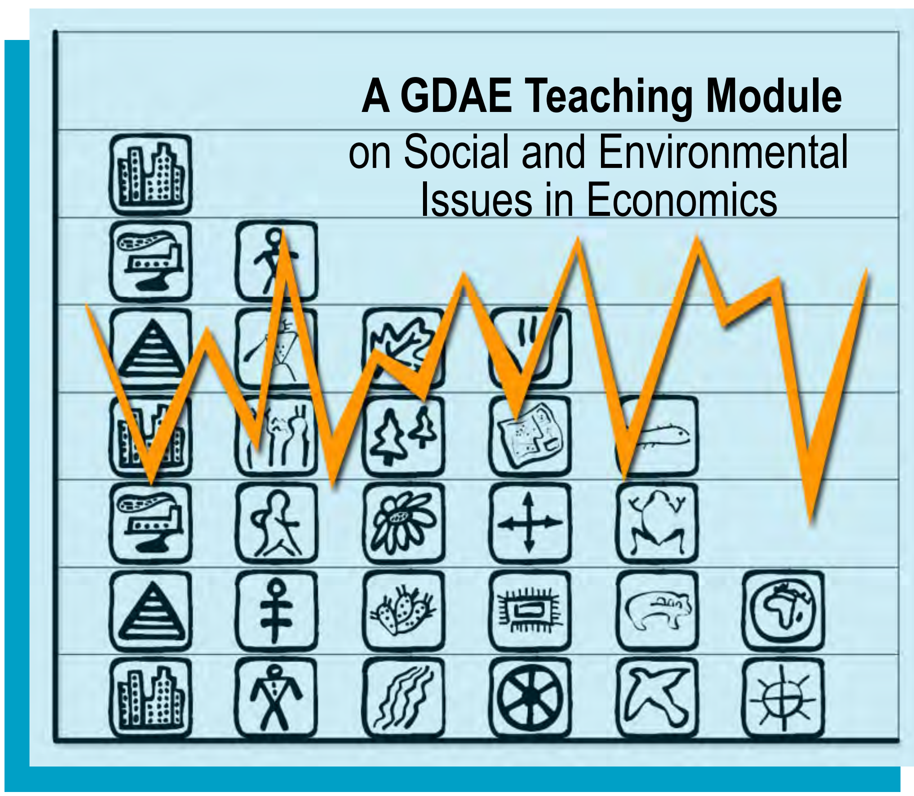
The Economics of Global Climate Change

by Jonathan M. Harris,
Brian Roach and Anne-Marie Codur



Global Development And Environment Institute
Tufts University
Medford, MA 02155
http://ase.tufts.edu/gdae

Comments and feedback from course use are welcomed:
Global Development And Environment Institute
Tufts University
Somerville, MA 02144
http://ase.tufts.edu/gdae

E-mail: gdae@tufts.edu

NOTE – terms denoted in **bold face** are defined in the **KEY TERMS AND CONCEPTS** section at the end of the module.

The Economics of Global Climate Change

Table of Contents

The Economics of Global Climate Change

1. CAUSES AND CONSEQUENCES OF CLIMATE CHANGE

Scientists have been aware since the nineteenth century of the planetary impacts of carbon dioxide (CO_2) and other **greenhouse gases** in the atmosphere. In recent decades, concern has grown over the issue of **global climate change** caused by increased accumulations of these gases.[1]

Multiple studies published in peer-reviewed scientific journals show that 97 percent or more of actively publishing climate scientists agree: Climate-warming trends over the past century are extremely likely to be due to human activities.[2] The 2013 and 2014 reports of the Intergovernmental Panel on Climate Change clearly attribute the majority of recently observed global climate change to human-made greenhouse gas emissions. The IPPC projects a temperature increase by 2100 of between 1.5°C (2.7°F) and 4.8°C (8.6°F), relative to pre-industrial levels (see Box 1).[3]

Recent statements by the U.S. Global Research Program and the American Geophysical Union indicate the widespread scientific acceptance of the reality of climate change, and the human role in its recent pattern:

> Evidence for climate change abounds, from the top of the atmosphere to the depth of the oceans. Scientists and engineers from around the world have meticulously collected this evidence, using satellites and networks of weather balloons, observing and measuring changes in location and behaviors of species and functioning of ecosystems. Taken together, this evidence tells an unambiguous story: the planet is warming, and over the half century, this warming has been driven primarily by human activity.
>
> – U.S. Global Change Research Program, 2014[4]

> Humanity is the major influence on the global climate change observed over the past 50 years. Rapid societal responses can significantly lessen negative outcomes.
>
> – American Geophysical Union, 2014[5]

The horizon of projections for major consequences of climate change has become closer as scientific understanding of the physical processes has increased in recent years. What appeared ten years ago as a future threat for generations to come, in

---

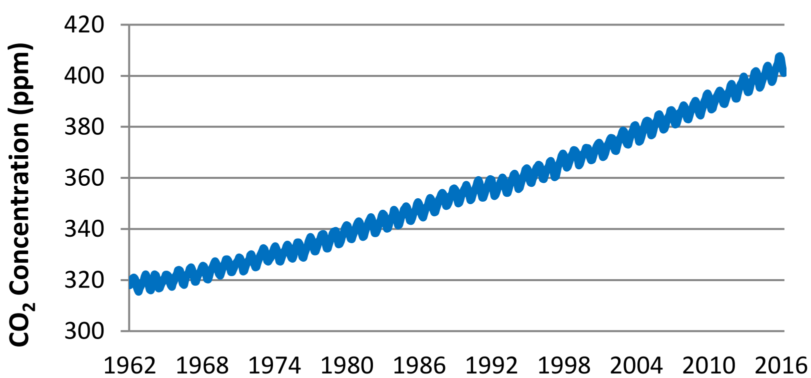
[1] The problem often referred to as **global warming** is more accurately called global climate change. A basic warming effect will produce complex effects on climate patterns—with warming in some areas, cooling in others, and increased climatic variability and extreme weather events.
[2] Cook et al., 2016.
[3] IPCC, 2014a, *Summary for Policymakers*, pp. 4, 15, 21; IPCC 2014d, *Summary for Policymakers*, p. 8.
[4] U.S. Global Change Research Program, p.7.
[5] American Geophysical Union, 2014.

the late twenty-first century and beyond, is increasingly understood as an immediate and urgent issue, as many countries are already experiencing some of the disruptive consequences of climate change (See Box 1).

Putting climate change in the framework of economic analysis, we can consider greenhouse gas emissions, which cause planetary warming and other changes in weather patterns, as both a cause of environmental externalities and a case of the overuse of a **common property resource**.

The atmosphere is a **global commons** into which individuals and firms can release pollution. Global pollution creates a "public bad" affecting everyone—a negative externality with a wide impact. Many countries have environmental protection laws limiting the release of local and regional air pollutants**.** In economic terminology, such laws to some degree internalize externalities associated with local and regional pollutants. But until relatively recently, few controls existed for carbon dioxide (CO_2), the major greenhouse gas, and concentrations of CO_2 in the atmosphere have risen steadily, recently crossing the benchmark of 400 parts per million (ppm) atmospheric concentration (see Figure 1).

Figure 1. Atmospheric Carbon Dioxide Levels



Source: National Oceanic and Atmospheric Administration, Earth System Research laboratory, Global Monitoring Division http://www.esrl.noaa.gov/gmd/ccgg/trends/data.html
Note: Seasonal variations mean that CO_2 concentrations rise and fall each year with growth and decay of vegetation and other biological systems, but the long-term trend, measured in parts per million or ppm, is a steady increase due to human emissions of CO_2.

Impacts of climate change have already begun to affect climate patterns (see Box 1). These effects range in scope from melting polar ice to raising sea levels, from collapse of marine ecosystems to increasingly severe water stress in large parts of the world, from changing weather patterns accompanied by more frequent and more violent climactic episodes (hurricanes, floods, droughts) to wider spreading of pathogens and diseases. The World Health Organization (WHO) has estimated that more than 140,000 people per year are already dying as a direct result of climate change, primarily in Africa and Southeast Asia.

BOX 1. WHAT IS THE GREENHOUSE EFFECT?

The sun's rays travel through a greenhouse's glass to warm the air inside, but the glass acts as a barrier to the escape of heat. Thus, plants that require warm weather can be grown in cold climates. The global greenhouse effect, in which the earth's atmosphere acts like the glass in a greenhouse, was first described by French scientist Jean Baptiste Fourier in 1824.

Clouds, water vapor, and the natural greenhouse gases carbon dioxide (CO_2), methane, nitrous oxide, and ozone allow inbound solar radiation to pass through but serve as a barrier to outgoing infrared heat. This creates the natural **greenhouse effect,** which makes the planet suitable for life. Without it, the average surface temperature on the planet would average around –18° C (0° F), instead of approximately 15°C (60° F).

"The possibility of an *enhanced* or *man-made* greenhouse effect was introduced by the Swedish scientist Svante Arrhenius in 1896. Arrhenius hypothesized that the increased burning of coal, which had paralleled the process of industrialization, would lead to an increased concentration of carbon dioxide in the atmosphere and warm the earth." (Fankhauser, 1995).

Since Arrhenius's time, emissions of greenhouse gases have grown dramatically. CO_2 concentrations in the atmosphere have increased by 40% over pre-industrial levels. In addition to increased burning of fossil fuels such as coal, oil and natural gas, manmade chemical substances such as chlorofluorocarbons (CFCs) as well as methane and nitrous oxide emissions from agriculture and industry contribute to the greenhouse effect.

Scientists have developed complex models that estimate the effect of current and future greenhouse gas emissions on the global climate. While considerable uncertainty remains in these models, a broad scientific consensus has formed that the human-induced greenhouse effect poses a significant threat to the global ecosystem. The Intergovernmental Panel on Climate Change (IPCC) has concluded in all its reports that the global atmospheric concentrations of greenhouse gas (GHG) emissions have increased markedly as a result of human activities since 1750.

According to the report, "Human influence on the climate system is clear, and recent anthropogenic emissions of greenhouse gases are the highest in history… Warming of the climate system is unequivocal, and since the 1950s many of the observed changes are unprecedented over decades to millennia. The atmosphere and ocean have warmed, the amounts of snow and ice have diminished, and sea level has risen." The IPCC projected a global average temperature increase by 2100 of between 1.5°C and 4.8°C, (between 2.7°F and 8.6°F) above pre-industrial levels. By 2015, the world had already reached an average increase of temperatures of 1°C compared with pre-industrial times, and global temperatures broke heat records three years in a row in 2014, 2015 and 2016.

Sources: Fankhauser 1995; IPCC, 2014a, b, and c. Damian Carrington, "World's climate about to enter "uncharted territory" as it passes 1°C of warming", *The Guardian*, November 9, 2015. *The New York Times*, January 18, 2017.

If indeed the effects of climate change are likely to be severe, it is in everyone's interest to lower emissions for the common good. Climate change can thus be viewed as a **public good** issue, requiring collaborative action to develop adequate policies. In the case of climate change, such action needs to involve all stakeholders, including governments and public institutions as well as private corporations and individual citizens.

After decades of failures at the international level to produce an agreement including all countries, significant progress was achieved in Paris in December 2015, when 195 nations, under the auspices of the United Nations Framework Convention on Climate Change, signed the first global agreement aiming at keeping the overall increase in global average temperature under 2 degrees Celsius (compared with pre-industrial times). In addition to the actions taken by national governments, hundreds of cities, regions, and corporations have pledged to make significant reductions in their CO_2 emissions over the next 5 to 25 years, although the withdrawal of the United States under the Trump Administration may throw the success of the agreement into doubt. We will return to the specifics of the Paris Agreement in details in the last section of this module.

Because CO_2 and other greenhouse gases continuously accumulate in the atmosphere, stabilizing or "freezing" emissions will not solve the problem. Greenhouse gases persist in the atmosphere for decades or even centuries, continuing to affect the climate of the entire planet long after they are emitted. This is a case of a **stock pollutant**. Only major reductions in emissions levels of a stock pollutant will prevent ever-increasing atmospheric accumulations. Development of national and international policies to combat global climate change is a huge challenge, involving many scientific, economic, and social issues.

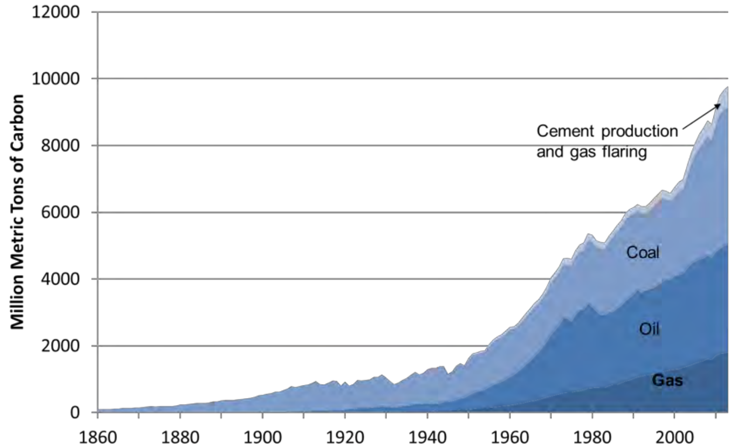
Trends in Global Carbon Emissions

Global emissions of CO_2 from the combustion of fossil fuels have increased dramatically since about 1950, as illustrated in Figure 2. In 2013, total global carbon emissions were 9.776 billion tons or Gigatons (Gt) of carbon. Coal burning is currently responsible for about 42 percent of global carbon emissions, while liquid fuels (primarily oil) are the source of another 33 percent, combustion of natural gas accounts for 19 percent, with 6% from cement production and gas flaring.[6] Figure 2 shows emissions over the period 1965-2015, expressed in million metric tons of CO_2.[7]

[6] Boden et al, 2016.

[7] To convert from tons of carbon to tons of CO_2, multiply by a factor of 3.667, which is the ratio 44/12, derived from CO_2's molecular weight of 44, and carbon's molecular weight of 12).

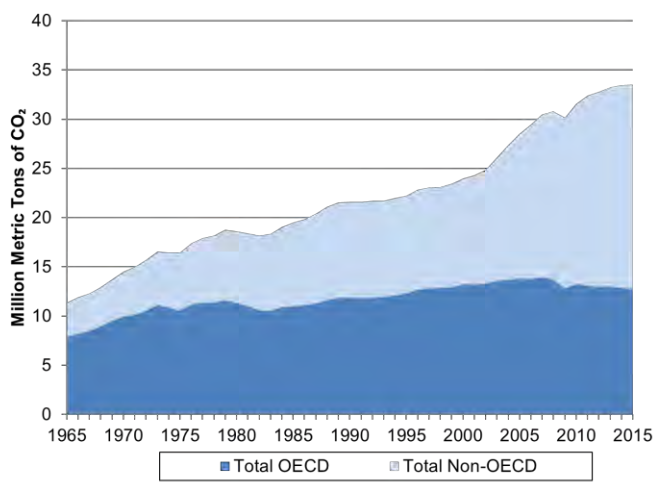
Figure 2. Carbon Emissions from Fossil Fuel Consumption, 1860–2013



Source: Carbon Dioxide Information Analysis Center (CDIAC)
http://cdiac.ornl.gov/ftp/ndp030/global.1751_2013.ems accessed June 2016.
Note: Emissions in million metric tons of carbon. To convert to MMt of CO_2, multiply by 3.67

Figure 3 focuses on the distribution of emissions between two groups of countries, the OECD, including primarily industrialized countries, and the rest of the world, comprising developing countries and including China. The share of OECD's emissions has steadily declined since 2007, and the developing world's share has increased significantly, though there has also been a recent slowdown of its growth.

Figure 3. Carbon Dioxide Emissions, 1965-2015,
Industrialized and Developing Countries (Million Metric Tons of CO_2)



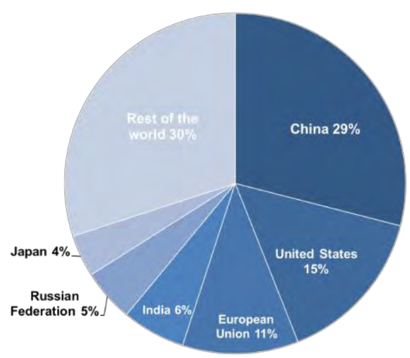
Source: U.S. Energy Information Administration
http://www.eia.gov/forecasts/aeo/data/browser/#/?id=10-IEO2016&sourcekey=0, accessed June 2016.
Note: OECD = Organization for Economic Cooperation and Development (primarily industrialized countries, while non-OECD are developing countries). The vertical axis in Figure 3 measures million metric tons of CO_2 (a given amount of emissions measured in tons of carbon dioxide is ~ 3.67 times the total weight in carbon). The emissions estimates of the U.S. EIA shown here differ slightly from those of the CDIAC shown in Figure 2.

Emissions are closely connected with the economic cycles, and the 2008-2009 recession is clearly visible in Figure 3. Also noteworthy is the apparent leveling off of CO_2 emissions in the years 2014, 2015, and 2016 around the figure of 33 billion tons (33 gigatons) of CO_2. This is partly explained by a slowing down of global economic growth (with a decrease in China's economic growth rate). It also reflects new energy investments in renewables (solar and wind), which have dominated additional energy production capacity in recent years. This trend is starting to make a significant impact in curtailing CO_2 emissions from the energy sector.

In developed countries, there has been a rapid switch from coal to natural gas and renewable energy, lowering overall CO_2 emissions. In developing countries, coal production is still expanding, but an increasing share of new energy production is also coming from renewables.[8] It is currently unclear if the leveling-off of emissions is a temporary phenomenon, or signals a turnaround in total emissions trends.

Figure 4 shows the distribution of CO_2 emissions among the main emitters: China (29%), the United States (15%), the European Union (11%), India (6%), Russia (5%), Japan (4%), and the rest of the world (30%). Most of the future growth in carbon emissions is expected to come from rapidly expanding developing countries such as China and India. China surpassed the United States in 2006 as the largest carbon emitter in the world.

Figure 4. Percentage of Global CO_2 Emissions by Country/Region



Source: Jos G.J. Olivier et al., European Commission's Joint Research Centre, 2014. "Trends in global CO_2 emissions: 2014 Report" http://edgar.jrc.ec.europa.eu/news_docs/jrc-2014-trends-in-global-co2-emissions-2014-report-93171.pdf

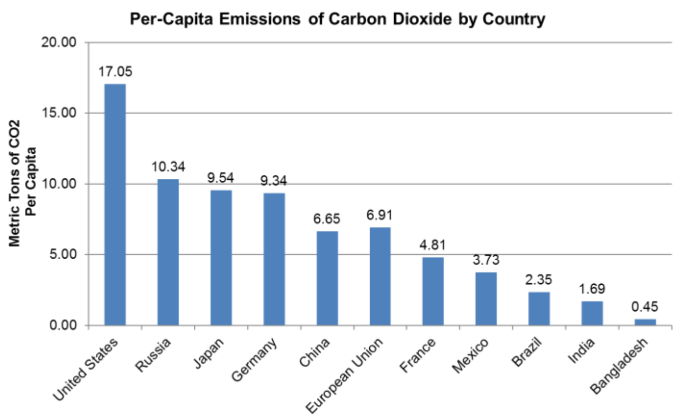
In addition to total emissions by country, it is important to consider per capita emissions. Per capita emissions are much higher in developed countries, as shown in Figure 5. The highest rates are observed in Gulf countries, such as Qatar (40 tons of CO_2 per person), Kuwait (34 tons per person) or the United Arab Emirates (22

[8] International Energy Agency, 16 March 2016 https://www.iea.org/newsroomandevents/pressreleases/2016/march/decoupling-of-global-emissions-and-economic-growth-confirmed.html

tons per person). The United States has the highest rate among major countries, with 17 metric tons of CO_2 emissions per person.

