) and nitrous oxide (N_2O) (Table 15). The AFOLU sector emits 40% of total global methane emissions and 75% of total global nitrous oxide emissions. These emissions are due to livestock digestive processes, manure management, rice cultivation, deforestation and burning stubble after harvesting. Livestock alone accounts for around 15% of global GHG emissions each year, roughly equal to emissions from all of the world's autos, trucks, aircraft and ships.[36] According to the IMF, three things are needed to make the agricultural sector sustainable: first, a dramatic reduction in the consumption of red meat and dairy (by around 50%) and a shift towards plant-based meat substitutes; second, a large scale shift from monoculture agriculture towards organic and mixed crop-livestock farming; and third, a dramatic reduction in deforestation and an increase in reforestation and afforestation. These changes would both reduce emissions and increase the earth's natural carbon sinks.

Table 15: Global sectoral emissions
% of total emissions

	Total GHG	CO_2
Electricity and heat production	25	59
Agriculture, forestry and land use	24	8
Industry	21	7
Transportation	14	16
Buildings	6	10
Other	10	0

Source: IPCC, IEA, World Bank, J.P. Morgan

Industry emits close to 20% of total GHG emissions. These are from industrial processes, such as metals, cement and chemicals production; electricity use by industry is excluded from this estimate of emissions. Improvements here include a greater emphasis on materials efficiency, recycling and a shift in designs away from steel and concrete.

Transportation accounts for around 15% of both CO_2 emissions and total GHG emissions. Mitigation here covers greater fuel efficiency, increased car sharing, increased use of public transport, better fleet management and improved design in trains and aircraft (improved aerodynamics and weight reduction). However, without dealing with the dominance of coal in power generation, other developments, such as a shift to electric vehicles, will not necessarily reduce CO_2 emissions. Indeed, they could increase emissions, depending on where the additional electricity is coming from. Electricity from coal-fired power stations is more CO_2 intensive than petrol in a car.

Buildings, excluding their consumption of electricity, emit only a modest amount of GHG and CO_2. Reduced emissions here involve better insulation and more energy efficient appliances, lighting and air conditioners. Also the lifespan of buildings could be extended.

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[36] IMF, Finance and Development: The Economics of Climate Change, 2019

Moving on to the emissions intensity of energy production (GHG/E), there have also been declines over recent decades, but in order to meet the Paris objective the pace of improvement needs to pick up around fourfold. This would require a massive decarbonisation of the electricity generating sector. Power generation is the biggest source of CO_2 emissions, accounting for 59% of global CO_2 emissions. The reason is that power generation still involves huge use of fossil fuels, especially coal. According to the IEA, coal accounts for 74% of global CO_2 emissions from electricity generation (Table 16). This means that coal-fired power stations account for around 44% of all global CO_2 emissions.

Table 16: Annual CO_2 emissions from the power sector
Million tonnes

	2000	2018
Electricity generation	8247	12655
Coal	5920	9357
Natural gas	1341	2656
Oil	986	641
Heat production	1055	1163
Coal	532	708
Natural gas	415	403
Oil	108	51
Total	**9302**	**13818**

Source: IEA, World Energy Outlook, 2019; J.P. Morgan

The most important shift needed in energy production is a move from CO_2 intensive sources of energy (coal, oil and gas) to nuclear and renewables, although a switch from coal to gas would also reduce emissions due to the elevated CO_2 intensity of coal for each terawatt of electricity produced (Table 17).

Table 17: CO_2 intensity per terawatt hour of electricity produced
Terawatt hours (TWh)

	Electricity, TWh	CO_2, Mt	CO_2 Mt/TWh
Coal	10123	9357	0.92
Natural gas	6118	2656	0.43
Oil	808	641	0.79

Source: IEA, J.P. Morgan

But the key to a significant emissions reduction in energy production is greater penetration of nuclear and renewables. According to the IEA, in 2018 nuclear and renewables contributed 36% of global electricity production (Table 18). This will have to rise to 79% by 2040 to meet the Paris 2°C objective. Meanwhile, the contribution of coal to global electricity generation needs to decline from 38% in 2018 to 6% by 2040.

