Mitigation, Adaptation or Climate Engineering?

*Guy P. Brasseur and Claire Granier**

Concerns about climate change have led to the development of legal frameworks, including national regulations and international protocols to limit the emissions of greenhouse gases. Current mitigation measures, however, may not be sufficient to limit global warming to an average of 2°C since the pre-industrial period. Other approaches may therefore be required, including adaptation measures and climate engineering initiatives. Only a few legal frameworks are available to regulate adaptation initiatives and to constrain climate engineering approaches whose potential side-effects are not always sufficiently well known.

This Article provides a brief overview of scientific progress made to better assess climate change and addresses possible societal responses, including the mitigation, adaptation and climate engineering strategies. It provides a brief summary of current knowledge about expected climate change as a basis for the definition of future international climate policies and associated legal frameworks.

Introduction

Climate models indicate that, if the atmospheric abundance of carbon dioxide (CO_2) and other greenhouse gases (GHGs) continues to increase, the global average temperature will rise, with potential consequences for weather patterns.

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Even though many uncertainties remain in the quantitative estimates of regional manifestations of climate change, specifically of potential disturbances in precipitation intensity and frequency, it is very likely that changes in the global climate system during the twenty-first century will be larger than those observed during the twentieth century.

To address this issue of highest importance for future generations, several options are available. The first is to reduce drastically the emissions of GHGs at the global scale, which would require a rapid de-carbonization of our energy system and other measures. The alleviation of GHG emissions is known as climate *mitigation*. If the international negotiations that would have to accompany the development of a global mitigation strategy fail, or if this approach is felt to be too cumbersome economically by some nations, society will have to develop *adaptation* measures that limit the physical, economic and social consequences of climate change. Many countries, provinces and urban entities are already developing comprehensive adaptation plans directly relevant to different sectors of the economy and to public services. Finally, it has been suggested that technologies should be developed that reduce the intensity of climate change, either by capturing a considerable amount of the CO_2 present in the atmosphere or by generating a physical mechanism at the planetary scale that would compensate for greenhouse warming. This approach, known as *climate engineering* or *geo-engineering*, has triggered lively scientific, economic and even ethical discussions and is often regarded as a last recourse if the two other options fail or are insufficient. The potential side-effects of implementing climate engineering methods remain poorly known.

The objective of this Article is to discuss the different approaches available to address climate change from the specific point of view of physical climate scientists. In Part I, we briefly review the current state of climate science, specifically providing a summary of recent climate projections. In Part II, we highlight the implications of a mitigation strategy for anthropogenic CO_2 emissions. In Part III, we briefly introduce the concept of climate adaptation, and in Part IV, we discuss the two classes of climate engineering approaches.

I. Current Situation and Projections

Already in 1896, Nobel Prize laureate Svante Arrhenius suggested that burning coal from our mines would considerably enhance the atmospheric abundance of CO_2 in the atmosphere and that a doubling of this concentration would produce approximately a 5°C warming of the planet.[1] Since this pioneering

1 Svante Arrhenius, *On the Influence of Carbonic Acid in the Air upon the*

study, much work has been devoted to a better understanding of the physical, chemical and biological processes affecting the Earth's climate. Systematic atmospheric and oceanic observations have revealed the existence of complex dynamical patterns and modes of variability, such as El Niño in the Pacific, the Madden-Julian Oscillation in the tropics, or the North Atlantic Oscillation, which have considerable influence on weather features, including the occurrence of extreme weather events (i.e., heat waves, extreme precipitation, etc.). These studies have highlighted the importance of coupling mechanisms between the components of the Earth system, specifically between the atmosphere and the ocean.

These observations have also revealed the existence of long-term trends in key climatic variables such as temperature and precipitation. Statistical analyses conducted in parallel by different groups have shown that, globally, the planet is currently 0.8°C warmer than in 1850 and that this warming trend is occurring in all regions of the world.[2] The trend is more pronounced over the continents than over the oceans and at high latitudes than in the tropics. Substantial changes have also been reported in the hydrological cycle.

Different types of climate models have been developed for many years. Simple energy balance models based on radiative transfer laws have been complemented by more complex general circulation models that account for the three-dimensional exchanges of mass, momentum and energy both within the atmosphere and the ocean, and between these components of the Earth. Contemporary models also account for exchanges with the land surface and its ecosystems, and include a detailed representation of the hydrological cycle, including ice energetics and dynamics, cloud microphysics and precipitation, aerosol physics, biophysics including vegetation dynamics, as well as biogeochemistry including the carbon cycle and atmospheric chemical transformations.[3]

These models have been used to simulate the natural variability in the climate system with the objective of analyzing observed patterns and better understanding the complex nonlinear interactions that take place in the Earth system. These investigations constitute an important prerequisite for reliable

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Temperature of the Ground, London, Edinburgh, and Dublin, 41 PHIL. MAG. 237 (1896).

2 INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE (IPCC), CLIMATE CHANGE 2007: THE PHYSICAL SCIENCE BASIS (2007).