Other high-emitting countries are Australia with 16.7 tons per capita and Canada with 14.6. Russia has an average of 10 tons per person, while most other developed countries are in the range of 4 to 10 metric tons per capita[9]. Most developing countries have low rates per capita, typically less than 2 tons of CO_2 per person, except China, whose per capita emissions have grown to 6.6 tons per person.

Figure 5. Per-Capita Carbon Dioxide Emissions, by Country



Source: British Petroleum, Energy Charting Tool 2015.

Trends and Projections for Global Climate

The earth has warmed significantly since reliable weather records began to be kept in the mid-nineteenth century (Figure 6). In the past hundred years, the global average temperature has risen about 1°C, or about 1.8°F. Fourteen of the fifteen warmest years in the modern meteorological record have occurred from 2000 to 2015.[10] The record of 2014 as the hottest year ever recorded was broken by the year 2015, which in turn was broken by 2016,[11] which was about 1.1°C above preindustrial levels.[12] Evidence indicates that the rate of warming, currently about 0.13°C per decade, is increasing. The US Department of Energy's Pacific Northwest National Laboratory estimates that the rate at which temperatures are rising could be 0.25°C per decade by 2020.[13]

[9] The ranking of all countries' per capita emissions is accessible at http://cotap.org/per-capita-carbon-co2-emissions-by-country/

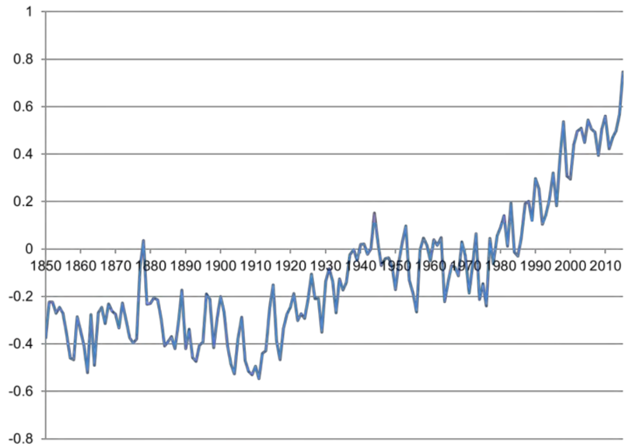
[10] NOAA 2012; Damian Carrington, "14 of the 15 hottest years on record have occurred since 2000, UN says", *The Guardian*, February 2, 2015.

[11] NASA, January 18, 2017. https://www.nasa.gov/press-release/nasa-noaa-data-show-2016-warmest-year-on-record-globally

[12] *New York Times*, January 18, 2017. https://www.nytimes.com/2017/01/18/science/earth-highest-temperature-record.html?_r=0

[13] *The Guardian*, March 9, 2015. "Global warming "set to speed up to rates not seen for 1,000

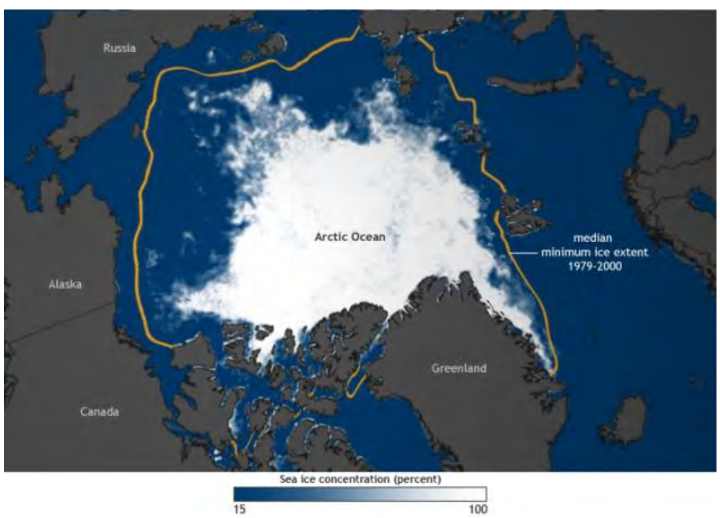
Figure 6. Global Annual Temperature Anomalies (°C), 1850–2015



Source: CDIAC, Global Monthly and Annual Temperature Anomalies (degrees C), 1850-2015, relative to the 1961-1990 mean, May 2016.
http://cdiac.ornl.gov/ftp/trends/temp/jonescru/global.txt
Note: The zero baseline represents the average global temperature from 1961-1990.

Not all areas are warming equally. The Arctic and Antarctica have been warming at about double the global rate.[14] Melting ice in the Arctic is both a result of global warming and a cause of further warming, since open ocean absorbs more of the sun's energy than ice, a phenomenon known as reduced albedo (see Figure 7).

Figure 7: Shrinking Arctic Ice in the Arctic



Source: http://thinkprogress.org/climate/2014/02/18/3302341/arctic-sea-ice-melt-ocean-absorbs-heat/. Figure is based on data from the National Snow and Ice Center.
Credit: climate.gov

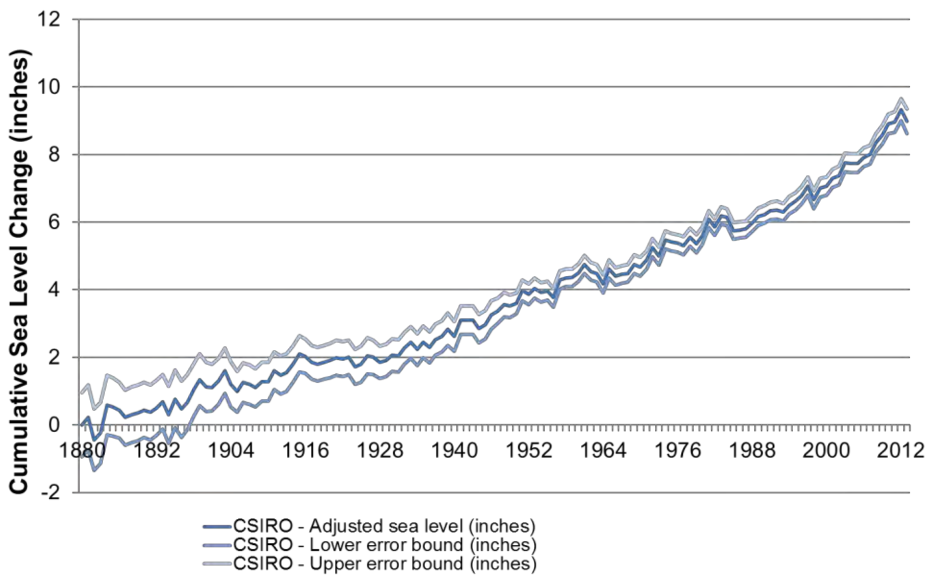
years". https://www.theguardian.com/environment/2015/mar/09/global-warming-set-to-speed-up-to-rates-not-seen-for-1000-years

[14] IPCC, 2007a, Working Group I: The Physical Science Basis.

Warmer temperatures have produced noticeable effects on ecosystems. In most regions of the world, glaciers are retreating. For example, Glacier National Park in Montana had 150 glaciers when the park was established in 1910. As of 2010 only 25 glaciers remained, and by 2030 it is estimated that the park will no longer have any of its namesake glaciers.[15]

Climate change is also leading to rising sea levels. Sea-level rise is attributed to the melting of glaciers and ice sheets and to the fact that water expands when it is heated. In 2012, the global average ocean temperature was about 0.5°C above the twentieth-century average. The combination of warmer oceans and melting ice has led sea levels to rise about 2 millimeters per year, and in 2012 the sea level was already 9 inches (23 cm) above the level of 1880 (see Figure 8 and Box 2).[16]

Figure 8. Sea-Level Rise, 1880–2012



Source: IPCC, 2014a
Note: The line in the middle shows an average estimate based on a large number of data sources. The shaded area represents the high level and low level margins of error (smaller for recent data).

[15] https://www.usgs.gov/centers/norock/science/retreat-glaciers-glacier-national-park?qt-science_center_objects=0
[16] NOAA, 2012.

BOX 2. PACIFIC ISLANDS DISAPPEAR AS OCEANS RISE

The island nation of Kiribati, a collection of 33 coral atolls and reef islands, lying no higher than 6 feet above sea level, scattered across a swath of the Pacific Ocean about twice the size of Alaska, is facing the risk of going under in the next few decades.

Two of its islands, Tebua Tarawa and Abanuea, have already disappeared as a result of rising sea level. Others, both in Kiribati and in the neighboring island country of Tuvalu, are nearly gone. So far the seas have completely engulfed only uninhabited, relatively small islands, but the crisis is growing all around the shores of the world's atolls.

The people of Tuvalu are finding it difficult to grow their crops because the rising seas are poisoning the soil with salt. Many islands will become uninhabitable long before they physically disappear, as salt from the sea contaminates the underground freshwater supplies on which they depend. The situation is so bad that the leaders of Kiribati are considering a plan to move the entire population of 110,000 to Fiji. The inhabitants of some villages have already moved.

Sources: Mike Ives, "A Remote Pacific Nation, Threatened by Rising Seas." *New York Times*, July 2, 2016. "Kiribati Global Warming Fears: Entire Nation May Move to Fiji," *Associated Press*, March 12, 2012

The impact of rising seas threatens numerous coastal areas; for example, the U.S. government has identified 31 Alaskan towns and cities at imminent risk, and cities in Florida are already witnessing significant damage from a major increase in flooding.[17] Miami Beach has already invested more than $400 million to deal with recurrent flooding, happening not only during hurricane episodes but also at "king tides" which occur once or twice a year (when the orbits and alignment of the Earth, moon, and sun combine to produce the greatest tidal effects of the year).[18] Residents of several coastal cities experiencing higher frequencies of flooding are worried about the loss of real estate value of their homes. There are major implications for the insurance industry; according to the president of the Reinsurance Association of America, "it is clear that global warming could bankrupt the industry."[19]

Recent research on the West Antarctic Ice sheet shows that this area, larger than Mexico, is potentially vulnerable to disintegration from a relatively small amount of

[17] Erica Goode, "A Wrenching Choice for Alaska Towns in the Path of Climate Change," *New York Times*, November 29, 2016; "Intensified by Climate Change, 'King Tides' Change ways of Life in Florida," *New York Times*, November 17, 2016

[18] *New York Times*, November 17, 2016. ibid.

[19] Eugene Linden, "How the insurance industry sees Climate Change", *Los Angeles Times,* June 16, 2014

global warming, and capable of raising the sea level by 12 feet or more should it happen. Even if this most pessimistic scenario did not materialize, researchers found that the total sea rise could reach 5 to 6 feet by 2100, and would continue to increase, with the seas rising by more than a foot per decade by the middle of the 22nd century.[20]

In addition to rising ocean temperatures, increased CO_2 in the atmosphere results in **ocean acidification**. The U.S. National Oceanic and Atmospheric Administration finds:

> Around half of all carbon dioxide produced by humans since the Industrial Revolution has dissolved into the world's oceans. This absorption slows down global warming, but it also lowers the oceans pH, making it more acidic. More acidic water can corrode minerals that many marine creatures rely on to build their protective shells and skeletons.[21]

A 2012 report in *Science* magazine found that the oceans are turning acidic at what may be the fastest pace in 300 million years, with potential severe consequences for marine ecosystems.[22] Among the first victims of ocean warming and acidification are coral reefs, because corals can form only within a narrow range of temperatures and acidity of seawater. The year 2015 saw a record die-off of coral reefs, known as coral bleaching, due to a combination of the most powerful El Niño (Pacific warming) climate cycle in a century and water temperatures already elevated due to climate change. [23] Oyster hatcheries, which have been referred to as "canaries in a coal mine" since they may predict effects on a wide range of ocean ecosystems as ocean acidification increases, are also affected, threatening the Pacific Northwest shellfish industry.[24] Other ecosystems are also severely impacted by climate change (Box 3).

---

[20] DeConto and Pollard, 2016.

[21] NOAA, 2010.

[22] Hönish et al., 2012; Deborah Zabarenko, "Ocean's Acidic Shift May Be Fastest in 300 Million Years," *Reuters*, March 1, 2012

[23] Roger Bradbury, "A World Without Coral Reefs," *New York Times,* July 14, 2012; NOAA, "Scientists find rising carbon dioxide and acidified waters in Puget Sound," 2010; Michelle Inis, "Climate-related death of coral around the world alarms scientists" *New York Times*, April 9, 2016

[24] Coral Davenport, "As oysters die, climate policy goes on the stump," *New York Times* August 3, 2014.

BOX 3. FORESTS, CLIMATE CHANGE, AND WILDFIRES

Wildfires were once primarily a seasonal threat, taking place mainly in hot, dry summers. Now they are burning nearly year-round in the Western United States, Canada, and Australia. In May 2016, the state of Alberta was devastated by wildfires expanding over 350 miles, leading to the evacuation of the 80,000 inhabitants of the city of Fort McMurray, which suffered extensive damage.

Global warming is suspected as a prime cause of the increase in wildfires. The warming is hitting northern regions especially hard: Temperatures are climbing faster there than for the Earth as a whole, snow cover is melting prematurely, and forests are drying out earlier than in the past. Dry winters mean less moisture on the land, and the excess heat may even be causing an increase in lightning, which often sets off the most devastating wildfires.

According to a research ecologist for the United States Forest Service: "In some areas, we now have year-round fire seasons, and you can say it couldn't get worse than that. But we expect from the changes that it can get worse." The United States Forest Service spent more than half of its budget on firefighting in 2015, at the expense of programs such as controlled burning aimed at reducing the risk of fires. Scientists see a risk that if the destruction of forests from fires and insects keeps rising, the carbon that has been locked away in the forests will return to the atmosphere as carbon dioxide, accelerating the pace of global warming — a dangerous feedback loop.

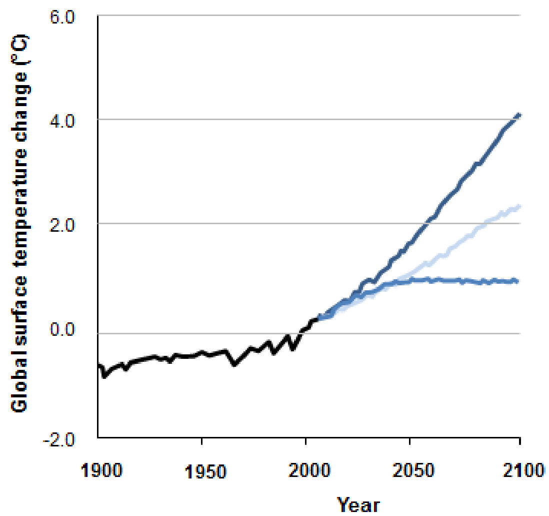
Sources: Matt Richtel and Fernanda Santos, "Wildfires, once confined to a season, burn earlier and longer" *New York Times*, April 12, 2016; Ian Austen, "Wildfire empties Fort McMurray in Alberta's oil sands region," *New York Times*, May 3, 2016.

Future projections of climate change depend on the path of future emissions. Even if all emissions of greenhouse gases ended today, the world would continue warming for many decades, and effects such as sea-level rise would continue for centuries, because the environmental effects of emissions are not realized immediately.[25]

Based on a range models with different assumptions about future emissions, the IPCC estimated in its 2014 report that during the twenty-first century global average temperatures will rise within a range most likely to be between 1.5°C (3°F) and 4.8°C (8.6°F) above pre-industrial levels, unless drastic policy action to reduce emissions occurs.[26] The range of possible temperature increases is shown in Figures 9 and 10, with Figure 10 showing the probable distribution of temperature increases across the planet for low-end and high-end temperature increase scenarios.

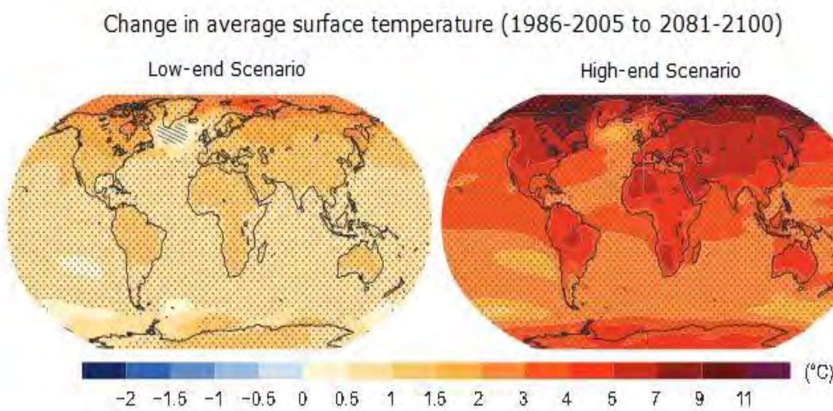
[25] Jevrejeva et al., 2012; http://www.skepticalscience.com/Sea-levels-will-continue-to-rise.html.
[26] IPCC, 2014b, pp. 59-60.

Figure 9. Global Temperature Trends, 1900–2100



Source: IPCC 2014c, Summary for Policymakers, p. 13.
Note: The graph shows mean projections for high-, medium-, and low-emissions scenarios. The possible range of temperature increases in all IPCC models is wider, ranging between 0.3 and 4.8°C

Figure 10. Global Temperature Trends Projected to 2100 – two scenarios



Source: IPCC, 2013

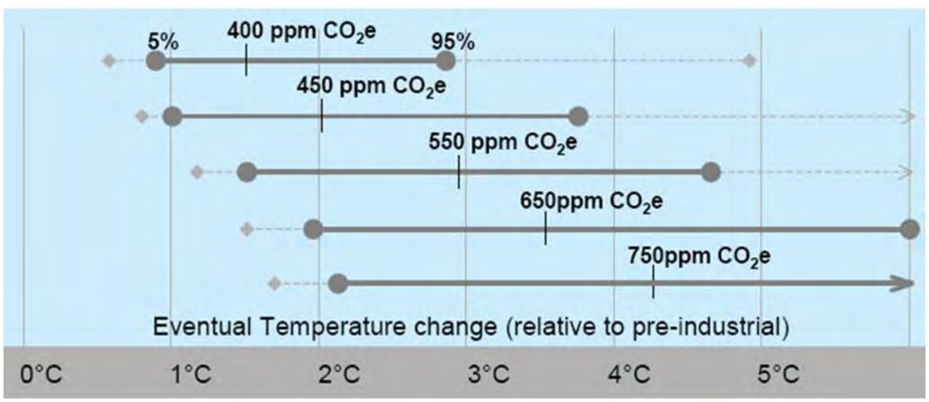
The magnitude of actual warming and other effects will depend upon the level at which atmospheric concentrations of CO_2 and other greenhouse gases are ultimately stabilized. Pre-industrial levels of concentration were around 280 parts per million (ppm). A 2008 scientific paper by climate scientists James Hansen and Rajandra Pachauri, the chairperson of the IPCC, declared that: "If humanity wishes to preserve a planet similar to that on which civilization developed and to which life on Earth is adapted, paleoclimate evidence and ongoing climate change suggest that CO_2 will need to be 350 ppm."[27]

[27] Hansen et al, 2008.

In 2015, the atmospheric CO_2 concentration passed the milestone of 400 ppm.[28] When we also include the contribution of other greenhouse gases, the overall effect is equivalent to a concentration of 430 ppm of CO_2 or more referred to as **CO_2 equivalent (CO_2e)**. This level of CO_2 equivalent has not been experienced for over 800,000 years.[29]

Figure 11 relates the stabilization level of greenhouse gases, measured in CO_2e, to the resulting rise in global average temperatures, incorporating the degree of uncertainty. The solid bar at each level of CO_2e represents a range of temperature outcomes that is likely to occur with a 90 percent probability. The dashed line at either end represents the full range of predicted results from the major existing climate models. The vertical line around the middle of each bar represents the midpoint of the different predictions.

Figure 11. Relationship between Level of Greenhouse Gas Stabilization and Eventual Temperature Change



Source: Stern, 2007.
Note: CO_2e = CO_2 equivalent; ppm = parts per million.

