ROBERT SCHUMAN CENTRE FOR ADVANCED STUDIES

EUI Working Papers

RSCAS 2012/72
ROBERT SCHUMAN CENTRE FOR ADVANCED STUDIES
Global Governance Programme-34

IMPLICATIONS OF CLIMATE SCIENCE FOR POLICY

Henry D. Jacoby

EUROPEAN UNIVERSITY INSTITUTE, FLORENCE
ROBERT SCHUMAN CENTRE FOR ADVANCED STUDIES
GLOBAL GOVERNANCE PROGRAMME

Implications of Climate Science for Policy

HENRY D. JACOBY

EUI Working Paper **RSCAS** 2012/72

ISSN 1028-3625

Printed in Italy, December 2012
European University Institute
Badia Fiesolana
I – 50014 San Domenico di Fiesole (FI)
Italy
www.eui.eu/RSCAS/Publications/
www.eui.eu
cadmus.eui.eu

Robert Schuman Centre for Advanced Studies

The Robert Schuman Centre for Advanced Studies (RSCAS), created in 1992 and directed by Stefano Bartolini since September 2006, aims to develop inter-disciplinary and comparative research and to promote work on the major issues facing the process of integration and European society.

The Centre is home to a large post-doctoral programme and hosts major research programmes and projects, and a range of working groups and *ad hoc* initiatives. The research agenda is organised around a set of core themes and is continuously evolving, reflecting the changing agenda of European integration and the expanding membership of the European Union.

Details of the research of the Centre can be found on:
http://www.eui.eu/RSCAS/Research/

Research publications take the form of Working Papers, Policy Papers, Distinguished Lectures and books. Most of these are also available on the RSCAS website:
http://www.eui.eu/RSCAS/Publications/

The EUI and the RSCAS are not responsible for the opinion expressed by the author(s).

The Global Governance Programme at the EUI

The Global Governance Programme (GGP) is research turned into action. It provides a European setting to conduct research at the highest level and promote synergies between the worlds of research and policy-making, to generate ideas and identify creative and innovative solutions to global challenges.

The GGP comprises three core dimensions: research, policy and training. Diverse global governance issues are investigated in *research* strands and projects coordinated by senior scholars, both from the EUI and from other internationally recognized top institutions. The *policy* dimension is developed throughout the programme, but is highlighted in the GGP High-Level Policy Seminars, which bring together policy-makers and academics at the highest level to discuss issues of current global importance.The Academy of Global Governance (AGG) is a unique executive *training* programme where theory and “real world” experience meet. Young executives, policy makers, diplomats, officials, private sector professionals and junior academics, have the opportunity to meet, share views and debate with leading academics, top-level officials, heads of international organisations and senior executives, on topical issues relating to governance.

For more information:

www.globalgovernanceprogramme.eu

Abstract

Climate change presents the greatest challenge ever faced by our domestic and international institutions, and great deal of the difficulty lies in the science of the issue. Because human influence on global climate differs in important ways from other environmental threats these peculiarities set the context for discussion of what can be done to reduce greenhouse gas emissions and to adapt to change that cannot be avoided. Following a brief summary of current understanding of how Earth's climate works, five ways are presented by which the science of climate impinges on attempts to construct a policy response.

Keywords

Climate change, climate science, policy.

Contents

.

1. The climate challenge

Societies have been dealing with environmental threats for centuries, each problem presenting its own set of institutional difficulties. Managing human influence on the Planet's climate presents a challenge beyond any confronted before, however, and the roots of the difficulty lie in the underlying science of the issue. Here we review our understanding of how the Earth system works and ways our activity is influencing it, and explore the reasons why the issue so severely challenges the mental capability developed in human evolution and the political institutions developed along the way.

1.1 Origins of the Science of Earth's Climate

Knowledge of the threat of climate change, and the policy challenges it presents, are founded mainly on scientific calculation. There is anecdotal evidence in our day-to-day experience that changes projected by scientific analysis are already taking place—for example in the earlier flowering of plants in some parts of the world, changes in migration patterns of birds, and increases in record high temperatures and intense storms. Also, thermometer and other measurements show an increase in global temperature over the past 150 years, but even these estimates require scientific analysis to convert widely distributed and sometimes sparse measurements into a global picture. Looking forward, projection of the response of the climate to human intervention is wholly a matter of research on the complicated interactions within the earth system, and simulation in computer models. So where does this knowledge base come from? The history is a long one, dating at least to the early 19th Century when Jean Baptiste Joseph Fourier, the great French mathematician and physical scientist, calculated that, given its distance from the Sun, the Earth should be cooler than it is. Among his hypotheses was the possibility that something in the atmosphere was acting as an insulator. Discovery of what might be the cause came with the work of the Irish scientist John Tyndall who in 1861 showed that water vapor and CO_2 can trap radiant energy. Then in 1896 a Swedish scientist, Svante Arrhenius, who was seeking to understand what caused the ice ages, concluded that the CO_2 added to the atmosphere could raise global temperature. He computed that a doubling of its atmospheric concentration would yield a 4°C increase, an estimate somewhat higher than current calculations but amazingly close considering the climate system knowledge and computation facilities at his disposal. One forecast Arrhenius got wrong: based on his expectation for the emerging industrial age and the absorption of CO_2 in the Earth system he thought it would take several thousand years to burn enough fossil fuels to yield an atmospheric doubling. In fact we are on a track to pass that milestone in the next few decades.

During World War II substantial advances were made in meteorology, and in following decades the computer revolution produced dramatic increases in the capacity for numerical calculation. Over time, facilities developed originally for numerical weather forecasting were extended to longer-term climate projections; eventually these were coupled to models of ocean behavior; and still later representations were added of the influence of the terrestrial biosphere. Also, governments supported growing programs of earth observations to support this research and analysis, so that by the turn of the 21st Century several billion U.S. dollars per year were being spent on climate research and observation in the U.S. Europe, Japan, Australia and several other countries.

This activity gained a major push in the 1970s when environmental threats were gaining greater salience in many countries, and summaries of then-current scientific knowledge supported the expectation that human emissions were at levels that could change the climate. In the U.S., for example, the so-called Charney Report commissioned by the President's Office of Science and Technology Policy (US NAS, 1979) played an important role in raising concern about the issue and increasing public and policymaker confidence in the ability of the emerging science to understand it. By the late 1990s political concern with the issue was rising and, to gain some coherence and quality control in the information being developed, governments created the Intergovernmental Panel on Climate Change (IPCC) with the task of periodically summarizing the research and analysis.

As of this writing work on the science of climate has spread around the world, and the IPCC is near completion of its Fifth Assessment Report (the AR-5). The science volume of the AR-5 will summarize results of climate projections by over a dozen large-scale models from the U.S. EU, Japan and Australia. The most complete of these models—the atmospheric-ocean general circulation models—are among of the largest numerical calculations ever attempted. Not surprisingly considering the complexity of the earth system, these efforts yield different projection of future climate, and even the spread among the models does not fully reflect the uncertainty. Thus in exploring the implications of the climate science for policy we are talking in the main about knowledge developed in these research and analysis activities, and the Earth observation systems that underlie them, and about the level of understanding of this work among the media, political leaders and the public.

1.2 Where the Science Impinges on Policy

Five characteristics of the issue can be identified that are particularly important in conditioning potential responses to the threat—either by reducing greenhouse emissions and other influences or by taking measures to ease adaptation to change that cannot be avoided:

- Scientific understanding of the planet contradicts our common mental model of environmental threats.
- There is not just one source of the climate change threat. Many and varied types of activities contribute to the human influence and some are hard to measure.
- Reduction of the threat requires emissions mitigation by many nations, rich and poor, creating a “commons” problem more complex than the world has confronted before.
- Uncertainty in scientific analysis of the response of global climate to greenhouse emissions complicates the process of deciding mitigation action.
- The effects of climate change at the local level are even more uncertain than at a global scale, yet it is at the local and regional levels where adaptation takes place.

In combination they present a challenge that thus far is proving to be beyond the coping capacity of our national and international institutions.

To see the depth of the problem, consider a comparison with another familiar environmental insult: health issues from the pollution of surface waters by human waste. We understand the main source of the problem—the sewer outflow of urban areas—and we have developed ways to allocate the cleanup cost in a politically acceptable manner. Moreover, we understand pretty well what will happen to stream quality if various treatment methods are applied. And finally, conditions at local scale are not hard to predict, and effects of adaptation to any residual risk (e.g., boiling water, purchase of bottled water) are easy to understand. It is not that these issues present no challenges to private decisions and public institutions, but what problems as there are do not reside in the science of water pollution.

We will return to these peculiar aspects of the climate threat, but first it is useful to work through a brief summary of current scientific understanding of how our planet works, to prepare a shared base of knowledge of system function and the terminology use to describe it.[1]

---

[1] A useful supplement to what follows is the Policymakers Summary if the IPCC’s Fourth Assessment Report (IPCC, 1997a) available at http://www.ipcc.ch/publications_and_data/ar4/syr/en/spm.html.

