POLICY FORUM: CLIMATE CHANGE

Dangerous Climate Impacts and the Kyoto Protocol

Brian C. O'Neill and Michael Oppenheimer

Defining a long-term goal for climate change policy remains a critical international challenge. Article 2 of the UN Framework Convention on Climate Change defines the long-term objective of that agreement as stabilization of greenhouse gas concentrations at a level that avoids "dangerous anthropogenic interference" with the climate system. "Dangerous interference" can be viewed from a variety of perspectives, and the choice will ultimately involve a mixture of scientific, economic, political, ethical, and cultural considerations, among others (*1*). In addition, the links among emissions, greenhouse gas concentrations, climate change, and impacts are uncertain. Furthermore, what might be considered dangerous could change over time.

However, both proponents and detractors of the Kyoto Protocol, which was designed as an initial step to implement the Framework Convention, have begun to demand a definition of long-term objectives. For example, on 11 June 2001, U.S. President George W. Bush stated that the emissions targets embodied in the Kyoto Protocol "were arbitrary and not based upon science" and "no one can say with any certainty what constitutes a dangerous level of warming, and therefore what level must be avoided."

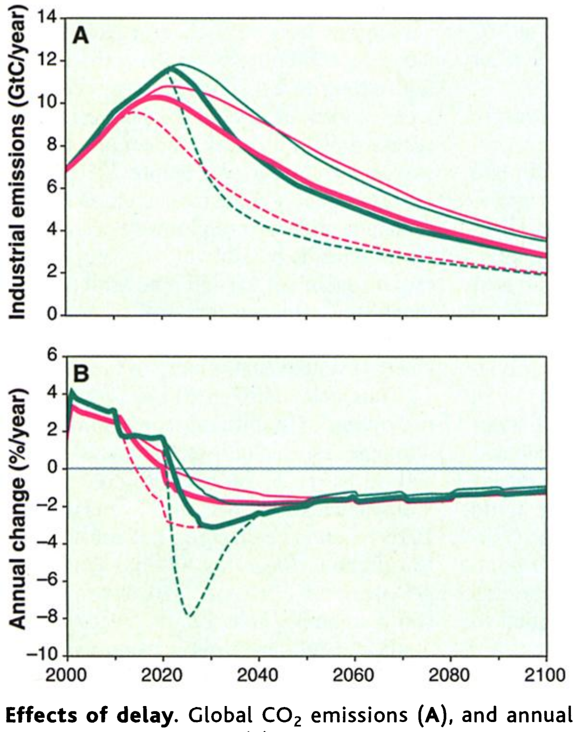
Here, we propose several plausible interpretations of dangerous interference in terms of particular environmental outcomes (*2*) and examine the consistency between the Kyoto Protocol and emissions changes over time that would avoid these outcomes. Although the emissions limits required by the Kyoto Protocol would reduce warming only marginally (*3*), we show that the accord provides a first step that may be necessary for avoiding dangerous interference.

What Impacts Are "Dangerous"?

Attempts to develop limits to warming predate the Framework Convention and have taken a variety of analytical approaches (*4*), including the recent elaboration in the Intergovernmental Panel on Climate Change (IPCC) Third Assessment Report of a detailed ecological and geophysical framework for interpreting Article 2. We examine the implications of defining "dangerous" according to two of the criteria of "concern" identified by the IPCC (*1*): warming involving risk to unique and threatened systems and warming engendering a risk of large-scale discontinuities in the climate system. These choices can be used to infer an upper limit for future concentrations (*5*, *6*).

Large-scale eradication of coral reef systems provides one marker for policy-makers. Even before the development of the Framework Convention, which calls for a long-term target that will "allow ecosystems to adapt naturally," coral reefs were cited as a potential indicator system (*4*). Coral reefs are charismatic ecosystems with high local economic value and a high degree of biodiversity. They can be found in most of the world's oceans in the latitude belt between 30°N and 30°S. By and large, coral reefs are thought to thrive in climate conditions that are close to their thermal limits for existence. As waters warm toward this limit, corals expel symbiotic zooxanthellae in a process called bleaching. Sustained bleaching over consecutive warm seasons increases the risks permanent loss of the reefs. Widespread bleaching has occurred in the Northern Hemisphere during recent El Niño events, indicating that for some coral reefs, the climate limit is only slightly above current seasonal maximum temperatures. Hoegh-Guldberg (*7*) has estimated that sustained global warming in excess of 1°C would cause bleaching to become an annual event in most oceans, leading to "severe" effects worldwide, even allowing that some acclimation and/or genetic adaptation may occur (*8*).

Outcomes that have even a low probability of occurrence at a given level of warming, particularly within a century or two, but that clearly would be disruptive to societies, could provide markers for policy-makers. Alternatively, so could outcomes that have high probability but a low risk of causing widespread disruption. An example of the first case would be disintegration of the West Antarctic Ice Sheet (WAIS). An example of the second may be the weakening or shutdown of the density-driven, large-scale circulation of the oceans (thermohaline circulation or THC). Complete disintegration of WAIS would raise sea level by 4 to 6 meters, an outcome that certainly ranks as disruptive, even if it occurs gradually. Views on the probability and rate of disintegration for a given global warming vary widely (*9*), largely because current models do not adequately capture certain dynamical features of ice sheets. In general, the probability is thought to be low during this century, increasing gradually thereafter. Limited evidence from proxy data suggests WAIS may have disintegrated in the past during periods only modestly warmer (~2°C global mean) than today; other estimates suggest that disintegration could ultimately occur from about 3°C (global mean) to 10°C (local mean) (*9*). The process of disintegration could extend over anywhere from 5 to 50 centuries, although shorter time scales have also been proposed.