This projection suggests that stabilizing greenhouse gas concentrations at 450 ppm CO_2e would be 90 percent likely to eventually result in a temperature increase between 1.0 and 3.8°C, with a median expectation of 2°C and a small probability that the rise could be significantly more than this. With current greenhouse gas concentrations in the atmosphere at over 430 ppm CO_2e, stabilization at 450 ppm is likely impossible to achieve without significant withdrawal of CO_2 from the atmosphere – implying net emissions below zero at some point in the future. Even stabilization at 550 ppm CO_2e, implying a median global temperature increase of about 3°C, would require strong and immediate policy action.

[28] Adam Vaughan, "Global carbon dioxide levels break 400ppm milestone," *The Guardian*, May 6, 2015.
[29] Andrea Thompson, "2015 begins with CO_2 above 400ppm mark", *Climate Central*, January 12, 2015, www.climatecentral.org/news/2015-begins-with-co2-above-400-ppm-mark-18534

2. ECONOMIC ANALYSIS OF CLIMATE CHANGE

Scientists have modeled the results of a projected doubling of accumulated CO_2 in the earth's atmosphere. Some of the many negative predicted effects are:

- Loss of land area, including beaches and wetlands, because of sea-level rise
- Loss of species and forest area
- Disruption of water supplies to cities and agriculture
- Increased air conditioning costs
- Health damage and deaths from heat waves and spread of tropical diseases
- Loss of agricultural output due to drought

Some beneficial outcomes might include:

- Increased agricultural production in cold climates
- Lower heating costs
- Fewer deaths from exposure to cold

The potentially beneficial outcomes would be experienced primarily in northern parts of the Northern hemisphere, such as Iceland, Siberia and Canada. Most of the rest of the world, especially tropical and semi-tropical areas, are likely to experience strongly negative effects from additional warming. According to IPCC projections, with increasing emissions and higher temperatures, negative effects will intensify and positive effects diminish (see Table 1).

Other less-predictable but possibly more damaging and permanent effects include:

- Disruption of weather patterns, with increased frequency of hurricanes, droughts, and other extreme weather events.
- A possible rapid collapse of the Greenland and West Antarctic Ice Sheets, which would raise sea levels by 12 meters or more, drowning major coastal cities
- Sudden major climate changes, such as a shift in the Atlantic Gulf Stream, which could change the climate of Europe to that of Alaska.
- Positive **feedback effects**[30], such as an increased release of CO_2 from warming arctic tundra, which would speed up global warming.

As shown in Figure 9, there is considerable uncertainty about the expected global warming in the coming century. We need to keep such uncertainties in mind as we try to evaluate economic impacts of global climate change.

[30] A feedback effect occurs when an original change in a system causes further changes that either reinforce the original change (positive feedback) or counteract it (negative feedback).

Table 1. Possible Effects of Climate Change

Type of Impact	Eventual Temperature Rise Relative to Pre-Industrial Temperatures				
	1°C	**2°C**	**3°C**	**4°C**	**5°C**
Freshwater Supplies	Small glaciers in the Andes disappear, threatening water supplies for 50 million people	Potential water supply decrease of 20-30% in some regions (Southern Africa and Mediterranean)	Serious droughts in Southern Europe every 10 years 1-4 billion more people suffer water shortages	Potential water supply decrease of 30-50% in Southern Africa and Mediterranean	Large glaciers in Himalayas possibly disappear, affecting ¼ of China's population
Food and Agriculture	Modest increase in yields in temperature regions	Declines in crop yields in tropical regions (5-10% in Africa)	150-550 million more people at risk of hunger; Yields likely to peak at higher latitudes	Yields decline by 15-35% in Africa; Some entire regions out of agricultural production	Increase in ocean acidity possibly reduces fish stocks
Human Health	At least 300,000 die each year from climate-related diseases Reduction in winter mortality in high latitudes	40-60 million more exposed to malaria in Africa	1-3 million more potentially people die annually from malnutrition	Up to 80 million more people exposed to malaria in Africa	Further disease increase and substantial burdens on health care services
Coastal Areas	Increased damage from coastal flooding	Up to 10 million more people exposed to coastal flooding	Up to 170 million more people exposed to coastal flooding	Up to 300 million more people exposed to coastal flooding	Sea level rise threatens major cities such as New York, Tokyo, and London
Ecosystems	At least 10% of land species facing extinction Increased wildfire risk	15-40% of species potentially face extinction	20-50% of species potentially face extinction; Possible onset of collapse of Amazon forest	Loss of half of Arctic tundra; Widespread loss of coral reefs	Significant extinctions across the globe

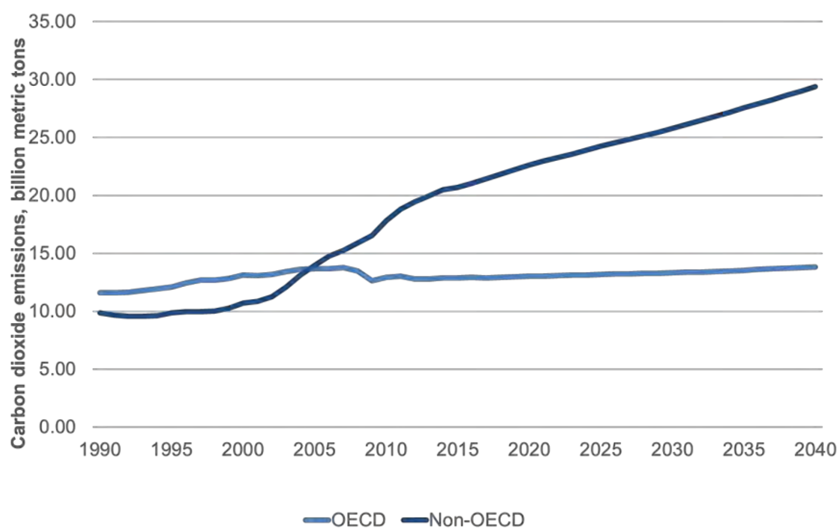
Sources: IPCC, 2007b; Stern, 2007

Given these uncertainties, some economists have attempted to place the analysis of global climate change in the context of **cost-benefit analysis**. Others have criticized this approach as an attempt to put a monetary valuation on issues with social, political, and ecological implications that go far beyond dollar value. We will first examine economists' efforts to capture the impacts of global climate change through cost-benefit analysis, and then return to the debate over how to implement greenhouse gas reduction policies

Cost-Benefit Studies of Global Climate Change

Without policy intervention, carbon emissions in a business-as-usual scenario would be expected to continue to rise as shown in Figure 12. These projections, however, are based on current trends without considering the impacts of future emissions reductions policies. Aggressive and immediate policy action is required first to stabilize and then to reduce total CO_2 emissions in the coming decades. This is the goal of the 2015 Paris Agreement. To understand the issues involved in reducing emissions, we need to look at the economic implications of such policy initiatives.

Figure 12. Energy-Related Carbon Dioxide Emissions, Projected to 2040



Source: EIA, 2016.
Note: The Organization for Economic Cooperation and Development (OECD) includes primarily industrialized countries, and non-OECD comprises the rest of the world, including developing countries and including China.

When economists perform a cost-benefit analysis, they weigh the consequences of the projected increase in carbon emissions versus the costs of current policy actions to stabilize or even reduce CO_2 emissions. Strong policy action to prevent climate change will bring benefits equal to the value of damages that are avoided. These benefits of preventing damage can also be referred to as **avoided costs.** The estimated benefits must then be compared to the costs of taking action.

Various economic studies have tried to estimate the benefits and costs of policy action on climate change. Attempting to measure the costs of climate change in monetized terms, or as a percentage of GDP, poses several inherent problems. In general, these studies can only capture effects of climate change insofar as they impact economic production, or create non-market impacts that can be expressed in monetary terms. Some sectors of the economy are potentially vulnerable to the effects of climate change, including farming, forestry and fishing, coastal real estate, and transportation. But these compose only about 10% of GDP. Other major areas, such as manufacturing, services, and finance are seen as only lightly affected by climate change.[31]

Thus, an estimate of GDP impacts may tend to omit some of the most powerful ecological effects of climate change. According to William Nordhaus, who has authored many cost-benefit studies of climate change over the past twenty years:

> …the most damaging aspects of climate change – in unmanaged and unmanageable human and natural systems – lie well outside the conventional marketplace. I identified four specific areas of special concern: sea-level rise, hurricane intensification, ocean acidification, and loss of biodiversity. For each of these the scale of the changes is at present beyond the capability of human efforts to stop. To this list we must add concerns about earth system singularities and tipping points, such as those involved in unstable ice sheets and reversing ocean currents. These impacts are not only hard to measure and quantify in economic terms; they are also hard to manage from an economic and engineering perspective. But to say that they are hard to quantify and control does not mean that they should be ignored. Quite the contrary, these systems are the ones that should be studied most carefully because they are likely to be the most dangerous over the longer run.[32]

Cost-benefit analysis can also be controversial since it puts a dollar figure on the value of human health and life. Most studies follow a common cost-benefit practice of assigning a value of about $8 – 11 million to a life, based on studies of the amounts that people are willing to pay to avoid life-threatening risk, or are willing to accept (e.g., in extra salary for dangerous jobs) to undertake such risks. But lower human life values tend to be assigned in developing nations, since the methodology for determining the value of a "statistical life" depends on monetary measures such as incomes and contingent valuation. Since many of the most serious impacts of climate change will be experienced in developing nations, this economic valuation bias clearly raises both analytical and moral issues.

[31] Nordhaus, 2013, p. 137.
[32] Nordhaus, 2013, p. 145.

The issue of uncertainty is central to cost-benefit analysis of climate change. Damage estimates tend to omit the possibility of the much more catastrophic consequences that *could* result if weather disruption is much worse than anticipated. A single hurricane, for example, can cause tens of billions in damage, in addition to loss of life. Hurricane Katrina in August 2005, for example, caused over $100 billion in damage, in addition to loss of over 1,800 lives. Hurricane Sandy, in 2012, caused about $50 billion in damages, disrupting power to nearly 5 million customers and leaving lasting effects on an extensive area of shoreline in New York and New Jersey.

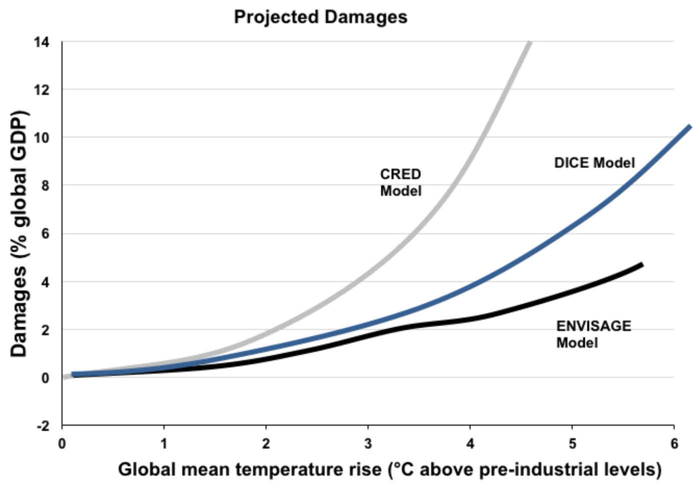
If climate change causes severe hurricanes to become much more frequent, cost-benefit analyses would have to estimate the costs of destruction at a much higher level than they have done previously. Another of the unknown values—human morbidity, or losses from disease—could well be enormous if tropical diseases extend their range significantly due to warmer weather conditions.

"Integrated assessment" models have been used by scientists and economists to translate scenarios of population and economic growth, and resulting emissions into changes in atmospheric composition and global mean temperature. These models then apply "damage functions" that approximate the global relationships between temperature changes and the economic costs from impacts such as changes in sea level, cyclone frequency, agricultural productivity and ecosystem function. Finally, the models attempt to translate future damages into present monetary value.[33]

Higher ranges of temperature change lead to dramatically increased damage estimates at the global level, as shown in Figure 13. Different models yield different estimates for future damages and in turn different impacts on the economy, ranging from 2% to 10% or more of global GDP per year, depending on the global mean temperature rise. The values in Figure 13 show results from three widely used models with damage estimates based on the IPPC estimates of likely temperature change by 2100.

[33] Revesz, Arrow et al., 2014.

Figure 13. Increasing Damages from Rising Global Temperatures



Source: R. Revesz, K. Arrow et al., 2014. http://www.nature.com/news/global-warming-improve-economic-models-of-climate-change-1.14991
Note: The three different models (ENVISAGE, DICE, and CRED) shown in this figure give damage estimates that are similar at low to moderate levels of temperature change, but diverge at higher levels, reflecting different assumptions used in modeling.

These monetized estimates of damage may be subject to controversy and may not cover all aspects of damage, but suppose that we decide to accept them—at least as a rough estimate. We must then weigh the estimated benefits of policies to prevent climate change against the costs of such policies. To estimate these costs, economists use models that show how inputs such as labor, capital, and resources produce economic output.

To lower carbon emissions, we must cut back the use of fossil fuels, substituting other energy sources that may be more expensive and investing in new infrastructure for renewables, energy efficiency, and other carbon abatement strategies. Economists calculate a measure of **marginal abatement costs –** the cost of reduction of one extra unit of carbon – for various measures such as energy efficiency, shifting to solar and wind power, or avoided deforestation.

Some of these measures are low-cost, or even negative cost (meaning that they bring a net economic benefit in addition to their carbon-reducing contribution). But especially for very substantial carbon reduction, most economic models predict some negative impact on GDP. One summary of a broad array of studies, known as a meta-analysis, found that estimates of the impact on GDP vary based on assumptions about the possibilities for substitution of new energy sources, technological learning, and economic flexibility.[34]

[34] Stern, 2007, Chapter 10, "Macroeconomic Models of Costs".

One estimate of the costs of meeting the Paris agreement target of no more than 2°C temperature increase is that it would require about 1.5% of world income (about the equivalent of one year's growth in real income). But this is under best-case assumptions of international cooperation. Under less favorable assumptions, costs are estimated to rise to above 4% of global GDP. [35] Similarly, the meta-analysis referred to above finds that costs could vary from 3.4% of global GDP under worst-case assumptions to an *increase* in global GDP of 3.9% using best-case assumptions.[36]

If costs and benefits of an aggressive carbon abatement policy are both in the range of several percent of GDP, how can we decide what to do? Much depends on our evaluation of **future costs and benefits**. The costs of taking action must be borne today or in the near future. The benefits of taking action (the avoided costs of damages) are further in the future. Our task, then, is to decide today how to balance these future costs and benefits.

Economists evaluate future costs and benefits by the use of a **discount rate**. The problems and implicit value judgments associated with discounting add to the uncertainties that we have already noted in valuing costs and benefits. This suggests that we should consider some alternative approaches—including techniques that can incorporate the ecological as well as the economic costs and benefits.

Economic studies dealing with cost-benefit analysis of climate change have come to very different conclusions about policy. According to early studies (2000 to 2008) by William Nordhaus and colleagues, the "optimal" economic policies to slow climate change involve modest rates of emissions reductions in the near term, followed by increasing reductions in the medium and long term, sometimes referred to as a gradual "ramping up" of climate policy.[37]

Most early economic studies of climate change reached conclusions similar to those of the Nordhaus studies, although a few recommended more drastic action. The debate on climate change economics changed significantly in 2007, when Nicholas Stern, a former chief economist for the World Bank, released a 700-page report, sponsored by the British government, titled "The Stern Review on the Economics of Climate Change."[38] While most previous economic analyses of climate change suggested relatively modest policy responses, the Stern Review strongly recommended immediate and substantial policy action:

[35] Nordhaus, 2013, Chapter 15, "The Costs of Slowing Global Climate Change".
[36] Stern, 2007, p.271.
[37] Nordhaus 2007, 2008; Nordhaus and Boyer, 2000.
[38] Stern, 2007.

> The scientific evidence is now overwhelming: climate change is a serious global threat, and it demands an urgent global response. This Review has assessed a wide range of evidence on the impacts of climate change and on the economic costs, and has used a number of different techniques to assess costs and risks. From all these perspectives, the evidence gathered by the Review leads to a simple conclusion: the benefits of strong and early action far outweigh the economic costs of not acting.

Using the results from formal economic models, the Review estimates that if we don't act, the overall costs and risks of climate change will be equivalent to losing at least 5 percent of global GDP each year, now and forever. If a wider range of risks and impacts is taken into account, the estimates of damage could rise to 20 percent of GDP or more. In contrast, the costs of action—reducing greenhouse gas emissions to avoid the worst impacts of climate change—can be limited to around 1 percent of global GDP each year.[39] This benefit/cost ratio of at least 5:1 implies a strong economic case for immediate and major policy action, as opposed to a slower "ramping up".

What explains the difference between these two approaches to economic analysis of climate change? One major issue is the choice of the discount rate to use in valuing future costs and benefits. The present value (PV) of a long-term stream of benefits or costs depends on the discount rate. A high discount rate will lead to a low present valuation for benefits that are mainly in the longer term, and a high present valuation for short-term costs. In contrast, a low discount rate will lead to a higher present valuation for longer-term benefits. The estimated net present value of an aggressive abatement policy will thus be much higher if we choose a low discount rate (Box 4).

While both the Stern and Nordhaus studies used standard economic methodology, Stern's approach gives much greater weight to long-term ecological and economic effects. The Stern Review uses a low discount rate of 1.4 percent to balance present and future costs. Thus, even though costs of aggressive action appear higher than benefits for several decades, the high potential long-term damages sway the balance in favor of aggressive action today. These are significant both for their monetary and nonmonetary impacts. In the long term, damage to the environment from global climate change will have significant negative effects on the economy, too. But the use of a standard discount rate has the effect of reducing the present value of significant long-term future damages to relative insignificance (see Box 4).

[39] Stern, 2007, Short Executive Summary, vi.

BOX 4. DISCOUNTING

Economists calculate the present value of a cost or benefit of $X that occurs in years in the future using the equation:

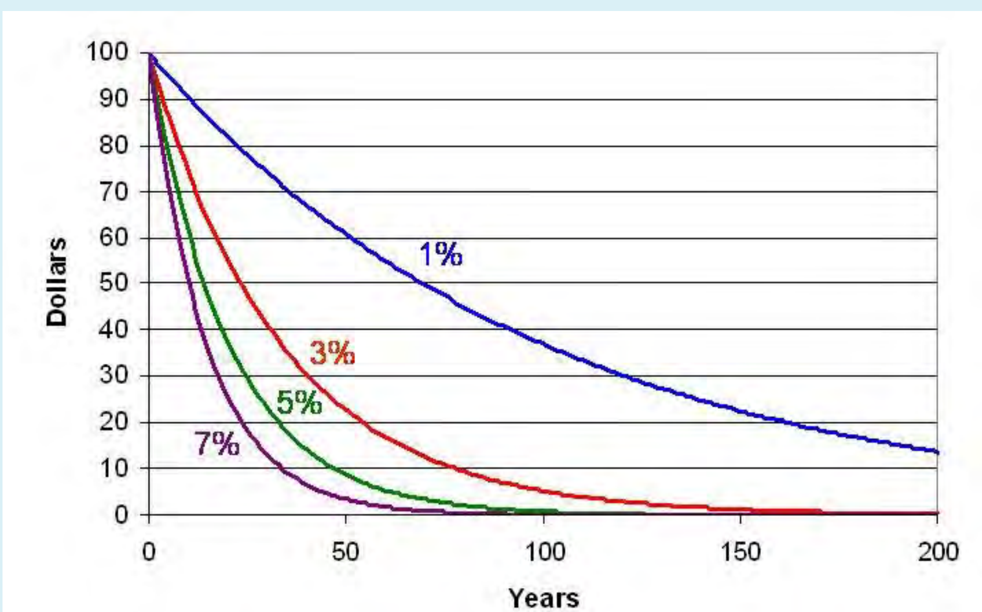
$$\textit{Present Value (\$X)} = \$X / (1 + r)^n$$

where *r* is the discount rate. So, for example, if we want to determine the present value of a benefit of $50,000 received 25 years from now with a discount rate of 5%, it would be:

$$\$50{,}000 / (1 + 0.05)^{25} = \$14{,}765$$

The choice of a discount rate becomes more important the further out in time one goes. Figure 14 shows the present value of $100 of costs or benefits experienced at different times in for different time periods into the future using several discount rates that have been used in climate change cost-benefit analyses. We see that when a discount rate of 5% or 7% is used, costs or benefits that occur 100 years into the future are negligible in terms of present value – worth only $0.76 and $0.12 respectively. Even with a discount rate of 3%, the value of $100 is only $5.20 after 100 years. But when the discount rate is 1%, impacts 100 years into the future are still significant – worth about $37 in present value; even when discounting over a period of 200 years, the present value is still nearly $20.