3 Peter R. Gent et al., *The Community Climate System Model Version 4*, 24 J. CLIMATE 4973 (2011); Marco A. Giorgetta, Guy P. Brasseur, Erich Roeckner & Jochem Marotzke, *Preface to Special Section on Climate Models at the Max Planck Institute for Meteorology*, 19 J. CLIMATE 3769 (2006).

climate simulations or projections. The models have also been used with some success to simulate the past evolution of the Earth's climate in response to estimated radiative forcing related to the growing atmospheric concentration of GHGs and aerosol particles.[4] In addition to the rapidly increasing anthropogenic emissions of CO_2, a rather large contribution to greenhouse forcing (warming) results from the radiative effects of other GHGs or air pollutants, including methane, nitrous oxide, tropospheric ozone and black carbon (soot).[5] Sulfate aerosols, a product of coal combustion, produce a cooling of the Earth's surface, either directly by scattering a fraction of solar radiation back to space or indirectly by affecting the optical and physical properties of clouds.[6] Different indirect effects of aerosols on clouds have been identified,[7] and their formulation in climate models remains a challenge with which large uncertainties are associated.

Climate models have also been used to project how the climate system would respond to changing radiative forcing. Since the future evolution of GHG emissions depends directly on the unpredictable level of the world's future development and related economic cycles, climate projections must be based on prescribed scenarios for these emissions. International projects supporting the activities of the Intergovernmental Panel on Climate Change (IPCC) have provided such scenarios. The results of such simulations by a large number of models have been analyzed in the successive IPCC reports, and will not be discussed in detail here. As an illustration, however, Figure 1 shows globally averaged temperature changes calculated by Gerald A. Meehl et al.,[8] using the NCAR Community Earth System Model (CESM)[9] and different GHG emissions projections developed for the fifth IPCC Assessment Report, which is in preparation.

4 IPCC, *supra* note 2.

5 Veerabhadran Ramanathan & Gregory R. Carmichael, *Global and Regional Changes Due to Black Carbon*, 1 Nature Geoscience 221 (2008); Drew T. Shindell et al., *Improved Attribution of Climate Forcing to Emissions*, 326 Sci. 716 (2009).

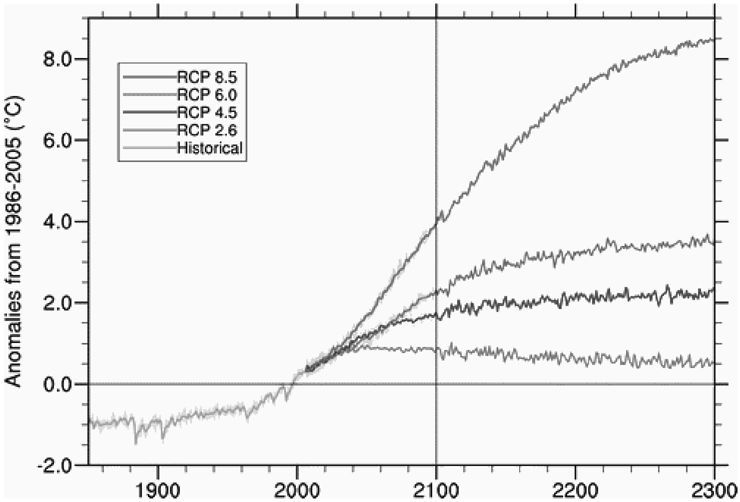
6 Jean-Louis Dufresne et al., *Contrast of the Climate Effects of Anthropogenic Sulfate Aerosols Between the 20th and 21st Century*, 32 Geophysical Res. Letters (2005), *available at* http://www.lmd.jussieu.fr/~jldufres/publi/2005/Dufresne.Quaas.ea-grl-2005_bw.pdf.

7 Sean Twomey, *The Nuclei of Natural Cloud Formation Part II: The Supersaturation in Natural Clouds and the Variation of Cloud Droplet Concentration*, 43 Geofisica Pura e Applicata 243 (1959).

8 Gerald A. Meehl et al., *Climate System Response to External Forcings and Climate Change Projections in CCSM4*, 25 J. Climate 3681 (2011).

9 Gent et al., *supra* note 3.

Figure 1: Global Surface Temperature (1850-2300)



Projected evolution of the globally averaged surface temperature for different GHG emission scenarios (RCP 2.6; 4.5; 6.0; 8.5[10]). The historical evolution of the temperature since 1850 is simulated on the basis of recorded past emissions (results from the NCAR Community Earth System Model).

Details of these recently developed IPCC scenarios are provided by Detlef P. van Vuuren et al.[10] What is striking about this figure is that the temperature will increase over the next forty years at a rate that is almost independent of the adopted emissions scenario (due in large part to climate inertia). The temperature increase beyond these next forty years will be largely determined by the mitigation decisions made in the very near future.

Figure 2 shows an estimate by the NCAR CESM[11] of future surface temperature changes for three scenarios (RCP 2.6, 4.5 and 8.5). Clearly, the expected warming will be largest in the two Polar Regions and will at first be more pronounced over the continents. Figure 2 (right) shows future changes in precipitation between the periods 1980-1999 and 2080-2099 derived from multi-model simulations. Even though there are some inconsistencies between individual models, specifically in the white areas of the map, all of them show a substantial reduction in the precipitation abundance in the subtropical belts, with severe droughts to be expected in several regions, including the Mediterranean basin, Mexico, the Southwestern part of the

