Chapter 9: The Impact of Climate Change

> Changes in climate policies, new technologies, and growing physical risks will prompt reassessment of the values of virtually every financial asset. Firms that align their business models with the transition to a net-zero world will reap handsome rewards. Those that fail to adapt will cease to exist. The longer meaningful adjustment is delayed, the greater the disruption will be.
>
> —*Mark Carney*

Climate Change Skews Us More Than We Might Expect

Climate change is, as I mentioned in the introduction to this book, a global problem and arguably the most pressing problem we face in the 21st century. Yet climate change is also a political hot potato, particularly in such countries as the United States and Australia. On the one hand, the science of climate change is clear. Our global climate is changing, and these changes are going to significantly affect our way of life. The debate is not about whether climate change is real, nor is it about whether climate change is caused by humans. Both of these debates were settled long ago, despite the protestations and fake news campaigns of oil billionaires and conspiracy theorists. That this increase in temperature has been triggered by the rise in greenhouse gases in the Earth's atmosphere has been proven beyond a reasonable doubt.[1]

Our concern in this chapter is the likely economic impact of climate change. And unfortunately, this is where things get really uncertain. As we will see in this chapter, standard economic models of climate change predict a GDP impact that is so small as to be almost negligible. A lot of nonlinear effects are in play, however. Once global warming pushes some processes beyond a tipping point, the resulting damage to the global economy could be

[1]What also has been proven beyond a reasonable doubt is that climate change is overwhelmingly driven by human activity rather than by natural variation in solar radiation as past episodes of climate change. I worked for three years as an astrophysicist on a project designed to determine the sun's contribution to climate change, and explaining climate change by solar phenomena is entirely impossible. In fact, back in the day, it was already clear that more than two-thirds of the total climate change seen in the past 150 years had to come from human activity.

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much, much higher than anything our standard models predict. For example, the impact of sea-level rise (SLR) on the economy is typically modeled in standard models, but as we will see in this chapter, evidence is increasing that Arctic and Antarctic ice shelves melt faster than previously known and could face a tipping point at which complete destruction of the ice shelf becomes inevitable. In this case, SLR might accelerate to levels far beyond those typically modeled today. And because so many people live in coastal areas, the economic loss due to SLR might quickly become a multiple of what standard models predict.

In other words, this chapter will show that although the economic damage from climate change is currently expected to be manageable and primarily localized, the risks are significantly skewed to the upside and toward much higher levels of damage than we currently expect. We certainly have no reason to be complacent about climate change.

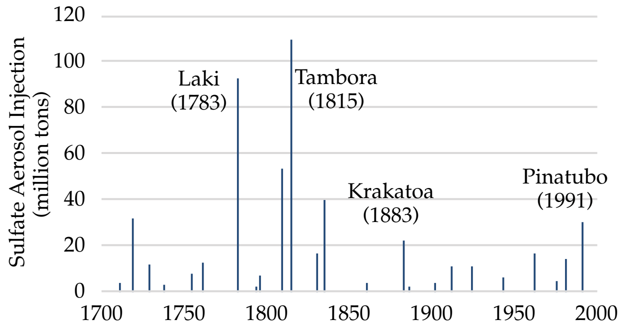
How a Volcano in Iceland Might Have Caused the French Revolution

On 8 June 1783, a volcano called Laki erupted in Iceland. That in itself would not be too big a deal, given that Iceland has plenty of volcanoes that erupt all the time, except that Laki was not your usual volcano, and this eruption was not your usual eruption. For starters, Laki looks nothing like the postcard volcanoes we are used to. It is not a cone-shaped mountain with a crater at the top through which it spits lava and smoke from time to time. Instead, Laki is a crack in the ground 25 km (16 miles) long, with approximately 130 individual craters in it. Imagine the Grand Canyon with mini volcanoes lined up like pearls on a string, and you get an idea of what it looks like.

On that fateful day in 1783, the volcano erupted and blew tons of steam into the air when its magma made contact with groundwater, evaporating it instantaneously. Once the water reservoir had been exhausted, lava rose to the surface and slowly spread across the countryside. This eruption continued for several more days. But what made the eruption special was not the lava emitted from the volcano but the sulfuric aerosols that were ejected and made their way high up in the atmosphere. The volcano continued to eject sulfur for eight months, creating one of the biggest climatic events of the past thousand years.

Exhibit 1 shows the quantity of sulfuric aerosols injected into the atmosphere by volcanoes over the past 300 years. In the chart, I have marked the Laki eruption alongside other prominent volcanic eruptions. Except for the eruption of Mount Tambora in Indonesia in 1815, no volcanic event had a

Exhibit 1. Atmospheric Sulfate Injection from Volcanoes



Source: Gao, Robock, and Ammann (2008).

higher sulfur injection. Laki injected approximately four times as much sulfur into the atmosphere as did the famous eruption of Krakatoa in 1883 and approximately three times as much as the eruption of Mount Pinatubo in 1991. And sulfuric aerosols are potent greenhouse gases that have a significant impact on the weather. The sulfur poisoned the wells in Iceland and destroyed harvests. An estimated 20% to 25% of the population of Iceland died as a result of the failed harvests in the subsequent years, and approximately 80% of the sheep and the majority of cows and horses on the island died as well.

But unlike Mount Tambora, Laki was located in Europe, close to the most developed countries in the world at the time. In total, the Laki eruption injected approximately three times as much sulfur aerosols into the atmosphere as the global annual emission of that substance in 2006. Because the aerosols were injected high in the atmosphere, they stayed there longer. Throughout much of the autumn and winter of 1783–1784, a thick haze drifted across Europe, moving from Iceland to Denmark, Berlin, Prague, and finally Paris. The haze was apparently so thick that boats had to stay in their harbors, unable to navigate, and thousands of people died from the smog. Furthermore, the aerosols caused a series of droughts and crop failures across Europe for the next several years.

This, in turn, created widespread poverty and hunger across Europe. Wood (1992) showed that the Laki eruption caused a very hot summer in France in 1785, creating a surplus harvest that led to widespread poverty for rural workers as grain prices dropped. Over the next few years, France was haunted by a series of droughts and severe winters that created famines. Finally, poverty and hunger led to a rebellion of peasants in France in 1789 that we know today as the French Revolution.

Although the Laki eruption certainly was not the sole cause of the French Revolution, it likely contributed to the revolution's outbreak, showing once more that severe climate events can have significant geopolitical consequences. In the case of the French Revolution, the king and queen lost their heads (literally) and were replaced by the First Republic. After that republic failed, Napoleon took the reins as emperor and conquered most of Europe and North Africa, bringing with him a fundamental reordering of European nation-states, laws, and regulations.

Whether climate change and climate events can trigger the outbreak of war remains a debated topic, but at least several prominent examples are known of volcanic eruptions and other natural disasters hastening the decline of civilization in the Americas, Asia, and Africa. Anecdotal evidence points to the possibility that the current civil war in Syria might have been triggered by a severe drought related to climate change. Kelley, Mohtadi, Cane, Seager, and Kushnir (2015) argued that the unusually long drought of 2007–2010 in Syria led to the displacement of a large number of young men and women. Even though Syria is located in what is called the Fertile Crescent, reaching from the south of Turkey to the Nile Delta in Egypt, the country suffered failed harvests for several years in a row. Faced with poverty and potential hunger, many rural workers and farmers moved to the cities to find work. With ample work unavailable, youth unemployment soared in Syria, creating fertile ground for radical Islamists to recruit followers and for others to rebel against the Assad regime.

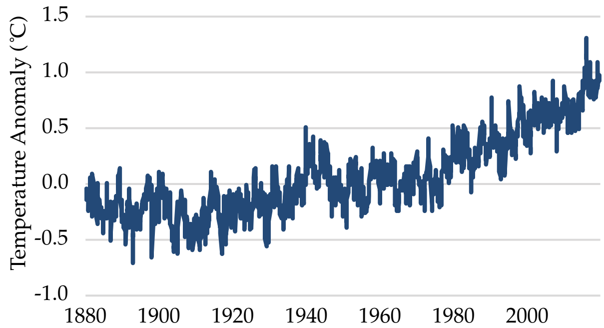
That climatic events can trigger significant geopolitical events, therefore, is at least possible. But although predicting volcanic eruptions and other natural disasters is impossible, we can anticipate climate change, which gives us warning of increased geopolitical risks from the weather events it creates.

Global Warming and Global Weirding

The key observation in the discussion about climate change is the rising average temperature on Earth, as shown in **Exhibit 2**. The chart is normalized so that the average temperature in the 20th century is set to zero. Average temperatures have clearly risen since the 1960s, and in 2019, the average global temperature was approximately 1°C (1.8°F) higher than the average global temperature of the 20th century.

This increase in global temperature is why climate change is often referred to as "global warming," although that is actually a misnomer. While the average temperature does increase, climate change does not imply that summers are always getting hotter and winters milder. Instead, more energy is trapped in the atmosphere, and this energy leads to more explosive and extreme weather events. These events can take the form of droughts and heat waves,

Exhibit 2. Global Temperature Anomaly



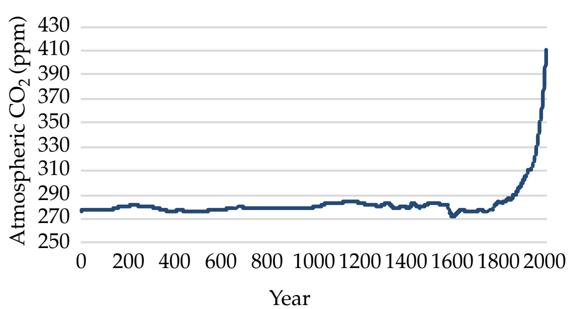
Note: Normalized, 1901–2000 = 0.
Source: US Department of Energy Carbon Dioxide Information Analysis Center.

or they can take the form of massive rainstorms (hurricanes and typhoons), floods, and extreme cold snaps in winter. In essence, we should call it "global weirding" rather than global warming because climate change creates weirder and more extreme weather phenomena.

A plethora of greenhouse gases exists, ranging from carbon dioxide (CO_2) to methane (which is far more potent than CO_2 but has a much shorter life span in the atmosphere) and other gases such as sulfur dioxide and nitrous oxide. Because CO_2 is by far the most prevalent greenhouse gas and the main driver of climate change, we restrict our discussion in this chapter to CO_2 and largely ignore the other gases.