Figure 14: Present Value of a Future $100 Cost or Benefit: The Effects of Different Discount Rates



Another difference between the two studies concerns their treatment of uncertainty. Stern's approach gives a heavier weighting to uncertain but potentially catastrophic impacts. This reflects the application of a **precautionary principle**: If a particular outcome could be catastrophic, even though it seems unlikely, strong measures should be taken to avoid it. This principle, which has become more widely used in environmental risk management, is especially important for global climate change because of the many unknown but potentially disastrous outcomes possibly associated with continued greenhouse gas accumulation (see Box 5).

A study by Martin Weitzman argues that a serious consideration of the possibilities of catastrophic climate change can outweigh the impacts of discounting, suggesting substantial investment in mitigation today to avoid the possibility of future disaster – on the same principle as insuring against the uncertain possibility of a future house fire.[40]

A third area of difference concerns the assessment of the economic costs of action to mitigate climate change. Measures taken to prevent global climate change will have economic effects on GDP, consumption, and employment, which explains the reluctance of governments to take drastic measures to reduce significantly emissions of CO_2. But these effects will not all be negative.

The Stern Review conducted a comprehensive review of economic models of the costs of carbon reduction. These cost estimates depend on the modeling assumptions that are used. As noted above, the predicted costs of stabilizing atmospheric accumulations of CO_2 at 450 ppm could range from a 3.4 percent decrease to a 3.9 percent *increase* in global GDP. The outcomes depend on a range of assumptions including:

- The efficiency or inefficiency of economic responses to energy price signals
- The availability of noncarbon "**backstop**" **energy technologies**
- Whether countries can trade **least-cost options** for carbon reduction using a tradable permits scheme.
- Whether revenues from taxes on carbon-based fuels are used to lower other taxes
- Whether external benefits of carbon reduction, including reduction in ground-level air pollution, are taken into account.[41]

[40] Weitzman, 2009.
[41] Ibid.

BOX 5. CLIMATE TIPPING POINTS AND SURPRISES

Much of the uncertainty in projections of climate change relates to the issue of feedback loops. A feedback loop occurs when an initial change, such as warmer temperatures, produces changes in physical processes, which then amplify or lessen the initial effect (a response that increases the original effect is called a positive feedback loop; a response that reduces it is a negative feedback loop). An example of a positive feedback loop is when warming leads to increased melting of arctic tundra, releasing carbon dioxide and methane, which add to atmospheric greenhouse gas accumulations and speed up the warming process.

As a result of various feedback loops associated with climate change, recent evidence suggests that warming is occurring faster than most scientists predicted just five or ten years ago. This is leading to increasing concern over the potential for "runaway" feedback loops, which could result in dramatic changes in a short period. Some scientists suggest that we may be near certain climate tipping points, which, once exceeded, pose the potential for catastrophic effects.

Perhaps the most disturbing possibility is the rapid collapse of the Greenland and West Antarctic Ice Sheets. A 2016 study argued that large chunks of the polar ice could melt over the next 50 years, causing a sea rise of 20 to 30 feet. The paper suggests that fresh water pouring into the oceans from melting land ice will set off a feedback loop that will cause rapid disintegration of ice sheets in Greenland and Antarctica. "That would mean loss of all coastal cities, most of the world's large cities and all their history," according to lead author Dr. James Hansen.

While rapid melting scenarios remain controversial, other dangerous feedback loops have been identified. In recent studies, scientists found that methane emissions from the Arctic have risen by almost one-third in just five years. The discovery follows a string of reports from the region in recent years that previously frozen boggy soils are melting and releasing methane in greater quantities. Such arctic soils currently lock away billions of tons of methane, a far more potent greenhouse gas than carbon dioxide, leading some scientists to describe melting permafrost as a ticking time bomb that could overwhelm efforts to tackle climate change. They fear the warming caused by increased methane emissions will itself release yet more methane and lock the region into a destructive cycle that forces temperatures to rise more rapidly than predicted.

Sources: David Adam, "Arctic Permafrost Leaking Methane at Record Levels, Figures Show," *The Guardian*, 2010, www.guardian.co.uk/environment/2010/jan/14/arctic-permafrost-methane/; Justin Gillis, "Scientists warn of perilous climate shift within decades, not centuries", New York Times March 22, 2016; DeConto and Pollard, 2016.

Depending on which assumptions are made, policies for emissions reduction could range from a minimalist approach of slightly reducing emissions to drastic CO_2 emissions reduction of 80 percent or more. In recent years, however, the positions of Nordhaus and Stern have converged. Nordhaus, in his latest publications, uses an updated version of his model (DICE-2013) projecting a temperature increase of 3°C or more by 2100. He advocates a carbon tax of $21 per ton of CO_2 emitted, rising rapidly over time.[42] A modification of his model by Simon Dietz and Nicholas Stern, taking into account increased damages and the possibility of climate "tipping points" (see Box 5), suggests carbon taxes that are two to seven times higher, to limit atmospheric CO_2 accumulations to 425-500 ppm and global temperature change to 1.5 to 2.0°C.[43] Thus while differences remain, the trend is generally towards recommendations for more drastic policy measures:

> While Nordhaus and Stern may differ on whether a carbon tax should be imposed either as a ramp or a steep hill, and on the appropriate discount rate for converting anticipated future damages to present terms, this debate is progressively less relevant as they both agree that the steepness of this ramp would increase, with model sophistication and with the further delay of a carbon tax.[44]

Climate Change and Inequality

The effects of climate change will fall most heavily upon the poor of the world. Regions such as Africa could face severely compromised food production and water shortages, while coastal areas in South, East, and Southeast Asia will be at great risk of flooding. Tropical Latin America will see damage to forests and agricultural areas due to drier climate, while in South America changes in precipitation patterns and the disappearance of glaciers will significantly affect water availability.[45] While the richer countries may have the economic resources to adapt to many of the effects of climate change, poorer countries will be unable to implement preventive measures, especially those that rely on the newest technologies.

Recent studies have used geographically distributed impacts models to estimate the impacts of climate change across the global domain. As Table 2 indicates, the number of coastal flood victims and population at risk of hunger by 2080 will be relatively larger in Africa, South America, and Asia, where most developing countries are located. A study published in Nature predicted that:

> If societies continue to function as they have in the recent past, climate change is expected to reshape the global economy by substantially reducing global economic output and possibly amplifying existing global economic inequalities,

[42] Nordhaus, 2013.
[43] Dietz and Stern, 2014.
[44] Komanoff, 2014.
[45] IPCC, 2007b; Stern, 2007, Ch. 4.

relative to a world without climate change. Adaptations such as unprecedented innovation or defensive investments might reduce these effects, but social conflict or disrupted trade could exacerbate them.[46]

Overall, the study projects that "the likelihood of large global losses is substantial", with the heaviest proportional losses being borne by the poorest countries.

Table 2. Regional-Scale Impacts of Climate Change by 2080 (millions of people)

Region	Population living in watersheds with an increase in water-resources stress	Increase in average annual number of coastal flood victims	Additional population at risk of hunger*
Europe	382–493	0.3	0
Asia	892–1197	14.7	266 (–21)
North America	110–145	0.1	0
South America	430–469	0.4	85 (–4)
Africa	691–909	12.8	200 (–2)

*Figures in parentheses assume maximum CO_2 enrichment effect
Source: Adapted from IPCC, 2007b.
Note: These estimates are based on a business-as-usual scenario (IPCC A2 scenario). The CO_2 enrichment effect is increased plant productivity, which at maximum estimates could actually decrease the number at risk of hunger.

The way in which economists incorporate inequality into their analyses can have a significant impact on their policy recommendations. If all costs are evaluated in money terms, a loss of, for example, 10 percent of GDP in a poor country is likely to be much less, measured in dollars, than a loss of 3 percent of GDP in a rich country. Thus, the damages from climate change in poor countries, which may be large as a percentage of GDP, would receive relatively little weight because the losses are relatively small in dollar terms. The Stern Review asserts that the disproportionate effects of climate change on the world's poorest people should increase the estimated costs of climate change. Stern estimates that, without the effects of inequity, the costs of a business-as-usual scenario could be as much as 11–14 percent of global GDP annually. Weighing the impacts on the world's poor more heavily gives a cost estimate of 20 percent of global GDP.[47]

Assumptions about the proper way to evaluate social and environmental costs and benefits can make a big difference to policy recommendations. As we have seen, cost-benefit analyses mostly recommend action to mitigate climate change, but differ in the strength of their recommendations based on assumptions about risk

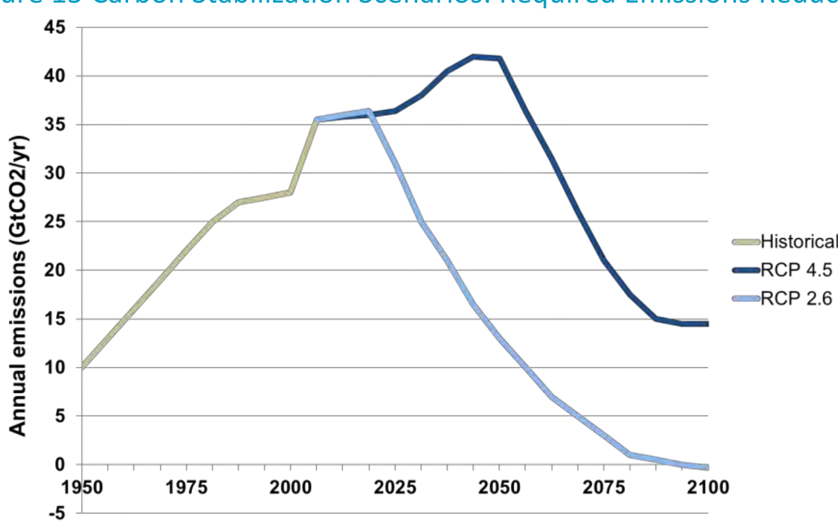
[46] Burke, Hsiang and Miguel, 2015.
[47] Stern, 2007, Ch. 6.

and discounting. An ecologically oriented economist would argue that the fundamental issue is the stability of the physical and ecological systems that serve as a planetary climate-control mechanism. This means that **climate stabilization**, rather than economic optimization of costs and benefits, should be the goal.

Stabilizing greenhouse gas *emissions* is insufficient; at the current rate of emissions carbon dioxide and other greenhouse gases will continue to accumulate in the atmosphere. Stabilizing *accumulations* of greenhouse gases will require a significant cut below present emission levels. Figure 15 shows the IPCC estimates of required reductions in CO_2 emissions to achieve stabilization at levels of 430 – 480 pm and 530 – 580 ppm of CO_2 in the atmosphere. Note that for the lower stabilization level, total emissions need to fall essentially to zero in the second part of the twenty-first century. This could likely only be achieved with substantially increased global absorption of CO_2, possibly through expanding forests and modifying agricultural techniques in addition to drastic emissions reductions.

Clearly, reductions of this magnitude would imply major changes in the way that the global economy uses energy. Energy efficiency and the use of renewable energy could have a significant effect in reducing emissions. Other policies could reduce emissions of other greenhouse gases and promote CO_2 absorption in forests and soils. What combination of policies can provide a sufficient response, and how have the countries of the world reacted to the issue thus far? We will now turn to these issues in more detail.

Figure 15 Carbon Stabilization Scenarios: Required Emissions Reductions



Source: IPCC, 2014d, p. 11.
Note: Upper line represents IPCC RCP 4.5 scenario (moderate stabilization in the range of 530 – 580 ppm CO_2 accumulation) and lower line represent IPCC RCP 2.6 scenario (stronger stabilization at 430 – 480 ppm CO_2 accumulation).

3. POLICY RESPONSES TO CLIMATE CHANGE

Adaptation and Mitigation

Policy responses to climate change can be broadly classified into two categories: **adaptive measures** to deal with the consequences of climate change and **mitigation**, or **preventive measures**, intended to lower the magnitude or timing of climate change.

Adaptive measures include:

- Construction of dikes and seawalls to protect against rising seas and extreme weather events such as floods and hurricanes.
- Shifting cultivation patterns in agriculture to adapt to changing weather conditions.
- Creating institutions that can mobilize the needed human, material, and financial resources to respond to climate-related disasters.

Mitigation measures include:

- Reducing emissions of greenhouse gases by meeting energy demands from sources with lower greenhouse gas emissions (e.g., switching from coal to wind energy for electricity).
- Reducing greenhouse gas emissions by increasing energy efficiency.
- Enhancing natural **carbon sinks**. Carbon sinks are areas where carbon may be stored; natural sinks include soils and forests. Human intervention can either reduce or expand these sinks through forest management and agricultural practices. Forests recycle carbon dioxide (CO_2) into oxygen; preserving forested areas and expanding reforestation can have a significant effect on net CO_2 emissions. Soils are also vast carbon repositories, with three times more carbon stored in soils than in the atmosphere. Restoring degraded soils could capture large quantities of CO_2.

Economic analysis can provide policy guidance for nearly any particular preventive or adaptive measure. **Cost-benefit analysis**, as seen above, can present a basis for evaluating whether a policy should be implemented. However, as discussed previously, economists disagree about the appropriate assumptions and methodologies for cost-benefit analyses of climate change. A less controversial conclusion from economic theory is that we should apply **cost-effectiveness analysis** in considering which policies to adopt. The use of cost-effectiveness analysis avoids many of the complications associated with cost-benefit analysis. While cost-benefit analysis attempts to offer a basis for deciding upon policy goals, cost-effectiveness analysis accepts a goal as given by society and uses economic techniques to determine the most efficient way to reach that goal.

In general, economists usually favor approaches that work through market mechanisms to achieve their goals. Market-oriented approaches are considered cost effective; rather than attempting to control market actors directly, they shift incentives so that individuals and firms will change their behavior to take external costs and benefits into account. Examples of market-based policy tools include **pollution taxes** and **transferable, or tradable, permits**. Both of these are potentially useful tools for greenhouse gas reduction. Other relevant economic policies include measures to create incentives for the adoption of renewable energy sources and energy-efficient technology.

Most of this section focuses on mitigation policies, but it is becoming increasingly evident that mitigation policies need to be supplemented with adaptation policies. Climate change is already occurring, and even if significant mitigation policies are implemented in the immediate future, warming and sea-level rise will continue well into the future, even for centuries.[48] The urgency and ability to institute adaptive measures varies across the world. It is the world's poor who face the greatest need to adapt but also most lack the necessary resources.

> [Climate change's] adverse impacts will be most striking in the developing nations because of their geographical and climatic conditions, their high dependence on natural resources, and their limited capacity to adapt to a changing climate. Within these countries, the poorest, who have the least resources and the least capacity to adapt, are the most vulnerable.[49]

The Intergovernmental Panel on Climate Change (IPCC) has identified adaptation needs by major sectors, as shown in Table 3. Some of the most critical areas for adaptation include water, agriculture, and human health.

Climate change is expected to increase precipitation in some areas, mainly the higher latitudes including Alaska, Canada, and Russia, but decrease it in other areas, including Central America, North Africa, and southern Europe. A reduction in water runoff from snowmelt and glaciers could threaten the water supplies of more than a billion people in areas such as India and parts of South America. Providing safe drinking water in these regions may require building new dams for water storage, increasing the efficiency of water use, and other adaptation strategies.

Changing precipitation and temperature patterns have significant implications for agriculture. With moderate warming, crop yields are expected to increase in some colder regions, including parts of North America, but overall the impacts on agriculture are expected to be negative, and increasingly so with greater warming. In the

[48] IPCC, 2007, p. 46; IPCC, 2014b *Summary for Policymakers,* p. 16; Kahn, 2016.
[49] African Development Bank et al., 2003, p. 1.

US, climate change has lengthened and worsened the episodes of drought in the Western States, notably California, which, as a result, has already forced farmers to adapt to less water-intensive crops, replacing orange groves and avocado trees with other tree crops such as pomegranates or cactus-like dragonfruit.[50] Agricultural impacts are expected to be most severe in Africa and Asia. More research is necessary to develop crops that can grow under anticipated drier weather conditions. Agriculture may need to be abandoned in some areas but expanded in others.[51]

The impacts of climate change on human health are already occurring. The World Health Organization (WHO) estimates that more than 140,000 people per year are already dying as a direct result of climate change, primarily in Africa and Southeast Asia. It also estimates that after 2030, climate change will result in 250,000 additional deaths per year, caused by malnutrition, malaria, diarrhea, and heat stress. The WHO estimates direct damage costs to health at US$2–4 billion per year by 2030. WHO policy recommendations include strengthening public health systems, with increased education, disease surveillance, vaccination, and preparedness.[52]

Table 3. Climate Change Adaptation Needs, by Sector

Sector	Adaptation strategies
Water	Expand water storage and desalination Improve watershed and reservoir management. Increase water use and irrigation efficiency and water re-use Urban and rural flood management
Agriculture	Adjust planting dates and crop locations Develop crop varieties adapted to drought, higher temperatures Improved land management to deal with floods/droughts Strengthen indigenous/traditional knowledge and practice
Infrastructure	Relocate vulnerable communities Build and strengthen seawalls and other barriers Create and restore wetlands for flood control Dune reinforcement
Human health	Health plans for extreme heat Increase tracking, early-warning systems for heat-related diseases Address threats to safe drinking water supplies Extend basic public health services

[50] http://www.npr.org/sections/thesalt/2015/07/28/426886645/squeezed-by-drought-california-farmers-switch-to-less-thirsty-crops.
[51] Cline, 2007; U. S. Global Change Research Program, 2009, Agriculture Chapter; Kahsay and Hansen, 2016..
[52] World Health Organization, 2009; WHO, *Climate Change and Health*, June 2016, http://www.who.int/mediacentre/factsheets/fs266/en/

Transport	Relocation or adapt transport infrastructure New design standards to cope with climate change
Energy	Strengthen distribution infrastructure Address increased demand for cooling Increase efficiency, increase use of renewables
Ecosystems	Reduce other ecosystem stresses and human use pressures Improve scientific understanding, enhanced monitoring Reduce deforestation, increase reforestation Increase mangrove, coral reef, and seagrass protection

Source: IPCC, 2007; IPCC, 2014c.

Various estimates exist for the cost of appropriate adaptation measures. The United Nations Environment Program (UNEP) estimates that the cost of adaptation for developing nations could rise to between $140 and $300 billion per year by 2030, and between $280 and $500 billion per year by 2050. These sums significantly exceed the $100 billion per year pledged by developed nations in the 2015 Paris Agreement. UNEP warns that there will be a significant finance gap, "likely to grow substantially over the coming decades, unless significant progress is made to secure new, additional and innovative financing for adaptation". Adaptation costs are already two to three times higher than current international public funding for adaptation. [53]

Climate Change Mitigation: Economic Policy Options

The release of greenhouse gases in the atmosphere is a clear example of a negative externality that imposes significant costs on a global scale. In the language of economic theory, the current market for carbon-based fuels such as coal, oil, and natural gas takes into account only private costs and benefits, which leads to a market equilibrium that does not correspond to the social optimum. From a social perspective, the market price for fossil fuels is too low and the quantity consumed too high.

