What GHG Concentration Targets are Reachable in this Century?

Sergey Paltsev, John Reilly and Andrei Sokolov

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To inform processes of policy development and implementation, climate change research needs to focus on improving the prediction of those variables that are most relevant to economic, social, and environmental effects. In turn, the greenhouse gas and atmospheric aerosol assumptions underlying climate analysis need to be related to the economic, technological, and political forces that drive emissions, and to the results of international agreements and mitigation. Further, assessments of possible societal and ecosystem impacts, and analysis of mitigation strategies, need to be based on realistic evaluation of the uncertainties of climate science.

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Sergey Paltsev[*†], John Reilly[*], and Andrei Sokolov[*]

Abstract

We offer simulations that help to understand the relationship between GHG emissions and concentrations, and the relative role of long-lived (e.g., CO_2) and short-lived (e.g., CH_4) emissions. We show that, absent technologies to remove CO_2 from the atmosphere, the 350 CO_2 ppm target is out of reach in this century, even if all emissions drop to zero almost immediately (i.e. in 2015). A 350 ppm CO_2-equivalent target is potentially achievable, but would require CH_4 concentrations falling below preindustrial levels, and thus elimination of emissions from human activities such as rice and livestock agriculture. More realistically, even some of the most aggressive targets proposed through 2035 would lead to concentrations (CO_2 or CO_2-eq) in the 415–450 ppm range. This is only feasible if after 2035 emissions continued a downward path toward zero. Only in these cases would the temperature target of no more than 2 °C above preindustrial be achieved, and only after peaking above that level before declining.

Contents

1. INTRODUCTION

Given the growing evidence that the world faces substantial risks associated with changing climate there are increasing questions about what concentrations of atmospheric carbon dioxide and greenhouse gases are achievable. Some have called for an atmospheric target for CO_2 as low as 350 ppm (Hansen et al., 2008). Since CO_2 levels are already reaching 400 ppm this means concentrations would need to fall. Some authors note the general difficulty people have in grasping the relationship between changes in flow (emissions) and stock (concentrations) as it applies to the climate problem (Sterman, 2008).

In this paper we provide several scenarios to illustrate the link between GHG emission trajectories and the targets proposed by the international community to address the challenges of climate change. The United Nations Framework Convention on Climate Change (UNFCCC) has reached an accord in 2009 for the so called Copenhagen pledges (United Nations, 2009), which are further specified in the Cancun agreements (United Nations, 2010). Even though, the targets in these agreements are provided mostly for 2020, they also express a longer-term objective of keeping the average global temperature rise below two degrees Celsius relative to the preindustrial levels.

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This paper is organized in the following way. In the next section we discuss the scenarios that we consider to illustrate emissions trajectories and the proposed targets. Section 3 provides a discussion about the resulting atmospheric concentrations. In Section 4 we discuss the radiative forcing and temperature effects. Section 5 concludes.

2. EMISSION SCENARIOS

There are several studies that look at the temperature impacts of eliminating emissions (e.g., Matthews and Caldeira, 2008; Solomon et al., 2009; Gillett et al., 2011; Matthews and Zickfeld, 2012). Most of the studies focus on CO_2 emissions, neglecting or highly simplifying the effects of non-CO_2 greenhouse gases and aerosols. Here we use the MIT Integrated Global Systems Model (IGSM) that tracks GHG gases and aerosols. The MIT IGSM (Sokolov et al., 2005; Prinn et al., 2011) is an integrated assessment model (IAM) model of intermediate complexity, i.e. it represents the dynamics of the atmosphere and ocean in less detail than conventional general circulation models (GCMs), but goes beyond the approach taken by atmospheric energy balance models (EBMs) or ocean box models by using sophisticated parameterizations of the unresolved flows or by explicitly resolving the equations of geophysical fluid dynamics, albeit at coarse spatial resolution.