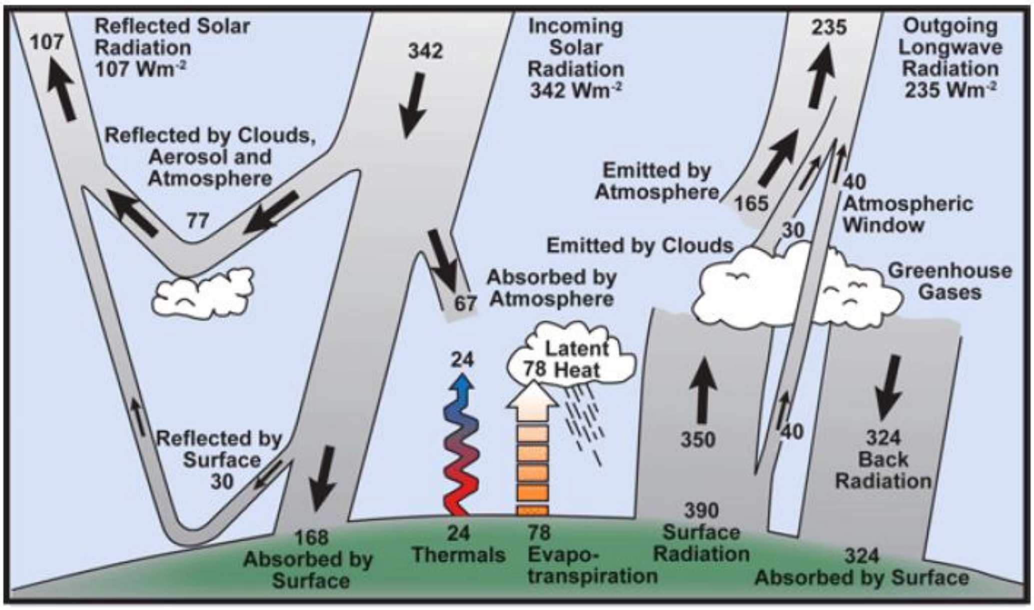
2. How our climate system works

2.1 The Earth, the Sun and the Greenhouse Effect

At the most fundamental level our climate is determined by the Earth's relationship to the Sun. Energy comes in from the Sun and is radiated back to space, and if these two are in balance the global temperature will be constant. If the energy sent out is less than that coming in the Planet will warm, and vice versa. It's as simple as that at one level: human-emitted greenhouse gases hold more of the incoming energy in the system.

The story at a more complete level is illustrated in **Figure 1**, which shows the flows of energy in and out of the Earth and the feedbacks within the system. A common unit of energy flow in climate analysis, used in this figure, is Watts per square meter of the Earth's surface (W/m^2).[2]

Figure 1. Estimates of the Earth's global mean energy balance (Kiehl and Trenberth, 2007)



The figure shows the Earth in balance with the sun and outer space, with these exchanges shown across the top of the figure. Incoming solar radiation, mainly at short wave lengths, is 342 W/m^2, and this is balanced by 107 W/m2 reflected to space at its original wavelengths, some from clouds and some from the surface, and 235 W/m^2 outgoing as longwave (infrared) radiation. Longwave radiation is given off by any warm body (the phenomenon exploited by the night scope on a soldier's weapon).

The key to a livable planet is shown in the right hand part of the figure. While reflected solar radiation passes back out of the system without interacting with molecules in the atmosphere, the longwave radiation does interact, reflecting 324 W/m2 back to the surface. The most important of these substances is water vapor, but also significant even in this picture of balance is a set of other natural greenhouses (GHGs) such as CO_2, methane, nitrous oxide and others to be discussed below. Now enter humans. We contribute additional volumes of the natural GHGs plus some we have

---

[2] Think of it this way: if you hold you hand at a distance of 3 meters from a 100 Watt radiant heater (which is sending heat in all directions) then your hand is receiving a bit more than 1 Watt of energy flow per m^2 of its area, because the surface area of a sphere is $4\pi r^2$, so the area of a sphere with r=3 m is 113 m^2.

invented, which has the effect of augmenting the 324 W/m^2 back radiation in the figure. More trapped heat warms the planet until the its hotter surface augments the previous outflow of longwave radiation to space by enough to restore balance.

Then there are additional phenomena that can be discussed using this figure. Human activity affects the reflection of solar radiation in two ways. White aerosols—mainly sulfate particles formed from sulfur emissions of coal-fired powerplants—increase reflection, with a cooling influence. And we influence the reflectivity of the surface, its so-called albedo, by changes in land use and by cutting the reflectivity of snow and ice by dirtying it with soot, which is produced mainly by Diesel engines and biomass burning. Not shown in the figure is another influence: black aerosols which absorb radiation, warming the atmosphere. The combined influence of these various effects is commonly referred to the anthropogenic “forcing” of the climate, also in W/m^2.

Also to be noted while looking at Figure 1 are positive feedbacks that accompany warming of the planet, to be discussed later. Warmer ocean and atmospheric temperatures lead to loss of snow and ice, which lowers the reflection of solar radiation from the surface, and aerosols have an effect on cloud formation, which influences their complex role in the energy budget. And, most important, a warmer atmosphere will hold more water vapor, increasing the power of the most important of the greenhouse substances.

2.2 Agents Forcing the Climate

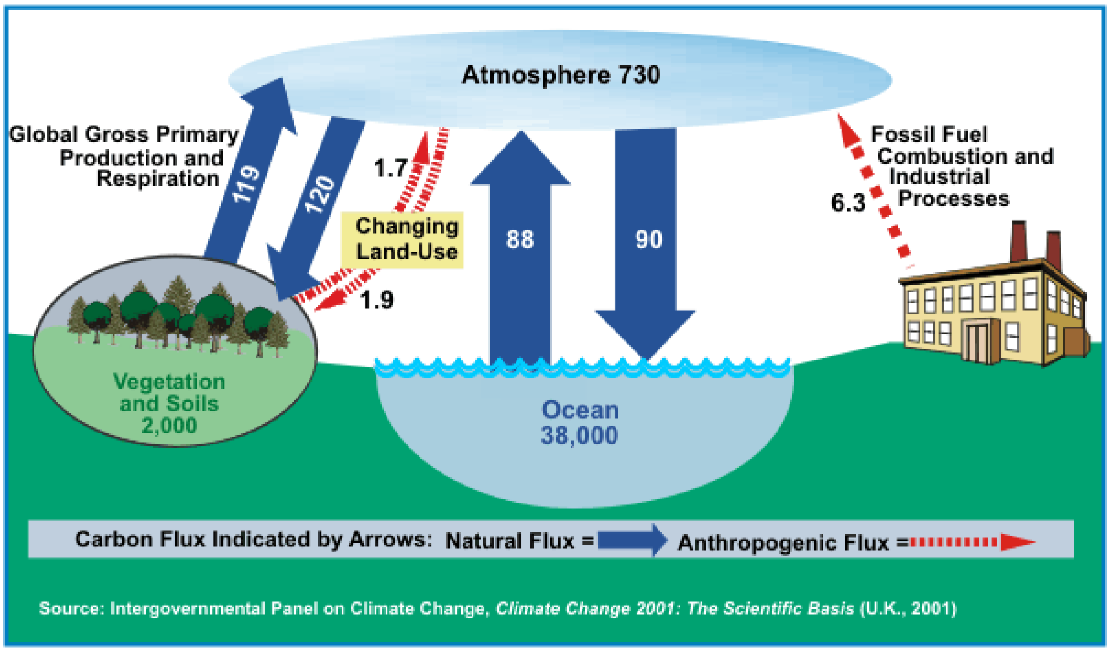
2.2.1 Carbon Dioxide and the Carbon Cycle

The increase in atmospheric carbon dioxide is the largest and most complex of the human climate forcings. The quantity of this element in the Earth system is fixed and (abstracting from the carbon locked up in carbonate rocks) it is in four pools that can be seen in **Figure 2**: fossil deposits (from which it is released by combustion), the oceans (surface and deep oceans and sediments), vegetation and soils, and the atmosphere.[3] Absent industrial development the carbon in fossil deposits was locked up on human time scales, but once released as CO_2 it enters a process of continual cycling among the other pools. As shown by the blue arrows in the figure, there are large natural flows of CO_2 in and out of the terrestrial biosphere (roughly 120 billion metric tons (Gt) per year) and somewhat smaller exchanges of CO_2 in and out of the oceans.

---

[3] The figure is in terms of carbon quantities: to convert the flows to CO_2 multiply by 3.6.

Figure 2. Global Carbon Cycle for the 1990s. Main annual fluxes shown in Gt of carbon per year (US DOE EIA, 2004).



Source: Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (U.K., 2001)

Then comes the human influence, indicated by the dashed red arrows. In the 1990s we removed 6.3 Gt per year of carbon from fossil deposits and converted it to atmospheric CO_2. Where did it go? There is a good deal of uncertainty about these numbers but, on average, part was taken up by the terrestrial biosphere (the difference between the two large arrows) and part by the oceans (also summarized by two arrows). The rest, about half, is accumulating in the atmosphere. An excellent illustration of how this process works is provided in a web video at http://www.youtube.com/carbontracker which shows the process from 1979 to 2011.[4] The bulk of the Planet's vegetation and soils are in the Northern Hemisphere, so they dominate the exchange with plants taking up CO_2 in the spring and summer and releasing it in the fall and winter. The gradual buildup over time in the atmosphere is dramatically portrayed. Since the 1770s, CO_2 in the atmosphere has increased from around 270 parts per million (ppm) to 390 ppm today. The video goes on to plot the CO_2 levels back in time for several hundred thousand years using data from ice cores and other sources. The CO_2 levels are correlated with temperature, so the path roughly traces the ice ages and warm periods of the distant past.