Exhibit 3 shows the atmospheric concentration of CO_2 (measured in parts per million, or ppm) over the past 2,000 years. This is the famous "hockey stick chart," showing that CO_2 concentrations have entered a phase

Exhibit 3. Atmospheric CO_2 Concentration over the Past 2,000 Years



Source: Etheridge (2010) and National Oceanic and Atmospheric Administration (NOAA).

of exponential growth since the Industrial Revolution. In 2015, the concentration of CO_2 in the atmosphere surpassed 400 ppm for the first time ever.

That CO_2 is a powerful greenhouse gas that can render an entire planet uninhabitable can be seen by looking at our closest neighbor in the solar system, Venus. Venus is roughly the same size as Earth (the radius of Venus is approximately 5% less than the radius of Earth) and has similar density and mass. Thus, not surprisingly, perhaps, NASA simulations have shown that approximately three billion years ago, Venus was covered by water and had an average temperature of 11°C (52°F), again very similar to Earth today (Way et al. 2016). But Venus is much closer to the sun than Earth is, so solar irradiation is stronger there.

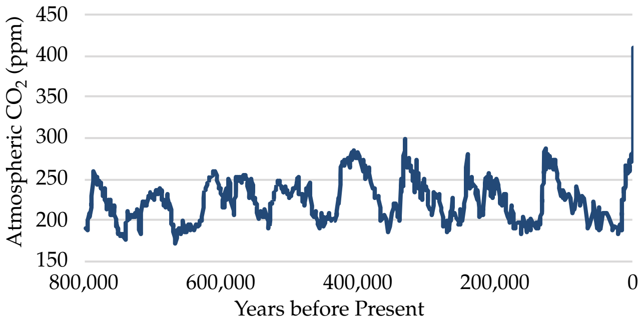
As a result, the water on Venus's surface evaporated before plants and other life could form. On our planet, these early life-forms began to draw CO_2 out of the atmosphere and transform it into oxygen and other gases. On Venus, the CO_2 concentration did not drop but stayed at high levels. And while Venus remained habitable for approximately 715 million years, the CO_2 created a massive greenhouse gas effect that heated the planet's atmosphere, accelerating the evaporation of water and in turn creating an even stronger greenhouse effect, which led to the dissipation of additional CO_2 from the soil and the evaporating oceans. This runaway greenhouse gas effect made the planet uninhabitable, and today, the temperature on Venus is a balmy 462°C (864°F).

Luckily, the CO_2 concentration on our planet is not even close to that observed on Venus today, but as Exhibit 3 shows, it is higher than at any time in the past 2,000 years and rising fast. Indeed, the CO_2 concentration today is higher than at any other point in humankind's existence. Humans have roamed the Earth for approximately 250,000 years now, but we can trace the CO_2 concentration in the Earth's atmosphere back roughly 800,000 years.

The Antarctic ice shelf is made up of layers of ice that were formed from snow that fell centuries and millennia ago. The deeper one drills into the ice shelf, the farther one can go back in history. As snow fell in Antarctica, tiny air bubbles became trapped in the ice that formed from the snow. By analyzing these air bubbles, one can measure the concentration of CO_2 in the air far back in time. As **Exhibit 4** shows, natural fluctuations in the CO_2 concentration have always occurred and were caused primarily by changes in the surface radiation of the sun. These fluctuations created ice ages (when the CO_2 concentration was low) and warm periods (when the CO_2 concentration was high). What is most obvious from the chart, however, is that today's CO_2 concentration is far above anything we have seen in the past 800,000 years.

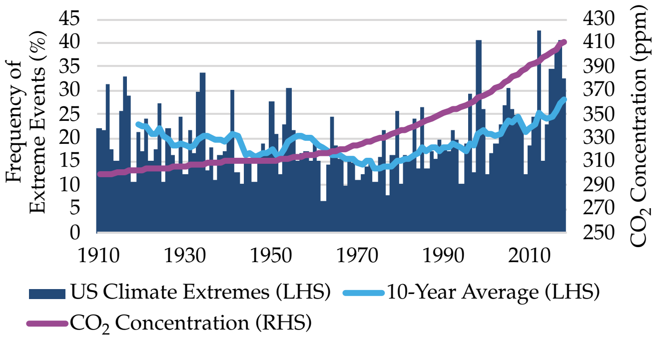
Along with this higher concentration of CO_2 comes not only a higher average temperature on Earth but also, as mentioned, an increase in extreme

Exhibit 4. 800,000 Years of CO_2 Data from Antarctic Ice Samples



Source: Lüthi et al. (2008), Etheridge (2010), and NOAA.

Exhibit 5. Frequency of Extreme Climate Events in the United States



Source: NOAA.

weather events such as floods, droughts, wildfires, and windstorms. **Exhibit 5** shows the number of extreme weather events in the United States since 1910 as measured by the National Oceanic and Atmospheric Administration (NOAA). Since the 1960s, CO_2 concentrations have increased more rapidly, and during that decade, the number of extreme weather events also began to increase.[2]

Climate Change and Investment Risk

As the number of extreme weather events increases because of climate change, the economic damage these events cause also increases. Wouter

[2]The 10-year average begins to rise in the early 1970s, indicating that the actual number of events began to increase in the early 1960s.

Botzen, Deschenes, and Sanders (2019) reviewed the empirical and theoretical literature on the economic impact of natural disasters and found that increasing population (particularly in coastal regions), along with economic development, led to rising costs of natural disasters. But the literature by now also shows that, all else equal, climate change leads to stronger storms that cause more damage than past events.

Felbermayr and Gröschl (2014) conducted a panel regression of the economic damages from natural disasters. Controlling for location (poorer countries obviously suffer lower monetary damages than richer countries) and other factors, they found that natural disasters had a significantly negative effect on GDP growth. This relationship also seems highly nonlinear, however, with economic growth dropping far more for major disasters. A disaster in the top 5% of the historic distribution reduced GDP growth by approximately 0.33 percentage points over the subsequent 12 months, whereas a disaster in the top 1% of the historic distribution reduced GDP growth by 6.83 percentage points on average.

Hurricanes—Large and Lasting Economic Damages. A special focus is placed on hurricanes (also called cyclones or typhoons, depending on where they form) in the research on the economic effects of natural disasters. Strobl (2011) investigated the damages caused by hurricanes in the United States and found that in the counties where a hurricane made landfall, GDP growth was reduced by 0.8 percentage points in the first year after the storm and by 0.2 percentage points in the second year.

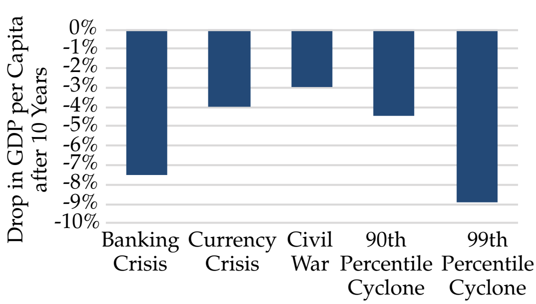
Different parts of the economy are affected differently. Agriculture, wholesale, retail, and tourism are hit the hardest, whereas the construction sector experiences a boost in activity after a storm because of rebuilding efforts. Another effect of hurricanes is that economic growth and county tax revenues decline because richer people in the affected regions move to other counties (often farther inland), whereas poorer people do not have the means to move and thus remain located in the affected region.

This geographic mobility after a storm has hit a coastal region is an expression of rising risk aversion by the people the storm affects. Ironically, this increased risk aversion can be found in the investment decisions of fund managers. Bernile, Bhagwat, Kecskes, and Nguyen (2018) investigated the performance of equity funds managed by individual fund managers across the United States. They found that fund managers located in a storm area become more risk averse in their funds and reduce volatility significantly. This increase in risk aversion means that their performance declines by 1.7% in the first year after a storm compared with that of fund managers who were personally unaffected by the storm, and declines by 0.7% in the second year. On average, the fund managers take three years to overcome their increased risk aversion.

But cyclones and hurricanes also have long-lasting effects that extend far beyond the immediate impact of the destruction of property. Looking at economic growth in areas hit by 6,700 cyclones globally, Hsiang and Jina (2014) estimated that even 20 years after the incident, GDP remains below the levels of that of comparable regions that were unaffected by the storm. For every additional meter per second in windspeed of a cyclone, GDP per capita was reduced by 0.2% 10 years after the storm hit and by 0.4% 20 years after the storm hit. The effect was similar in size for both rich and poor countries, even though many poor countries tend to experience larger economic damages immediately after a storm because buildings are often not built as durably as they are in rich countries, and building codes are ignored or not as strict.

Exhibit 6 shows the estimated impact on GDP per capita 10 years after a catastrophic event as calculated by Hsiang and Jina (2014). A cyclone in the top 10% of the historical distribution causes damages that reduce GDP per capita in the affected country by 4.4% 10 years after the cyclone hit, whereas a top 1% cyclone causes a drop in GDP per capita of 8.9%. In comparison, 10 years after a civil war ends, GDP per capita tends to be 3% lower, a currency crisis reduces income by 4%, and a banking crisis reduces income by 7.5%. In other words, a severe windstorm has a more pronounced long-term effect than a civil war or a currency crisis, and an extreme storm has a more pronounced effect than a banking crisis. Because these extreme storms are likely to become more frequent as climate change progresses, the economic impact of climate change might well increase rapidly over the next couple of decades—at least locally.

Exhibit 6. Estimated Impact of Human-Caused and Natural Disasters on GDP per Capita after 10 Years



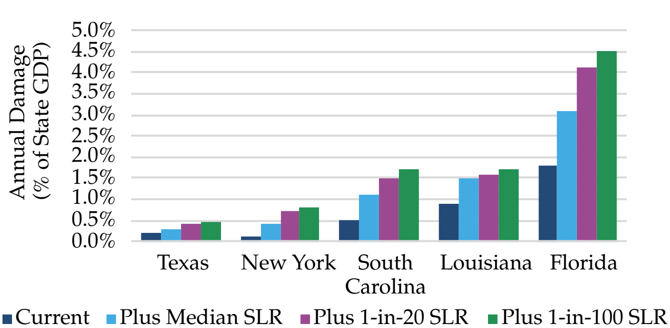
Source: Hsiang and Jina (2014).