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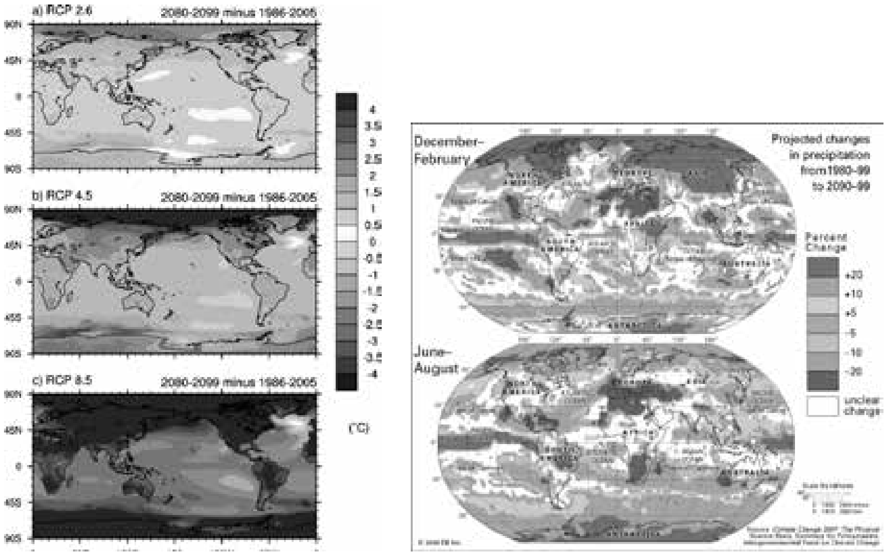
10 Detlef P. van Vuuren et al., *The Representative Concentration Pathways: An Overview*, 109 Climatic Change 5 (2011).

11 Gent et al., *supra* note 3.

United States, Australia and South Africa. The situation is particularly critical for Southern Europe, North Africa and the Middle East and will have severe societal impacts, including adverse effects on the availability of water, with consequences for the agricultural food system and food availability. A recent report of the National Research Council summarizes expected impacts as a function of the mean warming of the planet (Figure 3).[12]

Figure 2: Future Climate Change



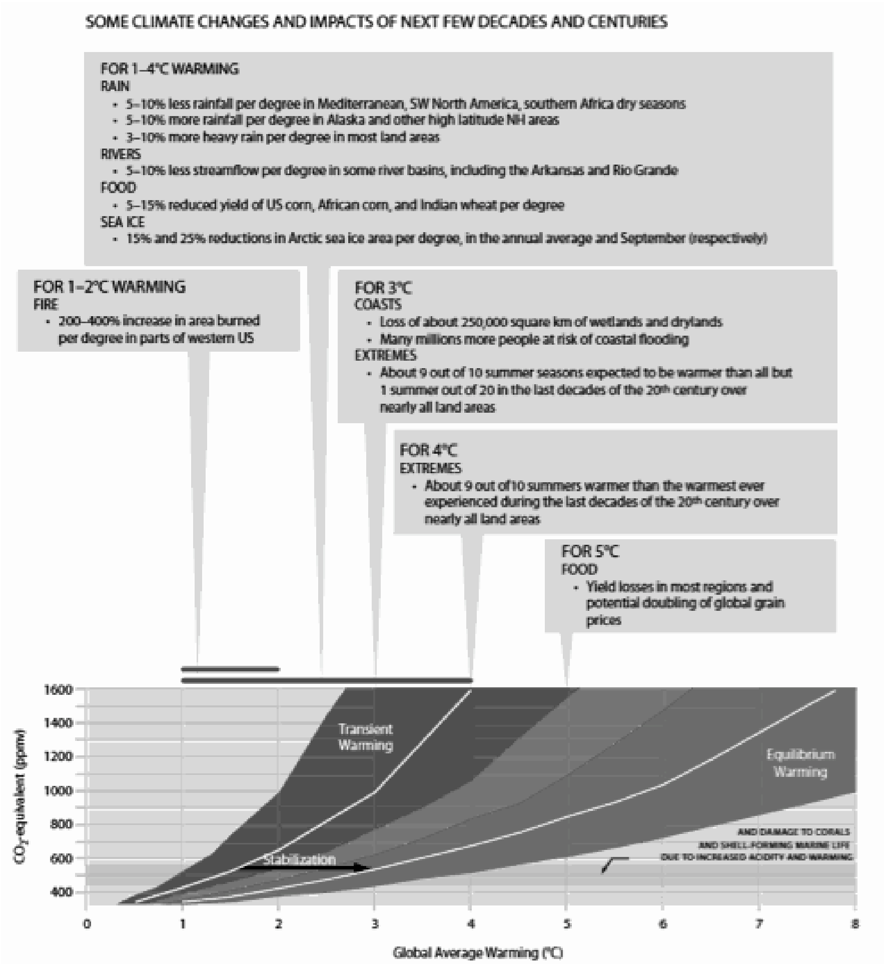
Left: Calculated temperature change (Celsius) between the period 1986-2005 and the period 2080-2099 for three climate forcing scenarios (RCP 2.6, 4.5 and 8.5), as derived by the NCAR Community Earth System Model. Right: Projected change in precipitation between 1980-1999 and 2080-2099 based on different global climate models.[13] Regions in white correspond to areas where models do not provide a consistent picture and the expected changes are therefore very uncertain.

The need to limit climate change through a vigorous mitigation policy at the international level is therefore central to any international climate policy. Society, however, has recently realized that this approach may not be sufficient, and that the development of adaptation strategies to unavoidable climate change will be needed; furthermore, that a mix of mitigation and adaptation

12 Nat'l Acad. of Sci., Climate Stabilization Targets: Emissions, Concentrations, and Impacts over Decades to Millennia (2010).

13 IPCC, *supra* note 2.

Figure 3: Future Climate Changes and Its Impacts



Top Panel: Climate impacts (water cycle, food, coasts, extremes) for different possible increases in the global mean temperature of the planet. Lower Panel: Relation between global warming and equivalent CO_2 concentration for transient (short-term) and equilibrium (long-term) warming.

measures may not be enough to address the challenge of climate change, which may require some additional actions involving climate engineering. This last option, however, is not without potential technical and political problems, so that understanding the technical opportunities and environmental risks of climate engineering should be considered as a high research priority.