Figure 2, also highlights a fact about this greenhouse gas to which we will return later: its "stock pollutant" nature. It can be illustrated by the following calculation, which is not exact given the complexities of the carbon cycle but nonetheless informative. We have added 160 to 170 GtC as of the 1990s. If all human emissions were halted immediately, at what rate would the system return to its earlier state? Answer: the oceans and terrestrial biosphere would begin to remove the carbon at a rate of only around 4 GtC per year. Thus the climate influence of change already made to the Planet will continue for a very long time, even under the fantasy that we could halt all global emissions immediately.

---

[4] If this youtube version is not clear, the original file can be found at ftp://ftp.cmdl.noaa.gov/ccg/co2/carbontracker/movies/Globalview2011_pumphandle.mp4. It requires the facility to play an mp4 movie.

2.2.2 Non-CO2 Gases

Many gases can trap longwave energy, but the primary ones are listed in Table 1. Most are present in nature, but are augmented by industrial and farming activities. The most important is methane, which is released in fossil energy production and by agricultural activities that create conditions for methane-producing bacteria such as rice growing, releases from the intestines of ruminant animals like cows and sheep, and manure management. Another important source of methane is leakage from natural gas pipelines and consumer appliances. Nitrous oxide also is released in fossil combustion and in some industrial activities, but has its main source in agriculture where nitrogen fertilizer stimulates the activity of other bacteria that produce this gas.

Table 1. Non-CO_2 Greenhouse Contributors

	Sources	**Sinks**
Primary warming effects		
Methane (CH_4)	Biogenic, fossil	Destruction by OH
Nitrous Oxide (N_2O)	Biogenic, industrial	UV radiation
Sulfur Hexafluoride (SF_6)	Industrial, natural	Extremely stable
Hydrofleurocarbons (HFCs & HCFCs)	Industrial, natural	Destruction by OH
Perfleurocarbon (PFCs)	Industrial, natural	Extremely stable
Black carbon (aerosols)	Fossil, biofuels, dust	Deposition
Knock-on warming effects		
Ozone (O_3)	Fossil	Photochemistry
Cooling effects		
Sulfate aerosol (SO_2)	Fossil	Deposition

Then there are the industrial gases—HFCs and HCFCs used in air conditioning and various solvent applications, PFCs which are a by product of aluminum processing and are also manufactured for use in the electronics industry and other applications, and SF_6 which is used mainly as an insulator in electric transformers.[5]

Also shown in the table are the aerosols mentioned earlier, both the warming black aerosols and the reflecting sulfate aerosols that have a cooling effect. Then there is ozone, another greenhouse gas, which is emitted directly in infinitesimal quantities by human activity but is produced in the atmosphere by chemical action of two by-products of fossil fuel use: organic compounds from incomplete combustion and methane release, and NOx. (These influences will show up again below in discussion of mitigation strategies.)

Each of the non-CO_2 gases has limited residence time in the atmosphere (see Table 2). Carbon dioxide, which cycles in and out of the various pools, cannot be said to have a “lifetime”. At best estimates can be made of the approximate time an emitted molecule spends in the atmosphere before being absorbed into the terrestrial biosphere or the oceans—generally estimated to be somewhat over a century. All of the non-CO_2 substances, on the other hand, are subject to some process of chemical destruction or deposition, so lifetimes can be estimated which range from around a dozen years for methane to thousands of years for some of the industrial gases.

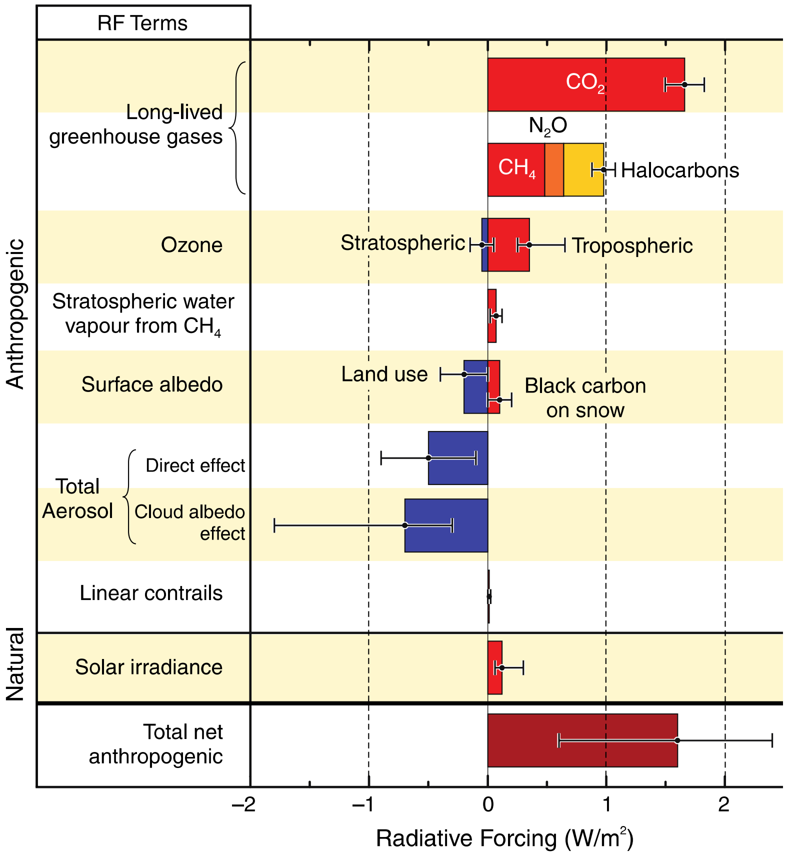
---

[5] Other greenhouse gases, which are already controlled under the Montreal Protocol for protection of the Ozone layer, are not shown here.

2.2.3 The Magnitude of Natural and Human Forcings

The contribution of these various substances in the long-run climate problem depends of course on the time each spends in the atmosphere, but an impression of their relative impact can be seen in an estimate of the changes in forcing by each over the period 1850 to 2005 (**Figure 3**).

Figure 3. Major Natural and Human Forcings, W/m^2, 1850-2005 (IPCC, 1997b)



The effect of each is shown in W/m^2, with a total anthropogenic forcing at the bottom. The longer-lived greenhouse gases, which are the ones included under the Kyoto protocol, are at the top of the figure, with CO$_2$ being the dominant influence over this period. Ozone is shown, with a cooling influence in the stratosphere but a dominant warming effect in the lower atmosphere or troposphere. Also shown are the changes in surface albedo as a result of land-use change and the dirtying of snow and ice with black aerosols. The effects of the cooling aerosols are shown to be relatively large over this period, both by direct reflection of solar radiation and through their estimated effect on clouds.

The whiskers shown for each greenhouse effect indicate levels of uncertainty in climate forcing. The heat trapping effect of the long-lived gases is pretty-well known. They are well mixed around the globe, and measurements of atmospheric concentrations are available for 1850 and 2005, so the uncertainty in their effects is small relative to the other influences. Uncertainty is greatest for the cloud albedo effect.

One natural forcing is included in the figure, because it has been argued that observed warming may be due to changes in the Sun's output. In fact the Sun is estimated to have brightened over the 55 years, but the effect is small compared to the sum of human influences. Note also that the small forcing from water vapor is a direct effect of methane emissions and not the much larger feedback effect of increased water in the atmosphere in response to higher temperature. Indeed, because the water vapor feedback is so large it is (along with the aerosol effect) a major source of uncertainty about the climate response going forward. Another big source of uncertainty is the behavior of the ocean.