Sea Level Rise—A Major Source of Risk for Real Estate. Hsiang et al. (2017) focused on the impact of natural disasters on coastal property because most of the damages in the short to medium term are inflicted on these assets. After all, real estate cannot move out of the way of an approaching hurricane. **Exhibit 7** shows the current average annual damage caused by hurricanes in the US states most affected by these storms. Florida already experiences significant property damage each year because of its geographic location. Now add the threat of rising sea levels because of melting polar ice caps, and the flood risk increases quickly. With the projected SLR until 2100, the average annual damage to property is expected to double in Texas and South Carolina, quadruple in New York State, and almost double in Florida.

If we use a higher estimate of future SLR, the situation quickly becomes worse. If SLR were to end up in the top 1% of the projected range, Florida would lose approximately 4.5% of state GDP every year as a result of floods and windstorms. In New York State, the average annual damage would approach 1% of state GDP. The United States is not alone in facing this risk. Globally, approximately 600 million people live in coastal areas that are 10 meters or less above sea level. Because of rising urbanization and population growth, this number is expected to increase to one billion by 2050. Faster-than-expected SLR brings with it the risk of catastrophic floods and harvest destruction because many fertile lands are located close to the sea.

Climate Risks in Equity Markets. These economic damages directly create additional investment risk across many asset classes. Bansal, Kiku, and Ochoa (2016) argued that global warming creates economic volatility and that this in turn should command a risk premium for investments exposed to these risks. Looking at consumption growth, the authors found that extreme

Exhibit 7. Expected Annual Property Damage Due to Cyclones and SLR in 2100



Source: Hsiang et al. (2017).

temperature events (e.g., droughts, extreme heat, cold snaps) trigger an average increase in consumption volatility of 0.18%. As consumption volatility increases, the discount factor for equity valuations should reflect this higher volatility through a higher equity risk premium.

Using a discounted cash flow model with stochastic discount factors, Bansal et al. (2016) measured the contribution of rising temperature to equity valuations and prices in excess of traditional market risks and consumption risks. In their model, they found that virtually all US equity portfolios have a negative beta to long-term temperature fluctuations, but the impact of temperature changes is not homogenous. High book-to-market stocks (i.e., value stocks) tend to have more negative betas than low book-to-market stocks (i.e., growth stocks). This might simply be a reflection of the sector composition of value and growth stocks, given that the industries that are most exposed to heat (and that show the largest sensitivity to temperature changes) are transport, construction, utilities, mining, and oil and gas, all of which currently are classified as value stocks. All these industries have in common that their economic activities are performed primarily outside, and shielding these activities from the impact of heat is difficult, if not impossible.

Averaging across the entire US stock market, Bansal et al. (2016) estimated that the equity risk premium due to rising temperatures is small but not negligible. A 1°C increase in long-term temperature averages increases the risk premium for US equities by an estimated 0.15%. The size of the risk premium is not stable, however, but rather grows as the average temperature rises. For every degree Celsius increase in the starting temperature, the risk premium increases by an estimated 0.18%, so that by 2015, the equity risk premium for US equities affected by rising temperatures was estimated to be in the neighborhood of 0.4%. A back-of-the-envelope calculation with a simple Gordon growth model shows that this 0.4% increase in equity risk premium could lower equity valuations by 10% to 20%.

Going down the path of global weirding rather than global warming, Donadelli, Jüppner, Paradiso, and Schlag (2019) recently investigated the risk premium inherent in UK and EU stocks resulting from the observed increase in temperature volatility. Along with the increase in average temperature, annual and intra-annual temperature volatility also increased.

To test the impact this temperature risk has on stock prices and the risk-free rate, Donadelli et al. (2019) split their observations into two subperiods. For the period 1900–1950, they could not find a risk premium for temperature volatility, but for the period 1950–2015, they found an immediate and highly significant effect of temperature volatility on stock prices and the risk-free rate. A 1°C increase in annual temperature volatility reduced the risk-free rate by a few basis points, but that impact was not statistically significant. In contrast, a 1°C increase in temperature volatility increased the equity risk premium by 0.65% in the United Kingdom and 0.37% in the European Union. Both values were derived after controlling for market risk and consumption risks and were statistically significant. Whether this risk premium for temperature volatility is the same as the one measured by Bansal et al. (2016) for changes in temperature overall is unknown at this point, but markets likely would not price what is essentially the same risk twice.

Scenarios for the Future

Although the investment risks from climate change seem manageable at the moment, they are likely to increase as our planet continues to heat up. Modeling the likely pathway of climate change is therefore important to assess the impact it might have on both geopolitics and the economy. Over the past decade, the main tools used to simulate climate change have been the Representative Concentration Pathways (RCPs) introduced by Moss et al. (2010). These pathways formed the foundation of the most recent Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), published in 2014 (IPCC 2014a), and the Paris climate accord of 2015.

These models make different assumptions about the future development of the emissions of CO_2 and other greenhouse gases. The models are calibrated in such a way that a specific forcing is achieved by 2100. Forcing describes the amount of energy absorbed by the Earth. For example, a forcing parameter of 2.6 watts per square meter corresponds to an increase in the global average temperature of no more than 2°C above the levels seen before the Industrial Revolution. Effectively, this is the level of forcing agreed to as a goal within the Paris climate accord; thus, the RCP2.6 pathway is often used to simulate declared policy goals for the next couple of decades. Higher levels of forcing correspond to bigger increases in temperature and correspondingly more damage caused by climate change. Unfortunately, we are currently moving along the RCP8.5 pathway and are on track to increase the global temperature by 3°C (5.4°F) by 2050 (Schwalm, Glendon, and Duffy 2020). As a result, the RCP8.5 scenario is also often referred to as the baseline or business-as-usual scenario in climate models.

Although the RCPs can inform us about the likely consequences of different climate scenarios, they make no assumption about the feasibility of achieving these pathways. IPCC (2014b) showed formally that socioeconomic and political developments have a significant influence on possible climate paths as well as on the adaptation paths of different countries and societies. Politics and socioeconomic developments could make achieving the Paris climate accord goals impossible or might support these goals.

Shared Socioeconomic Pathways. Riahi et al. (2017) introduced the Shared Socioeconomic Pathways (SSPs) that will be the foundation of the IPCC's sixth Assessment Report, due to be published in 2021. The SSPs provide assumptions about crucial social and economic developments, whereas the RCPs provide assumptions for the required climate change mitigation efforts. Together, these two kinds of pathways form a matrix architecture for simulating the future of climate change.

The main advantage of the SSPs is that they are based on a common set of input parameters used by otherwise-different models around the world. To develop the SSPs, Riahi et al. (2017) began with a set of qualitative narratives for geopolitical and socioeconomic scenarios. These qualitative scenarios were then populated with quantitative projections for crucial socioeconomic drivers, such as population growth, economic activity, urbanization, and education. Specifically, the long-term economic projections included in the SSPs were developed by a team of economists at the OECD who also develop the most frequently used long-term economic forecasts for nearly 200 different countries (Dellink, Chateau, Lanzi, and Magné 2017).

Once the qualitative narratives had been agreed upon, Riahi et al. (2017) tested the basic input parameters with a range of Integrated Assessment Models (IAMs) that derived other important variables, such as land use, energy use, and greenhouse gas scenarios. The different IAMs were tested against each other to determine the range of possible outcomes and to check for consistency between the models.

Finally, for each SSP, Riahi et al. (2017) derived a baseline scenario that assumed no new climate regulation and, crucially, no price on carbon emissions. For each SSP, different RCPs were run to show whether a specific concentration pathway is feasible and, if it is, what measures would be needed to achieve desired outcomes and what stresses these measures would put on society and the economy. The new SSPs allow for a more comprehensive modeling of the interaction between climate change, politics, society, and economy. They are ideal for the purposes of this book and likely will dominate the headlines in coming years.

The following qualitative narratives for each SSP are from Riahi et al. (2017):

SSP1

Sustainability—Taking the Green Road (Low challenges to mitigation and adaptation)

The world shifts gradually, but pervasively, toward a more sustainable path, emphasizing more inclusive development that respects perceived environmental boundaries. Management of the global commons slowly improves, educational and health investments accelerate the demographic transition, and the emphasis on economic growth shifts toward a broader emphasis on human well-being. Driven by an increasing commitment to achieving development goals, inequality is reduced both across and within countries. Consumption is oriented toward low material growth and lower resource and energy intensity.

SSP2

Middle of the Road (Medium challenges to mitigation and adaptation)

The world follows a path in which social, economic, and technological trends do not shift markedly from historical patterns. Development and income growth proceeds unevenly, with some countries making relatively good progress while others fall short of expectations. Global and national institutions work toward but make slow progress in achieving sustainable development goals. Environmental systems experience degradation, although there are some improvements and overall the intensity of resource and energy use declines. Global population growth is moderate and levels off in the second half of the century. Income inequality persists or improves only slowly and challenges to reducing vulnerability to societal and environmental changes remain.

SSP3

Regional Rivalry—A Rocky Road (High challenges to mitigation and adaptation)

A resurgent nationalism, concerns about competitiveness and security, and regional conflicts push countries to increasingly focus on domestic or, at most, regional issues. Policies shift over time to become increasingly oriented toward national and regional security issues. Countries focus on achieving energy and food security goals within their own regions at the expense of broader-based development. Investments in education and technological development decline. Economic development is slow, consumption is material-intensive, and inequalities persist or worsen over time. Population growth is low in industrialized and high in developing countries. A low international priority for addressing environmental concerns leads to strong environmental degradation in some regions.

SSP4

Inequality—A Road Divided (Low challenges to mitigation, high challenges to adaptation)

> Highly unequal investments in human capital, combined with increasing disparities in economic opportunity and political power, lead to increasing inequalities and stratification both across and within countries. Over time, a gap widens between an internationally-connected society that contributes to knowledge- and capital-intensive sectors of the global economy, and a fragmented collection of lower-income, poorly educated societies that work in a labor intensive, low-tech economy. Social cohesion degrades and conflict and unrest become increasingly common. Technology development is high in the high-tech economy and sectors. The globally connected energy sector diversifies, with investments in both carbon-intensive fuels like coal and unconventional oil, but also low-carbon energy sources. Environmental policies focus on local issues around middle and high income areas.
>
> SSP5
>
> Fossil-Fueled Development—Taking the Highway (High challenges to mitigation, low challenges to adaptation)
>
> This world places increasing faith in competitive markets, innovation and participatory societies to produce rapid technological progress and development of human capital as the path to sustainable development. Global markets are increasingly integrated. There are also strong investments in health, education, and institutions to enhance human and social capital. At the same time, the push for economic and social development is coupled with the exploitation of abundant fossil fuel resources and the adoption of resource and energy intensive lifestyles around the world. All these factors lead to rapid growth of the global economy, while global population peaks and declines in the 21st century. Local environmental problems like air pollution are successfully managed. There is faith in the ability to effectively manage social and ecological systems, including by geo-engineering if necessary.