The scenarios considered in this study were motivated by a proposed abatement scenario (de Frondeville, 2012) through 2035 that was put forward as a candidate scenario for achieving a concentration level of 350 ppm of CO_2. We consider five emissions scenarios (**Figure 1**) using the MIT IGSM. These include: (1) a Copenhagen Scenario reflecting commitments under the UNFCC through 2020 and extended through 2100 (Paltsev et al., 2012); (2) the Copenhagen Scenario with zero anthropogenic emissions after 2035 (Natural Only after 2035*)*; (3) the Copenhagen Scenario with zero anthropogenic emissions immediately (Natural Only after 2015*)*; (4) the IEA 450 ppm CO_2 Scenario with other gases constrained proportionally to CO_2 through the International Energy Agency's (IEA) horizon of 2035 (IEA, 2011) and then dropping linearly to zero at the rate for the decade 2025–2035; and (5) an Alternative Abatement Scenario proposed to us as an alternative to the IEA 450 Scenario intended to achieve 350 ppm of atmospheric CO_2 concentrations. In this latter scenario, cumulative emissions from 2010 to 2035 in the alternative scenario are about 77% of cumulative emissions in the IEA 450 Scenario, and the number 350 is about 77% of 450.

The heuristic used here to relate emissions and concentrations appears to be that a reduction in cumulative emissions would give a proportional reduction in concentrations. We make no attempt to evaluate the economic or political feasibility of these scenarios. Those that drop emissions to zero in one year are purposely extreme and intended to illustrate the earth system response to such a change. We have not evaluated the economic implications of the IEA 450 Scenario and the Alternative Abatement Scenario but these were developed with the idea that, at least through 2035, there were technological options that could lead to these outcomes. We contrast these to the internationally agreed goals in the Copenhagen Scenario and see that those commitments are far from adequate to achieve even the IEA 450 Scenario.