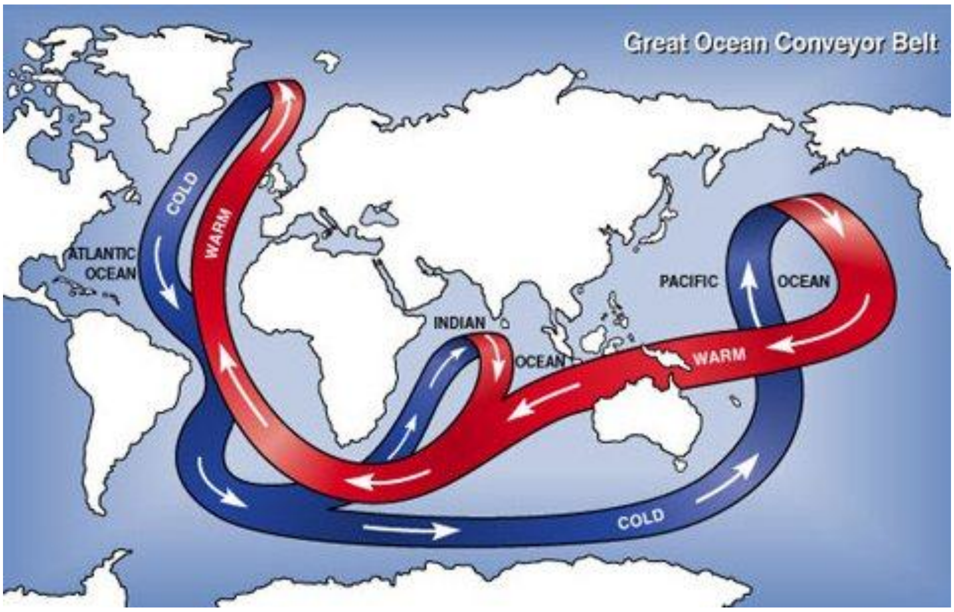
2.3 The Role of the Ocean

The oceans play a dual role in the climate system, involving both CO_2 and heat. They breathe CO_2 in and out as seen in Figure 2, with an overall net annual uptake now because of the human emissions of CO_2 into the atmosphere. And, as the atmospheric temperature rises the oceans absorb heat, in effect creating a “flywheel” effect that introduces a time lag in the effect of the human forcing. As a result the surface temperature is not yet in equilibrium with the current level of forcing shown in Figure 3; there is a yet unrealized “commitment” to further change in the climate even if human forcing were to stay at the current level.

The driver of this process is the deep circulations in the ocean. The top hundred meters or so is will mixed by wave action, so on a global average this top layer stays in close equilibrium with the atmosphere in terms of CO_2 and temperature. But this top layer alone could not hold the amount of additional CO_2 implied by the estimates in Figure 2, or take up a great amount of heat in adjusting to a rising atmospheric temperature. The flywheel effect occurs because CO_2-rich and warm water is taken from the so-called “mixed” layer and carried into the ocean deeps.

The process is complex, even chaotic, but a cartoon of one of the main components is shown in **Figure 4**. This is the thermohaline (i.e., heat and salt) circulation. Warm water from the tropics is driven by the Gulf Stream to latitudes around New England or Southern Europe. Farther north, in the Norwegian Sea, the surface water becomes very cold (and therefore heavier than the water beneath), and in the formation of sea ice the salt is left in the surrounding water (also increasing its density). So patches of this water sink, drawing the Gulf Stream waters further north, and creating a return flow along the bottom of the Atlantic as shown in the figure. In the process CO_2 is buried, and ocean regions below the mixed layer are warmed, taking up atmospheric heat. A similar process is initiated on the margins of Antarctica.

Figure 4. Cartoon of the Deep Ocean Circulation (US NASA, 2004)



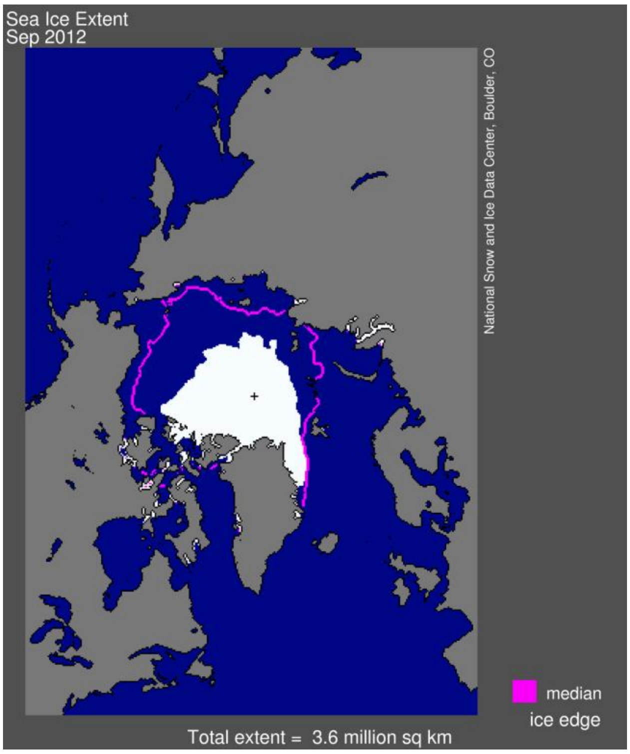
The time scale of these circulations if very long; some of these global circuits are estimated to take 800 to 1000 years. They are only partially understood, and therefore ocean uptake is an important source of uncertainty in the pace of the climate's response to human forcing.

2.4 Feedbacks with Rising Temperature

If these human forcings were all there was to climate change the threat would be much less serious than it is. But unfortunately there a number of system feedbacks to a rise in temperature, overwhelmingly positive ones that magnify the warming influence. Most important is the water vapor feedback. At warmer temperatures there is greater evaporation off the oceans, and a warmer atmosphere will hold more of the resulting water vapor, which is the most powerful greenhouse influence.

Then there are changes in the Earth's surface with warming. Rising temperatures are melting the Arctic sea ice, which returns solar energy back into space (see Figure 1). Over recent decades the loss of this reflective surface has been substantial. **Figure 5** shows the satellite record of the ice extent in near the end of the Northern Hemisphere melting period in fall 2012 compared to its size in 1979-2000. Changes in vegetation with climate can change reflectivity and emissions as well, with one of the more significant influences being increases in forest fires with rising temperature, releasing CO_2 to the atmosphere.

Figure 5. Fall Arctic Sea Ice Extent, 2012 Compared with 1979-2000 (NSIDC, 2012)



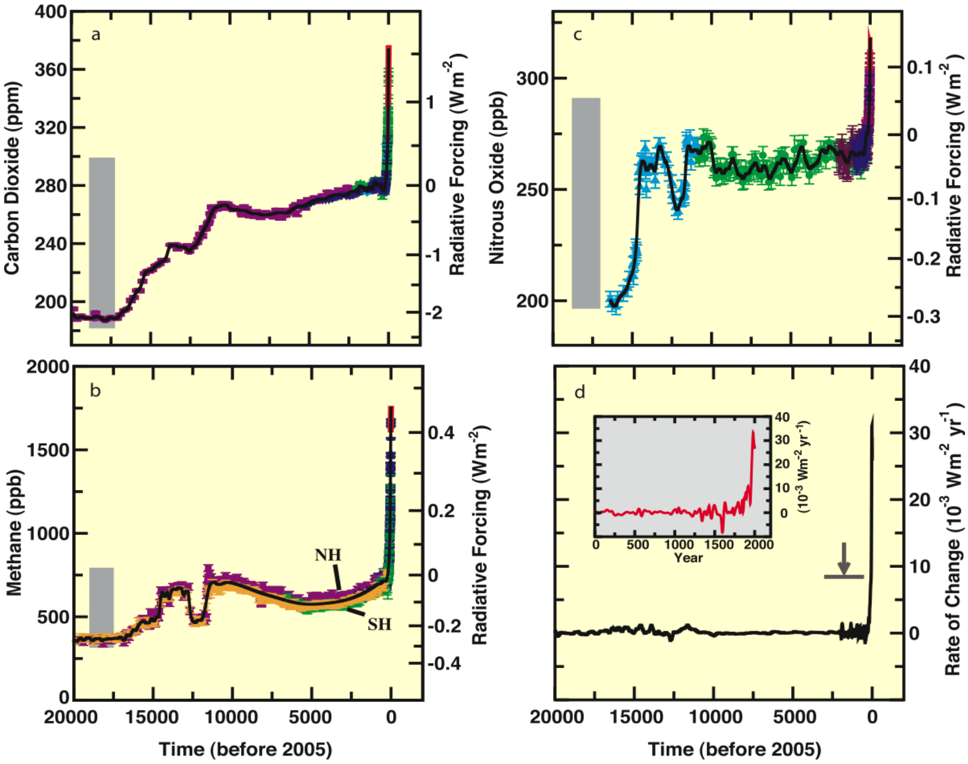
Finally, the deep ocean circulations may respond as well to rising temperature. Salinity in the northern seas will decrease if less sea ice is formed, and their surface temperature will rise. Both changes are expected to contribute to a slowing of thermohaline circulation. Though the potential is yet insufficiently understood, and likely is a multi-century process, it is another positive feedback serving to multiply the direct effects of human influences.

3. Where Are We Now, and where are we headed?

The globe is well into the process of climate change projected to result from these human activities and the feedbacks in the system. The scale of the influence, in relation to Earth's history over the past 20,000 years can be seen in **Figure 6** which shows the atmospheric concentrations of the three most important human greenhouse gases, CO_2, methane and nitrous oxide. For at least the past 20,000 years these concentrations were roughly constant, up to the beginning of the industrial age. On the lower right panel is displayed the pace of change in forcing in W/m^2, which integrates these influences.