Today, we can find the seeds of all these SSPs in the global political landscape:

- SSP1 closely resembles a pathway the United States would take if the proposed Green New Deal becomes a reality. It is also the pathway that the activists of Extinction Rebellion and other organizations advocate for, even if they do not realize it.
- SSP2 resembles the socioeconomic pathway that most countries were on until the rise of populism in the past few years. It is the pathway that most countries probably had in mind when they signed up for the Paris climate accord in 2015.
- SSP3 is the pathway that populist and nationalist politicians around the globe are moving toward. From Jair Bolsonaro in Brazil to

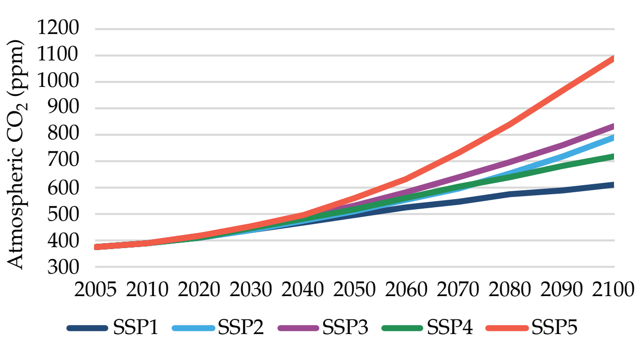
Narendra Modi in India, such politicians place much more emphasis on domestic growth than on environmental protection. Climate change is considered a far-off or manageable risk at best, a hoax or distraction at worst.

- SSP4 is the pathway the world would take if we were to continue following the dreams of Silicon Valley entrepreneurs. In this world, the rich would mitigate the impact from climate change with the help of increasingly expensive technological solutions, with the poor and less educated increasingly being left behind.
- SSP5 is the pathway US oil majors would like to take because it assumes that we can continue burning fossil fuels as we have been in the past while technological innovations, such as carbon capture and storage (CCS), could mitigate climate change over time.

Which of these pathways (or what combination of them) we will eventually take is unknown today, and we will likely fluctuate between several of these scenarios. Yet the potential impact on the environment of each of these pathways is quite different. **Exhibit 8** shows the projected baseline CO_2 emissions for each of the five SSPs. Remember that the baseline scenario assumes that we do not introduce any new climate regulation.

SSP1 is the pathway with the lowest projected CO_2 emissions, whereas SSP5 would lead to a dramatic increase in CO_2 concentration in the atmosphere. By 2050, the CO_2 concentration in pathway SSP1 would reach 500 ppm, whereas under SSP5, it would reach 560 ppm. By 2100, the CO_2 concentration under SSP5 would be almost twice that of SSP1.

Exhibit 8. Baseline Scenarios for CO_2 Concentration



Source: Riahi et al. (2017).

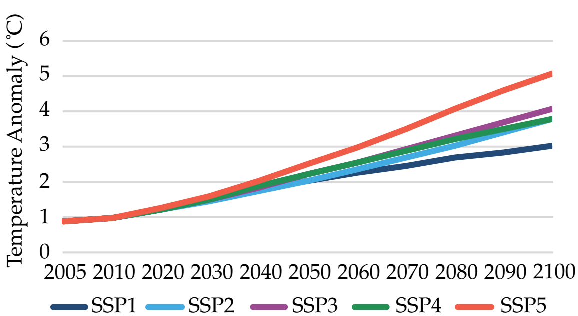
By 2100, however, it would be too late anyway because we need to keep CO_2 concentrations below 450 ppm if we want to keep the global temperature increase below 2°C and achieve the goals of the Paris climate accord. Thus, it should be no surprise that in the baseline scenarios of each SSP, global warming would rise above 2°C quickly and continue to rise into the 22nd century, as **Exhibit 9** shows.

What Policies Are Needed to Fight Climate Change? Given that none of the baseline scenarios can keep climate change under control, we need to simulate different mitigation scenarios that correspond to the different RCPs. To do that, the different climate models need to share some basic assumptions about policies and the range of possible outcomes. After all, it would make little sense to simulate a world in which the socioeconomic pathway followed by different countries is SSP3, with its emphasis on noncooperation and exploitation of natural resources, while at the same time assuming that climate change mitigation successfully employs reforestation as a means to reduce atmospheric CO_2 concentrations.

Thus, the climate models use some shared policy assumptions (SPAs) that define the degree of international cooperation, how much mitigation efforts are enforced and followed, and whether or not some crucial sectors, such as agriculture and forestry, are covered by mitigation efforts. In the past, expanding mitigation efforts to agriculture and forestry was particularly difficult. The resulting SPAs integrated into the simulations are summarized in **Exhibit 10**.

The SPAs are deliberately broad so that the models can make a wide range of assumptions about mitigation strategies. Whether climate change mitigation is achieved through increased energy efficiency or energy conservation, reduction of power generation from fossil fuels, or large-scale development of

Exhibit 9. Baseline Scenarios for Global Temperature Anomaly



Source: Riahi et al. (2017).

Exhibit 10. Shared Policy Assumptions

Policy stringency in the near term and timing of regional participation	Coverage of land use emissions
SSP1, SSP4	SSP1, SSP5
Early accessions with global collaboration as of 2020.	Effective coverage at the level of emissions control in the industrial and energy sectors.
SSP2, SSP5	SSP2, SSP4
Some delays in establishing global action, with regions transitioning to global cooperation between 2020 and 2040.	Effective coverage of agricultural emissions but limited emissions reduction from deforestation and forest degradation.
SSP3	SSP3
Late accession—higher-income countries join global cooperation between 2020 and 2040 and lower-income regions follow between 2030 and 2050.	Very limited coverage (implementation failures and high transaction costs).

Source: Riahi et al. (2017).

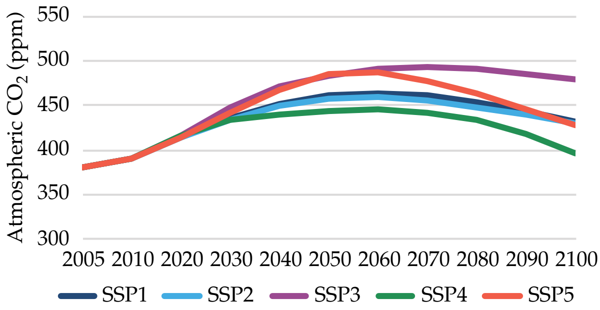
CCS is left for the researchers to figure out. Even geoengineering approaches are fair game. Basically, anything goes.

Nevertheless, not all mitigation scenarios are achievable in all SSPs. Under SSP3, achieving the goals of the Paris climate accord was impossible no matter what Riahi et al. (2017) did with their models. Under SSP5, some models were not able to provide a solution that met the goals of the Paris climate accord, whereas others were.

Despite the wide variety of possibilities for mitigating climate change, the models produced a few results in common (Riahi et al. 2017). To achieve the goals of the Paris climate accord and keep the increase in global temperature below 2°C, the amount of electricity generated from renewable energy sources must be much higher than it is today. The midpoint estimate was for renewables to produce 60% of global electricity by 2050, with a range of 40% to 70%, depending on the model. Contrast that with the baseline projections of the SSPs, wherein none of the five pathways would even come close to this share of renewables in the global energy mix, and in SSP3 and SSP5, the share of renewables in global energy production would even decline.

Another shared result of the different mitigation scenarios is that CCS will have to play an important role if we want to achieve the goals of the Paris climate accord. Estimates for the amount of CO_2 captured and stored by CCS range from 200 gigatons (Gt) to 1,800 Gt between today and 2100. Another important carbon sink (i.e., a technology that reduces CO_2 in the atmosphere)

Exhibit 11. Scenarios for CO_2 Concentration under the Paris Climate Accord



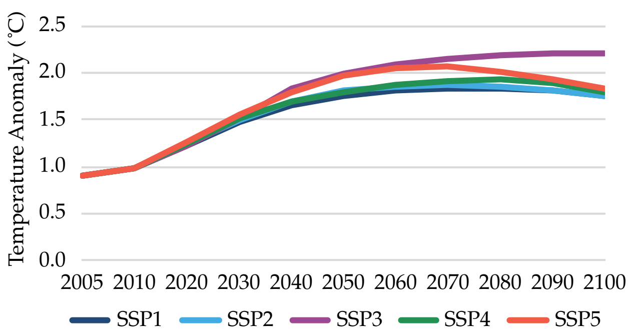
Source: Riahi et al. (2017).

will be reforestation and the revitalization of existing forests. These reforestation efforts are particularly important for SSP1, SSP2, and SSP4 if we want to be able to effectively mitigate climate change under these pathways.

If we can successfully mitigate climate change, then the CO_2 concentration in our atmosphere could follow the pathways shown in **Exhibit 11**. Note that SSP3 does not achieve the Paris climate goals, so we show the best possible result under SSP3 in that chart. For all other SSPs, the results shown in the chart correspond to limiting the increase in global temperature to less than 2°C by the year 2100.

For SSP5, however, the global temperature anomaly will likely surpass that level, at least temporarily (see **Exhibit 12**), because in SSP5, the world continues to burn a lot of fossil fuels. Only with the large-scale introduction

Exhibit 12. Scenarios for Global Temperature Anomaly under the Paris Climate Accord



Source: Riahi et al. (2017).

of CCS technology and massively higher prices for CO_2 will the incentives be sufficient to take CO_2 out of the atmosphere again and reduce the concentration of CO_2 and the global average temperature.

Can We Innovate Ourselves Out of Our Problems?

This brings us to the question of whether we can reduce the emission of CO_2 and other greenhouse gases over time. Our experience with the development and rollout of renewable energy shows that the potential for technological advances in green technology not only is vast but also has been consistently underestimated by experts in the past. This should make us optimistic that we will, over time, develop the technological solutions to mitigate climate change and achieve the goals we set for ourselves, even if today we appear poised to miss these goals by a wide margin.