Carbon Taxes

A standard economic remedy for internalizing external costs is a per-unit tax on the pollutant. In this case, what is called for is a **carbon tax**, levied on carbon-based fossil fuels in proportion to the amount of carbon associated with their production and use. Such a tax will raise the price of carbon-based energy sources and so give consumers incentives to conserve energy overall (which would reduce their tax burden), as well as shifting their demand to alternative sources of energy that produce lower carbon emissions (and are thus taxed at lower rates).

[53] UNEP, 2016.

In economic terms, the level of such a tax should be based on the social cost of carbon – an estimate of the financial impact on society of carbon emissions. The U.S. Environmental Protection Agency estimates the social cost of carbon, based on varying assumptions, as being between $11 and $212, with a median range around $50.[54] As noted earlier, a major reason for differing estimates is assumptions regarding discount rates and risk/uncertainty.

Table 4 shows the impact that different levels of a carbon tax would have on the prices of coal, oil, and natural gas. The tax here is given in dollars per ton of CO_2. A common point of confusion is that a carbon tax can be expressed as either a tax per unit of carbon or a tax per unit of carbon dioxide. To compare the two, one needs to take into account the ratio between CO_2's molecular weight (44), and Carbon's molecular weight (12) - one ton of Carbon is equivalent to 44/12 tons of CO_2. If we want to convert a tax of $100 per ton of carbon into a tax per ton of CO_2, we would need to multiply that $100 tax by 12/44 = 0.2727: this means a tax of $100 per ton of Carbon is equivalent to a tax of $27.27 per ton of CO_2.

Table 4. Alternative Carbon Taxes on Fossil Fuels

Impact of Carbon Price on Retail Price of Gasoline	
kg CO_2 per gallon	8.89
tonnes CO_2 per gallon	0.00889
$/gal., $50/tonne tax	$0.44
$/gal., $100/tonne tax	$0.88
Retail price (2016) per gallon	$2.20
% increase, $50/tonne tax	20.2%
% increase, $100/tonne tax	40.4%
Impact of Carbon Price on Retail Price of Coal	
kg CO_2 per short ton	2100
tonnes CO_2 per short ton	2.1
$/short ton, $50/tonne tax	$105
$/short ton, $100/tonne tax	$210
Retail price (2016) per short ton	$40
% increase, $50/tonne tax	262.5%
% increase, $100/tonne tax	525.0%

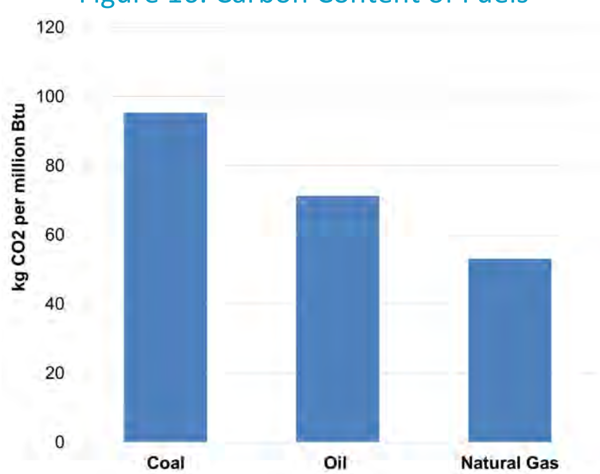
[54] U.S. EPA, *The Social Cost of Carbon,* https://www3.epa.gov/climatechange/EPAactivities/economics/scc.html

Impact of Carbon Price on Retail Price of Natural Gas	
kg CO_2 per 1000 cu. ft.	53.12
tonnes CO_2 per 1000 cu. ft.	0.05312
$/1000 cu. ft., $50/tonne tax	$2.66
$/1000 cu. ft., $100/tonne tax	$5.31
Retail price (2016) per 1000 cu. ft.	$12
% increase, $50/tonne tax	22.1%
% increase, $100/tonne tax	44.2%

Source: Carbon emissions calculated from carbon coefficients and thermal conversion factors available from the U.S. Department of Energy. All price data from the U.S. Energy Information Administration.

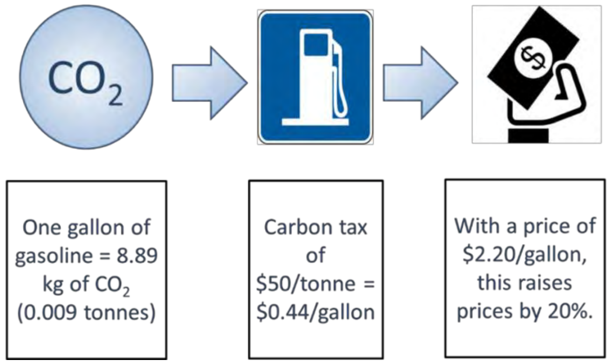
Based on energy content, measured in British Thermal Units (Btus), coal is the most carbon-intensive fossil fuel, while natural gas produces the lowest carbon emissions per Btu (Figure 16). Calculating the impact of a carbon tax relative to the standard commercial units for each fuel source, we see that a carbon tax of $50/ton of CO_2, for example, raises the price of a gallon of gasoline by about 44 cents, or 20%, based on 2016 prices (Figure 17). A tax of $100/ton of CO_2 equates to an increase in gasoline prices of about 88 cents per gallon. The impact of a carbon tax would be even greater for coal prices—a tax of $50/ton of CO_2 would increase coal prices by 262%. And a $100/ton tax would raise coal prices by a factor of five. For natural gas, the percent impact is about the same as for gasoline. For natural gas, although its carbon content is lower than that of gasoline, its low price (as of 2016) means that the percentage impact on price is about the same as for gasoline.

Figure 16. Carbon Content of Fuels



Source: Calculated from U.S. Department of Energy data.

Figure 17. Impact of a carbon tax on gasoline price



Source: Calculated from U.S. Department of Energy data.

Will these tax amounts affect people's driving or home heating habits very much, or impact industry's use of fuels? This depends on the **elasticity of demand** for these fuels. Elasticity of demand is defined as:

$$Elasticity\ of\ \ demand = \frac{Percent\ change\ in\ quantity\ demanded}{percent\ change\ in\ price}$$

Economists have measured the elasticity of demand for different fossil fuels, particularly gasoline. (Elasticity of demand is generally negative, since a positive percent change in price causes a negative percent change in quantity demanded.) Studies indicate that in the short term (about one year or less) elasticity estimates ranged from −0.03 to −0.25. This means that a 10 percent increase in the price of gasoline would be expected to decrease gasoline demand in the short term by about −0.3 to −2.5 percent.[55]

In the long term (about five years or so) people are more responsive to gasoline price increases, as they have time to purchase different vehicles and adjust their driving habits. The average long-term elasticity of demand for motor fuels, based on fifty-one estimates, is −0.64.[56] According to Table 4, a tax of \$50 per ton of CO_2 would increase the price of gasoline by about 20 percent, adding 44 cents per gallon to the price of gasoline based on 2016 prices. A long-term elasticity of –0.64 suggests that after people have time to fully adjust to this price change, the demand for gasoline should decline by about 13 percent.

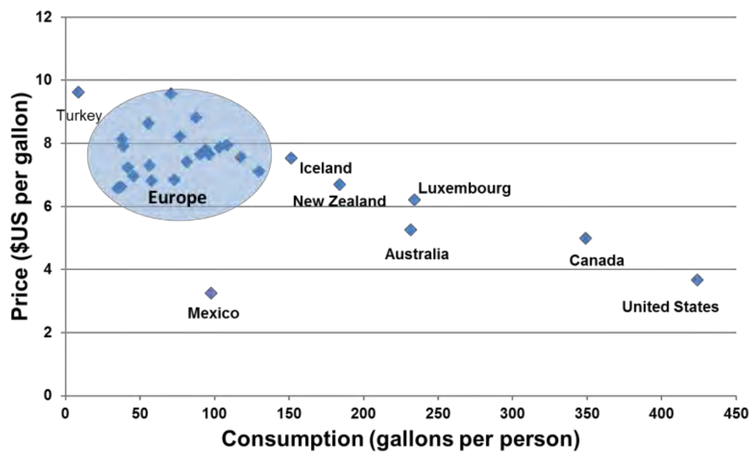
Figure 18 shows a cross-country relationship between gasoline prices and per capita consumption. (Since the cost of producing a gallon of gasoline varies little across countries, variations in the price of a gallon in different countries is almost solely a function of differences in taxes.) Note that this relationship is similar to that of a

[55] Goodwin et al., 2004; Hughes et al., 2008.
[56] Goodwin et al., 2004.

demand curve: Higher prices are associated with lower consumption, and lower prices with higher consumption. The relationship shown here, however, is not exactly the same as a demand curve; since we are looking at data from different countries, the assumption of "other things equal," which is needed to construct a demand curve, does not hold.

Differences in demand may, for example, be in part a function of differences in income levels rather than prices. Also, people in the United States may drive more partly because travel distances (especially in the western United States) are greater than in many European countries, and public transportation options fewer. But there does seem to be a clear price/consumption relationship. The data shown here suggest that it would take a fairly big price hike—in the range of \$0.50–\$1.00 per gallon or more—to affect fuel use substantially.

Figure 18. Gasoline Price Versus Consumption in Industrial Countries, 2012



Sources: U.S. Energy Information Administration database, *International Energy Statistics; GIZ,* International Fuel Prices 2012/2013; World Bank, *World Development Indicators* (Population).
Note: Shaded area represents price/consumption range typical of West European countries.

Would a large gasoline tax increase, or a broad-based carbon tax, ever be politically feasible? Especially in the United States, high taxes on gasoline and other fuels would face much opposition. As Figure 18 shows, the United States has by far the highest gasoline consumption per person and the lowest prices outside the Middle East. But let us note two things about the proposal for substantial carbon taxes:

- First, revenue recycling could redirect the revenue from carbon and other environmental taxes to lower other taxes. Much of the political opposition to high energy taxes comes from the perception that they would be an *extra* tax—on top of the income, property, and social security taxes that people already pay. If a carbon tax were matched, for example, with a substantial cut in income or social security taxes, it might be more politically acceptable.

- The idea of increasing taxes on economic "bads," such as pollution, while reducing taxes on things we want to encourage, such as labor and capital investment, is fully consistent with principles of economic efficiency. Rather than a net tax increase, this would be **revenue-neutral tax shift**—the total amount that citizens pay to the government in taxes is essentially unchanged. Some of the tax revenues could also be used to provide relief for low-income people to offset the burden of higher energy costs.
- Second, if such a revenue-neutral tax shift did take place, individuals or businesses whose operations were more energy efficient would actually save money overall. The higher cost of energy would also create a powerful incentive for energy-saving technological innovations and stimulate new markets. Economic adaptation would be easier if the higher carbon taxes (and lower income and capital taxes) were phased in over time.

Tradable Permits

An alternative to a carbon tax is a system of tradable carbon permits, also called **cap-and- trade**. A carbon trading scheme can be implemented at the state or national level, or could include multiple countries. A national permit system could work as follows:

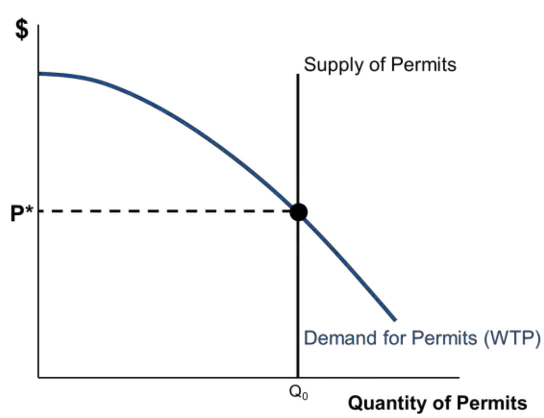
- Each emitting firm would be allocated a specific permissible level of carbon emissions. The total number of carbon permits issued would equal the desired national goal. For example, if carbon emissions for a particular country are currently 40 million tons and the policy goal is to reduce this by 10 percent (4 million tons), then permits would be issued to emit only 36 million tons. Over time, the goal could be increased, with the result that fewer permits would be issued in future periods.
- Permits are allocated to individual carbon-emitting sources. Including all carbon sources (e.g., all motor vehicles) in a trading scheme is generally not practical. It is most effective to implement permits as far upstream in the production process as possible to simplify program administration and cover the most emissions. ("upstream" here denotes an early stage in the production process). Permits could be allocated to the largest carbon emitters, such as power companies and manufacturing plants, or even further upstream to the suppliers through which carbon fuels enter the production process—oil producers and importers, coal mines, and natural gas drillers.
- These permits could initially be allocated for free on the basis of past emissions or auctioned to the highest bidders. The effectiveness of the trading system should be the same regardless of how the permits are allocated. However, there is a significant difference in the distribution of costs and benefits: Giving permits out for free essentially amounts to a windfall gain for polluters, while auctioning permits imposes real costs upon firms and generates public revenues.

- Firms are able to trade permits freely among themselves. Firms whose emissions exceed the number of permits they hold must purchase additional permits or else face penalties. Meanwhile firms that are able to reduce their emissions below their allowance at low cost will seek to sell their permits for a profit. A permit price will be determined through market supply and demand. It may also be possible for environmental groups or other organizations to purchase permits and retire them—thus reducing overall emissions.
- In an international system, countries and firms could also receive credit for financing carbon reduction efforts in other countries. For example, a German firm could get credit for installing efficient renewable electric generating equipment in China, replacing highly polluting coal plants.

A tradable permit system encourages the least-cost carbon reduction options to be implemented, as rational firms will implement those emission-reduction actions that are cheaper than the market permit price. Tradable permit systems have been successful in reducing sulfur and nitrogen oxide emissions at low cost. Depending on the allocation of permits in an international scheme, it might also mean that developing countries could transform permits into a new export commodity by choosing a non-carbon path for their energy development. They would then be able to sell permits to industrialized countries that were having trouble meeting their reduction requirements. Farmers and foresters could also get carbon credits for using methods that store carbon in soils or preserve forests.

While the government sets the number of permits available, the permit price is determined by market forces. In this case, the supply curve is fixed, or vertical, at the number of permits allocated, as shown in Figure 19. The supply of permits is set at Q_0. The demand curve for permits represents firms' willingness to pay for them. Their maximum willingness to pay for permits is equal to the potential profits they can earn by emitting carbon.

Figure 19. Determination of Carbon Permit Price



Note: WTP = Willingness to pay.

Assume that the permits will be auctioned off one by one to the highest bidders (a process known as a sequential auction). Figure 19 shows that the willingness to pay for the first permit would be quite high, as a particular firm stands to make a relatively large profit by being allowed to emit one unit of carbon. For the second permit, firms that failed to obtain the first permit would be expected to simply repeat their bids. The firm that successfully bid for the first permit could also bid for the second permit, but would be expected to bid a lower amount assuming their marginal profits are declining (i.e., their supply curve slopes upward, as is normal).

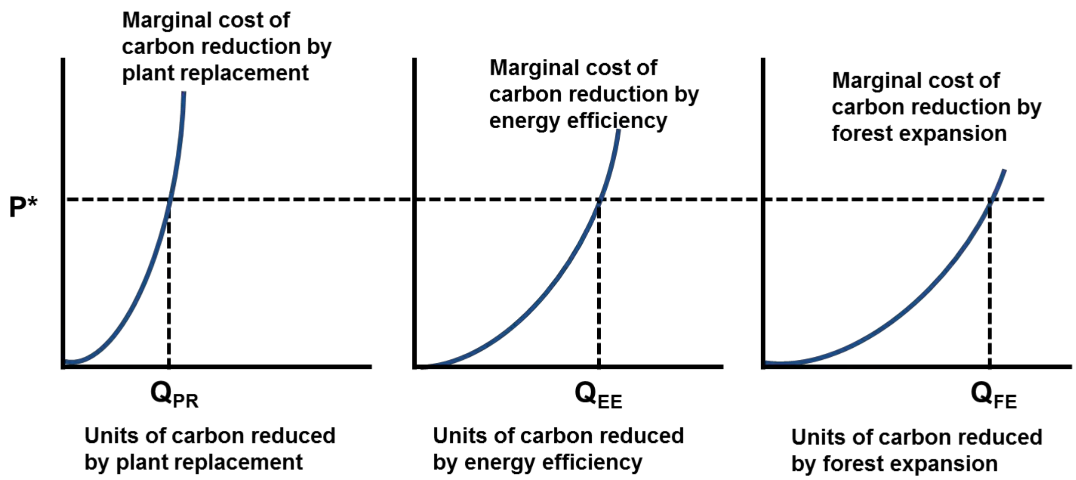
Regardless of whether the same firm wins the bid for the second permit, or a new firm, the selling price for the second permit would be lower. This process would continue, with all successive permits selling for lower prices, until the last permit is auctioned off. The selling price of this permit, represented by P^* in the graph, is the market-clearing permit price. We can also interpret P^* as the marginal benefit, or profit, associated with the right to emit the Q_0^{th} unit of carbon.

While permits could theoretically sell for different prices in a sequential auction, tradable permit markets are normally set up so that all permits sell for the market-clearing price. All parties interested in purchasing permits make their bids, indicating how many permits they are willing to purchase at what price. Whoever bids the highest gets the number of permits that were requested. Then the second-highest bidders get the number of permits they applied for, and so on until all permits are allocated. The selling price of all permits is the winning bid for the very last permit available. This would be P^* in Figure 19. All bidders who bid below this price do not receive any permits.

Another important point is that each firm can choose to reduce its carbon emissions in a cost-effective manner. Firms have various options for reducing their carbon emissions. Figure 20 shows an example in which a firm has three carbon reduction strategies: replacing older manufacturing plants, investing in energy efficiency, and funding forest expansion to increase carbon storage in biomass. In each case, the graph shows the marginal costs of reducing carbon emissions through that strategy. These marginal costs generally rise as more units of carbon are reduced, but they may be higher and increase more rapidly for some options than others.

In this example, replacement of manufacturing plants using existing carbon-emitting technologies is possible but will tend to have high marginal costs—as shown in the first graph in Figure 20. Reducing emissions through greater energy efficiency has lower marginal costs, as seen in the middle graph. Finally, carbon storage through forest area expansion has the lowest marginal costs. The permit price P^* (as determined in Figure 19) will govern the relative levels of implementation of each of these strategies. Firms will find it profitable to reduce emissions using a particular strategy so long as the costs of that option are lower than the cost of purchasing a permit.

Figure 20. Carbon Reduction Options with a Permit System



Note: Marginal costs shown here are hypothetical.

The analysis indicates that forest expansion would be used for the largest share of the reduction (Q_{FE}), but plant replacement and energy efficiency would also contribute shares (Q_{PR} and Q_{EE}) at the market equilibrium. Firms (and countries if the program is international) that participate in such a trading scheme can thus decide for themselves how much of each control strategy to implement and will naturally favor the least-cost methods. This will probably involve a combination of different approaches. In an international program, suppose that one country undertakes extensive reforestation. It is then likely to have excess permits, which it can sell to a country with few low-cost reduction options. The net effect will be the worldwide implementation of the least-cost reduction techniques.

This system combines the advantages of economic efficiency with a guaranteed result: reduction in overall emissions to the desired level. The major problem, of course, is achieving agreement on the initial number of permits, and deciding whether the permits will be allocated freely or auctioned off.

There may also be measurement problems and issues such as whether to count only commercial carbon emissions or to include emissions changes that result from land use changes such as those associated with agriculture and forestry. Including agriculture and forestry has the advantage of broadening the scheme to include many more, reduction strategies, possibly at significantly lower cost, but it may be more difficult to get an accurate measure of carbon storage and release from land use change.

Carbon Taxes or Cap and Trade?

There is a lively debate regarding which economic approach should be used to reduce carbon emissions. Carbon taxes and a cap-and-trade approach have important similarities but also important differences.