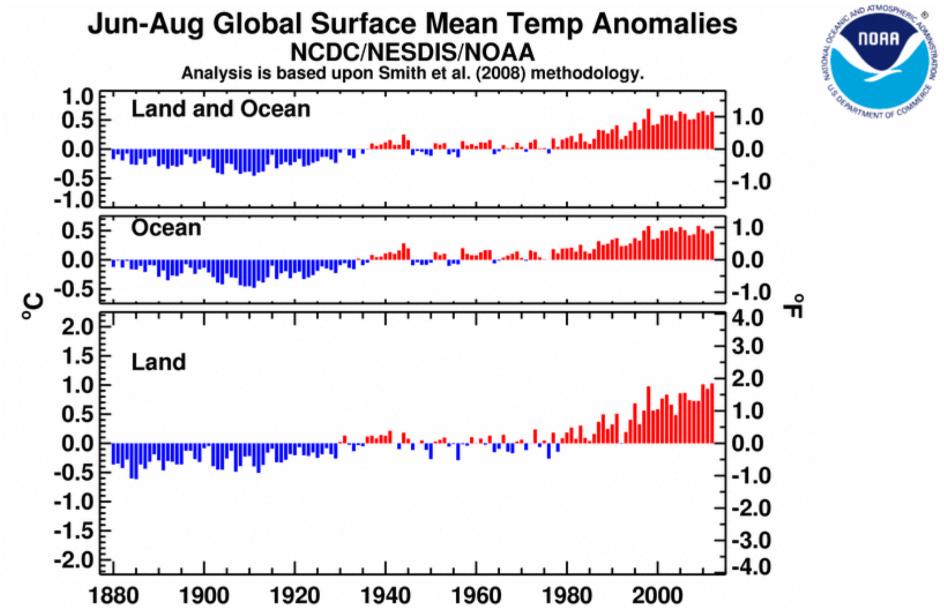
The gases controlled under the Kyoto protocol are CO_2, methane, nitrous oxide and a set of industrial gases (see Table 1) and a multi-gas total of the current concentrations can be estimated in CO_2 equivalents (noted as CO_2-e) using a set of relative weights discussed below. A concentration of around 450 parts per million (ppm) CO_2-e of the Kyoto gases is the stabilization level that some studies associate with a 50% chance of meeting a widely agreed goal of a maximum 2°C global temperature increase over the pre-industrial level (Webster et al., 2012). In 2012 the globe is at about 445 ppm CO_2-e and increasing at approximately 3 ppm per year.

Figure 6. Atmospheric GHG Concentrations, 20,000 years (IPCC, 2007)



The associated change in the surface temperature over the past 130 years is laid out in **Figure 7**. The change is shown as the anomaly or change from an average of 1940-1960. The oceans can cool themselves by evaporation, so note that the change over land is greater than the global total.

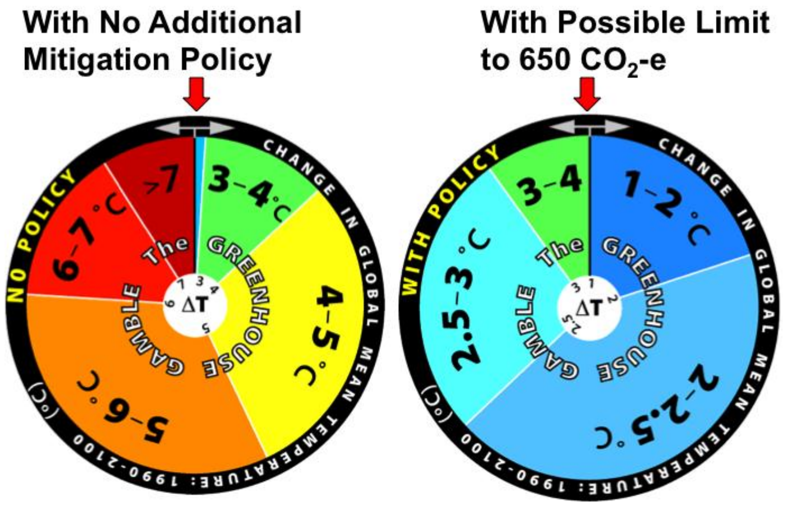
Figure 7. Global Surface Temperature Anomalies, January-August (US NOAA, 2012)



The global temperature increase over the period is about 0.8°C, with nine of the ten warmest years since 2000. In addition, it is estimated (IPCC, 1997b) that with current concentrations we are already committed to additional 0.6°C which we will experience only after the delay caused by ocean uptake of heat mentioned earlier.

Projections vary, but analysis by the MIT Joint Program on the Science and Policy for Global Change (Sokolov et al., 2009; Webster et al., 2012) indicates a wide range of global temperature outcomes if no further mitigation is undertaken, with a median (50% above, 50% below) of around 5°C by 2100 (and this is above 1990). This result is shown in the form of a roulette wheel on the left side of **Figure 8**. To illustrate the effect on the climate risk of mitigation policy, the wheel on the right shows the gamble if it proved possible to limit the concentrations (of Kyoto gases) to 650 ppm. Even then, the globe is expected to be in for substantial change, although the high-end of the risk is greatly diminished.

Figure 8. Global Climate Risk (Sokolov et al., 2009; Webster et al., 2012)



4. Where the Science Impinges on Policy Action

4.1 Contradicts Common Mental Models of System Behavior

The first challenge presented by the science of the climate change is the difficulty in understanding the nature and magnitude of the threat. Research on human behavior shows that most of us carry around a mental model of emissions and their effects—of pollution, that is—that is seriously at odds with these effects at planetary scale. It is not just that much of the population lacks scientific literacy, or that the heuristics all of us use in decision-making are subject to a number of errors biases (for a summary, see Kahneman, 2011). We are particularly bad at thinking though the effects of intervention in a complex system like the Earth's climate (Sterman, 2011).

For example, misunderstanding is created by the fact that we are dealing with long-term change in a system that is very noisy at the scale that most people experience it. The result is frequent confusion, in the media and in lay understanding, between climate (where change is only seen over many decades) and weather (our year-to-year experience). We have a tendency to base impressions of change on recent experience (an availability bias) and thus to credit the projections of global warming in a particularly hot month, but question the science in an unusually cold one.

To see the seriousness of the challenge, take a look at the pattern of temperature change over the globe in the past century in a video prepared by the U.S. NASA (http://www.nasa.gov/topics/earth/features/2011-temps.html). First, view the sequence while focusing on the place where you are. What would your experience tell about change over time? Then back off and view again, taking in the global picture. People experience the temperature and rain or snowfall where they live, and it is a challenge to overcome this impression based on global measurements and scientific calculations that most have scant basis to understand. (A map of precipitation would show even more variation over space and time.)

Another source of difficulty is poor understanding of systems of stocks and flows. It is not that we lack experience with such dynamics: we deal with them all the time in filling a bathtub, managing a bank account or worrying about our weight. But there is ample evidence of widespread difficulty in grasping the fundamental stock-flow aspect of greenhouse gases (Sterman, 2011). As emphasized above, what matters to the climate are the concentrations of CO_2 and other substances in the atmosphere, and to stabilize concentrations the rate of emissions must be brought down to equal the rate of uptake or destruction. Unfortunately, it is widely perceived that simply stabilizing emissions will stabilize concentrations. It is a mental model consistent with other pollution problems—like noise or river pollution—but wrong in this context.

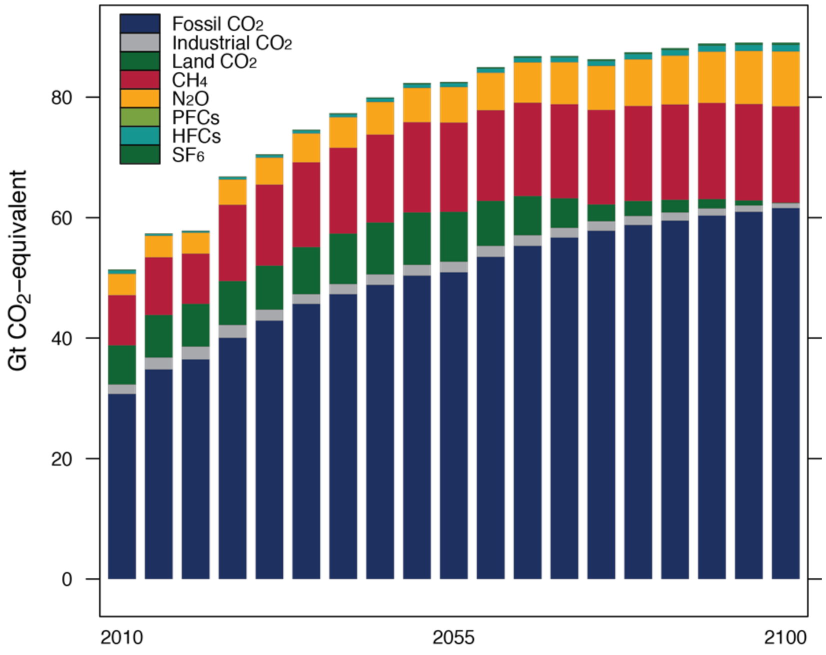
Related to the stock-flow problem is an incorrect appreciation of the role of time delays in the system. Two examples will make the point. A common argument in policy discussions, in the face of uncertainty, is to "wait and learn". Again, for many environmental issues this is a sound mental model, because the seriousness of the problem will be roughly the same in a few years and we may then know better how to deal with it. But it is wrong in this case: for a stock pollutant the threat *does* get worse with delay because the stock in the atmosphere is increasing. Contributing to this problem is poor understanding of ocean circulations, and the time delay they introduce into climate response to forcing. Because we are committed to change we have not yet seen, impressions of the threat based on current conditions or change to date are further flawed.