Effects of delay. Global CO_2 emissions (**A**), and annual change in CO_2 emissions (**B**), 2000 to 2100, leading to stabilization of atmospheric CO_2 at 450 ppm by 2100 for a scenario consistent with the Kyoto Protocol (magenta) and a scenario with a 10-year delay (green). Three carbon-cycle parameterizations are used (see text): best guess (thick solid lines), strong uptake (thin solid lines), and weak uptake (thin dashed lines).

B. C. O'Neill is at the Watson Institute for International Studies and the Center for Environmental Studies, Brown University, Providence, RI 02912 USA. E-mail: bconeill@brown.edu. M. Oppenheimer is at the Woodrow Wilson School of Public and International Affairs and the Department of Geosciences, Princeton University, Princeton, NJ 08544, USA. E-mail: omichael@princeton.edu

There is strong evidence that the THC had shut down in the past, in association with abrupt regional and perhaps global climate changes (*10*). Most coupled atmosphere-ocean model experiments show weakening of the THC during this century in response to increasing concentrations of greenhouse gases, with some projecting a shutdown if the trends continue (*11*).

Whether a shutdown results in large consequences is sensitive to the timing of regional cooling from shutdown versus regional warming [e.g., in northwest Europe (*12*)], as well as the magnitude of ocean heat transport to the North Atlantic region. The influence of the latter on regional climate may be smaller than some investigators have previously supposed (*13*). We interpret the current state of affairs as a substantial likelihood that forcing due to unrestrained emissions would slow or shut down the THC, but modest probability that THC changes will yield unmanageable outcomes beyond a local scale.

Plausible Targets

A long-term target of 1°C above 1990 global temperatures would prevent severe damage to some reef systems. Taking a precautionary approach because of the very large uncertainties, a limit of 2°C above 1990 global average temperature is justified to protect WAIS. To avert shutdown of the THC, we define a limit at 3°C warming over 100 years, based on Stocker and Schmittner (*14*).

The implications of the temperature limits for concentrations of CO_2 are subject to uncertainties in both the climate sensitivity and future levels of other radiatively active trace gases. For CO_2 stabilization at 450, 550, or 650 ppm, corresponding ranges of global warming over the next 100 years are about 1.2° to 2.3°C, 1.5° to 2.9°C, and 1.7° to 3.2°C, respectively (*11*).

Full protection of coral reefs is probably not feasible for this concentration range. It is plausible that achieving stabilization at 450 ppm would forestall the disintegration of WAIS, but it is by no means certain, because additional warming would occur beyond 2100 (*15*). Avoiding the shutdown of the THC is likely for 450 ppm. We adopt 450 ppm for our illustration as one that could conceivably be applied to these examples.

Implications of Timing

Some studies find justification for preferring reductions sooner rather than later in order to account for the inertia of energy systems, to stimulate technological development, or to hedge against uncertain future concentration limits (*16*). Others conclude that although early investment in research and development may be justified, undertaking emissions reductions later can lower costs, even when accounting for uncertain concentration limits, by avoiding premature retirement of capital, taking advantage of the marginal productivity of capital, and allowing for technical progress (*17*). However, at a certain point, postponing mitigation requires unrealistically rapid emissions reductions, especially for low stabilization targets (*18*). Our ability to identify this point is constrained by our incomplete understanding of the carbon cycle.

The consequences of delay if one assumes a goal of stabilization of atmospheric CO_2 at 450 ppm by 2100 is illustrated in the figure. Because assumptions about the strength of carbon uptake by the terrestrial biosphere are an important determinant of required emissions, we include estimates that span a plausible range of levels of terrestrial uptake (*19*). In one scenario, industrialized countries are assumed to meet the cumulative Kyoto emissions target in 2010; the rest of the world follows a reference path (*20*). Beyond 2010, global emissions necessary to achieve stabilization are calculated with a global carbon-cycle model (*21*). In a second scenario, mitigation is delayed by 10 years, with industrialized countries meeting the Kyoto target in 2020. If reductions are delayed by a decade, growth in global emissions must then be quickly reversed. The subsequent rates of decline in global emissions depend critically on the carbon cycle: with strong terrestrial uptake, required emissions reductions peak at 2% per year; if terrestrial uptake is weak, reductions reach a staggering 8% per year before 2040. Given inertia in energy systems, such high rates of reduction may be prohibitively costly (*22*). Some relief is possible by allowing temporary overshoot of the 450 ppm limit (*23*), although this strategy may still require rapid reductions and also leads to greater climate change over the next century or more (*24*).