Several anticipated effects and impacts of global warming expressed per degree of warming. The graphical part of the diagram shows that the transient, or near-term, warming produced by increasing CO_2 concentrations is only a fraction of the total warming — the equilibrium warming — expected to occur.

II. Mitigation

Discussions within the scientific community have led to the conclusion that, to avoid dangerous impacts to society, the global mean temperature of the planet should not increase by more than 2°C above its pre-industrial level.[14] This clear and simply stated objective has been adopted by many nations (including the European Union) and by the G-8 summit as an important goal to be achieved through appropriate actions.[15] Figure 4, based on two climate models of intermediate complexity (the Bern model and the University of Victoria model), shows that a decrease of eighty percent in the CO_2-equivalent emissions will be required to limit the Earth's warming to 2°C, with the CO_2 concentration limited to a peak at about 450 ppmv. This requirement sets ambitious technical and political goals for the nations in the future.

Dirk Messner et al. have analyzed the implications of such drastic mitigation measures.[16] They conclude that, if the total emissions of CO_2 are limited to 750 gigatons (Gt), the probability of exceeding the warming limit of 2°C is only thirteen percent. With such a value serving as a constraint for the world, an international mitigation strategy can be developed. It is clear from Figure 5 that the rate at which the CO_2 emissions need to decrease depends on how rapidly mitigation measures are taken. The maximum rate is of the order of 3.7% per year if emission reductions are in effect as soon as year 2011, but reach almost ten percent per year if a business-as-usual emissions scenario continues to apply until year 2020.

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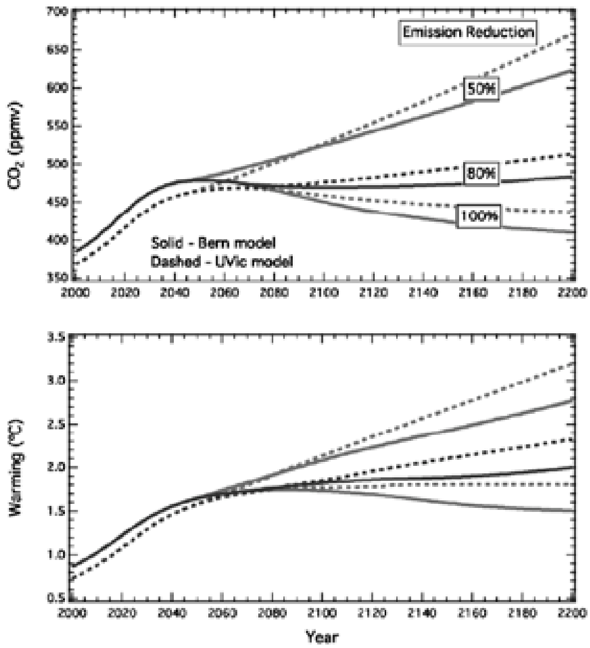
14 Ramanathan & Carmichael, *supra* note 5; Shindell et al., *supra* note 5.

15 Presidency Conclusions, Brussels European Council (Mar. 23, 2005), *available at* http://www.consilium.europa.eu/ueDocs/cms_Data/docs/pressData/en/ec/84335.pdf.

16 Dirk Messner et al., *The Budget Approach: A Framework for a Global Transformation Towards a Low Carbon Economy*, 2 J. Renewable & Sustainable Energy 031003 (2010).

Figure 4: Strategy to Limit Global Warming to 2°C[17]



CO_2 concentrations (upper panel) and related mean temperature increase (lower panel) derived by two models (Berne and University of Victoria) in which the emissions first increase and then decrease by three percent per year to a value of fifty percent, eighty percent, or a hundred percent below the peak. The mean temperature increase does not exceed 2°C if the CO_2 emissions decrease by at least eighty percent.

The German Wissenschaftlichen Beirats der Bundesregierung Globale Umweltveränderungen (WGBU), as well as Messner et al.,[18] have proposed a method to distribute the 750 Gt constraint among the nations of the world.[19] This organization bases its suggestion on different principles: (1) the industrialized nations carry a particular responsibility; (2) damages to future generations should be avoided or minimized; (3) each individual on the planet has the right to emit the same amount of GHGs; and (4) international negotiations on emissions should allow improvements to the system.

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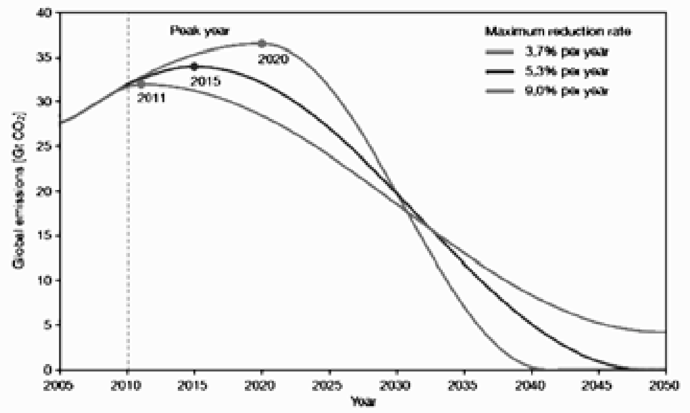
17 Nat'l Acad. of Sci., *supra* note 13.