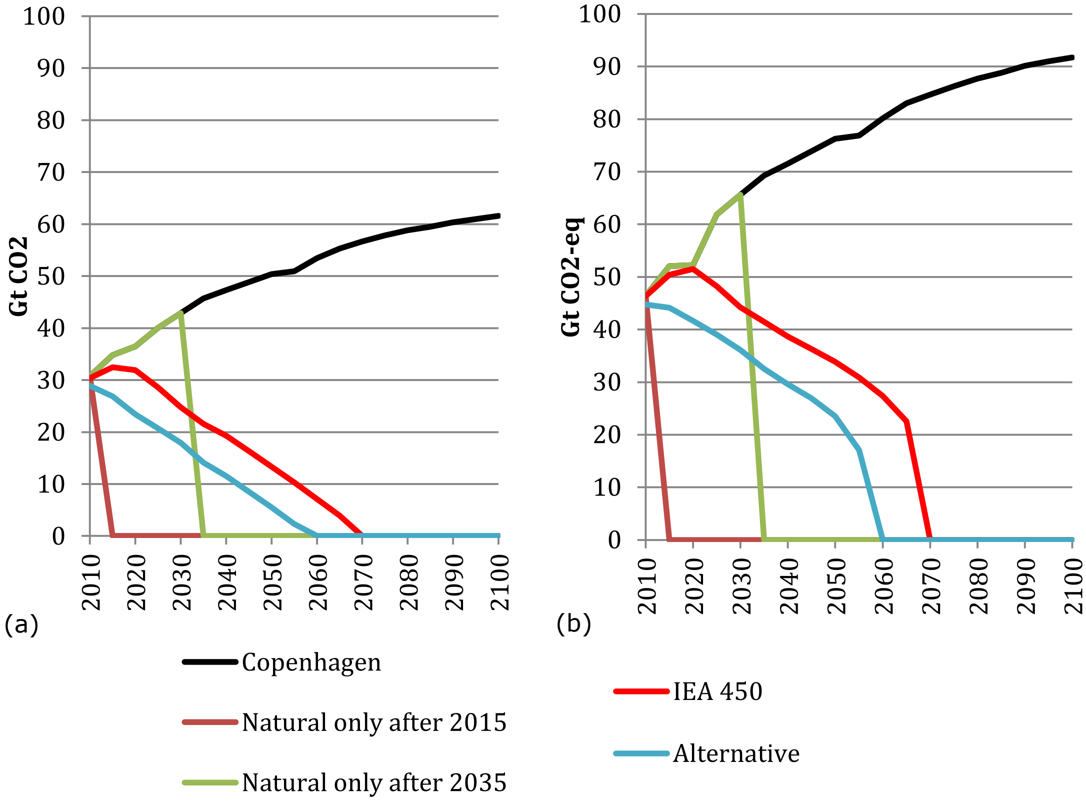


Figure 1. Global emissions scenarios. (a) fossil CO_2 and (b) all GHGs in CO_2-eq, with gases weigthed by their 100-year GWP.

In our scenarios we do not explicitly consider the “negative emissions technologies” to remove CO_2 from the atmosphere, such as an industrial process of direct air capture (e.g., Zeman, 2007), or using biomass for energy and capturing and storing the carbon when the biomass is burned (e.g., Azar et al., 2010). Economics and technical aspects of such options are highly uncertain (House et al., 2011). In addition, there are issues of biomass availability and storage capacity to store carbon at a required scale (Azar et al., 2010). We also do not consider geo-engineering options, such as, for example, solar radiation management (e.g., van Vuuren and Stehfest, 2013), because of the high risks, some of which are known, such as ozone depletion from the introduction of geoengineering aerosol into the stratosphere, but many are still unknown.

3. RESULTING ATMOSPHERIC CONCENTRATIONS

We simulate the atmospheric concentration (**Figure 2**) and climate implications of these scenarios using the MIT IGSM with median setting for earth system response in terms of climate sensitivity, aerosol forcing, and ocean response. All of these scenarios have concentrations levels remaining above 350 ppm through to the end of the century, even when we immediately drop all emissions to zero (**Figure 2a**). In that scenario CO_2 concentrations fall to about 360 ppm by 2100. The gradual decline in concentrations in scenarios where CO_2 emissions drop to zero reflects primarily the initial imbalance between levels of CO_2 in the atmosphere and in the ocean.

The decline in concentrations is relatively rapid in early years as CO_2 levels in the mixed layer of the ocean are more strongly out of balance with levels in the atmosphere. As the ocean's mixed layer comes into balance with the atmosphere, ocean uptake of CO_2 slows. Mixing into the deep ocean is much slower and will continue for hundreds to thousands of years. For example, in the scenario where emissions drop immediately to zero the CO_2 concentration falls by about 10 ppm in the first decade after emissions are cut; this rate of decline falls to only about 1 ppm over the final decade of the century. Eventually this scenario would result in concentrations of 350 ppm of CO_2 or lower, but it would take another 100 years or more.