Both pollution taxes and cap-and-trade can, in theory, achieve a given level of pollution reduction at the least overall cost. Both approaches will also result in the same level of price increases to final consumers, and both create a strong incentive for technological innovation. Both approaches can raise the same amount of government revenue, assuming all permits are auctioned off, and can be implemented upstream in production processes to cover the same proportion of total emissions.

Yet the two policies have several important differences. Some of the advantages of a carbon tax include:

- In general, a carbon tax is considered simpler to understand and more transparent than a cap-and-trade approach. Cap-and-trade systems can be complex and require new bureaucratic institutions to operate.
- With technological change that lowers the cost of carbon reduction, a carbon tax will automatically further reduce carbon emissions. In a cap-and-trade program, technological change will instead reduce the price of permits, probably resulting in some firms actually emitting more carbon.
- A carbon tax could probably be implemented more quickly. Given the need to address climate change as soon as possible, it may be inadvisable to spend years working out the details and implementation of a cap-and-trade program.
- Perhaps the most important advantage of a carbon tax is that it provides greater price predictability. If businesses and households know what future taxes will be on fossil fuels and other greenhouse gas–emitting products, they can invest accordingly. For example, whether a business invests in an energy efficient heating and cooling system depends on its expectations of future fuel prices. In a cap-and-trade system, permit prices could vary considerably, leading to **price volatility** that makes planning difficult. A carbon tax, by contrast, provides a degree of price stability, especially if carbon tax levels are published years into the future.

The advantages of a cap-and-trade system include:

- Even though a cap-and-trade system ultimately results in the same level of price increases to consumers and businesses, it avoids the negative connotations of a "tax." So a cap-and-trade system often generates less political opposition than a carbon tax.
- Some businesses favor cap-and-trade because they believe that they can

successfully lobby governments for free permits, rather than having to purchase them at auction. Distributing permits for free in the early stages of a cap-and-trade program can make it more politically acceptable to businesses.

- The greatest advantage of a cap-and-trade approach is that emissions are known with certainty because the government sets the number of available permits. Since the policy goal is ultimately to reduce carbon emissions, a cap-and-trade approach does this directly while a carbon tax does it indirectly through price increases. Using a cap-and-trade approach, we can achieve a specific emissions path simply by setting the number of permits. In a carbon tax system, achieving a specific emissions target may require numerous adjustments to the tax rates, which may be politically very difficult.

The choice of instrument—carbon tax or cap-and-trade—mainly depends on whether policy makers are more concerned with price uncertainty or emissions uncertainty. If you take the perspective that price certainty is important because it allows for better long-term planning, then a carbon tax is preferable. If you believe that the relevant policy goal is to reduce carbon emissions by a specified amount with certainty, then a cap-and-trade approach is preferable, although it may lead to some price volatility.

Another practical difference appears to be that carbon tax revenues are more often refunded to taxpayers or used in general government spending, while cap-and-trade auction revenues are more often used to support such "green" investments as renewable energy, energy efficiency, and forest conservation.[57]

Other Policy Tools: Subsidies, Standards, R&D, and Technology Transfer

Political hurdles may prevent the adoption of sweeping carbon taxes or transferable permit systems. Fortunately, a variety of other policy measures have the potential to lower carbon emissions. Even with implementation of a widespread carbon tax or cap-and-trade system, supplemental policies may still be necessary to reduce carbon emissions sufficiently to keep warming within acceptable levels. These policies are generally not considered to be sufficient by themselves, but they may be important components of a comprehensive approach. To some extent these policies are already being implemented in various countries. These policies include:

- Shifting subsidies from carbon-based to non–carbon-based fuels. Many countries currently provide direct or indirect subsidies to fossil fuels. The elimination of these subsidies would alter the competitive balance in favor of alternative fuel sources. If these subsidy expenditures were redirected to

[57] Carl and Fedor, 2016.

renewable sources, it could promote a boom in investment in renewables.

- The use of efficiency standards for machinery and appliances, and fuel-economy standards or requirements for low-carbon fuels. By imposing standards that require greater energy efficiency or lower carbon use, technologies and practices can be altered in favor of a low-carbon path.
- Research and development (R&D) expenditures promoting the commercialization of alternative technologies. Both government R&D programs and favorable tax treatment of corporate R&D for alternative energy can speed commercialization. The existence of non-carbon "backstop" technologies significantly reduces the economic cost of measures such as carbon taxes, and if the backstop were to become fully competitive with fossil fuels, carbon taxes would be unnecessary.
- Technology transfer to developing countries. The bulk of projected growth in carbon emissions will come in the developing world. Many energy development projects are now funded by agencies such as the World Bank and regional development banks. To the extent that these funds can be directed toward non-carbon energy systems and alternative energy development, it will be economically feasible for developing countries to turn away from fossil-fuel intensive paths, achieving significant local environmental benefits at the same time.

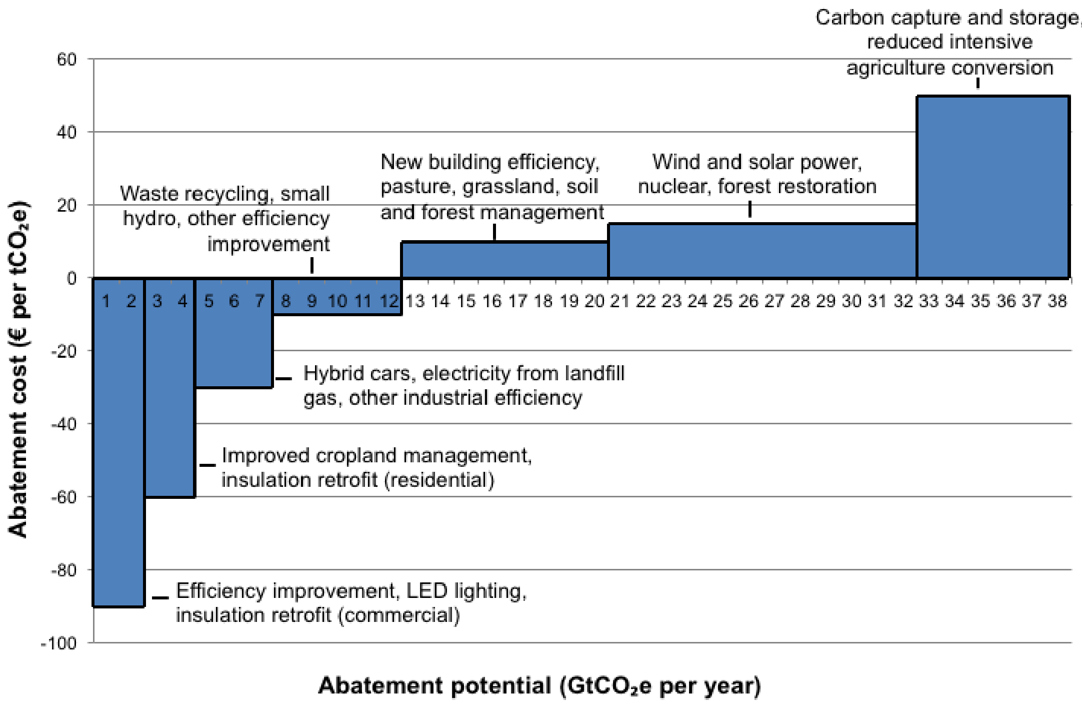
Climate Change: The Technical Challenge

Meeting the climate change challenge requires both behavioral change and technological change. Economic policy instruments such as carbon taxes, cap and trade, and subsidies use incentives to motivate changes in behavior. For example, a carbon tax that raises the price of gasoline will create incentives to drive less or buy a more fuel-efficient vehicle. But we can also look at climate change from a technical perspective rather than a behavioral perspective. Economic policies can create powerful incentives for technological changes. Because of higher gas prices as a result of a carbon tax, the increased demand for high-efficiency vehicles would motivate automobile companies to direct more of their investments to hybrid and electric vehicles.

A well-known analysis, by McKinsey & Company, examined different technical options that would have an impact on greenhouse gas mitigation, or abatements, on a global scale. The results of McKinsey's analysis are presented in Figure 21. The various options are arranged in order of cost, from lowest cost to highest. The economic logic is that it makes sense to implement actions that reduce carbon at the lowest per-unit costs first and then proceed to more costly actions.[58]

[58] McKinsey & Company, 2007 and 2009.

Figure 21. Global Greenhouse Gas Abatement Cost Curve for 2030



Source: Adapted from McKinsey & Company, 2009, and 2013.
Note: Costs are estimated in euros, but the analysis covers worldwide reduction possibilities.

This figure takes a little explanation. The *y*-axis indicates the cost range for each abatement option, measured in euros per ton of CO_2 reduction per year (or an amount equivalent to one ton of CO_2 for reductions in other gases such as methane). The thickness of the bar represents the amount of CO_2 emissions that can be avoided by each action. The cost of policies such as building insulation, increased efficiency, and waste recycling is in the *negative* range. This means that these policies would actually save money, regardless of their effect on CO_2 emissions. So even if we did not care about climate change and the environment, it would make sense to insulate buildings, increase appliance and recycle wastes, solely on long-term financial grounds.

The *x*-axis tells us the cumulative reduction in CO_2 equivalent emissions, relative to a "Business As Usual" scenario, if we were to implement all the actions to the left. So if we were to implement all negative-cost options including improving efficiency of air-conditioning, lighting systems, and water heating, total CO_2 equivalent reduction would be about 12 billion tons (Gt) per year, all while saving money!

Moving farther to the right, actions are identified that do entail positive costs. In other words, for all these other actions it does cost us money to reduce CO_2 emissions. Figure 21 shows all actions that reduce CO_2 emissions for a cost of less than

€60 per ton, including expanding wind and solar energy, expanding nuclear energy, improved forest management and reforestation, and implementing carbon capture and storage (CCS).

If all these actions were implemented, total CO_2-equivalent reduction would be 38 billion tons/year. Total global CO_2 equivalent emissions, including all greenhouse gases and emissions from land use change, are currently about 50 billion tons per year, projected to rise to about 70 Gt by 2030. Thus, instead of emitting 70 Gt/year in 2030, we would be emitting only 32 Gt—a decrease of 18 Gt below current levels. Further reduction could be achieved at slightly higher cost, especially by more extensive expansion of wind and solar energy. (This analysis does not take into account likely cost reductions for renewable energy).

The total cost of implementing all options in Figure 21, considering that some options actually save money, is estimated to be less than 1 percent of global GDP in 2030. The report notes that delaying action by just ten years makes keeping warming under 2°C extremely difficult.

Policy recommendations to achieve the reductions represented in Figure 21 include:

- Establish strict technical standards for efficiency of buildings and vehicles.
- Establish stable long-term incentives for power producers and industrial companies to invest in and deploy efficient technologies.
- Provide government support for emerging efficiency and renewable energy technologies, through economic incentives and other policies.
- Ensure efficient management of forests and agriculture, particularly in developing countries.[59]

[59] Ibid.

4. CLIMATE CHANGE POLICY IN PRACTICE

Climate change is an international environmental issue. In economic theory terms, climate change is a public good issue, requiring global collaboration to achieve effective results. Since the United Nations Framework Convention on Climate Change (UNFCCC) was first established in 1992, there have been extensive international discussions, known as "Conferences of the Parties" or COPs, aimed at reaching a global agreement on emissions reduction (See Table 5).

Table 5. Important Events in International Climate Change Negotiations

Year, Location	Outcome
1992, Rio de Janeiro	UN Framework Convention on Climate Change (UNFCCC). Countries agree to reduce emissions with "common but differentiated responsibilities."
1995, Berlin	The first annual Conference of the Parties to the framework, known as a COP. U.S. agrees to exempt developing countries from binding obligations.
1997, Kyoto	At the third Conference of the Parties (COP-3) the Kyoto Protocol is approved, mandating developed countries to cut greenhouse gas emissions relative to baseline emissions by 2008-2012 period.
2001, Bonn	(COP-6) reaches agreement on terms for compliance and financing. Bush administration rejects the Kyoto Protocol; U.S.is only an observer at the talks.
2009, Copenhagen	COP-15 fails to produce a binding post-Kyoto agreement, but declares the importance of limiting warming to under 2°C. Developed countries pledge $100 billion in climate aid to developing countries.
2011, Durban	(COP-17) participating countries agreed to adopt a universal legal agreement on climate change as soon as possible, and no later than 2015, to take effect by 2020.
2015, Paris	COP-21 195 nations sign the Paris Agreement, providing for worldwide voluntary actions (NDC's) by individual countries.

The first comprehensive international agreement on climate change was the Kyoto Protocol, adopted at the third COP in 1997, which has now expired. Under the Kyoto treaty, industrial countries agreed to emission reduction targets by 2008–2012 compared to their baseline emissions, set to 1990 levels. For example, the United States agreed to a 7 percent reduction, France to an 8 percent reduction, and Japan to a 6 percent reduction. The average target was a cut of around 5%

relative to 1990 levels. Developing countries such as China and India were not bound to emissions targets under the treaty, an omission that the United States and some other countries protested. Under President George W. Bush, the U.S. refused to ratify the Kyoto Protocol. But despite the U.S. withdrawal, the Kyoto Protocol entered into force in early 2005.

The results of the Kyoto Protocol were mixed. Some nations, such as Canada and the U.S., increased rather than reduced emissions; Canada withdrew from the Protocol, and the U.S. never entered it. Some European countries met or exceeded their targets, while others fell short. Russia and most East European countries considerably exceeded their targets, not as a result of deliberate policy but rather as a byproduct of communism's economic collapse in the early 1990s. The overall Kyoto target was technically achieved, but only as a result of this significant drop in Russian and Eastern European emissions.

In addition, we need to consider the effects of trade. In the Kyoto framework, emissions released during production of goods were assigned to the country where production takes place, rather than where goods are consumed. Therefore the "outsourcing" of carbon emissions through imports from developing countries, especially China, was not included in official accounting. Considering the full country carbon footprint taking trade into account, the progress made under Kyoto was very limited, with Europe's savings reduced to just 1% from 1990 to 2008, and the developed world as a whole seeing its emissions rise by 7% in the same period (25% for the US, when trade is included). Moreover, Kyoto placed no restrictions on emissions from developing countries, and overall global emissions continued to grow during the Kyoto period.[60]

But if the Kyoto protocol was a failure in its inability to slow down global emissions, it nevertheless provided an important first step in global climate diplomacy, and from the failures of Kyoto and its aftermath, countries learned lessons that proved useful in the later phases of those global negotiations.

The Paris Agreement of 2015

After efforts to secure a binding global agreement on emissions reductions failed at the fifteenth COP in Copenhagen in 2009, it became increasingly obvious to negotiators that another approach would be needed. The Copenhagen conference parties agreed only that the goal for future rounds of negotiations would be to keep the global temperature warming below the threshold of 2°C above pre-industrial levels. The most contentious point of disagreement was the question of whether developing countries should be bound by mandatory cuts in emissions. While some coun-

[60] Clark, 2012.

tries, particularly the United States, argued that all participants should agree to reductions, developing countries contended that mandatory cuts would limit their economic development and reinforce existing global inequities.

After the failure of Copenhagen, the idea of a binding agreement was rejected as unfeasible. In its place, negotiators came up with the idea that countries would instead propose their own voluntary goals– the hope being that countries would eventually feel “peer-pressure” to set the most ambitious possible goals within their reach. This new negotiating strategy laid the foundations for the global agreement reached at the twenty-first Conference of the Parties (COP21) in Paris. In the months that preceded the COP21, 186 countries submitted their proposed nationally determined contributions (NDCs) – indicating their willingness to contribute to the reduction of global CO_2 emissions.

The Paris Agreement, negotiated by 195 national delegations, formally expresses the global aim of holding temperatures to no more than 2° C above preindustrial levels, with a more ambitious target of 1.5° C. Since the current total of country pledges (NDCs) is not sufficient to secure the global goal of keeping warming under 2° C, the agreement includes 5 year cycles for countries to review their goals and ratchet up their targets, in order to reach more ambitious goals. The negotiating process has been designed to put pressure on every country to comply with its own pledges and to increase them over time.

A strong transparency and accountability regime is built into the agreement, based on regular inventories, regular reporting of the progress countries are making towards their targets, and regular review by expert teams. The Paris agreement entered into force, with over 80 countries representing over 60 percent of global emissions ratifying the agreement by the end of 2016, just a year after it was negotiated, a record speed for international agreements. Despite subsequent rejection of the agreement by the United States Trump Administration, the agreement remains in force – though compliance with the targets is voluntary. A related binding agreement establishing specific timetables to eliminate the production of hydrofluorocarbons (HFCs), powerful greenhouse gases used in air-conditioners and refrigerators, was agreed on in October 2015.[61]

The Paris agreement also provides for continuing financial and technical support to developing countries to help them adapt to the disruptive consequences of climate change, as well as support for a transition away from fossil fuels toward cleaner renewable energy sources. The agreement included a loss-and-damage clause

[61] Coral Davenport, “Paris Climate Deal Reaches Milestone as 20 More Nations Sign On,” *New York Times*, September 21, 2016; Coral Davenport, “Nations, Fighting Powerful Refrigerant that Warms Planet, Reach Landmark Deal,” *New York Times*, October 15, 2016.

recognizing the importance of addressing the adverse effects of climate change in developing countries. While the agreement does not accept liability or provide for compensation, it does offer several conditions where support may be given. Starting in 2020, industrialized nations have pledged $100 billion a year in financial and technical aid to developing countries to fight climate change.[62]

Many voices in the developing world have warned that $100 billion will fall far short of what is really needed, and that a conservative figure would be closer to $600 billion, which is about 1.5% of the GDP of industrialized nations. Some of the estimates, by organizations from the World Bank to the International Applied Systems Analysis, in Vienna, suggest that the sums needed would be as high as 1.7 or even 2.2 trillion dollars per year.[63]

How adequate or inadequate are the commitments?

An independent organization, Climate Action Tracker, provides assessments and ratings of submitted NDCs.[64] According to its grading system, the USA is rated "medium" for its commitment, China is rated as "medium with inadequate carbon intensity target", and the European Union is also rated as "medium". This "medium" range rating of the USA applied to the Obama Administration's commitment to reducing its greenhouse gas emissions by 26-28 per cent below its 2005 level in 2025 and to make best efforts to reduce its emissions by 28%. It is likely that this rating is now obsolete, as the Trump Administration has expressed its unwillingness to comply with the former administration's climate commitment, and has withdrawn from the Paris Agreement altogether.

The Climate Action Tracker rates as "inadequate" the commitments by a long list of countries, including Russia, Japan, Australia, New Zealand, Canada, Argentina, South Africa, Chile, and Turkey.[65] Figure 22 shows the differences between a business-as-usual emissions trajectory, the trajectory that would result from the current aggregation of NDCs commitments, and the path that would be necessary to reach 2°C (3.6°F) or less.

---

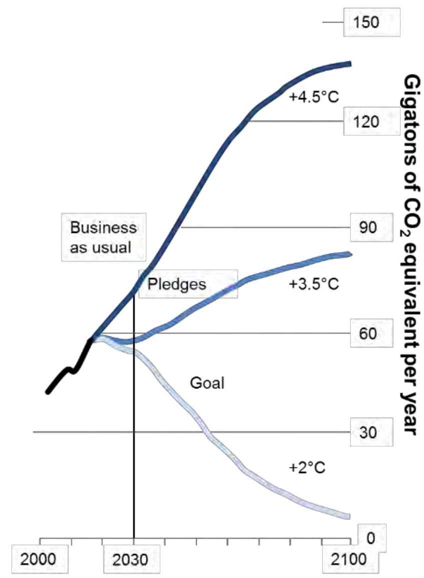
[62] "Adoption of the Paris Agareement" http://unfccc.int/resource/docs/2015/cop21/eng/l09r01.pdf

[63] www.scientificamerican.com/article/poorer-nations-demand-more-aid-to-deal-with-climate-change/; http://roadtoparis.info/2014/11/06/climate-finance-too-little-too-late/

[64] For a more detailed analysis, see GDAE's Climate Policy brief #2, "After Paris: the new landscape for Climate Policy." http://www.ase.tufts.edu/gdae/Pubs/climate/ClimatePolicyBrief2.pdf

[65] http://climateactiontracker.org/methodology/85/Comparability-of-effort.html; http://www.wri.org/blog/2015/07/japan-releases-underwhelming-climate-action-commitment

Figure 22. Business as Usual, Paris Pledges, and 2°C Path



Source: http://www.nytimes.com/interactive/2015/11/23/world/carbon-pledges.html?_r=1
Note: 2°C = 3.6°F; 3.5°C = 6.3°F; 2 4.5°C = 8.1°F.