18 *Id.*

19 German Advisory Council on Global Change (WBGU), Solving the Climate Dilemma: The Budget Approach (2009), *available at* http://eeac.hscglab.nl/files/D-WBGU_SolvingtheClimateDilemma_Dec09.pdf.

Figure 5: Reduction of Anthropogenic CO_2 Emissions Required to Limit Global Warming to 2°C[17]



Three possible trajectories in the annual global CO_2 emissions to reduce the total anthropogenic CO_2 released to the atmosphere to 750 Gt.

Table 1 shows how emissions should be distributed among several nations according to these principles, specifically according to criterion (3). Under these assumptions, Germany, for example, which represents 1.2% of the world's population, should not release a total of more than nine Gt CO_2 or, if distributed uniformly over the 2010-2050 period, 0.22 Gt CO_2 per year. This last number needs to be compared with the 2008 emissions of 0.95 Gt per year. The last column in the table shows after how many years the available total "stock" of CO_2 emissions will be fully used. Again, this table shows how difficult it will be not to exceed the 750 Gt CO_2 and the 2°C goals defined at the international level. Mitigation will require partnerships with newly industrialized countries and the recognition that climate protection is a cross-cutting theme in development policies. If this limit of 2°C is transgressed, adaptation measures will have to be implemented. This represents another challenge for society. Even if the 2°C goal is achieved, however, society will still need to adapt to the unavoidable changes expected over the next three to four decades.

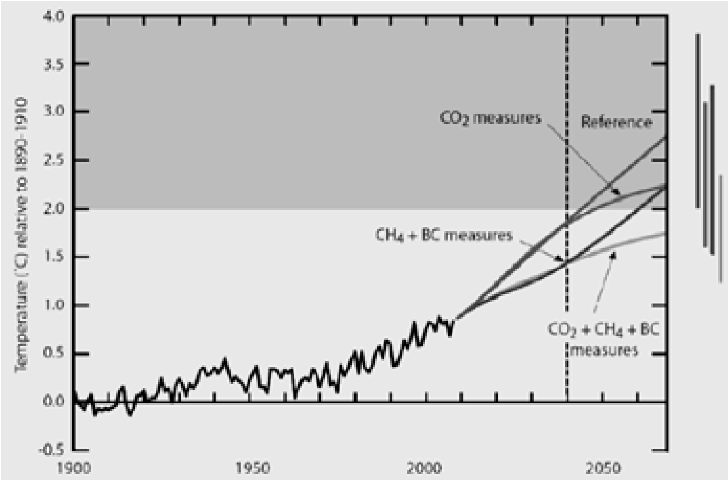
The lifetime of CO_2 in the Earth system is very long and, as a result, even immediate reductions in CO_2 emissions, which are crucial when considering long-term climate change, will not have a substantial effect on the climate of the coming decades. It has therefore been suggested that the atmospheric concentration of other radiative active compounds be reduced, including methane, a very powerful GHG, and black carbon (soot). Methane is a product of agricultural activity as well as natural resources extraction. Black carbon is

Table 1: Share of World's Population, Related Annual Emission Constraints Compared to Real Emissions for Several Countries

	Share of the world population in 2010 (%)	Budget 2010-2050 (Gt CO_2)		Estimated emissions in 2008 (Gt CO_2)	Reach of the budget lifetime, assuming annual emissions as in 2008 (year)
		Total period	Per year		
Germany	1.2	9.0	0.22	0.91	10
USA	4.6	35	0.85	6.1	6
China	20	148	3.6	6.2	24
Brazil	2.8	21	0.52	0.46	46
Burlina Faso	0.24	1.8	0.043	0.00062	2892
Japan	1.8	14	0.34	1.3	11
Russia	2.0	15	0.37	1.6	9
Mexico	1.6	12	0.29	0.46	26
Indonesia	3.4	25	0.62	0.38	67
India	18	133	3.2	1.5	88
Maldives	0.0058	0.043	0.0011	0.00071	61
EU	7.2	54	1.3	4.5	12
World	100	750	18	30	25

released in the atmosphere as a result of industrial and domestic combustion as well as biomass burning. Figure 6 shows the high sensitivity of the global mean surface temperature of the Earth to a reduction in the emission of CO_2 and relatively short-lived species, i.e. methane and black carbon. Under the adopted scenarios, limiting global warming to 2°C requires emission reductions not only for CO_2 but also for the short-lived species. Immediate reduction in the emissions of these compounds in addition to CO_2 would substantially increase the likelihood of keeping global warming below 2°C. There would be other positive effects of such actions for air quality (human health) and food security.

Figure 6: Evolution of the Global Mean Temperature Relative to 1890-1910[20]



Evolution of the global mean temperature relative to 1890-1910. The past evolution corresponds to the observation. The mean temperature evolution fort he future is a function to different measures taken to limit the atmospheric concentration of methane (CH_4), black carbon (BC) and carbon dioxide (CO_2).

III. Adaptation

If mitigation policies fail and the Earth's warming exceeds 2°C, specific measures will have to be taken to moderate the adverse impacts of climate change. In light of the fact that the poorest populations are the most vulnerable to climate disturbances, the actions will have to be taken in an international framework, but with regionally differentiated implementations. Exploiting the potential beneficial opportunities resulting from climate change is another aspect that will have to be considered.

The vulnerability of a society to the potential impacts of climate change is determined by several aspects: the degree to which it is exposed to change; how capable individuals and organizations are of adapting effectively to that change; and the extent to which adaptation options may be limited by competing pressures. Actions to reduce vulnerability and increase resilience are schematically described by Figure 7.