These problems of inadequate mental models of climate change not only influence public understanding of the science and choices faced; they also provide opportunities for argument by those opposed to action. Thus policy in this area needs to include a continuing effort to inform, putting scientific results into language that avoids further increasing these difficulties.

4.2 Requires Attention to Multiple, Diverse, Poorly Measured Influences

Managing an environmental threat is easier if there is one focus for a response. For example, if overfishing is depleting ocean stocks, then the solution is limits on catch. Unfortunately, climate-forcing activities are spread across the modern industrial/agricultural economy; no such simple control is adequate. **Figure 9** shows a projection of total GHG emissions assuming no further control beyond those in place in 2011. Most discussions of climate policy naturally focus on fossil CO_2 emissions, the largest component of human influence. Whatever the global target, however, stabilization of atmospheric concentrations by the end of the century requires control of *all* these GHG sources (plus black carbon aerosols not shown here) at a level of stringency sufficient to cut their total contribution to levels that can be absorbed or destroyed by Earth processes.

Figure 9. Global Greenhouse Gas Emissions (MIT JP, 2012)



The atmospheric concentrations of all these gases are accurately measured around the globe on a regular basis. Emissions present greater measurement problems. For some GHGs the sources are known and well measured. This is true, for example, for fossil CO_2 emissions and the industrial gases (PFCs, HFCs and SF_6). For others, however, the science does not support accurate quantification. As noted above, farming practices the main sources of methane and nitrous oxide and these sources are highly dispersed, which also is the case for methane released from natural gas infrastructure. Estimates are made, to support emissions inventories prepared by national governments and by individual sectors and emitters. But means are lacking to measure these so-called non-point sources at sufficient accuracy to support regulatory or price penalties.

Similar problems arise in the measurement of emissions from forests destruction, mainly in the tropics, which is the main component to the land CO_2 component in Figure 9. Despite a great deal of effort to combine on-ground and satellite measurement the irreducible error creates problems in application to systems of penalty and reward.

A further problem of emissions quantification arises in calculations that appear to be grounded in the science of climate but that in fact contain elements that lie beyond the domain of scientific disciplines. In deciding the allocation of mitigation effort there is a need to be able to express the relative importance of the various GHGs. The mix of these gases varies among nations, and some weighting scheme is also needed to be able to compute totals for discussion of equity among parties. Also, such weights are required if there is to be emissions trading among the gases. The ideal would be a measure of relative future economic and ecological damage attributable to each, or even a measure of the contribution to future temperature increase. Such measures raise insurmountable obstacles of uncertainty and estimation, however, so the solution has been to pick an intermediate level of climate influence: the effect of each on radiative forcing over time—the Global Warming Potential or GWP (**Table 2**). The GWP provides the relative weights needed to convert all gases into CO_2 equivalents, as applied in Figures 8 and 9.

Table 2. Global Warming Potentials for Different Integration Periods (IPCC, 2007b)

	Lifetime (Years)	Time Horizon (TH) in Years		
		20	100	500
Methane	12	72	25	7.6
Nitrous Oxide	114	289	298	153
HFC-23	270	12,000	14,800	12,200
HFC-134a	14	3,830	1,430	435
SF_6	3200	16,300	22,800	32,600

The GWPs are calculated by simulating a pulse of each gas in a climate model, tracking the influence on W/m^2 over time, and summing the influences.[6] The results then differ by the heat-trapping power of each substance and the speed by which it is either taken up by the oceans and terrestrial biosphere or destroyed in the atmosphere. In this calculation there is one key input that the science cannot resolve: what should be the integration period over which the calculation is made? A short period gives more weight to shorter-lived gases and vice versa. Table 2 shows the effect of using a 20, 100 or 500 year period. Through agreements in the IPCC nations have decided to use the 100-year GWPs for reporting, trading agreements, etc., but much controversy remains. For example, when there is a focus on climate effects over the next few decades there is an argument for using the 20-year GWP in order to give a proper weight to methane on this time horizon. If done the change would triple the weight given a ton of methane in relation to a ton of CO_2. A question also remains whether an additional relative weight should be imposed on methane for its knock-on effect on the generation of ozone, a greenhouse gas that also damages CO_2-absorbing vegetation.

4.3 Demands Cooperative Effort by Parties with Diverse Interests

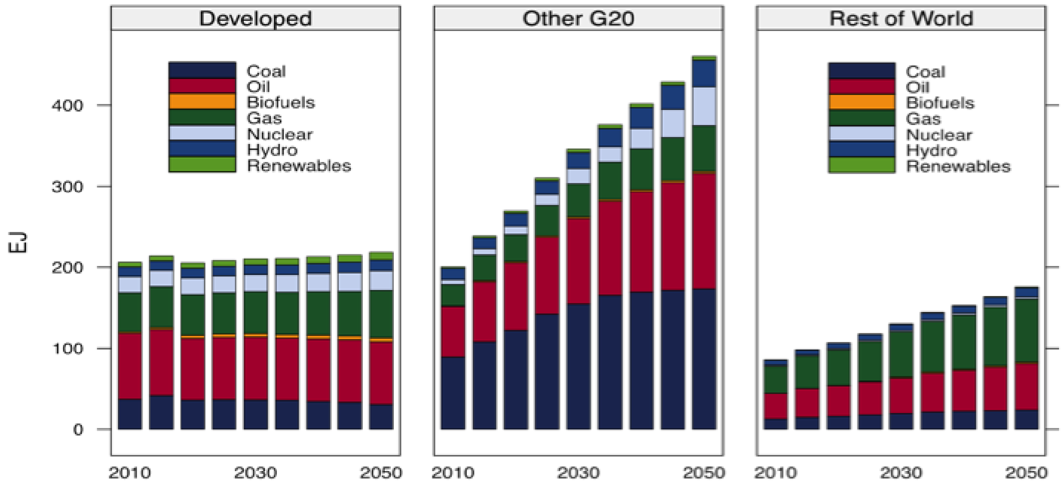
Over past decades nations have developed policy regimes to deal with a number of international environmental problems ranging from the disposal of toxic waste to protection of endangered species. For some the number of major players was small, simplifying the process of agreement if interests in the issue were aligned. For example, only a small number of nations are relevant to agreements to lower stockpiles of nuclear weapons, and in the case of the Montreal Protocol on Substances that Deplete the Ozone Layer only a few nations were producing the offending chemicals. For the climate issue the commons problem is truly global. Though not all nations are essential to reducing the risk, a large number are. Moreover their interests lack alignment in crucial dimensions.

The nature of this aspect of the challenge can be seen in **Figure 10**, a projection to 2050 of energy use (the main source of GHG emissions) assuming no mitigation efforts beyond those in place in 2012. The Developed Country group includes the U.S., E.U., Japan, Canada, and

---

[6] The lifetimes in Table 2 do not indicate when the pulse has completely disappeared from the atmosphere but when the number of molecules is reduced by 1/e where e=2.72.

Figure 10. Projected Energy Use by Region (MIT JP, 2012)



Australia and New Zealand, and their energy use is projected to be flat over the period. The main growth is in the Other G20, which for the model applied in this analysis includes Brazil, China, India, Mexico, Russia and a set of dynamic Asian countries. The Rest of World aggregates everybody else. The science makes clear that the planet doesn't care where the long-lived GHG emissions originate, so to make any substantial reduction in human influence the G20 as a whole must be involved. For the tighter emissions targets those nations outside the G20 cannot be left unrestrained.

Obvious in this picture, then, is a serious misalignment of interests. A reduction in emissions can be imagined for the Developed group, because they are relatively rich, and even without additional effort their emissions are not expected to grow much. On the other hand all of the Other G20 are nations are at much lower income levels and so more sensitive to the costs of emissions control (**Table 3**). Moreover, most are either in a period of rapid economic development or aspiring to be so. Any effective international agreement must achieve perceived equity among participants while producing big cuts in emissions. The challenge to international institution is evident in the 20-year history of the Framework Convention on Climate Change.

Table 3. Projected Per-Capita GDP (2004 prices) and CO_2 Emissions (metric tons) in 2015 (MIT JP, 2011)

	Per Capita, 2015	
	GDP	CO_2 Emissions
U.S.	43,000	19.3
E.U.	28,000	7.9
Brazil	5,410	2.3
China	1,380	7.2
India	1,120	1.9

4.4 Reveals Uncertainty that Complicates Mitigation Decision

As noted above, each member of a large family of climate models projects change over this century and beyond, but they differ in important details of future patterns of temperature and precipitation. Moreover, uncertainty analysis using a single model (Figure 8) reveals great uncertainty even if emissions uncertainty is removed (as in the right-hand wheel in the figure). These results reflect the current state of the science as employed in projections of the behavior of the climate system in response to human influence. Nevertheless, they clearly suggest serious future risk to ecosystems and national economies.