Most current pledges do not extend beyond 2030, which is why emissions start to rise again after 2030 in Figure 22. Considerable strengthening of the pledges would clearly be needed before that date to keep overall emissions on a 2°C track – let alone 1.5°C.[66] According to analysis by the Climate Action Tracker, if policies of comparable strength to those in the current NDCs were maintained after 2030, they would lead to a median warming of about 2.7°C (4.8°F) by 2100 – better than the 3.5°C (6.3°F) shown in Figure 22 for the current commitments, but still far exceeding the Paris targets.67 (For a scientific perspective on the importance of reaching a 2°C or even 1.5°C target, see Box 6).

To see what is required to achieve a 2°C or 1.5° C target, the concept of a **global carbon budget** is useful. A global carbon budget attempts to quantify the cumulative emissions of carbon that can be added to the atmosphere without exceeding specified temperature increases. To reach a 2°C target, it is necessary to keep within a cumulative global carbon budget of no more than 270 additional gigatons of carbon – about 30 years of emissions at current levels. To reach the 1.5°C target, the budget would have to be a mere 110 gigatons – about 12 years of emissions at current rates.[68] The current Paris commitments are inadequate to meet these goals, without a significant strengthening of commitments in future rounds of negotiation.

[66] Millar et al., 2016.

[67] http://climateactiontracker.org/assets/publications/briefing_papers/CAT_Temp_Update_COP21.pdf

[68] The Global Carbon Project, "Global Carbon Budget," http://www.globalcarbonproject.org/; Schellnhuber et al, 2016.

BOX 6. THE SCIENTIFIC BASIS FOR THE PARIS CLIMATE TARGETS

The Paris Agreement codified a goal of no more than 2°C of temperature increase, with a more ambitious goal of no more than 1.5°C. What is the reason for these targets? A 2016 study argues that the temperature targets selected in Paris are the scientifically correct ones by comparing these targets to the probability that various catastrophic and irreversible losses will occur, such as the loss of alpine glaciers or the loss of the Amazon rainforest. The authors assessed the available research to determine the temperature range at which each impact is expected to occur. This is shown in Figure 23.

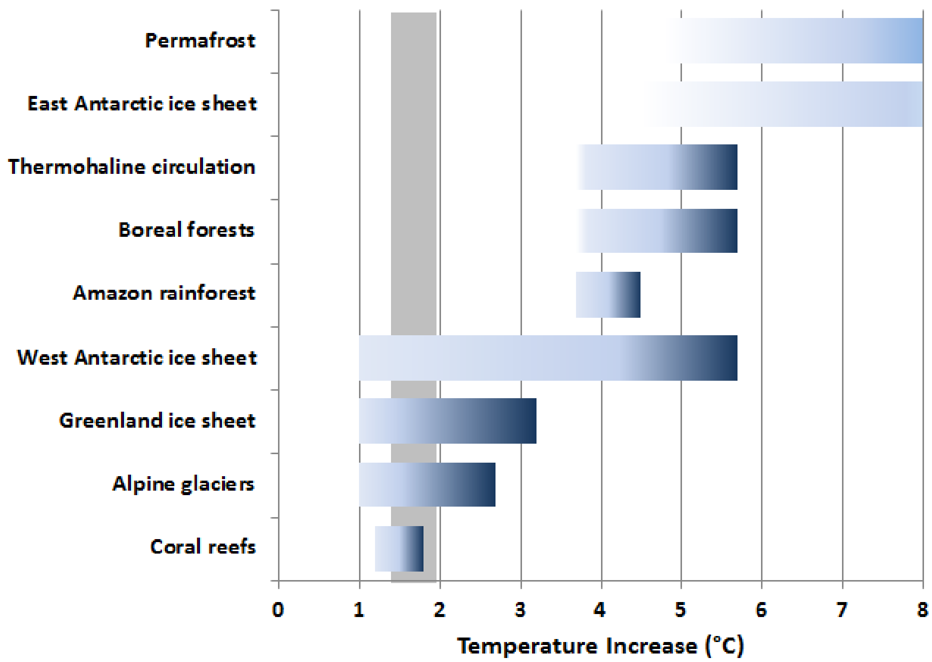
The bar for each impact reflects scientific uncertainty about how much temperatures must increase to make that impact inevitable. The darker the shading, the higher the probability the impact will occur. So, for example, if global average temperatures increase only 1°C there is a small probability alpine glaciers will be lost. But if temperatures increase more than 2.5°C it is nearly certain that alpine glaciers will be lost based on the current research.

The vertical bar represents the range of the Paris climate targets, from 1.5°C to 2.0°C. Comparing these targets to the various impacts, we see that limiting the temperature increase to 1.5°C offers a chance that the world's coral reefs will not be lost. But at 2°C it is virtually certain that coral reefs will not survive. If the 2°C target can be met, the outlook is better for avoiding the loss of alpine glaciers, the Greenland ice sheet, and the West Antarctic ice sheet, although considerable uncertainty remains. At 4−6°C the Amazon and boreal forests, the East Antarctic ice sheet, and permafrost are all endangered, as is the thermohaline circulation in the oceans, including the Gulf Stream, which keeps much of Europe relatively temperate despite high latitudes. The article concludes that achieving the Paris targets, while ambitious, is therefore essential:

> Beyond 2°C the course would be set for a complete deglaciation of the Northern Hemisphere, threatening the survival of many coastal cities and island nations. Global food supply would be jeopardized by novel extreme-event regimes, and major ecosystems such as coral reefs forced into extinction. Yet, staying within the Paris target range, the overall Earth system dynamics would remain largely intact. Progressing [further] on the other hand, with global warming reaching 3–5°C, would seriously [risk most impacts]. For warming levels beyond this range, the world as we know it would be bound to disappear.
>
> – Schellnhuber et al, 2016.

Sources: Schellnhuber et al, 2016.
Note: The vertical bar represents the range of the Paris climate targets, from 1.5°C to 2.0°C

Figure 23. The Paris Climate Targets and Catastrophic Global Impacts



Source: Schellnhuber et al, 2016.
Note: The vertical bar represents the range of the Paris climate targets, from 1.5°C to 2.0°C

Regional, National and Local Actions

While international efforts to establish a framework for emissions reduction have continued, policies have been implemented at regional, national, and local levels. These include:

- To help it meet its obligations under the Kyoto Protocol, the European Union set up a carbon trading system that went into effect in 2005 (see Box 7).
- Carbon trading systems have also been established in several regions in the United States. The Regional Greenhouse Gas Initiative (RGGI) is a cap-and-trade program for emissions from power plants in nine North-eastern states. Permits are mostly auctioned off (some are sold at a fixed price), with the proceeds used to fund investments in clean energy and energy efficiency. Permit auction prices have ranged from about $2 to $5 per ton of CO_2.[69] In 2013, California initiated a legally binding cap-and-trade scheme. "The program imposes a greenhouse gas emission limit that will decrease by two percent each year through 2015, and by three percent annually from 2015 through 2020."[70]

[69] www.rggi.org.
[70] http://www.c2es.org/us-states-regions/key-legislation/california-cap-trade

BOX 7. THE EUROPEAN UNION CARBON TRADING SYSTEM

In 2005, the European Union (EU) launched its Emissions Trading Scheme (EU-ETS), which covers more than 11,000 facilities that collectively emit nearly half the EU's carbon emissions. In 2012, the system was expanded to cover the aviation sector, including incoming flights from outside the EU. Under the EU-ETS, each country develops a national allocation plan to determine the overall number of permits available. Permits are both auctioned off and allocated to some firms for free based on historical emissions. Any unneeded permits can be sold on the open market.

The initial phase (2005–2007) of the EU-ETS produced disappointing results as permits were over-allocated, leading to a drop in the permit price from more than €30 per tonne to less than €1 by the end of 2007. In the second phase (2008–2012), fewer permits were initially allocated, leading to relatively stable prices of around €15–€20/tonne for a few years. But by mid-2012 prices had fallen to €5–€10/tonne as the market again experienced a glut of permits. Despite the volatility in prices, according to the EU the EU-ETS led to a reduction in emissions from large emitters of 8 percent between 2005 and 2010. Also, the costs of the EU-ETS have been less than expected, around 0.5 percent of European gross domestic product (GDP).

The EU has moved into the third phase of the ETS, covering 2013–2020. This phase will require more of the permits to be auctioned, include more greenhouse gases, and set an overall EU cap rather than allowing individual countries to determine their own cap. By the end of the third phase, the program's goal is to reduce overall EU emissions 21 percent relative to 1990 levels, with a further goal of a 43% reduction by 2030.

Sources: EU-ETS, http://ec.europa.eu/clima/policies/ets/index_en.htm; Grubb et al, 2009

- Carbon taxes have been instituted in several countries, including a nationwide tax on coal in India (about $1/ton, enacted in 2010), a tax on new vehicles based on their carbon emissions in South Africa (also enacted in 2010), a carbon tax on fuels in Costa Rica (enacted in 1997), and local carbon taxes in the Canadian provinces of Quebec, Alberta, and British Columbia (see Box 8).

BOX 8. BRITISH COLUMBIA'S CARBON TAX: A SUCCESS STORY

In 2008, the Canadian province of British Columbia, on the Pacific Coast, implemented a carbon tax of $10 per ton of CO_2 (Canadian dollars). The tax rose incrementally by $5 each subsequent year, until it reached $30 in 2012. This translates into an additional 26 cents per gallon of gasoline at the pump, with comparable price increases in other carbon-based energy sources.

The carbon tax is revenue neutral, meaning that the province has cut income and corporate taxes to offset the revenue it gets from taxing carbon. British Columbia now has the lowest personal income tax rate in Canada, and one of the lowest corporate rates among developed countries.

In the first six years of its implementation, consumption of fuels dropped by between 5% and 15% in B.C., while it rose by about 3% in the rest of Canada. During that time, GDP per capita continued to grow in British Columbia, at a slightly higher pace than for the rest of Canada. By lowering taxes on income and on corporations, this policy encouraged employment and investment, while discouraging carbon pollution.

British Columbia's experience has been heralded by the OECD and the World Bank as a successful example to follow. A recent study found that the tax had negligible effects on the economy, and had overcome initial opposition to gain general public support. As of 2016, the Canadian government planned to extend the tax to the whole of Canada.

Sources: The World Bank, Development in a changing climate. British Columbia's carbon tax shift: an environmental and economic success. Sept. 10, 2014; The Economist, British Columbia's carbon tax: the evidence mounts. July 31, 2014, Ministry of Finance, British Columbia, Carbon Tax: overview of the revenue-neutral carbon tax; Murray and Rivers, 2015; Metcalf, 2015; http://www.nationalobserver.com/2016/10/03/news/breaking-feds-announce-pan-canadian-carbon-price-plan-2018.

- Networks of cities have also organized to address climate change. The C40 network of megacities, representing 25% of global GDP has focused on measuring and reducing urban emissions. Another network, the Compact of Mayors, a global coalition of over 500 cities, was launched in 2014 with similar goals.[71] By 2050, between 65% and 75% of the world population is projected to be living in cities, with more than 40 million people moving to cities each year. Urban population will grow from approximately 3.5 billion people now to 6.5 billion by 2050. Estimates sug-

[71] http://www.c40.org/; https://www.compactofmayors.org/

gest that cities are responsible for 75 percent of global CO_2 emissions, with transport and buildings being among the largest contributors.[72]

- Following the withdrawal of the United States from the Paris agreement, a coalition of U.S. states formed the United States Climate Alliance, pledging to strengthen their efforts to curb greenhouse gases to offset the lack of federal action, and seek to meet or exceed the Paris goals.

Forests and Soils

While the major focus of climate policy has been on the reduction of emissions from carbon-based fuels, the role of forests and soils is also crucial. Currently about 11% of greenhouse gas emissions come from forest and land use change, especially tropical forest loss.[73] International negotiations have also led to the adoption of a program known as **REDD (Reduction of Emissions from Deforestation and Degradation).** The Copenhagen Accord (2009) acknowledged the need to act on reducing emissions from deforestation and forest degradation and established a mechanism known as REDD-plus. The Accord emphasizes funding for developing countries to enable action on mitigation, including substantial finance for REDD-plus, adaptation, technology development and transfer and capacity building.

In addition to reducing emissions, forests and soils have huge potential for absorbing and storing carbon. The Earth's soils store 2500 billion tons of carbon – more carbon than the atmosphere (780 billion tons) and plants (560 billion tons) combined. But it is estimated that soils have been depleted of 50 to 70 percent of their natural carbon in the last century. Globally, those depleted soils could reabsorb 80 to 100 billion metric tons of carbon per year, through regenerative agriculture including: polyculture, cover cropping, agroforestry, nutrient recycling, crop rotation, proper pasture management, and organic soil amendments like compost and biochar.[74] It is likely that this vast unexploited potential for carbon storage will be a major focus of future climate policy[75] – a crucial factor in the effort to move from the intermediate "pledges" path in Figure 22 to the "goals" path necessary to hold global temperature change to no more than 2°C.

[72] http://www.theguardian.com/cities/2015/nov/17/cities-climate-change-problems-solution; http://www.unep.org/urban_environment/issues/climate_change.asp

[73] IPCC, 2014b, *Summary for Policymakers*, p. 5; Harris and Feriz, 2011; Sanchez and Stern, 2016.

[74] Lal, 2010; Chris Mooney, "The Solution to Climate Change that has nothing to do with cars or coal," *Washington Post*, February 11, 2016; Beth Gardiner, "A boon for soils, and for the environment," *New York Times,* May 17, 2016; Center for Food Safety, "Soil & Carbon: Soil solutions to Climate problems," 2015.

[75] For a more detailed analysis of the soil solutions to climate change, see GDAE Climate Policy brief #4: "Hope below our feet: Soil as a Climate Solution." http://www.ase.tufts.edu/gdae/Pubs/climate/ClimatePolicyBrief4.pdf

CONCLUSION

Climate change is an issue that embodies issues of externalities, common property resources, public goods, renewable and nonrenewable resources, and the discounting of costs and benefits over time. It has economic, scientific, political, and technological dimensions. Economic analysis alone cannot adequately respond to a problem of this scope, but economic theory and policy have much to offer in the search for solutions.

An effective response to the climate change problem requires much more sweeping action on a global scale than anything so far achieved. Economic policy instruments that have the power to alter patterns of energy use, industrial development, and income distribution are essential to any plan for mitigating or adapting to climate change. Evidence of climate change impacts is already clear, and the issue will become more pressing as greenhouse gas accumulation continues and costs of damages and of climate adaptation rise (see Box 9).

BOX 9. FOR U.S. COASTAL CITIES, CLIMATE ADAPTATION IS URGENT

In August 2016, torrential downpours along the Gulf Coast led to deadly floods in Southern Louisiana. With $9 billion in estimated damages, this natural catastrophe qualified as the worst in the United States since Hurricane Sandy in October 2012. The National Oceanic and Atmospheric Administration found that global warming increases the chances of such intense rains by 40% due to increased moisture in a warmer atmosphere.

Already, coastal cities around the United States are investing massively to prepare for future floods. Fort Lauderdale, Florida, is spending millions of dollars fixing battered roads and drains damaged by increasing tidal flooding. Miami Beach increased local fees to finance a $400 million plan that includes raising streets, installing pumps and elevating sea walls. The cost of adapting to rising seas for the medium-size town of Norfolk, VA has been estimated at about $1.2 billion, or about $5000 for every resident. These costs for individual cities imply that the order of magnitude of costs for the whole East Coast and Gulf Coast will be several trillions. 1.9 million shoreline homes worth a combined $882 billion might be lost to rising sea levels by 2100.

According to some economic analysts, the possibility of a collapse in the coastal real estate market could rival the impacts of the dot-com and real estate crashes of 2000 and 2008. The Pentagon too faces major adaptation issues, as many naval bases are facing serious threats and their land is at risk of disappearing within this century.

Sources: Jonah Engel Bromwich, "Flooding in the South looks a lot like climate change" *New York Times*, August 16, 2016; Henry Fountain, "Scientists see push from climate change in Louisiana flooding" *New York Times* September 7, 2016; Justin Willis, "Flooding of coast, caused by global warming, has already begun" *New York Times*, September 3, 2016; Ian Urbina, "Perils of climate change could swamp coastal real estate," *New York Times*, November 24, 2016.

KEY TERMS AND CONCEPTS

adaptive measures/adaptive strategies actions designed to reduce the magnitude or risk of damages from global climate change.

avoided costs costs that can be avoided through environmental preservation or improvement

"backstop" energy technologies technologies such as solar and wind that can replace current energy sources, especially fossil fuels.

business as usual a scenario in which no significant policy, technology, or behavioral changes are expected.

cap and trade a tradable permit system for pollution emissions.

carbon footprint total carbon emissions, direct and indirect, resulting from the consumption of a nation, institution, or individual.

carbon intensity a measure of carbon emissions per unit of GDP.

carbon sinks portions of the ecosystem with the ability to absorb certain quantities of carbon dioxide, including forests and oceans.

carbon tax a per-unit tax on goods and services based on the quantity of carbon dioxide emitted during the production or consumption process.

climate justice equitable sharing both of the burdens of climate change and the costs of policy responses.

climate stabilization the policy of reducing fossil-fuel use to a level that would not increase the potential for global climate change.