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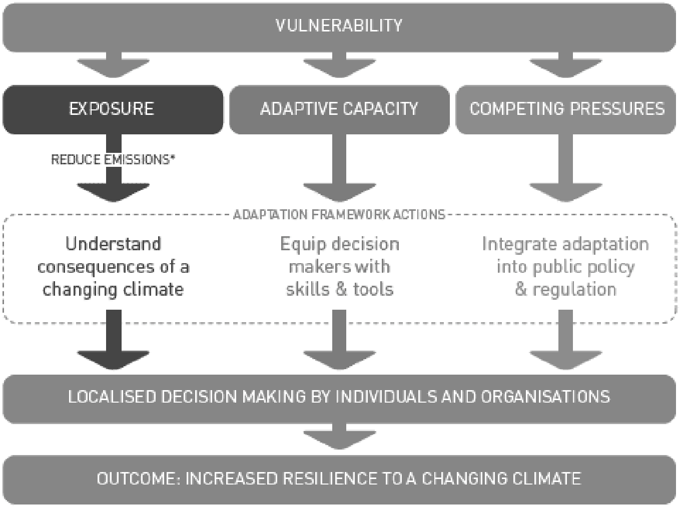
20 UNEP/WMO, Integrated Assessment of Black Carbon and Tropospheric Ozone: Summary for Decision Makers, Nairobi, Kenya: United Nations Environment Programme & World Meteorological Association, Pre-Publication (2011).

Figure 7: Determinants of Vulnerability and Actions to Build Resilience[21]



Vulnerability is defined as the degree to which a system is unable to cope with adverse effects, while the adaptive capacity is the ability of the system to adjust to climate change or to cope with its consequences. In order to assess the vulnerability of a system or community, the expected climate changes must be known (with some uncertainties), and the most probable effects of climate change on the elements of this system established. Once the vulnerabilities have been identified, adaptation plans must be prepared with clear goals and priorities. This process necessarily involves the participation of decision- and policy-makers, since an important part of the knowledge is provided by a variety of stakeholders.

Adaptation to climate change can be defined as a series of measures or actions to reduce the negative impacts of climate change (e.g., protecting coastal regions from sea level rise; protecting infrastructure from extreme precipitation; adapting health systems to changing disease patterns and more frequent heat waves; modifying agricultural practices to respond to climatically changing conditions, etc.) and take advantage of opportunities it may offer (e.g., developing business opportunities towards a green economy). Adaptation

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21 Taken from *Preparing for a Changing Climate: Second Consultation to Inform Scotland's Climate Change Adaptation Framework*, The Scottish Government, http://www.scotland.gov.uk/Publications/2009/04/23145206/4 (last visited Nov. 27, 2012).

can be either anticipatory, as when proactive steps are taken to reduce the risks associated with climate change, or reactive, as when addressing already occurring climate impacts. Anticipatory adaptation is often less costly than reactive adaptation measures. To determine the capacity of a region, city, community or corporation to adapt to climate change, a vulnerability assessment must be performed

The magnitude of adaptation measures needed to limit the impacts of climate change will depend on the success of mitigation measures. There are, however, limits to adaptation. If global temperature increases beyond some "dangerous limit," the size of the adaptation challenge will become considerably greater and eventually impossible to meet. The current research on planetary sustainability focuses on the identification of "planetary boundaries,"[22] which are physical limits (regarding climate, biodiversity, ocean acidification, chemical pollution, atmospheric aerosol loading, global freshwater use, biogeochemical cycles, etc.) that we should avoid crossing in order to maintain a safe environment for humankind

Climate services have been created in different countries of the world to contribute to the development of adaptation policies. Some of these services belong to meteorological services and focus very much on the physical aspects of climate change.[23] Others, with a more interdisciplinary perspective and a focus on social and economic aspects, have been established within a university framework,[24] or as an independent center supported by the government.[25] Their objective is to facilitate the transfer of climate-related knowledge to society and offer advice and policy options to decision-makers and other users from the economic and political communities and from civil society. Their task is thus to provide balanced, credible, cutting-edge scientific and technical information, and to engage a diversity of users in meaningful ways to ensure that their needs are being met. Climate services will provide and contribute science-based products to minimize climate-related risks, and to improve regional and local projections of climate change. They will also identify, quantify and put an economic value to the direct and indirect risks associated with climate change. An international Framework for Climate

22 Rockström, J. et al., *Planetary Boundaries: Exploring the Safe Operating Space for Humanity*, 14 Ecology & Soc'y 32 (2009).

23 In the United Kingdom, see, for example, *Climate Services*, Met Office, http://www.metoffice.gov.uk/services/climate-services (last visited Nov. 27, 2012).

24 In the United States, see, for example, The International Research Institute for Climate and Society (IRI), http://portal.iri.columbia.edu/portal/server.pt (last visited Nov. 27, 2012).

25 In Germany, see, for example, Climate Service Center (CSC), http://www.climate-service-center.de/ (last visited Nov. 27, 2012).

Services has been established by several U.N. agencies under the leadership of the World Meteorological Organization.[26] A Climate Services Partnership (CSP), which regroups many climate services information providers and users, provides an informal and interdisciplinary platform for knowledge sharing and collaboration aimed at promoting resilience and advancing climate service capabilities worldwide.[27]

By providing timely, customized, decision-relevant information, climate services help societies to better manage the risks associated with climate changes and to evaluate different possible responses. One of the latter, known as climate engineering, is to develop technologies that will reduce the magnitude of climate change.