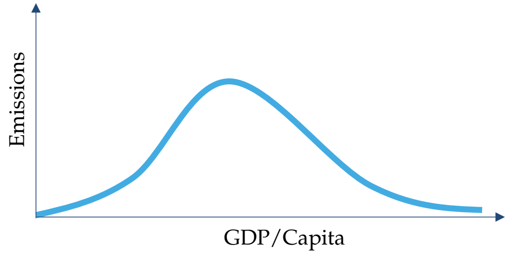
Technological progress must overcome our current limitations as well as the growth in economic activity and population we will face in future decades. In the beginning, as societies develop, their emissions of pollutants increase. The combination of population growth and strong economic growth leads to a substitution of low-carbon activities and technologies with high-carbon technologies.

Think of China. As the country became richer, people abandoned bicycles in favor of cars, which increased the quantity of pollutants in the air dramatically. Add to that the development of a large industrial base, and the end result is that cities in China are plagued by endless smog. But as the costs to society from these pollutants increase, so, too, does the incentive to clean up that mess and invest in clean technologies. Because strong economic growth increases income, the country also has the financial means to invest in these green technologies. China's pivot from fossil fuels to renewables is a case in point.

The pattern of pollutant emissions first rising, then peaking, and finally declining again in an inverted U-shape as a country (or the world) becomes wealthier is known as the environmental Kuznets curve (EKC). A stylized version of the curve appears in **Exhibit 13**. First introduced in the early 1990s, it has since become a standard model against which to test the empirical evidence.

Stern (2017) reviewed the literature on the validity of the EKC over the past 25 years and found mixed results. He found an inverted U-shape for the concentration of some pollutants, such as sulfur components, but not for emissions of other pollutants, such as CO_2. Furthermore, the relationship between GDP per capita and pollutant concentrations seems to have weakened in more recent studies, which more commonly have found a monotonic

Exhibit 13. The Environmental Kuznets Curve



Source: Author's creation.

increase in pollutants no matter the level of income per capita. In contrast, older studies from the 1990s and the 2000s seemed to find more evidence of the EKC hypothesis.

Intuitively, this disparity makes sense if we think about the kind of pollutants that are commonly investigated in these studies. Older studies focused more on classic pollutants, such as sulfur compounds, dust, and carbon particles. Only in the past decade or so has CO_2 become a dominant object of investigation.

If we think back to our rules for forecasting from chapter 5, the fifth rule states that we rarely fall off a cliff. People can change their habits but often do so only at the last minute to avert a catastrophe. For change to happen, the catastrophe must be *salient*, the outcome must be *certain*, and the solution must be *simple*. If you cannot breathe because of the smog in your city, the problem is salient, and you and many other people in your community will advocate for change. In the case of classical industrial pollutants, the outcome of the problem is quite certain because smog causes respiratory problems for many older people as well as infants and young children. Finally, the solution to the problem is simple. Just force factories, cars, and other emitters to include filters in their exhaust systems (or use different inputs, such as unleaded gasoline), and the problem is solved. This approach provides a relatively low-cost solution to a big problem.

The situation is different for CO_2. Because CO_2 is a colorless and odorless gas and is harmless to individuals in low concentrations, we do not notice when the concentration of CO_2 in our atmosphere increases. The very fact that CO_2 concentrations have been rising for 250 years without anyone becoming worried about them is proof that the problem of rising CO_2 emissions is not yet salient.

Only in recent years has climate change become increasingly salient through the prevalence of extreme weather events. This prevalence has given rise to mass environmental movements similar to the rise of the environmental movement in the early 1980s in the wake of acid rain that destroyed forests in Europe. (This was one of the world's first mass environmental movements, and it launched green parties in many Western European countries.)

Because the link between extreme weather events and CO_2 concentration in the atmosphere is not immediately salient to everyone, the current environmental movement faces a lot of pushback from people who advocate for symptomatic treatment of the problem. For example, floods can be prevented by building higher dams rather than by fighting the root cause of the floods.

Furthermore, although rising CO_2 concentrations affect us all, the direct impact on each of us as individuals is uncertain. If you do not live on the coast, you probably care less about hurricanes. If you do not live in a dry area, you probably care less about wildfires and droughts that much. Every problem caused by climate change affects other people but not you, so dismissing the specific problem in question is easy. The alliance to prevent wildfires is relatively small, as is the alliance to prevent hurricanes and floods. Although both try to fight the same root cause, their forces are often not combined.

Finally, the solution to climate change is anything but simple. It requires a widespread redesign of our economy and a drastic shift in consumption habits. As we will see later in this chapter, this shift imposes high costs on large parts of a society in the short term. With these adverse effects comes public resistance to mitigation efforts.

In summary, whether CO_2 emissions will truly follow an inverse U-shape as predicted by the EKC is unclear. Shahbaz and Sinha (2019) recently reviewed the empirical studies on CO_2 emissions from 1991 to 2017. They found that the studies showed no conclusive evidence for or against the EKC in single countries or across countries. For every time period investigated in the literature, one can find studies that confirm the EKC and find an inverted U-shape as well as studies that find monotonically rising CO_2 emissions. One can even find a series of studies that find an N-shaped relationship, in which emissions first increase, then decrease, and then increase again as income per capita rises.

In short, we do not yet know whether the EKC holds, and this means we also do not know whether we will be able to innovate ourselves out of the problems caused by climate change. Furthermore, even if the EKC holds, Shahbaz and Sinha (2019) pointed to one crucial aspect of the EKC that has not been investigated thoroughly. If the EKC is too tall—that is, if pollutants rise to very high levels before mitigation efforts take hold—this could trigger irreversible processes in our climate that are physically impossible to fix within reasonable policy time frames.

The Economic Cost of Carbon

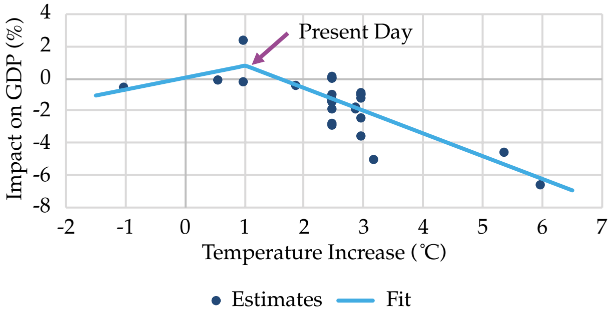
One might be forgiven for giving up hope, given all the uncertainties and unknowns about the future pathways of our society and economy. But this ignores that we do know some things, or at least can estimate them within an acceptable range of uncertainty. And one of the key areas of economic investigation has been the economic cost of rising CO_2 emissions.

Economists around the world agree that climate change and the emission of greenhouse gases like CO_2 are negative externalities that currently are not priced in markets (the studies quoted earlier on the risk premia of temperature changes notwithstanding). And every economist knows that if an externality is not priced, it leads to misallocation of resources and a decline in welfare. Thus, the consensus among economists is that greenhouse gases should be priced through either carbon taxes, cap-and-trade schemes, or emission-trading schemes. Prices for CO_2 should ideally start low and gradually increase so as to not shock the economy. The social cost of carbon is the incremental welfare impact of emitting an additional unit of CO_2 into the atmosphere and thus represents the marginal cost of carbon that should be set by policy makers to maximize welfare.

So far, so good, but how big are the economic and social costs of carbon? Dell, Jones, and Olken (2009) showed that the economic impact of climate change is subject to many competing developments. On one hand, extreme weather events lead to fewer harvest failures, particularly in coastal regions and in poor countries close to the equator, where droughts can severely reduce crop yields. On the other hand, CO_2 is a natural fertilizer for plants. Higher CO_2 concentrations lead to faster growth of most plants and potentially to higher yields. Similarly, while the Earth is getting hotter, energy demand for air conditioning is increasing in hotter regions, whereas areas closer to the poles will experience milder winters and therefore reduced demand for energy for heating.

Which one of these effects will win out is not always clear, but Tol (2018) collected evidence from several studies on the economic impact of climate change. **Exhibit 14** shows that climate change might initially have a positive impact on global welfare and global GDP. As the temperature increases more than 1°C, however, the marginal contribution of climate change to the economy becomes negative, and the total economic impact of climate change starts to drop. For temperature increases above 2°C, the studies show a negative total effect of climate change on global GDP in 2100 relative to that in 2010. Notably, we already seem today to be right at that tipping point at which we have reaped all the benefits of rising global temperatures and now face negative contributions from additional increases.

Exhibit 14. Estimated Impact of Climate Change on Global GDP



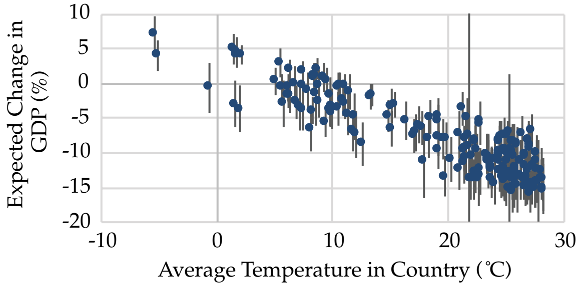
Source: Tol (2018).

Standard Economic Models Predict a Small Economic Impact. The estimated economic costs of climate change are, however, relatively small. The cumulative effect on global GDP between 2010 and 2100 is generally estimated at 1% to 5%, or less than 0.1% per year. These, however, are only the static losses in economic activity. If climate change has a negative impact on economic growth, the costs could accumulate much more rapidly and become much bigger. Research on the impact of climate change on long-term economic growth has so far been minimal, and the results generally have shown an insignificant impact on growth except in poor countries in the "Global South" (Dell, Jones, and Olken 2012). So, why bother with climate change at all if the economic costs over a century are roughly the same as one year's growth?

Every recession costs the economy more than 10 times what climate change costs in any given year. This is why climate change as a problem is not salient to economic decision makers today. But unlike the effects of a recession, the economic costs of climate change are permanent and cumulative (each year is, at least in principle, hotter than the previous one). And the effects are not equally distributed. Dell et al. (2012) showed that poorer countries will face higher costs from climate change than richer countries, primarily because poorer countries tend to be located in hotter regions. Tol (2018) showed the expected economic costs of climate change as a function of the average temperature in a country, as reproduced in **Exhibit 15**.[3] Hotter

[3]Canada (–5.4°C), Mongolia (–0.8°C), and Russia (–5.1°C) have negative average temperatures on the Celsius scale. Although economic activities in these countries are located in the warmer areas, the study used average temperatures across the entire country. And because both Canada and Russia have vast areas of land in the Arctic, their average temperature drops below 0°C.