Thus delay until 2020 risks foreclosing the option of stabilizing concentrations at 450 ppm, especially if the terrestrial carbon sink turns out to be weak. In contrast, the scenario consistent with the Kyoto targets in 2010 requires challenging but substantially lower reduction rates. Global emissions peak between 2010 and 2020, and fall at between 1 and 3% annually between 2020 and 2040, depending on the carbon-cycle parameterization. Beyond 2050, reductions proceed at about 1.5% per year in all cases.

Stabilizing CO_2 concentrations near 450 ppm would likely preserve the option of avoiding shutdown of the THC and may also forestall the disintegration of WAIS, although it appears to be inadequate for preventing severe damage to at least one unique ecosystem. Taking into account uncertainties in the working of the carbon cycle, the cumulative Kyoto target is consistent with this goal. Delaying reductions by industrial countries beyond 2010 risks foreclosing the 450 ppm option.

References and Notes

1. J. B. Smith *et al.*, in *Climate Change 2001: Impacts, Adaptation, and Vulnerability*, J. J. McCarthy *et al.*, Eds. (Cambridge Univ. Press, Cambridge, 2001), pp. 913–967.
2. Compare C. Azar, H. Rodhe, *Science* **276**, 1818 (1997).
3. T. M. L. Wigley, *Geophys. Res. Lett.* **25**, 2285 (1998).
4. F. R. Rijsberman, R. J. Swart, Eds., *Targets and Indicators of Climatic Change* (Stockholm Environment Institute, Stockholm, 1990).
5. M. D. Mastrandrea, S. H. Schneider, *Clim. Policy* **1**, 433 (2001).
6. Determining targets and trajectories by optimization of costs and benefits provides an alternative approach. See W. D. Nordhaus, J. Boyer, *Warming the World* (MIT Press, Cambridge, MA, 2000).
7. O. Hoegh-Guldberg, *Mar. Freshw. Res.* **50**, 839 (1999).
8. A. C. Baker, *Nature* **411**, 765 (2001).
9. M. Oppenheimer, *Nature* **393**, 325 (1998).
10. W. S. Broecker, *Science* **278**, 1582 (1997).
11. U. Cubasch *et al.*, in *Climate Change 2001: The Scientific Basis*, J. T. Houghton *et al.*, Eds. (Cambridge Univ. Press, Cambridge, 2001), pp. 525–582.
12. T. F. Stocker *et al.*, in *Climate Change 2001: The Scientific Basis*, J. T. Houghton *et al.*, Eds. (Cambridge Univ. Press, Cambridge, 2001), pp. 417–470.
13. R. Seager *et al.*, *Q. J. R. Meteorol. Soc.*, in press.
14. T. F. Stocker, A. Schmittner, *Nature* **388**, 862 (1997).
15. Temperature ranges at equilibrium for CO_2 stabilization at 450, 550, and 650 ppm are 1.5° to 3.9°C, 2.0° to 5.2°C, and 2.4° to 6.1°C, respectively. R. T. Watson *et al.*, *Climate Change 2001: The Synthesis Report* (Cambridge Univ. Press, Cambridge, 2001).
16. See, e.g., M. Ha-Duong *et al.*, *Nature* **390**, 270 (1997).
17. See, e.g., T. M. L. Wigley *et al.*, *Nature* **379**, 242 (1996).
18. C. Azar, *Int. J. Environ. Pollut.* **10**, 508 (1998).
19. Supporting online material is available on *Science* Online at www.sciencemag.org/cgi/content/full/296/5575/1971/DC1
20. The reference scenario is taken to be the IPCC A1B marker scenario. N. Nakicenovic *et al.*, *IPCC Special Report on Emissions Scenarios* (Cambridge Univ. Press, Cambridge, 2000).
21. A. Jain *et al.*, *Global Biogeochem. Cycles* **9**, 153 (1995).
22. For example, a cost function that depends on both the degree and rate of emissions reduction (*16*) yields estimated annual total costs peaking at 5 to 12% of gross world product (GWP) in the weak sinks case, depending on the assumed degree of socioeconomic inertia in the energy system. In contrast, in the Kyoto scenarios, costs peak at 1 to 3% of GWP if sinks are assumed to be weak. Calculations assume cost-lowering technical progress of 1% per year, and an inertia time scale of 20 to 50 years. If carbon backstop technologies turn out to be less expensive than implicit in this cost function, costs would be reduced.
23. T. M. L. Wigley, personal communication.
24. For example, we calculate that if the CO_2 concentration is allowed to rise to 500 ppm in 2075 and then return to 450 ppm 150 years later, peak emissions reduction rates fall from 8% per year to 3% per year in the weak sinks case, and the timing of this peak can be delayed from 2025 to 2045. However, global average temperature change is 0.2° to 0.4°C greater in 2100 in this case, depending on the climate sensitivity, which could be significant compared with the range for stabilization at 450 ppm.

25. The authors acknowledge partial support from Environmental Defense, and thank C. Azar, J. Smith, T. Stocker, R. Stouffer, F. Toth, T. Wigley, and anonymous reviewers for helpful comments.

Supporting Online Material
www.sciencemag.org/cgi/content/full/296/5575/1971/DC1