Table 18: Global electricity generation by source
Terawatt hours (TWh)

	2000	2018
Coal	5994	10123
Natural gas	2750	6118
Oil	1207	808
Nuclear	2591	2718
Renewables	2836	6799
Hydro	2613	4203
Bioenergy	164	636
Wind	31	1265
Solar PV	1	592
Geothermal	52	90
CSP	1	12
Marine	1	1
Total	**15427**	**26603**

Source: IEA, World Energy Outlook, 2019., J.P. Morgan; CSP: concentrated solar power

Nuclear energy does not directly contribute to GHG emissions, and is hence considered a clean source of power. Moreover, unlike other sources of clean energy, such as wind and solar, nuclear power is available 24 hour per day, making it highly reliable. Despite these attractive characteristics, the share of nuclear energy in global electricity generation has been shrinking since its peak of 17% in 1996. This is, in part, because a number of other obstacles and risks around nuclear energy remain, including issues of waste management, operational risks, the creation of nuclear weapons, and adverse public opinion.

Given that nuclear has fallen out of favor, and geothermal and hydro are both constrained by geography, the real issue is the ongoing development of wind, solar, bioenergy, concentrated solar power (CSP) and marine, which together accounted for 9.8% of electricity generation in 2018. This is up from 1.6% in 2000. Further penetration will happen, driven by lower costs and subsidies. But challenges remain due to a major reliance on either the wind or sunlight, which are not there all of the time. Advances in storage technology would help make renewables more reliable.

According to the IEA, a sizeable shift from fossil fuels to renewables is technically feasible, though it would be very challenging from a cost perspective. In their 2019 World Energy Outlook, the IEA conducted a detailed global geospatial analysis of the potential for offshore wind, based on the technology of offshore turbines, the quality of wind, the depth of the sea and the nature of the sea bed. Using only near-shore, shallow water sites, the IEA estimates that offshore wind could generate 36,000 TWh (terawatt hours) of electricity per year. This is higher than current electricity production of 26,600 TWh per year and not far short of the projected demand under a BAU policy of 41,400 TWh in 2040. Going for sites further from the shore and in deeper water creates a lot more potential. According to the IEA, the potential from offshore wind is 420,000 TWh of electricity production per year, around eleven times the projected production in 2040 under a scenario consistent with the Paris objective (38,700 TWh).

The issue is not the potential opportunities, but the cost. Coal remains the cheapest source of electricity and the stock of coal-fired power stations is relatively young. Around 60% of the stock is less than 20 years old, compared with a design lifespan of up to 50 years. According to the IEA, to meet the Paris 2°C objective on the global temperature, the lifespan of coal-fired power stations would need to be limited to 25 years, which would require the immediate elimination of 34% of the global coal-fired production capacity. The cost would involve not only the premature scrapping of these coal-fired power stations but also the increased investment in renewables. The end result could be energy shortages and higher electricity prices for consumers. It isn't going to happen.

Geoengineering as an extreme technology

Despite some dramatic things happening at the micro level (see here), and the political commitments of a number of governments, it is hard to see global warming being limited to less than 3°C, let alone the Paris objective of less than 2°C, relative to re-industrial times, without the introduction of a global carbon tax or a dramatic shift in technology which either reduces CO_2 concentrations or reduces their impact on the climate. One potentially transformational technology is geoengineering.

Geo-engineering, defined as intentional large-scale interventions in the climate system, is an external approach to tackling climate change, entirely separate from the mitigation strategies which address the Kaya identity. There are two categories of geo-engineering, both encompassing a number of innovations: carbon geo-engineering and solar geo-engineering.

The primary aim of carbon geo-engineering is to remove CO_2 from the atmosphere. There are natural based solutions, such as afforestation (planting more trees) and ocean fertilization (adding nutrients to the ocean) designed to hoover up atmospheric CO_2. There are also mechanical solutions, the most widely discussed being carbon capture and storage technology (CCS). CCS involves capturing and storing CO_2 emissions produced during electricity generation and industrial processes before they are released into the atmosphere. Emissions are captured, transported and stored several kilometers below the earth's surface[37]. It is also possible to capture carbon directly from the atmosphere. There are two problems at the moment with CCS technology: costs and storage. Hansen[38] argues that achieving a CO_2 concentration of 350ppm in 2100 would require the extraction and permanent storage of around 700Gt of CO_2. Assuming a unit cost at the lower end of the current estimated range, this degree of CCS would cost $1.3 trillion a year. Assuming a unit cost at the upper end of the estimated range, the required degree of CCS would cost over six times as much. This would be equivalent to around 10% of current global GDP.