Exhibit 15. Economic Impact of Climate Change Is Bigger for Hotter Countries



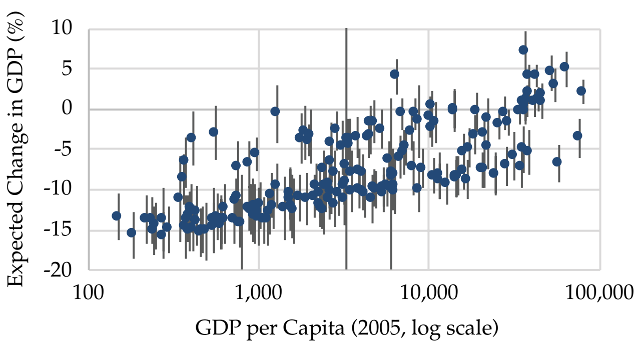
Source: Tol (2018).

countries face disproportionately higher economic costs, and for an increase of the average global temperature of 2.5°C, the majority of countries in the world will face costs in excess of 1.4% of GDP (Dell et al. 2012).

Dell et al. (2012) also looked at the relationship between income per capita and the economic impact of climate change. Unsurprisingly, they found that poorer countries suffer much more than richer countries, as shown in **Exhibit 16**. This is a result of both the geographic location of richer countries, most of which are located in the Northern Hemisphere at medium to high latitudes, and their ability to pay for climate change mitigation measures, as well as their lower reliance on agriculture.

The agriculture sector is most affected by climate change, and in regions where crop yields are already low because of adverse climatic conditions, relatively little is needed to trigger a major harvest failure. Poorer countries in South Asia, Africa, and South America tend to have an economy that

Exhibit 16. Economic Impact of Climate Change Is Bigger for Poorer Countries



Source: Tol (2018).

depends more on agricultural products and the export of these products. As the planet warms, these countries face climatic situations that are probably new in human history and that we cannot anticipate. In comparison, an industrial country such as the United Kingdom will experience climatic conditions similar to those of Spain as climate change progresses. We have lots of experience of how to live in such a climate (just ask the Spanish), and the United Kingdom has sufficient capital to pay for additional air conditioning and other amenities. In other words, the costs for rich countries tend to be lower, and mitigation is cheaper.

The reason we should care about the economic impact of climate change becomes obvious once we look at climate change through a geopolitical lens. If the poorest countries in the world are hardest hit, economic stress will be concentrated in these countries. And wherever economic stress arises, migration is a natural outcome. Climate change might increase global migration from the poor countries in the south to the rich countries in the north—something we investigate more deeply later in this chapter.

Fighting Climate Change Is Good for the Economy. Another reason we should care about climate change is that it can be avoided, and the economic costs of it can be reduced essentially to zero. Kahn et al. (2019) recently estimated the economic costs of climate change under the RCP8.5 scenario and the Paris climate accord scenario for a range of countries. **Exhibit 17** shows the results for a selection of countries. In their model, GDP per capita faces a decline of 0.5% to 1.0% over the next decade and of 1.0% to 3.0% until 2050, relative to what it otherwise would be. If we manage to achieve the goals set out in the Paris climate accord, the costs of climate change will be effectively zero, and some countries, such as China, will even experience economic gains. This result is due not only to the reduced costs from climate events but also to the boost in productivity from new, green technologies. In short, mitigating climate change is good for business.

What's the Right Price for Carbon? To avoid climate change and the corresponding social and economic damages, we need to put a price on carbon emissions and other greenhouse gases. Unfortunately, this is easier said than done because the fair price of carbon is uncertain and depends, on one hand, on the estimated economic impact of CO_2 emissions and, on the other hand, on the discount rate with which future carbon emissions (and their corresponding damages) are reduced to a present value. If we take a discount rate of 0%, then future damages accrue to the present value at the same rate as current damages, creating a large cost of emitting an additional metric ton of CO_2. If we take a discount rate of 3% or higher, then the future cost of carbon has a relatively small present value.

Exhibit 17. Estimated Impact of Climate Change on GDP per Capita over the Next 10 to 30 Years

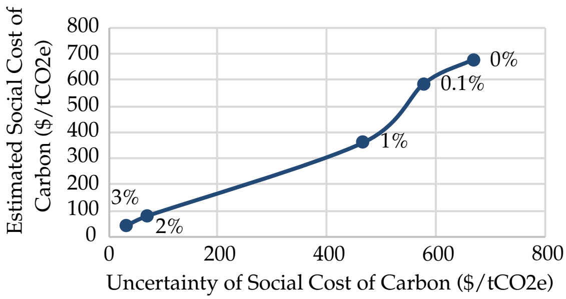
	2030		2050	
Country	Paris Agreement	Business as Usual	Paris Agreement	Business as Usual
World	0.0%	−0.8%	−0.1%	−2.5%
Rich Countries	−0.1%	−0.8%	−0.2%	−2.7%
Poor Countries	0.2%	−0.7%	0.2%	−2.2%
United States	−0.2%	−1.2%	−0.6%	−3.8%
United Kingdom	0.0%	−0.3%	0.1%	−1.2%
Germany	0.2%	−0.2%	0.4%	−0.6%
France	0.0%	−0.6%	0.1%	−1.9%
Japan	−0.3%	−1.1%	−1.1%	−3.7%
Australia	−0.1%	−0.6%	−0.2%	−2.3%
Brazil	0.0%	−1.0%	−0.1%	−2.8%
Russia	0.1%	−1.0%	0.3%	−3.1%
India	−0.3%	−1.2%	−0.8%	−3.6%
China	0.5%	−0.6%	0.8%	−1.6%
South Africa	0.0%	−0.7%	−0.1%	−2.5%

Source: Kahn et al. (2019).

The cost of carbon is therefore reduced essentially to the economic damage current emissions cause. **Exhibit 18** shows the social cost of carbon as estimated in Tol (2018), together with the uncertainty around that price. If we apply a 0% discount rate, the cost of emitting a metric ton of CO_2 should be set to $677, whereas a discount rate of 3% gives us an estimate of $43 per metric ton. Today, most countries assume a discount rate of somewhere between 2% and 3%, and the US government uses a social cost of carbon of $12 per ton of CO_2 emissions (tCO2e) to $58/tCO2e, in line with these assumptions. In the European Union, the price of a ton of CO_2 emissions in the Emissions Trading System is $25.

These low prices for carbon emissions are unlikely to be sufficient to incentivize emissions reductions that will keep climate change in check. Within the SSPs, the price of carbon that must be imposed over time is allowed to start low (roughly at current levels) and then gradually increase. Depending on the pathway we take in future decades, the cost of carbon has to increase more or less rapidly to provide enough of an incentive to achieve the goals we set ourselves in the Paris climate accord.

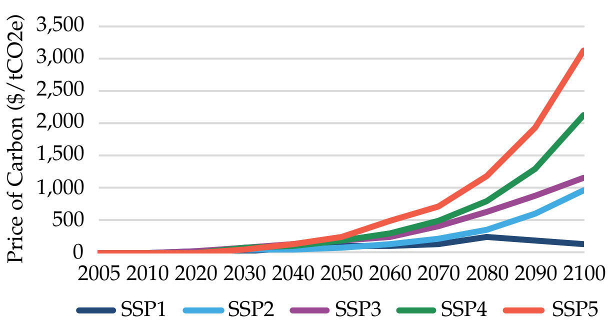
Exhibit 18. Estimates of the Social Cost of Carbon for Different Discount Rates



Source: Tol (2018).

Under SSP1, the price of carbon needs to increase to $33/tCO2e by 2030, whereas under SSP2 and SSP5, it needs to rise to approximately $42/tCO2e. Because of the lack of international cooperation and the excessive land use in SSP3, the price of carbon would have to rise to $87/tCO2e by 2030, a cost of carbon not reached under SSP1 and SSP2 before 2050. **Exhibit 19** shows the projected cost of carbon necessary to provide enough incentives to change the direction of the global economy in line with the Paris climate accord for the different SSPs. Not surprisingly, under SSP5, where the use of fossil fuels continues unabated, the price of carbon must rise the most and the fastest, but even under SSP4, the scenario of rising inequality, the cost of carbon must rise dramatically to $185/tCO2e in 2050 and to more than $2,000/tCO2e in 2100. This high cost of carbon is driven by the rising emissions of poor countries that cannot afford the high-tech solutions to climate change developed in the rich countries and therefore must rely on burning fossil fuels.

Exhibit 19. Scenarios for Carbon Pricing under the Paris Climate Accord



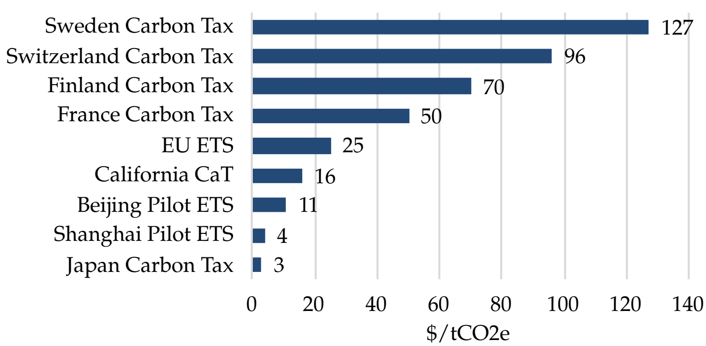
Source: Riahi et al. (2017).

The lesson we can learn from these scenarios is that one of the best investments we can make to reduce the future cost of carbon is in low-carbon infrastructure in low- and middle-income countries around the world. Helping emerging markets build solar and wind power plants and improving the local infrastructure to save energy is likely the best way to help these countries avoid the negative impacts of climate change. When the issue is viewed from this angle, Chinese initiatives such as the Belt and Road Initiative (see chapter 6) are beneficial for us all.

If we compare the projected cost of carbon in the different SSPs to the current cost of carbon shown in **Exhibit 20**, we can see that where implemented, the current price of carbon varies dramatically from place to place. In most countries, the cost of carbon is a few dollars per metric ton. In Japan, it was just $3/tCO2e in 2019, which was way too low to provide any incentives to reduce fossil fuel consumption. In the European Union, the price of carbon is $25/tCO2e, roughly in line with mainstream estimates of the social cost of carbon today and in line with the projections of the SSPs. But such countries as France, Finland, Switzerland, and Sweden have gone well above these values and have introduced carbon taxes ranging from $50/tCO2e to more than $100/tCO2e.