CO_2 **equivalent (CO_2e)** a measure of total greenhouse gas emissions or concentrations, converting all non-CO_2 gases to their CO_2 equivalent in warming impact.

cost-benefit analysis (CBA) a tool for policy analysis that attempts to monetize all the costs and benefits of a proposed action to determine the net benefit.

cost-effectiveness analysis a policy tool that determines the least-cost approach for achieving a given goal.

common property resource a resource that is available to everyone (nonexcludable), but use of the resource may diminish the quantity or quality available to others (rival).

cumulative or stock pollutant a pollutant that does not dissipate or degrade significantly over time and can accumulate in the environment, such as carbon dioxide and chlorofluorocarbons.

distributionally neutral tax shift a change in the pattern of taxes that leaves the distribution of income unchanged.

efficiency standards regulations that mandate efficiency criteria for goods, such as fuel economy standards for automobiles.

elasticity of demand the sensitivity of quantity demanded to prices; an elastic demand means that a proportional increase in prices results in a larger proportional change in quantity demanded; an inelastic demand means that a proportional increase in prices results in a small change.

environmental justice the fair treatment of people regardless of race, color, national origin, or income, with respect to the development, implementation, and enforcement of environmental laws, regulations, and policies.

discount rate the annual rate at which future benefits or costs are discounted relative to current benefits or costs.

feedback effect the process of changes in a system leading to other changes that either counteract or reinforce the original change.

future costs and benefits benefits and costs that are expected to occur in the future, usually compared to present costs through discounting.

global carbon budget the concept that total cumulative emissions of carbon must be limited to a fixed amount in order to avoid catastrophic consequences of global climate change.

global climate change: the changes in global climate, including temperature, precipitation, storm frequency and intensity, and changes in carbon and water cycles, that result from increased concentrations of greenhouse gases in the atmosphere.

global commons global common property resources such as the atmosphere and the oceans.

global warming the increase in average global temperature as a result of emissions from human activities.

greenhouse effect the effect of certain gases in the earth's atmosphere trapping solar radiation, resulting in an increase in global temperatures and other climatic impacts.

greenhouse gases gases such as carbon dioxide and methane whose atmospheric concentrations influence global climate by trapping solar radiation.

least-cost options actions that can be taken for the lowest overall cost.

marginal abatement costs costs of reduction for one extra unit of pollution, such as carbon emissions.

nationally determined contribution (NDC): a voluntary planned reduction in CO_2 emissions, relative to baseline emissions, submitted by participating countries at the Paris Conference of the Parties (COP-21) in 2015.

ocean acidification increasing acidity of ocean waters as a result of dissolved carbon from CO_2 emitted into the atmosphere.

pollution tax(es) a per-unit tax based on the level of pollution.

precautionary principle the view that policies should account for uncertainty by taking steps to avoid low-probability but catastrophic events.

preventive measures/preventive strategies actions designed to reduce the extent of climate change by reducing projected emissions of greenhouse gases.

price volatility rapid and frequent changes in price, leading to market instability.

progressive taxes taxes that comprise a higher share of income with higher income levels.

public goods goods that are available to all (nonexclusive) and whose use by one person does not reduce their availability to others (nonrival).

reduction of emissions from deforestation and degradation (REDD) a United Nations program adopted as part of the Kyoto process of climate negotiations, intended to reduce emissions from deforestation and land degradation.

regressive tax a tax in which the rate of taxation, as a percentage of income, decreases with increasing income levels.

revenue-neutral tax shift policies that are designed to balance tax increases on certain products or activities with a reduction in other taxes, such as a reduction in income taxes that offsets a carbon-based tax.

social cost of carbon an estimate of the financial cost of carbon emissions per unit, including both present and future costs.

technology transfer the process of sharing technological information or equipment, particularly among countries.

transferable (tradable) permits tradable permits that allow a firm to emit a certain quantity of a pollutant.

REFERENCES

Ackerman, Frank, and Elizabeth A. Stanton. 2008. "The Cost of Climate Change." Natural Resource Defense Council. www.nrdc.org/globalwarming/cost/cost.pdf.

———. 2011. "Climate Economics: The State of the Art." Stockholm Environment Institute—U.S. Center. http://sei-us.org/Publications_PDF/SEI-ClimateEconomics-state-of-art-2011.pdf.

Ackerman, Frank, Elizabeth A. Stanton, and Ramón Bueno. 2013. "CRED: A New Model of Climate and Development." Ecological Economics, 85: 166–176.

African Development Bank, Asian Development Bank, Department for International Development (UK), Directorate-General for Development (European Commission), Federal Ministry for Economic Cooperation and Development (Germany, Ministry of Foreign Affairs), Development Cooperation (The Netherlands), Organization for Economic Cooperation and Development, United Nations Development Programme, United Nations Environment Programme, and World Bank, 2003. *Poverty and Climate Change: Reducing the Vulnerability of the Poor Through Adaptation.* www.unpei.org/PDF/Poverty-and-Climate-Change.pdf.

American Geophysical Union. 2014. Human-Induced Climate Change Requires Urgent Action. www.agu.org.

Barnes, Peter, Robert Costanza, Paul Hawken, David Orr, Elinor Ostrom, Alvaro Umana, and Oran Young. 2008. "Creating an Earth Atmospheric Trust." *Science* 319:724.

Boden, T.A., G. Marland, and R.J. Andres. 2016. "Global, Regional, and National Fossil-Fuel CO_2 Emissions." Carbon Dioxide Information Analysis Center (CDIAC), Oak Ridge National Laboratory. http://cdiac.ornl.gov/ftp/ndp030/global.1751_2013.ems.

Burke, M., S. Hsiang, and E. Miguel. 2015. "Global Nonlinear Effect of Temperature on Economic Production." *Nature*, 527: 235–239.

Carl, Jeremy, and David Fedor. 2016. "Tracking Global Carbon Revenues: A Survey of Carbon Taxes versus Cap-and-trade in the Real World." *Energy Policy* **96**: 50-77.

Clark, Duncan. 2012. "Has the Kyoto Protocol made any difference to carbon emissions?" *The Guardian*, November 26. https://www.theguardian.com/environment/blog/2012/nov/26/kyoto-protocol-carbon-emissions

Climate Equity Reference Project. 2015. Fair Shares: A Civil Society Review of NDCs." http://civilsocietyreview.org/wp-content/uploads/2015/11/CSO_FullReport.pdf

Cline, William R. 2007. *Global Warming and Agriculture: Impact Estimates by Country.* Washington, D.C.: Center for Global Development and Petersen Institute for International Economics. http://www.cgdev.org/content/publications/detail/14090.

Codur, Anne-Marie, Seth Itzkan, William Moomaw, Karl Thidemann, and Jonathan Harris. 2017. "Hope Below Our Feet: Soil as a Climate Solution." *GDAE Climate Policy Brief*. http://www.ase.tufts.edu/gdae/Pubs/climate/ClimatePolicyBrief4.pdf

Cook J., *et al*. 2016. "Consensus on consensus: a synthesis of consensus estimates on human-caused global warming." *Environmental Research Letters* Vol. 11 No. 4, (13 April). DOI:10.1088/1748-9326/11/4/048002.

DeConto, R., and D. Pollard. 2016. "Contribution of Antarctica to Past and Future Sea-level Rise." *Nature*, 531: 591–597.

Dietz, Simon, and Nicholas Stern. 2014. "Endogenous Growth, Convexity of Damages and Climate Risk: How Nordhaus' Framework Supports Deep Cuts in Carbon Emissions." Grantham Research Institute on Climate Change and the Environment, Working paper No. 159, June.

Fankhauser, Samuel. 1995. *Valuing Climate Change: The Economics of the Greenhouse.* London: Earthscan.

Goodwin, Phil, Joyce Dargay, and Mark Hanly. 2004. "Elasticities of Road Traffic and Fuel Consumption with Respect to Price and Income: A Review." *Transport Reviews* 24(3): 275–292.

Grubb, Michael, Thomas L. Brewer, Misato Sato, Robert Heilmayr, and Dora Fazekas. 2009. "Climate Policy and Industrial Competitiveness: Ten Insights from Europe on the EU Emissions Trading System." German Marshall Fund of the United States, Climate & Energy Paper Series 09.

GIZ. 2013. "International Fuel Prices 2012/2013," 8th ed., on behalf of Federal Ministry for Economic Cooperation and Development (Germany).

Hansen, et al. 2008. "Target Atmospheric CO_2: Where should Humanity Aim?" *Open Atmospheric Science Journal*, 2: 217–231.

Harris, Jonathan M., and Maliheh Birjandi Feriz, 2011. *Forests, Agriculture, and Climate: Economics and Policy Issues***.** Tufts University Global Development and Environment Institute, http://www.ase.tufts.edu/gdae/education_materials/modules.html#REDD

Heal, Geoffrey and Anthony Millner. 2014. "Uncertainty and Decision-Making in Climate Change Economics." *Review of Environmental Economics and Policy* **8.1**: 120-137.

Hönisch, Bärbel, et al. 2012. "The Geological Record of Ocean Acidification." *Science*, 335(6072): 1058–1063.

Hughes, Jonathan E., Christopher R. Knittel, and Daniel Sperling. 2008. "Evidence of a Shift in the Short-Run Price Elasticity of Gasoline Demand." *Energy Journal* 29 (1), 113–134.

Intergovernmental Panel on Climate Change (IPCC). 2007a. Climate Change 2007: The Physical Science Basis. Cambridge, UK; New York: Cambridge University Press.

———. 2007b. *Climate Change 2007: Impacts, Adaptation, and Vulnerability*. Cambridge, UK; New York: Cambridge University Press.

———. 2007c. *Climate Change 2007: Mitigation of Climate Change.* Cambridge, UK; New York: Cambridge University Press.

Intergovernmental Panel on Climate Change (IPCC). 2014a. *Climate Change 2013, The Physical Science Basis*. http://ipcc.ch/.

———. 2014b. *Climate Change 2014 Synthesis Report.* http://ipcc.ch/

———. 2014c. *Climate Change 2014: Impacts, Adaptation, and Vulnerability*.

———. 2014d. *Climate Change 2014: Mitigation of Climate Change.*

Jevrejeva, S., J.C. Moore, and A. Grinsted, 2012. "Sea Level Projections to AD2500 with a New Generation of Climate Change Scenarios." *Journal of Global and Planetary Change*, 80/81: 14–20.

Kahn, Matthew E. 2016. "The Climate Change Adaptation Literature." *Review of Environmental Economics and Policy* **10.1:** 166-178.

Kahsay, Goytom Abraha and Lars Gårn Hansen. 2016. "The Effect of Climate Change and Adaptation Policy on Agricultural Production in Eastern Africa." *Ecological Economics* **121**: 54-64.

Kesicki, Fabian, and Paul Ekins. 2011. "Marginal Abatement Cost Curves: A Call for Caution." *Climate Policy* 12(2): 219–236.

Komanoff, Charles. 2014. "Is the Rift between Nordhaus and Stern Evaporating with Rising Temperatures?" Carbon Tax Center, August 21. http://www.carbontax.org/blog/2014/08/21/is-the-rift-between-nordhaus-and-stern-evaporating-with-rising-temperatures/

Lal, Rattan. 2010. "Managing soils and ecosystems for mitigating anthropogenic carbon emissions and advancing global food security." *Bioscience* **60.9**: 708-21. Oxford Journals.

McKinsey & Company. 2007. "A Cost Curve for Greenhouse Gas Reduction." The McKinsey Quarterly 1: 35–45, http://www.epa.gov/air/caaac/coaltech/2007_05_mckinsey.pdf

———. 2009. *Pathways to a Low-Carbon Economy.* http://www.mckinsey.com/business-functions/sustainability-and-resource-productivity/our-insights/pathways-to-a-low-carbon-economy

———. 2013. *Pathways to a Low-Carbon Economy, Version 2* http://www.mckinsey.com/business-functions/sustainability-and-resource-productivity/our-insights/pathways-to-a-low-carbon-economy

Metcalf, Gilbert E. 2007. "A Proposal for a U.S. Carbon Tax Swap." Washington, DC: Brookings Institution. Discussion Paper 2007–12.

———. 2015. "A Conceptual Framework for Measuring the Effectiveness of Green Tax Reforms." Green Growth Knowledge Platform Third Annual Conference on "Fiscal Policies and the Green Economy Transition: Generating Knowledge – Creating Impact". Venice, Italy, January 29–30.

Millar, Richard, Myles Allen, Joeri Rogelj, and Pierre Friedlingstein. 2016. "The Cumulative Carbon Budget and its Implications." *Oxford Review of Economic Policy* **32(2)**: 323-342.

Murray, Brian, and Nicholas Rivers. 2015. "British Columbia's Revenue-neutral Carbon Tax: A Review of the Latest "Grand Experiment" in Environmental Policy. *Energy Policy* **86**: 674-683.

National Oceanic and Atmospheric Administration (NOAA). 2010. "Ocean Acidification, Today and in the Future." www.climatewatch.noaa.gov/image/2010/ocean-acidification-today-and-in-the-future/.

———. 2012. "Global Climate Change Indicators." www.ncdc.noaa.gov/indicators/index.html.

———. 2012. *State of the Climate, Global Analysis Annual 2012*. National Climatic Data Center. www.ncdc.noaa.gov/sotc/global/.

Nordhaus, William. 2007. "The Stern Review on the Economics of Climate Change." http://nordhaus.econ.yale.edu/stern_050307.pdf

———. 2008. *A Question of Balance: Weighing the Options on Global Warming Policies*. New Haven: Yale University Press.

———. 2013. *The Climate Casino.* New Haven; London: Yale University Press.

Nordhaus, William D., and Joseph Boyer. 2000. *Warming the World: Economic Models of Global Warming*. Cambridge, MA: MIT Press.

Olivier, Jos G.J., Greet Janssens-Maenhout, Marilena Muntean, and Jeroen A.H.W. Peters. European Commission's Joint Research Centre, 2014. "Trends in Global CO_2 Emissions: 2014 Report," http://edgar.jrc.ec.europa.eu/news_docs/jrc-2014-trends-in-global-co2- emissions-2014-report-93171.pdf.

Parry, Martin, Nigel Arnell, Pam Berry, David Dodman, Samuel Fankhauser, Chris Hope, Sari Kovats, Robert Nicholls, David Satterthwaite, Richard Tiffin, and Tim Wheeler. 2009. "Assessing the Costs of Adaptation to Climate Change: A Review of the UNFCCC and Other Recent Estimates." Report by the Grantham Institute for Climate Change and the International Institute for Environment and Development. London.

Revesz R., K. Arrow *et al*. 2014. "Global Warming: Improve Economic Models of Climate Change." Nature, April 4. http://www.nature.com/news/global-warming-improve-economic-models-of-climate-change-1.14991.

Rosen, Richard A. and Edeltraud Guenther. 2014. "The Economics of Mitigating Climate Change: What Can We Know?" *Challenge* **57.4**: 57-81.

Sanchez, Luis F. and David I. Stern. 2016. "Drivers of Industrial and Non-industrial Greenhouse Gas Emissions." *Ecological Economics* **124**: 17-24.

Schellnhuber, Hans Joachim, Stefan Rahmstorf, and Ricarda Winkelmann. 2016. "Why the Right Climate Target was Agreed in Paris." *Nature Climate Change* **6**: 649-653.

Stanton, Elizabeth A. 2012. "Development Without Carbon: Climate and the Global Economy Through the 21st Century." Stockholm Environment Institute–U.S. Center. http://sei-us.org/Publications_PDF/SEI-Development-Without-Carbon-Ph1.pdf.

Stern, Nicholas. 2007. *The Economics of Climate Change: The Stern Review*. Cambridge: Cambridge University Press. www.hm-treasury.gov.uk/independent_reviews/stern_ review_economics_climate_change/sternreview_index.cfm.

———. 2009. *The Global Deal: Climate Change and the Creation of a New Era of Progress and Prosperity*. Philadelphia: Perseus Books Group.

United Nations Environmental Programme (UNEP). 2016. *The Adaptation Gap Report*. Nairobi, Kenya: UNEP. http://drustage.unep.org/adaptationgapreport/2016.

United Nations Framework Convention on Climate Change (UNFCCC). 2007. "Investment and Financial Flows to Address Climate Change." Climate Change Secretariat, Bonn.

U.S. Energy Information Administration (EIA). 2016. *International Energy Outlook*. http://www.eia.gov/forecasts/ieo/emissions.cfm334

United States Global Change Research Program. 2009. *Second National Climate Assessment.* http://globalchange.gov/publications/reports/scientific-assessments/us-impacts.

———. 2014. *Third National Climate Assessment*, (May) Overview and Report Findings.

Vale, Petterson Molina. 2016. "The Changing Climate of Climate Economics." *Ecological Economics* **121**: 12-19.

Weitzman, Martin. 2009. "On Modeling and Interpreting the Economics of Catastrophic Climate Change." *Review of Economics and Statistics*, 91(1): 1–19.

World Bank. 2010. *World Development Report 2010: Development and Climate Change.* Washington, DC.

———. 2010. "The Costs to Developing Countries of Adapting to Climate Change: New Methods and Estimates." Consultation Draft.

World Health Organization. 2009. "Protecting Health from Climate Change: Connecting Science, Policy, and People."

Zhou, P. and M. Wang. 2016. "Carbon Dioxide Emissions Allocation: A Review." *Ecological Economics* **125**: 47-59.

DISCUSSION QUESTIONS

1. What is the main evidence of global climate change? How serious is the problem, and what are its primary causes? What issues does it raise concerning global equity and responsibility for dealing with the problem?

2. Do you think that the use of cost-benefit analysis to address the problem of climate change is useful? How can we adequately value things like the melting of Arctic ice caps and inundation of island nations? What is the appropriate role of economic analysis in dealing with questions that affect global ecosystems and future generations?

3. What goals would be appropriate in responding to climate change? Since it is impossible to stop climate change entirely, how should we balance our efforts between adaptation and prevention/mitigation?

4. Which economic climate change policy do you prefer: a carbon tax or a cap-and-trade system? Why? What are the main barriers to effective policy implementation?

5. Climate change policies can focus on changing behaviors or changing technology. Which approach do you think could be more effective? What policies can be used to encourage changes in each?

6. The process for formulating and implementing international agreements on climate change policy has been plagued with disagreements and deadlocks. What are the main reasons for the difficulty in agreeing on specific policy actions? From an economic point of view, what kinds of incentives might be useful to induce countries to enter and carry out agreements? What kinds of "win-win" policies could be devised to overcome negotiating barriers?

EXERCISES

1. Suppose that under the terms of an international agreement, U.S. CO_2 emissions are to be reduced by 200 million tons and those of Brazil by 50 million tons. Here are the policy options that the United States and Brazil have to reduce their emissions:

United States:

Policy Options	Total emissions reduction (million tons carbon)	Cost ($ billion)
A: Efficient machinery	60	12
B: Reforestation	40	20
C: Replace coal-fueled power plants	120	30

Brazil:

Policy Options	Total emissions reduction (million tons carbon)	Cost ($ billion)
A: Efficient machinery	50	20
B: Protection of Amazon forest	30	3
C: Replace coal-fueled power plants	40	8

a. Which policies are most efficient for each country in meeting their reduction targets? How much will be reduced using each option, at what cost, if the two countries must operate independently? Assume that any of the policy options can be partially implemented at a constant marginal cost. For example, the United States could choose to reduce carbon emissions with efficient machinery by 10 million tons at a cost of $2 billion. (Hint: start by calculating the average cost of carbon reduction in dollars per ton for each of the six policies).

b. Suppose a market of transferable permits allows the United States and Brazil to trade permits to emit CO_2. Who has an interest in buying permits? Who has an interest in selling permits? What agreement can be reached between the United States and Brazil so that they can meet the overall emissions reduction target of 250 million tons at the least cost? Can you estimate a range for the price of a permit to emit one ton of carbon? (Hint: use your average cost calculations from the first part of the question.)

2. Suppose that the annual consumption of an average American household is 1,000 gallons of gasoline and 200 Mcf (thousand cubic feet) of natural gas. Using the figures given in Table 4 on the effects of a carbon tax, calculate how much an average American household would pay per year with an added tax of $50 per ton of carbon dioxide if there was no initial change in demand. Then assuming a short-term demand elasticity of −0.1, and a long-term elasticity of −0.5, calculate the reductions in household demand for oil and gas in the short and long term. If there are 100 million households in the United States, what would be the revenue to the U.S. Treasury of such a carbon tax, in the short and long term? How might the government use such revenues? What would the impact be on the average family? Discuss the difference between the short-term and long-term impacts.

WEB LINKS

1. http://www.ipcc.ch/ The web site for the Intergovernmental Panel on Climate Change, a United Nations-sponsored agency "to assess the scientific, technical, and socioeconomic information relevant for the understanding of the risk of human-induced climate change."
2. http://epa.gov/climatechange/index.html The global warming web site of the U.S. Environmental Protection Agency.
3. http://www.wri.org/our-work/topics/climate/ World Resource Institute's web site on climate and atmosphere. The site includes several articles and case studies, including research on Clean Development Mechanisms.
4. http://unfccc.int/2860.php/ Home page for the United Nations Framework Convention on Climate Change. The site provides data on the climate change issue and information about the ongoing process of negotiating international agreements related to climate change.
5. http://rff.org/focus_areas/Pages/Energy_and_Climate.aspx and www.rff.org/research/topics/climate-change/ Publications by Resources for the Future on issues of energy and climate change.
6. www.hm-treasury.gov.uk/sternreview_index.htm/ Web site for the Stern Review, providing an extensive analysis of the economics of climate change including impacts, stabilization, mitigation, and adaptation.