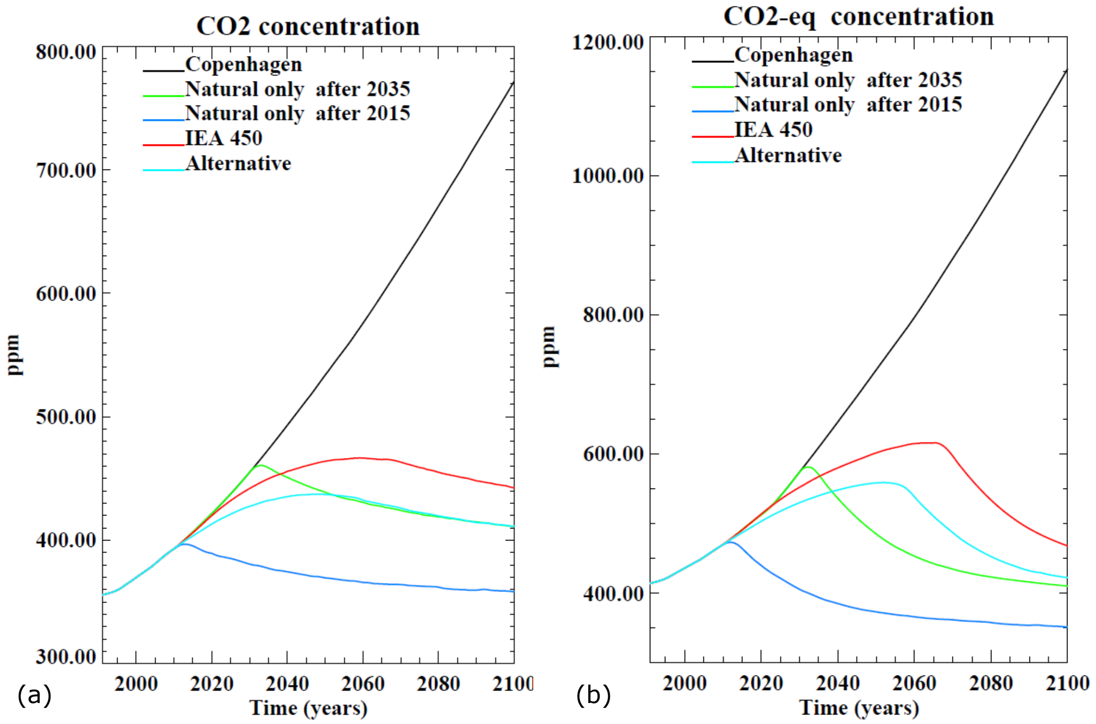


Figure 2. (a) CO_2 and (b) CO_2-equivalent concentrations. CO_2-eq determined as the CO_2 concentration that would produce the same radiative forcing as the mix of IPCC gases in the atmosphere in that year.

In the Alternative Abatement Scenario proposed as a candidate for achieving a 350 ppm concentration level, we see that instead of falling, concentrations continue to rise from present reaching about 432 ppm by 2035, and remain above 410 ppm through 2100 even with emissions continuing to decline to zero. Overall, these results illustrate Sterman's observation (Sterman, 2008) that the heuristics used in these stock–flow problems are often inaccurate—with the type of error we see here being more the rule than the exception. While the Alternative Abatement Scenario obviously fails to reduce levels to near the 350 ppm goal it was intended to achieve, concentrations are much lower than the Copenhagen Scenario, which reaches about 470 ppm by 2035, and continues rising to over 750 ppm. With emissions dropping to zero in 2035, concentrations only drift down to about 410 ppm by 2100. The IEA 450 Scenario is mostly successful in keeping CO_2 concentrations in the 450 ppm range, exceeding it by about 15 ppm at the concentration peak, if emissions continue downward toward zero.

Concentrations of all greenhouse gases in CO_2 equivalent behave somewhat differently (**Figure 2b**). First, the Alternative Abatement Scenario reaches over 540 ppm by 2035 but is close to 600 ppm in the Copenhagen Scenario, with the IEA 450 Scenario reaching about 570 ppm in 2035. Concentrations continue to rise for some time, with the Alternative Abatement Scenario and the IEA 450 Scenario topping out at about 550 and 615 ppm respectively. The Copenhagen Scenario continues to rise indefinitely and reaches 1150 ppm by 2100. By 2100 the CO_2-eq concentrations for the IEA 450 Scenario and the Alternative Abatement Scenario are similar to their CO_2 only concentrations, as they are for the Natural Only after 2035 Scenario and Natural Only after 2015 Scenario. In fact, the Natural Only after 2015 Scenario actually achieves a 350 ppm CO_2-eq level by 2100, below the CO_2 alone concentration of 350 ppm.