Unfortunately, this unavoidable level of uncertainty also impedes the formulation of commitment to reduce the risk. Some participants in the policy process simply don't trust the science. And even those with respect for the science may interpret the uncertainty to mean that understanding is yet insufficient to justify action to limit emissions. At worst, the issue is cast as a matter of "belief". In this formulation climate change is either real or it is not, like the virgin birth, and uncertainty in scientific analyses is taken as indicating a lack of proof. Proper application of the science will cast the climate threat not as a true-false question (act urgently if it is real; do noting if it is not) but as a challenge of risk management. This is a way of thinking about decision under uncertainty that we apply all the time in our private lives (e.g., how radically to change diet to lower cholesterol and the risk of heart disease) and in public decision (how aggressively to pursue a vaccination program to manage the risk of flu epidemic). The debate of climate policy has been too often driven away from this way of formulating the choice, however, and correction of this mis-definition would go a long way to overcoming the barriers created by unavoidable uncertainty about the magnitude of the threat.

Even given acceptance of climate change as a serious risk, limits to our understanding also lead to difficulties in deciding the proper response. This is in part because the science cannot yet support precise quantitative descriptions of what the uncertainties actually are—a shortcoming has come to be known as the problem of "fat tails". To frame the issue, consider the following question: What should be the CO_2 price in the European Trading System? Most observers would agree that the price at the time of this writing (around €7 per ton CO_2) is too low, but also that €150 would be too high. Where do these views come from? Apart from notions of political feasibility, which no doubt intervene, a substantial influence is a concept in economics that the policy task is to appropriately spread pain over time. Emissions now will cause damage in the future (say, in lost consumption), and we can lower future pain by taking some penalty now (diverting current consumption to emissions mitigation). Impressions of future economic and environmental damage may be foggy, and the way future and current costs are compared may be obscure, but the underlying conception is nonetheless common, and not just among economists. It leads to opinions about the price today and to the expectation that it should rise over time as future emissions are expected to cause larger incremental damage.

This benefit-cost way of thinking about mitigation effort is implemented in policy procedures. For example, for federal rulemakings and other policy decisions the U.S. Office of Management and Budget requires an analysis of monetary costs and benefits. To this end the U.S. Environmental Protection Agency must prepare an analysis of the monetary benefit of reducing a current ton of CO_2—what is called the Social Cost of Carbon (SCC)—to be compared with the cost of measures to limit emissions (US EPA, 2010). The estimation of the SCC is based on a set of computer models that simulate the temperature effect of an additional ton of CO_2 today, impose a mathematical function to represent estimated damage of that change in the future, and (employing some discount rate) smooth the pain over time in a way that maximizes some measure of human welfare.[7]

The same formulation is applied when the analysis includes formal representations of uncertainty in these processes. To highlight difficulties of the climate issue, consider the simpler case of river pollution by urban waste. For a given waste discharge there is uncertainty in the resulting water quality—because of uncertainty in flow, temperature, biological processes, etc. And whatever the water quality in the river there is uncertainty in the damage, say in fish kills and human disease. To calculate the benefit of reducing urban discharge the range of potential water quality outcomes can be weighted by their probabilities to compute an expected quality level. And potential but uncertain levels of damage, for that expected river quality, can be weighted by their probabilities to yield an

---

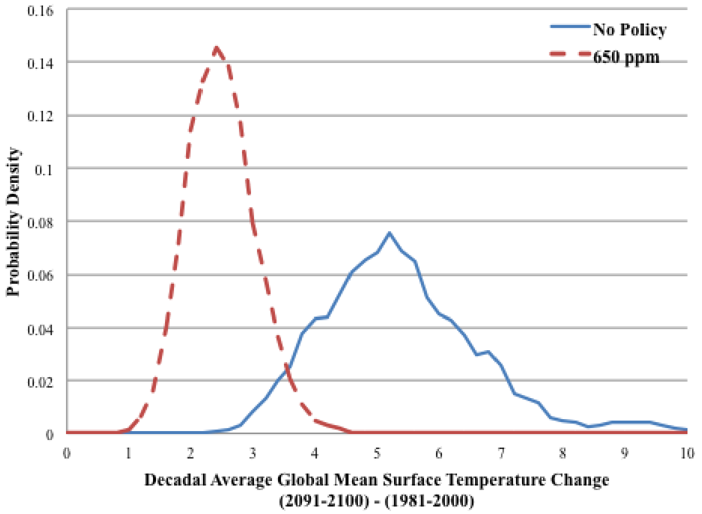
[7] There are, of course, many difficulties with such analyses, not least being the valuation of non-market effects and the choice of discount rate, but here the focus is on issues in the underlying climate science.

overall estimate of the expected benefit of a reduction in discharge.[8] For water pollution this is a credible and easily understood calculation because we have extensive experience with the biology of rivers and with the effects of polluted waters on fish and human health.

Now consider the difference with anthropogenic climate change. We have just one planet, and human greenhouse emissions are pushing some of its climate processes outside the experience of the past 20,000 years (see Figure 6) and longer. This means that estimates of the parameters of uncertainty measures of climate response are themselves uncertain. (Various names are given to this condition including deep uncertainty and structural uncertainty).

As an example, look again wheel on the right side of Figure 8, where policy constraint removes the uncertainty in emissions. Underlying the uncertainty in that projection are estimates, based heavily on analysis of climate behavior in the 20th Century, of the parameters (e.g., mean, variance) of probability distributions of cloud behavior and aerosol effects (Figure 3), deep ocean circulations (Figure 4), and aspects of CO_2 emissions from the terrestrial biosphere (Figure 2). The resulting probability distribution that was re-stated in the form of the Figure 8 roulette wheel is shown in Figure 11. The distribution for the policy (650 ppm) case looks like a bell-shaped curve (a normal distribution) whose tails are pretty "thin": under the 650 ppm target the probability of a temperature increase exceeding 4°C is near zero. However, given that the uncertainty parameters are based on a single planet, with limited data about this one, these parameters are themselves uncertain. So, if we *could* take this parameter uncertainty into account the resulting distribution would be more spread out. To use the term introduced earlier, it has an unseen "fat" upper tail. The science often cannot support a precise description of what is out there in the tail and when it might happen; moreover, even where events can be described scientific support may be lacking to estimate how likely they are.

Figure 11. PDFs of Temperature Change for No Policy and a 650 ppm Target (Webster et al., 2011)



Examples of such phenomena in the climate response include the potential for warming to release huge quantities of methane now trapped in clathrates (ice crystals in the Arctic and in ocean sediments), or a rapid slowdown in the deep ocean circulations. In the damage estimates such tail events include the potential for rapid melting of Greenland and collapse of the West Antarctic ice

---

[8] To see this done for climate using an integrated assessment model see Nordhaus, 2008.

sheet, leading to several meters of sea level rise; and the possible damage to ocean biota and the food web of CO_2-induced acidification of ocean waters.[9]

If societal aversion to these low-probability but high-consequence outcomes is very great, then the adequacy of the standard benefit-cost approach to informing mitigation effort is called into question. Indeed, some (admittedly restrictive) conditions of probability, consequence and risk aversion lead to a collapse of the concepts underlying benefit-cost analysis with its objective of appropriately smoothing consumption over time (Weitzman, 2009, 2011).[10] The policy objective then becomes focused on buying insurance against catastrophe. Even short of these extreme cases, however, the phenomenon of fat tails means that most benefit-cost estimates of mitigation effort—valuable as they are in tuning intuition—do not convey the whole story. Aversion to risks that the science cannot yet quantify will be an important influence on policy deliberations, leaning toward a more aggressive current response than the standard benefit-cost analysis would indicate, and to support for those who would inject the precautionary principle into policy debates.

This state of scientific understanding of the climate system calls for the use of policy instruments that can be flexible over time as earth-system knowledge is gained. (The same conclusion emerges from consideration of uncertainty in the costs of control. and this concern arises in decisions about adaptation as well as for mitigation.) As in most problems of risk management under uncertainty, climate policy is best thought of as facilitating a process of sequential decision: act now based on current knowledge, learn over time, and revise later based on any new information. It is a model of the policy process that is consistent with the fact that governments cannot make commitments for long periods of time, but its implications are not always considered in formulating the details of mitigation proposals.

4.5 Creates Special Difficulty in Formulating Adaptation Measures

Whatever success we may have in limiting greenhouse emissions the Planet faces changes in climate to which human and natural systems will have to adapt. Many of these adjustments will take place gradually, in response to change as experienced year to year, “on the ground” as it were. For example, shifts in rainfall and temperature will change the economics of different crops and where they are grown, leading to shifts over time; changes in atmospheric conditions and availability of food supplies will lead to changes in migration patterns of birds, other animals and insects. Indeed some of these effects are seen in the response of natural systems to the climate change already experienced.

However, some adaptation could be very expensive if it is not possible to anticipate what is coming. For example, large capital facilities underlie the water management systems that support irrigated agriculture and industrial and residential water services. These systems take a long time to develop and are very costly, so systems built now need to take account of conditions under projected climate change, and appropriate near-term revision of existing systems could lower the economic loss when the climate change comes. For instance, a change in mountain runoff from slowly melting snow to winter and spring rainfall may call for substantial revision in the design of irrigation systems and the water storage reservoirs that support them. Without a change in technology electric powerplants may not be able to depend on streams and rivers for the quantity and temperature of flow needed for cooling.