This high price of carbon is intended as an incentive for households and businesses alike to start looking for alternatives to fossil fuels now. In the long run, such efforts could foster a faster transition of these economies and provide businesses an advantage over foreign competitors, even if doing so involves additional costs today.

Exhibit 20. Current Cost of Carbon as Implemented in Selected Countries



Note: ETS = Emissions Trading System, CaT = Cap and Trade.
Source: Ramstein (2019).

Nevertheless, although these efforts by individual countries are laudable, on a global scale, hardly any CO_2 emissions are currently being priced. Today, less than 20% of global greenhouse gas emissions are priced in one way or another, and with the inception of the nationwide Chinese emissions trading scheme in 2020, the share of priced greenhouse gases will increase to only 20% of global emissions. And of these emissions, roughly one-half are priced at $10/tCO2e or less (Ramstein 2019).

Tipping Points and Black Swans

The economic cost of climate change is expected to be quite low, as we saw in the previous section, but unlike with other economic risk factors, climate change has been underestimated in the past and has the potential to be underestimated today as well. Plenty of black swan events and tipping points could significantly increase the damage.

According to Linden (2019), a climate scientist in the 1990s who predicted that within 25 years, a heat wave could measurably raise sea levels (by 0.5 mm), create temperatures above 0°C (32°F) at the North Pole, and cause desert-like temperatures in Paris and Berlin would have been dismissed as alarmist. Yet all these things happened in 2019. In 1990, the IPCC said climate change would happen slowly and that melting permafrost in the Arctic would not be an issue for at least another century. Yet this is happening today. If we go back to the 1950s, scientists thought climate change happened over time spans of several thousand years. Between the 1960s and 1980s, we learned more about climate change, and the consensus was that it could happen over centuries.

In the early 1990s, however, we got extensive climate data from Greenland and the Antarctic that showed for the first time that climate change could and did happen over much shorter time spans, sometimes years (Weart 2003). As our understanding of the science of climate change improved, the scientific community had to consistently shift its expectations toward the possibility of faster climate change with more devastating effects on our planet. In its 2002 consensus report, the National Research Council had to admit that we do not understand fully how rapidly climate change happened but that it clearly did happen in the past, and we must face the possibility that it will do so again in the future (National Research Council 2002).

DeFries et al. (2019) claimed that modeling these rapid shifts in our economic projections is almost impossible, so they are commonly excluded from the models. The researchers identified several candidates for possible black swan events in climate change modeling:

- The ice sheets in Antarctica and Greenland could enter an irreversible melting pattern that significantly enhances SLR beyond current expectations. Currently, the scientific consensus is that the ice sheets will melt completely over several thousand years and that sea levels will rise by only approximately 1 meter by 2100. But irreversible ice melt could accelerate this SLR to 2 meters and beyond. Indeed, in 2014, scientists estimated that an irreversible collapse of the Western Antarctic ice shield may already have begun, and Rignot et al. (2019) recently reviewed 40 years of satellite images of the East Antarctic ice shield and found that it was not stable but in fact shedding vast amounts of ice. The melting of the East Antarctic ice shield is already responsible for approximately one-third of the SLR caused by melting Antarctic ice. Lenton et al. (2019) also counted the reduction in the Arctic ice fields and accelerated ice loss in Greenland as tipping points that are currently in play.
- Because a hotter atmosphere can hold more water, the frequency and strength of extreme windstorms and heavy rainfall might increase beyond current projections. As a result, coastal regions would experience more frequent destruction, and crops would get flooded more often, increasing the likelihood of famines in poor countries.
- Extreme heat waves might become even more frequent than expected and hit approximately one-third of the world's population once every five years. We already observe more frequent wildfires in the boreal forests of the Northern Hemisphere, and the Amazon rainforest is experiencing droughts and wildfires increasingly often.
- In a warmer climate, some diseases can spread to regions where people and animals do not have a natural resistance to them, creating significant pandemics. We already see the spread among trees in the boreal forests of diseases that are almost impossible to stop, and we humans have to face the spread of tropical diseases such as malaria and dengue fever farther away from the equator.
- Since the 1960s, the Atlantic Ocean currents have been slowing, and warming ocean temperatures not only have destroyed coral reefs but also have changed the climate in large parts of the world. The mild weather in Ireland, the United Kingdom, and much of Northern Europe is almost exclusively owed to the stream of warm water from the Gulf of Mexico that acts like mild air conditioning for Northern Europe year-round. If the temperature difference between the North Atlantic and the Gulf of Mexico drops too much, the risk arises that the Gulf Stream could

collapse, in which case, we would have to expect cold weather fronts and blizzards to be able to drift farther to the south in winter, whereas hot weather fronts would be able to drift farther to the north in summer. In short, the temperature extremes in the United Kingdom and Ireland would increase. Similarly, the monsoon season in Asia and Africa could shift or break down altogether if ocean streams in the Indian Ocean break down, creating the potential for massive failed harvests in some of the poorest countries in the world.

- Finally, as we stated earlier, the Arctic permafrost is beginning to melt. Unfortunately, this is a major carbon sink because the ground in this region is full of composted trees and therefore of CO_2. If the Arctic permafrost melts, the CO_2 trapped therein will be released, creating a positive feedback loop that accelerates climate change even more, in turn increasing the speed of the permafrost melt, and so on. How much CO_2 is stored in the permafrost is largely unknown, as is the extent to which the release of this CO_2 would accelerate climate change.

We have only a limited understanding of the physics and chemistry behind all these potential black swans because they were considered highly unlikely until just a few years ago. Lots of resources have been directed toward a better understanding of areas such as ice sheet hydrology and dynamics, coastal erosion and its impact on infrastructure, cascading ecosystem losses, and the compound effect of independent climate disasters (e.g., SLR combined with coastal wildfires). As our understanding of these topics increases, we likely will have to revise our projections for climate change and its economic impact again and again. Unfortunately, history has shown us that the distribution of likely outcomes of these revisions is heavily skewed toward faster climate change and higher economic damages.

The Social Consequences of Climate Change

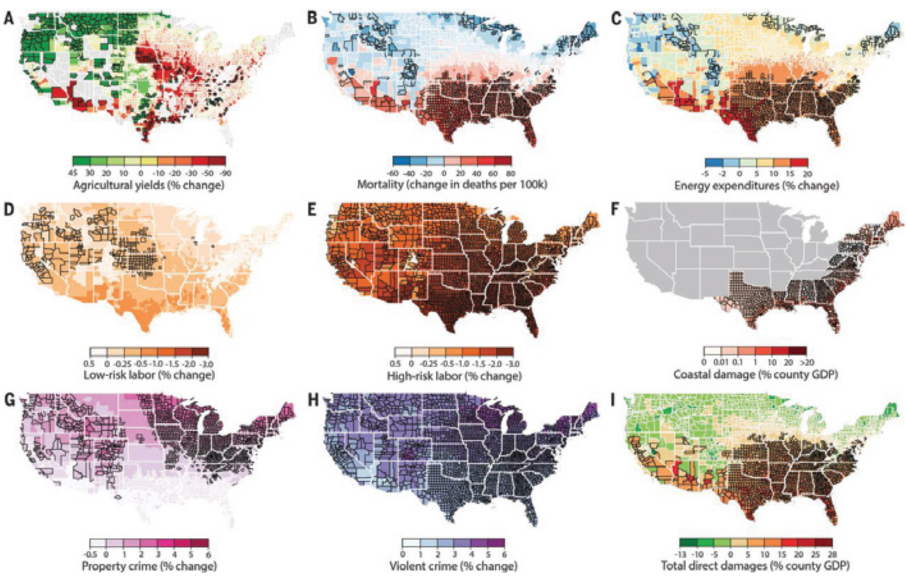
Economists have defined the social cost of carbon as the marginal cost to society of emitting an additional ton of CO_2. This is a pity because the biggest costs from climate change will not be economic and can hardly be priced. The biggest cost of climate change is the social impact that comes with the economic damages. Hsiang et al. (2017) modeled both the market and non-market economic effects of climate change in the United States. Because the United States is a large country with a broad range of climatic zones reaching from the deserts in the Southwest to the temperate climates in the Northwest, from the continental climate in the Midwest to the tropical climate in the

Southeast, the country can serve as a mini-model of the global trends of climate change.

Modeling the impact of climate change between 2010 and 2100 for a range of factors, Hsiang et al. (2017) showed that just as we would see on a global scale, the hotter and poorer regions of the United States will be harder hit by climate change, whereas the cooler and richer areas will suffer fewer damages. **Exhibit 21**, panel A, shows that the Southeast and the Midwest of the United States will likely experience the biggest reduction in crop yields, whereas the Northwest will likely experience increasing crop yields because of the milder winters. The rising heat in the South will increase mortality rates (especially among older people and small children) and lead to an increase in energy use to power air conditioning (Exhibit 21, panels B and C).

Forced Migration as a Major Source of Conflict. The response to these climatic changes within the United States will be migration away from the southern states to the cooler and more prosperous northern states. As a result, labor supply will likely decline for both indoor jobs (Exhibit 21, panel D)

Exhibit 21. Projected Change in Key Socioeconomic Indicators Due to Climate, 2100 vs. 2010 in the United States



Source: From "Estimating Economic Damage from Climate Change in the United States" by Solomon Hsiang, Robert Kopp, Amir Jina, James Rising, Michael Delgado, Shashank Mohan, D. J. Rasmussen, Robert Muir-Wood, Paul Wilson, Michael Oppenheimer, Kate Larsen, and Trevor Houser. *Science* 30 (June 2017): 1362–69. Reprinted with permission from AAAS.

and outdoor jobs (Exhibit 21, panel E) in these regions. Unfortunately, mass migration will bring its own set of problems to the northern parts of the country. Because the newly arrived immigrants from the southern states will face the possibility of unemployment and a lack of housing, the rate of both property crime and violent crime will likely rise in the northern parts of the United States (Exhibit 21, panels G and H).

I could have made almost the same statements with respect to the global social impact of climate change. The poor countries in the Global South will likely face the biggest decline of crop yields and the biggest increase in energy consumption and mortality rates. Meanwhile, the temperate countries of the north will likely benefit from rising crop yields but also have to deal with the arrival of millions of migrants from the south.