Why does this occur? The answer lies in short-lived substances, primarily methane. Since methane's lifetime is relatively short—12 to 15 years by most estimates—once emissions drop the concentration level will drop much faster than for longer-lived substances like CO_2. The concentration level in fact drops below preindustrial levels and so becomes a negative contribution to radiative forcing, given that the preindustrial level is used as the benchmark to compute the human contribution to forcing. Concentrations of methane and nitrous oxide are shown in **Figure 3**. Methane concentrations actually fall below preindustrial levels. While preindustrial concentrations are often considered to be unaffected by human activities, there is a body of work documenting likely effects of human activities on GHG concentrations that predate the fossil-fuel combusting, industrial period, mostly ascribing changes to periods of deforestation and reforestation and expansion of paddy rice agriculture (Ruddiman, 2007; Ruddiman et al., 2008). Our representation of anthropogenic versus natural emissions in our IGSM support at least the conclusion that preindustrial methane emissions include a human contribution because that level is not supported only by natural emissions.

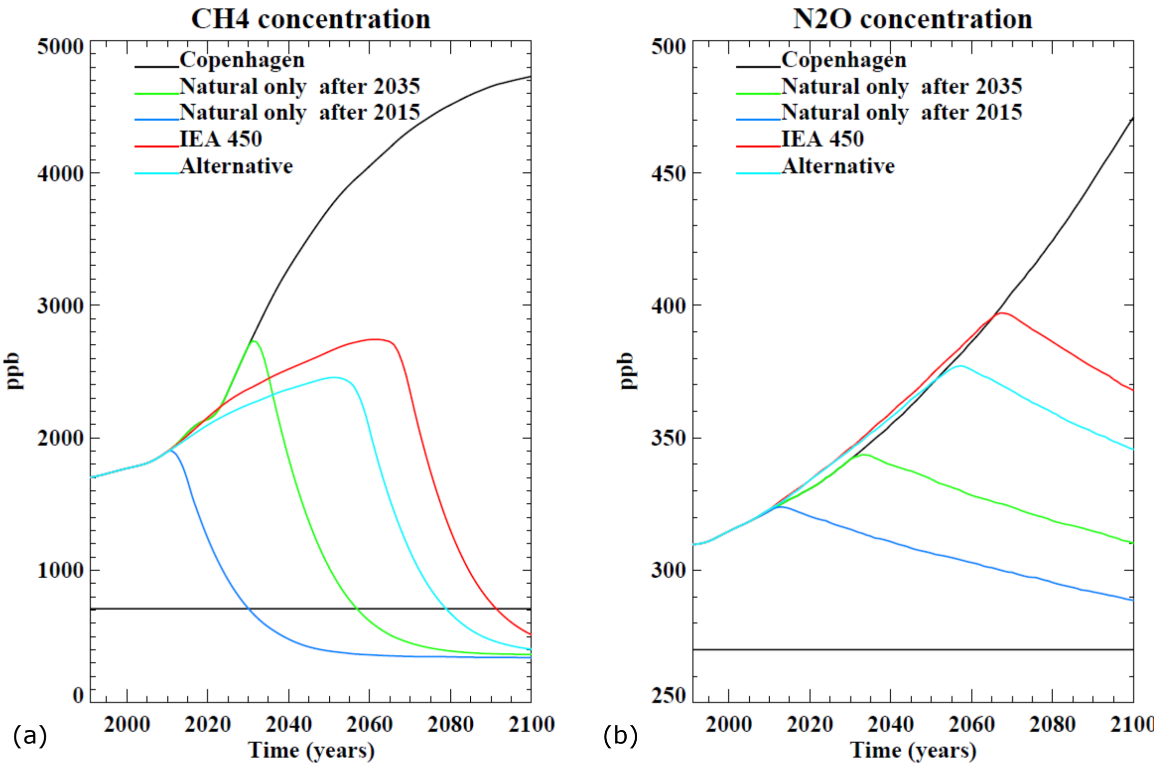
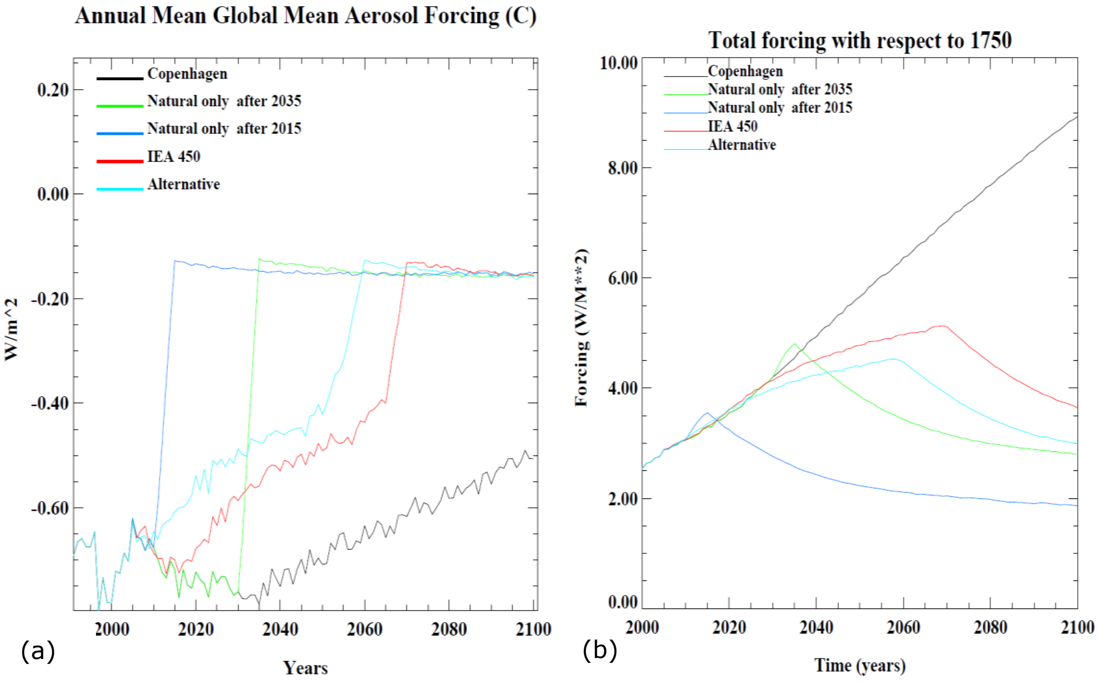