---

[9] The fat tail problem is not unique to climate change. For example, biotechnology research to engineer the bird flue virus to become transmittable among humans, seeking benefits in formulating ways to handle an epidemic should the mutation come naturally, carries an unquantifiable tail risk of escape from the lab into the wild. Similar concerns can be found in areas like genetically engineered crops, nanotechnology and nuclear proliferation.

[10] The relevance of the fat tails problem is intensively debated in the economics literature, with an informative exchange provided by Weitzman (2011) and Nordhaus (2011). The issue also troubles the estimate in the U.S. of the social cost of carbon: see the technical note that can be downloaded at US EPA (2010).

Or, to take a regulatory example, many governments compute maps of likely flooding from rivers and streams and use this information in determining zoning regulations, requirements for the design of structures flood zones, and insurance rates. These estimates determine the location of large swathes of urban and industrial activity and thus the risks to which they will be subject in the future. Many governments and private industries are already trying to formulate investment and regulatory policies that anticipate potential change in the hope of lowering the associated economic cost and social disruption.

But here again the climate science intercedes. The uncertainty in future change at global scale is already great, as indicated in Figure 8. But adaptation decisions depend on climate conditions at local scale: the particular agricultural zone, valley or river basin. At these local scales the uncertainty in future change is even greater. Even computer models of the climate that agree on change at global scale may yield estimates of the change in runoff in a particular river basin that differ not only in magnitude but also in sign: some project more water, some less. Indeed it is a general characteristic Earth systems that the smaller the region of interest the greater the additional uncertainty in modelling the climate change effects. Another pass through the 20th Century (http://www.nasa.gov/topics/earth/features/2011-temps.html) suggests this result should be no surprise.

The implication for policy of the higher level of uncertainty is that the planning of anticipatory adaptation, be it by investment or regulatory change, needs to be based on an expression of the full uncertainty of future projections at local scale. Decisions made on the basis of one or two scenarios could lead to costly decisions, and very often the proper response may be to provide more flexibility for adjusting to future conditions that cannot now be specified even though there is a high likelihood that *some* change is coming.

5. Combined effects on the Choice of Response Strategy

The formulation of strategy to deal with the climate change threat is greatly complicated by the combination of these various characteristics of the issue. The magnitude of the climate challenge can again be highlighted in contrast to a superficially similar problem: formulating a respond to the threat to the stratospheric ozone layer by a set of industrial gases. In negotiation of the Montreal Protocol the interest of the main parties (developed countries and firms that produced these gases) were aligned, a narrow set of gases were at issue, corresponding policy on adaptation to increased UV radiation was not an issue, and compensation of nations adjusting to the change was easily handled. It is not so easy with climate, where

- Participation is required by parties whose interests are not aligned
- Emissions with different origins and lifetimes, some poorly measured, must be dealt with
- Adaptation is a serious issue and not completely separate from mitigation
- Uncertainty is greater and harder to quantify
- Involvement of both rich and poor nations will require financial substantial differences in effort according to ability and likely some financial assistance.

And, of course these same issues serve to complicate not only international agreement but also the formulation of the domestic actions within each country.

Given these characteristics of the climate issue, the appropriate strategy for the needed international response remains unclear even after two decades of struggle. Is it to best to follow the Montreal Protocol model and seek a global agreement covering all nations and all these issues? This is the strategy underlying the various stages of negotiation under the Framework Convention on Climate Change, including the latest effort under the Durban Platform (UN FCCC, 2011). Is it likely more productive to focus on various "club" agreements, which may be build around groups where interests are more closely aligned (e.g., the Asia-Pacific Partnership, Major Economies Forum, G-20, G8+5)? Or is a set of bilateral agreements among major players the way forward?

There is even a choice of which of the human influences should be the focus in any agreement. Negotiations in the Framework Convention have taken (on all at once) long-lived and short-lived gases weighted by the Global Warming Potentials in Table 2. An alternative suggested by UNEP and WMO (2011) is to seek an agreement focused on short-lived substances—methane, and black carbon—motivated in part that agreement may be facilitated by the non-climate co-benefits that would result from the reduction in air pollution. Or is it likely that this combination of problem characteristics will necessarily lead to a combination of all, in a loosely coordinated regime “complex” (Keohane and Victor, 2010)?[11] Though one can hope national interests may come to be better aligned, the scientific characteristics of the climate threat are not likely to change in coming decades, so the complications it introduces will continue.

---

[11] Expectation of this outcome is consistent with a more formal analysis of “polycentric” governance as applied to climate change by Cole (2011).

6. References

Cole, D., 2011: From Global to Polycentric Climate Governance, EUI Working Paper RSCAS 2011/30, Robert Schuman Centre for Advanced Studies, European University Institute, Florence.

IPCC [Intergovernmental Panel on Climate Change], 2007a: *Synthesis Report, Summary for Policymakers*, R. Pachauri and A. Reisinger (eds.), Cambridge University Press, Cambridge, United Kingdom and New York, NY. http://www.ipcc.ch/publications_and_data/ar4/syr/en/spm.html

IPCC [Intergovernmental Panel on Climate Change], 2007b: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change,* S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Avery, M. Tignor and H.L. Miller (eds.), Cambridge University Press, Cambridge, United Kingdom and New York, NY.

Keohane, R., and D. Victor, 2010: The Regime Complex for Climate Change, Discussion Paper 10-33, Harvard Project on International Agreements, Kennedy School of Government, Harvard University, Cambridge, MA.

Kahneman, D., 2011: *Thinking Fast and Slow,* Farrar, Straus and Giroux, New York, NY.

Kiehl, J. and K. Trenberth, 1979: Earth's Annual Global Mean Energy Budget, *Bull. Amer. Meteor. Soc.* 78: 197-208.

MIT JP [MIT Joint Program on the Science and Policy of Global Change], 201: Energy and Climate Outlook 2012, Cambridge, MA. http://globalchange.mit.edu/research/publications/other/special/2012Outlook

NSIDC [National Snow and Ice Date Center], 2012: Press Release: Arctic sea ice shatters previous low records; Antarctic sea ice edges to record high, Boulder, CO. (http://nsidc.org/news/press/20121002_MinimumPR.html)

Nordhaus, W., 2008: *A Question of Balance: Weighing the Options on Global Warming Policies,* available for download at http://nordhaus.econ.yale.edu/cv_current.htm.

Nordhaus, W., 2011: The Economics of Tail Event with an Application to Climate Change, *Review of Environmental Economics and Policy* 5(2): 240-257.

Sokolov, A., P. Stone, C. Forest, R. Prinn, M. Sarofim, M. Webster, S. Paltsev, C.A. Schlosser, D. Kicklighter, S. Dutkiewicz, J. Reilly, C. Wang, B. Felzer, J. Melillo, and H. Jacoby, 2009: Probabilistic Forecast for 21st Century Climate Based on Uncertainties in Emissions (without Policy) and Climate Parameters, *Journal of Climate* 22(19): 5175-5204 [Erratum].

Sterman, J., 2111: Communicating climate change risks in a skeptical world, *Climatic Change* 108: 811-826.

UNEP and WMO [UN Environment Program and World Meteorological Organization], 2011: Integrated Assessment of Black Carbon and Tropospheric Ozone, United Nations Environment Program and World Meteorological Organization, UNEP/GC/26/INF/20.

UN FCCC [UN Framework Convention on Climate Change], 2011: Establishment of and Ad Hoc Working Group on the Durban Platform for Enhanced Action, Conference of the Parties, Seventeenth Session, FCCC/CP/2011/L.10.

US EPA [US Environmental Protection Agency], 2010: The Social Cost of Carbon: Estimating the Benefits of Reducing Greenhouse Gas Emissions, http://www.epa.gov/climatechange/EPAactivities/economics/scc.html

US NAS [US National Academy of Sciences, 1979: Carbon Dioxide and Climate: A Scientific Assessment, Washington, DC.

US NASA [US National Atmospheric and Space Administration], 2004: NASA Science Space News, Washington, DC. (http://science.nasa.gov/science-news/science-at-nasa/2004/05mar_arctic/)

US NOAA [US National Oceanic and Atmospheric Administration, National Climate Data Center], 2012: State of the Climate: Global Analysis for August 2012, published online September 2012, retrieved on October 1, 2012. http://www.ncdc.noaa.gov/sotc/global/2012/8.

Webster, M., A. Sokolov, J. Reilly, C. Forest, S. Paltsev, C.A. Schlosser, C. Wang, D. Kicklighter, M. Sarofim, J. Melillo, R. Prinn and H. Jacoby, 2012: Analysis of policy targets under uncertainty, *Climatic Change* 112(3-4): 569–583.

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

Weitzman, M., 2011: Fat-Tailed Uncertainty in the Economics of Climate Change, *Review of Environmental Economics and Policy* 5(2): 275-292.

Author contacts:

Henry D. Jacoby
MIT Sloan School of Management
Office: E19-429H
50 Memorial Drive
Cambridge, Massachusetts 02142
United States
Email: hjacoby@mit.edu

European
University
Institute

European University Press