IV. Climate Engineering

Climate engineering is defined as the deliberate large-scale manipulation of the planetary environment to counteract anthropogenic climate change.[28] The idea is not new;[29] more than thirty years ago, Cesare Marchetti, for example, proposed to partially or totally collect fossil-fuel-generated CO_2 and dispose it in the ocean by injection into suitable sinking thermohaline currents.[30] Reduction in the incoming solar radiation by placing, for example, solar reflectors in orbit between the Sun and the Earth could also counteract human-induced climate change.[31] Paul J. Crutzen indicated that the injection of sulfur in the lower stratosphere could also lead to a cooling of the planet and perhaps resolve a policy dilemma.[32] Tom M.L. Wigley proposed a combined mitigation/

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26 *High-Level Taskforce Towards the Global Framework for Climate Services (GFCS)*, World Meteorological Organization (WMO), http://www.wmo.int/hlt-gfcs/ (last visited Nov. 27, 2012).

27 Climate Services Partnership, http://climate-services.org/ (last visited Nov. 27, 2012).

28 John Shepherd et al., Geoengineering the Climate: Science, Governance and Uncertainty (2009).

29 Steven Schneider, *Geoengineering: Could — or Should — We Do It?*, 31 Climatic Change 291 (1996).

30 Cesare Marchetti, *On Geoengineering and the CO_2 Problem*, 1 Climatic Change 59 (1977).

31 Bala Govindasamy & Ken Caldeira, *Geoengineering Earth's Radiation Balance to Mitigate CO_2-Induced Climate Change*, 27 Geophysical Res. Letters 2141 (2000).

32 Paul J. Crutzen, *Albedo Enhancement by Stratospheric Sulphur Injections: A Contribution to Resolve a Policy Dilemma?*, 77 Climatic Change 211 (2006).

geo-engineering approach to climate stabilization,[33] while Ralph J. Cicerone suggested encouraging research in this area while overseeing implementation.[34] The more recent report of the Royal Society reviews possible approaches to geo-engineering, and recognizes the importance of ethical issues.[35]

Criticisms against geo-engineering have been voiced not only from purely ethical motivations, but because this approach treats the symptoms instead of preventing the cause of climate change. In addition, with the exception of carbon capture, it does not solve the problem of ocean acidification, and so emissions reduction is preferable by far. Reversing the planetary warming by attenuating solar radiation, while allowing atmospheric CO_2 to further increase, will lead to a modification of the ocean chemistry, with harmful impacts on ocean life and eventually on the food chain. On the other hand, several studies highlight the low cost of geo-engineering solutions versus mitigation options,[36] while Scott Barrett discusses the "incredible" economics of geo-engineering,[37] and Bala Govindasamy et al. stress the fact that maintaining elevated CO_2 concentrations in the atmosphere would enhance biological productivity and hence be beneficial to agriculture.[38]

Two general classes of climate geo-engineering must be distinguished: One includes several possible schemes intended to remove carbon dioxide from the atmosphere, while the other deals with the management of solar radiation. These methods are reviewed by Nem E. Vaughan and Tim M. Lenton,[39] and summarized in Table 2. Table 3 shows an estimate of the effectiveness of some of the proposed methods versus their costs.

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33 Tom M.L. Wigley, *A Combined Mitigation/Geo-Engineering Approach to Climate Stabilization*, 314 SCI. 452 (2006).

34 Ralph J. Cicerone, *Geoengineering: Encouraging Research and Overseeing Implementation*, 77 CLIMATIC CHANGE 221 (2006).

35 UNEP/WMO, *supra* note 20.

36 WILLIAM D. NORDHAUS, MANAGING THE GLOBAL COMMONS: THE ECONOMICS OF CLIMATE CHANGE (1994); Edward A. Parson & Lia N. Ernst, *International Governance of Climate Engineering*, 14 THEORETICAL INQUIRIES L. 307 (2013).

37 Scott Barrett, *The Incredible Economics of Geoengineering*, 39 ENVTL. & RESOURCES ECON. 45 (2008).

38 Bala Govindasamy et al., *Impact of Geoengineering Schemes on the Terrestrial Biosphere*, 29 GEOPHYSICAL RES. LETTERS 2061 (2002).

39 Nem E. Vaughan & Tim M. Lenton, *A Review of Climate Geo-Engineering Proposals*, 109 CLIMATIC CHANGE 745 (2011).

Table 2: Proposed Geo-Engineering Approaches[40]

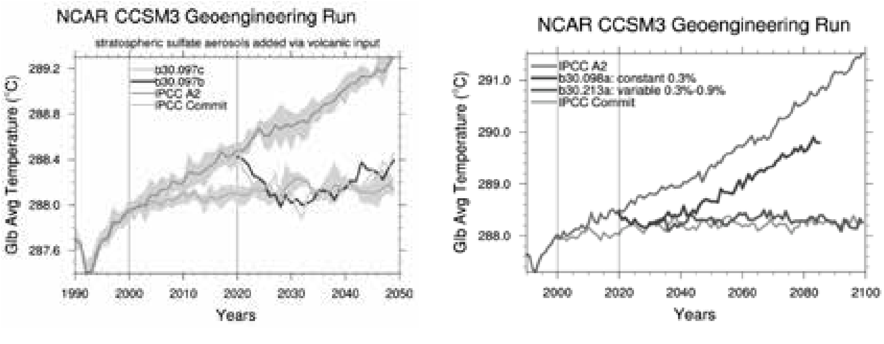
Carbon Dioxide Removal		
	Land carbon sink enhancement	
		Aforestation and reforestation
		Bio-char (Charcoal produced by pyrolysis of biomass)
		Bio-energy with carbon capture and storage
	Ocean carbon sink enhancement	
		Enhancing the solubility pump
		Increasing ocean alkalinity
		Enhancing the biological pump
		Iron fertilization
		Macronutrient fertilization
		Enhancing upwelling
	Air Capture and Storage	
Solar Radiation Management		
	Sunshades in space	
	Stratospheric aerosols	
	Tropospheric aerosols	
	Enhanced cloud albedo	
		Mechanically enhanced cloud albedo
		Biologically enhanced cloud albedo
	Surface albedo	
		Increasing grassland and cropland albedo
		Increasing human settlement albedo
	Increasing desert albedo	