Moore and Shellman (2004) investigated the drivers of forced migration and concluded that violence or fear and persecution is the main factor driving forced migration. Unfortunately, as the example of Syria at the beginning of this chapter showed, climatic events can trigger, or at least contribute to, the outbreak of civil wars and wars. Hsiang, Burke, and Miguel (2013) looked at the findings of 60 studies on the link between conflict and climate change since 1950 and found that all kinds of conflicts increase when temperatures rise or rainfall reaches extremes (either extremely high, causing floods, or extremely low, causing droughts).

In rich countries, these climatic events typically do not cause civil wars, but they increase the likelihood and prevalence of violent crime, police violence, and abrupt changes in political leadership. In poor countries, the stakes are even higher. A one-standard-deviation increase in temperature or precipitation extremes increases the likelihood of the onset of interpersonal violence by 2.3% and the onset of civil wars or wars by 11.1%. If we take only rising temperatures into account, Hsiang, Burke, and Miguel (2013) found that an increase of 1°C (1.8°F) in the average temperature leads to a 2.3% increase in the likelihood of interpersonal violence and a 13.2% increase in the likelihood of civil wars and wars. Because we expect the global temperature average to increase by another 1°C to 2°C by 2050, the likelihood of civil wars and wars in poor countries is going to increase substantially and with it, the potential for large migration to the rich countries in the north.

Abel, Brottrager, Crespo Cuaresma, and Muttarak (2019) found a significant link between climate change and the onset of conflict and then migration for the time period of 2010–2012 (including the Arab Spring in North Africa and the Middle East). They found no such link for the years before or after the Arab Spring, however, indicating that climate change alone is probably not enough to cause civil strife and forced migration.

Instead, climate change must interact with other developments to push a country off the cliff. As for the nations affected by the Arab Spring, they all were in a state of transformation (either economically or demographically, with lots of young people) and thus already more vulnerable to external shocks. These countries also did not necessarily have the infrastructure and resources to deal with climate events, such as severe droughts. All these factors combined to trigger the violent uprisings of the Arab Spring.

This is both good and bad news. It is bad news because it shows us that many countries we identified in the previous chapter as being vulnerable to the decline of petrostates are also vulnerable to the onset of civil war and other wars if extreme climatic events compound the countries' economic transformation process. But it is also good news because it shows that if these countries focus on preparing for climate change, they can avoid the outbreak of civil strife as a result of climatic events. And the rich countries can help the poor countries by financing investments in infrastructure, education, and other resources that help stabilize their societies. Such investments are in the rich countries' best interest because, otherwise, the question will be *when* rather than *if* they will have to deal with millions of migrants on their southern borders.

Unfortunately, current climate policies discussed and implemented in rich countries often fail to consider the unintended consequences they can have on society. The result is that ill-advised climate regulation can lead to protest and violence, even in rich countries. In late 2018, French President Emmanuel Macron introduced a higher fuel tax to help fight climate change. This increase in the fuel tax gave birth to the "yellow vest movement," which started in the countryside, where many people rely on their cars to get to and from work but cannot afford to pay a higher price for fuel. From the countryside, the movement quickly spread to Paris, where it became a mass movement that eventually turned violent and forced Macron to withdraw his proposed fuel tax.

Like every policy measure, climate mitigation policies are likely to have both positive and negative side effects (Markkanen and Anger-Kraavi 2019). The anticipated positive side effects of climate mitigation policies are a reduction of inequality between rich and poor countries as well as in social dimensions such as health outcomes and gender and racial inequality. These positive side effects are increasingly used as a justification for the implementation of climate mitigation policies in countries where economic concerns are of higher importance than fighting climate change.

In the industrial world, the positive side effect of climate mitigation policies is the creation of new jobs in green industries. International Renewable

Energy Agency (IRENA 2019) estimated that globally, approximately 11 million people were employed in the renewable energy sector in 2018, with 3.6 million people in the solar energy industry alone. China provides 39% of global renewable energy jobs, but Brazil is the largest employer in the area of biofuels, with more than 800,000 jobs in this industry. In the United States, approximately 300,000 people are employed in the biofuels industry and 250,000 in the solar energy industry, compared with 50,000 employees in the coal industry. And across the European Union, 1.2 million people are already employed in the renewable energy sector.

The problem, of course, is that although green industries create new jobs, the people who lose their jobs from the transition from fossil fuels to renewable energy are often not qualified for these new jobs, thus creating an effect similar to that of the outsourcing and digitalization trend in the manufacturing sector. Blue-collar workers with low educational attainment are likely to lose from the transition and the transformation of our societies for a greener future.

Inequality is likely to rise both within countries and among countries, unless policies are implemented to mitigate these effects. For example, taxes raised by putting a cost on carbon can be used to finance retraining programs for workers in the fossil fuel industries who lose their jobs as a result of these changes. Government subsidies and tax breaks for employers who hire workers from industries that are in decline or who build factories in areas where many people have lost their jobs because of the decline of fossil fuels are all measures that can mitigate the inequality created by the transition to a greener economy.

Environmental Regulation—An International Competitive Disadvantage?

As we learned in chapter 4, from a geo-economical perspective, countries compete with each other through regulation and taxes. A common claim is that stricter environmental regulation leads to an economic disadvantage for businesses. Two competing theories exist as to how environmental regulation affects businesses, particularly in countries that are at the forefront of climate regulation and that introduced a high price of carbon.

First is the "pollution haven hypothesis," which argues that industries that emit a lot of CO_2 and other greenhouse gases will engage in regulatory arbitrage and move their production facilities from countries with high emission standards to countries and regions with low emission standards. Rising pollution abatement costs and expenditures could make a steel mill in France too expensive to run, thereby forcing the owner of the mill to close it and open another mill in India or another country where the price of carbon is essentially zero.

In the European Union, the introduction of the Emissions Trading System in 2005 has increased the production costs of cement, electricity, iron, and steel by an estimated 5% to 8% (Dechezleprêtre and Sato 2017). Yet evidence in favor of the pollution haven hypothesis in the European Union is limited. Imports of cement, iron, and steel have hardly increased in the European Union after accounting for economic growth, indicating that production was not moved outside the European Union and that cheaper imports from foreign countries did not have a competitive advantage that was large enough to displace domestic production. Conversely, studies in the United States have shown that higher pollution abatement costs and expenditures have led to a small increase in imports of these goods from countries, such as Mexico and Guatemala. In general, tests of the pollution haven hypothesis tend to show no effect, or only a very small one, which is easily dominated by other effects, such as differences in labor costs and tariff barriers.

The second theory about the impact of environmental regulation on the competitiveness of businesses is the "Porter hypothesis" (named after business strategist Michael Porter, who first proposed it). It states that environmental regulation spurs innovation and the search for cost efficiencies and thereby could have a net positive effect on businesses. Some evidence has been found that stricter environmental regulation leads to the search for cost efficiencies and increased investments in research and development of green technologies—at least that is what could be observed in the European Union. But the net effect, considering both higher regulatory costs and increased productivity, is clearly not a benefit for corporations. No empirical evidence has been found in favor of the Porter hypothesis, even though the drive for innovation likely reduces the costs of more regulation (Dechezleprêtre and Sato 2017).

Finally, Fullerton and Muehlegger (2019) have shown that the cost of higher environmental regulation is ultimately borne by consumers and by producers that cannot substitute high-carbon technologies with high-tech, low-carbon technologies. In general, these are the poorer households in a country that cannot afford a new hybrid or electric car and the producers of carbon-intensive goods in poorer countries that cannot afford more modern production facilities. Again, the environmental regulations introduced to transform our economies to a more sustainable model are likely to increase inequality, something that needs to be kept in mind when designing environmental regulations.

Conclusions

In this chapter, we tackled what can be called the ultimate geopolitical risk: climate change. Because climate change is a truly global phenomenon that cannot be restricted to a single country or region, we must all think about its likely impact and ways to adapt to it. Today, we face concentrations of CO_2 and other greenhouse gases that are higher than at any time since we humans first populated this planet. With them comes not only a higher average temperature of our atmosphere but also a higher volatility of the weather, as well as stronger and more frequent weather extremes. The economic cost of weather extremes such as cyclones is high and, even in the long run, comparable to the effects of a currency crisis or civil war. Thus, unsurprisingly, climate risks should command a risk premium in asset markets, and we have seen some indication that rising global temperatures and rising temperature volatility do command a small but non-negligible risk premium for equities.

But extreme climatic events are localized phenomena and thus create significant economic damage in small areas. On a global scale, the direct economic damage from climate change is estimated to be relatively small. In this century, the expected economic damage is roughly the same as one year's growth, although this damage is not equally distributed around the globe.

Both economic and social damages from climate change accrue primarily in poor countries close to the equator, whereas richer countries in the Northern Hemisphere suffer a smaller impact and potentially even small benefits for the agriculture industry. These direct economic impacts are easy to manage for rich countries but much harder for poor countries.

Climate change's main geopolitical risk is thus not necessarily triggered by economic damages but instead by its social impact. Rising temperatures and more frequent and extreme climatic events substantially increase the likelihood of violence in the affected regions, particularly if these regions are undergoing a societal or economic transition or do not have the required infrastructure and resources to mitigate the impact of climate disasters. In the event of dramatic warming or flooding in vulnerable areas, increased violence, famines, and rising poverty would all conspire to create large migrant flows from the poor countries of the global south to the rich countries in the north. Even within rich countries such as the United States, migration from the South to the North is likely to materialize as climate change intensifies. These migrant flows will put additional pressures on the resources and infrastructure of the receiving countries and create rising political pressures that will likely be similar to what we have seen in Europe and the United States in recent years.

These political developments do not bode well for our future because our ability to mitigate and adapt to climate change will depend heavily on the socioeconomic pathways we follow in the coming decades. If we engage in strong international cooperation to mitigate climate change and reduce the global emission of greenhouse gases rapidly, we can keep both the costs of transformation and the expected damages low. But if we instead give in to our nationalistic tendencies and enter a race to the bottom, in which every country fights on its own and puts its national interests above the interests of all others, we not only will accelerate climate change but also increase our economic and social problems to such a degree that we will have to abandon any hope of ever keeping climate change under control. Between these two extremes are several alternatives that provide a middle ground that needs to be explored. The future of climate change and our global economy is not cast in stone, and neither are the geopolitical risks climate change creates. Instead, our job as investors and citizens is to work together in facing these challenges.

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