Solar geo-engineering, unlike carbon geo-engineering, is not intended to address GHG concentrations directly, but instead seeks to manipulate the link between CO_2 concentrations and temperature. Technologies under study include stratospheric aerosol scattering, marine cloud brightening and space-based techniques (that is, positioning sun shields in space). These ambitious technologies aim to reflect a fraction of the sun's energy back into space, helping to cool the planet[39].

Geo-engineering innovations have the potential to curb or even reverse the effects of climate change, but enormous scientific and technological uncertainties remain. With regards to solar geo-engineering in particular, considerably more research is required. Indeed, global policy makers are currently faced with the question over whether they should seriously support solar geo-engineering research; so far funding has been low, estimated at just USD10mn globally[40]. The reluctance comes from a host of governance and moral hazard concerns, namely, that geo-engineering will reduce incentives to cut GHG emissions and thus will not address the root cause of the climate problem. Moreover, since no international framework on geo-engineering exists, there are concerns that nations will operate independently, eventually deploying various technologies without proper consideration for the risks or unintended consequences.

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[37] Carbon Capture & Storage Association; Available at: http://www.ccsassociation.org/

[38] Hansen, J., Climate Change in a Nutshell: The Gathering Storm, Columbia University, 2018

[39] Burns, Keith, Irvine & Horton, Solar Geoengineering, Technology Factsheet Series, Belfer Center for Science and International Affairs, Harvard Kennedy School, 2019.

[40] Necheles, E., Burns, L., Chang, A., Keith, D., Funding for Solar Geoengineering from 2008 to 2018, Harvard's Solar Geoengineering Research Program, 2018

In the words of Nordhaus “geo-engineering resembles what the doctors call “salvage therapy"—a potentially dangerous treatment to be used when all else fails. Doctors prescribe salvage therapy for people who are very ill and when less dangerous treatments are not available.”[41]

It is hard to predict how technology will evolve, especially over a period of decades, but at the moment there is nothing feasible that is an alternative to the steady and hard work of climate mitigation, reducing the energy intensity of GDP and reducing the CO_2 intensity of energy production.

Conclusion

One powerful theme running through the climate change debate is uncertainty: uncertainty about the mechanics of climate change and uncertainty about the economic, social and environmental impact of climate change. The other powerful theme running through the climate change debate is fairness: fairness across time as emissions today will affect the climate that future generations will inherit, and fairness across countries between those who have contributed the most to the problem and those who have contributed the least.

Notwithstanding Weitzman’s argument (see page 9), both of these themes make responding to climate change more difficult. Due to the uncertainty, it is hard to be absolutely definitive about what lies ahead. It is possible that the future will not be too bad. More likely, the situation will continue to deteriorate, possibly more so than in any of the IPCC’s scenarios. No government seems willing to sacrifice the incomes of their current citizens either in favor of their children and grandchildren or in favor of citizens in other countries. Climate change is a global problem which demands a global response. Despite the efforts of the IPCC, this is not really happening. The summit in Madrid is the most recent example of countries failing to cooperate to create a global emissions trading regime. Changes are occurring at the micro level, involving shifts in behavior by individuals, companies and investors. This will push emissions in the right direction, but is unlikely to be enough with the involvement of the fiscal and financial stability authorities.

Most likely, business as usual will be the path that policymakers follow in the years ahead. It remains to be seen what the consequences of this will be, but one thing is sure: BAU opens the earth to a greater likelihood of a catastrophic outcome from the fat upper tail of the probability distribution. It also increases the likelihood that the costs of dealing with climate change will go up as action is delayed. And finally, it increases the likelihood that the changes in the climate will be irreversible.

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[41] Nordhaus, W., The Climate Casino, Yale University Press, 2013

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