40 MET OFFICE, *supra* note 23.

Table 3: Effectiveness, Affordability, Timeliness and Safety of Different Climate Engineering Schemes That Have Been Proposed to Reduce Climate Change, Estimated by the Royal Society[41] (1 = Lowest, 5 = Highest Ranking)

Method	Effectiveness	Affordability	Timeliness	Safety
Afforestation	2	6	3	4
BECS	2.5	2.5	3	4
Biochar	2	2	2	3
Enhanced weathering	4	2.1	2	4
CO_2 air capture	4	1.9	2	5
Ocean fertilization	2	3	1.5	1
Surface albedo (urban)	1	1	3	5
Surface albedo (desert)	2.5	1	4	1
Cloud albedo	2.5	3	3	2
Stratospheric aerosols	4	4	4	2
Space reflectors	3	1.5	1	3
CCS at source	3	3	4	5

Figure 8: Response of the Global Temperature to Geo-Engineering[42]



Left: Cooling due to the injection of stratospheric aerosols; right: cooling due to a reduction in the solar energy input.

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41 THE ROYAL SOC'Y, GEOENGINEERING THE CLIMATE: SCIENCE, GOVERNANCE AND UNCERTAINTY (2010).

42 Philip J. Rasch et al., *An Overview of Geoengineering of Climate Using Stratospheric Sulphate Aerosols*, 366 PHIL. TRANSACTION ROYAL SOC'Y A 4007 (2008).

Modeling of the climate response to climate engineering has been performed by several research groups and suggests that, on a global scale, compensation for the CO_2-related warming could occur by injecting aerosol particles in the stratosphere or by reducing the incoming solar energy (Figure 8), although the regional consequences regarding, for example, precipitation patterns remain poorly quantified. Even though models provide a power tool to investigate the response of the Earth system to different stressors without deleterious impacts,[43] they are not exempt from uncertainties and limitations. Little observational information is available because experimentation with geo-engineering is generally not feasible, and often not socially or politically acceptable. It would be important to know, for example, to what extent the global temperature compensation resulting from the manipulation of solar radiation would generate substantial and perhaps adverse effects at the regional scale. It would also be important to estimate the impact on the ozone layer of sulfate aerosols injected in the lower stratosphere, as long as industrially manufactured halocarbons remain present in the stratosphere. More research is clearly needed, while the ethical issues raised by the intentional manipulation of the earth's global environment must be pursued.

Conclusion

The future international climate policy will have to carefully consider a combination of mitigation and adaptation measures. To avoid large temperature changes in the second half of the twenty-first century, decisions on mitigation will have to be made in the very near future. Even with rapid measures, however, the temperature will increase in the coming decades due to the inertia of the climate system and some adaptation measures will have to be adopted. Failure to mitigate rapidly will lead to larger increases in the global temperature, which will make the adaptation challenge even greater. As adaptation becomes increasingly difficult, and if mitigation fails, other approaches such as "climate engineering" may have to be considered.

As stated by Alan Robock, however,

> [g]eo-engineering is not a panacea and we cannot delay the search for real solutions in the hope that geo-engineering will save us. Yes, geo-engineering research should continue: We need to better understand the efficacy and potential problems related to such measures. However, at the same time, we need a massive research program addressed toward mitigation. We may at some time need to consider some sort of geo-

43 Wigley, *supra* note 33.

> engineering as an emergency measure, but we have to know how well it would work and the dangers involved. And the faster we work toward mitigation, the less likely we are to need geo-engineering.[44]

Today, the results provided by the scientific community have been clearly stated, for example through the IPCC reports,[45] and are available to governments and to international organizations. The results of future negotiations will be driven only partly by scientific knowledge, since other economic and political constraints will also have to be taken into account. The message from the science, however, is clear. Mitigation should be the first objective of an international agreement. Adaptation will probably become necessary, and nations as well as the corporate world should rapidly indicate how they will cope with expected climate change. In both cases, some measures to financially compensate the damages encountered by developing nations as a result of large GHG emissions by the developed world will have to be discussed. Geo-engineering is not inevitable, but may become necessary if all other measures fail. Nations should therefore initiate research programs to assess the risks and perhaps the benefits of such an approach. In the meantime, it would be advisable to establish an international agreement that stipulates the conditions and limits under which climate engineering could be investigated and perhaps implemented.[46]

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44 Alan Robock, *Geoengineering: It's Not a Panacea*, 53 Geotimes 58 (2008).

45 *See* IPCC, *supra* note 2.

46 For a proposed outline of international climate engineering governance, see Parson & Ernst, *supra* note 36.