Figure 3. (a) CH_4 and (b) N_2O concentrations. Preindustrial concentrations, circa 1750, are represented by the horizontal lines at around 700 ppb and 270 ppb, respectively.

4. RADIATIVE FORCING AND TEMPERATURE EFFECTS

We turn now to the radiative forcing (**Figure 4**) and temperature effects (**Figure 5**) of these five scenarios. In the alternative scenarios we see that radiative forcing is above 8.5 W/m^2 in the Copenhagen Scenario and between 1.9 and 3.6 W/m^2 in stringent scenarios. The mean surface temperature reaches more than 5 °C above preindustrial by 2100 in the Copenhagen Scenario. All stringent scenarios keep the temperature increase in 2100 to less than 2 °C warmer than the preindustrial mean surface temperature, but they peak before declining. Also note that the temperature keeps warming for about a decade after emissions fall to zero and concentrations peak. This reflects the inertia of the climate system and the removal of negative aerosol forcing. The ocean has a large heat capacity and it takes a significant amount of time to come into equilibrium with changes in forcing. In other words, at any given time the climate system is still responding to the forcing changes in previous years. In addition, aerosol lifetime is much shorter than the lifetimes of greenhouse gases, and when emissions are reduced the immediate reduction in cooling from aerosols leads to an increase in total radiative forcing at that time. With falling concentrations we begin to see a decrease in radiative forcing and after about a decade temperatures begin to fall. In the case where we immediately drop emissions to zero the temperature falls by about 1 °C by 2100 from its peak, and remains about half of a degree above preindustrial levels. In the other cases where emissions drop to zero, the temperature falls back to a level between about 1.2 to 2 °C above preindustrial. In the Copenhagen Scenario where emissions continue to rise, temperature continues to rise and shows no sign of slowing. This obviously reflects the fact that concentrations continue to rise.



(a) (b)

Figure 4. Radiative forcing. (a) aerosol forcing and (b) total forcing from all GHG gases and aerosols.

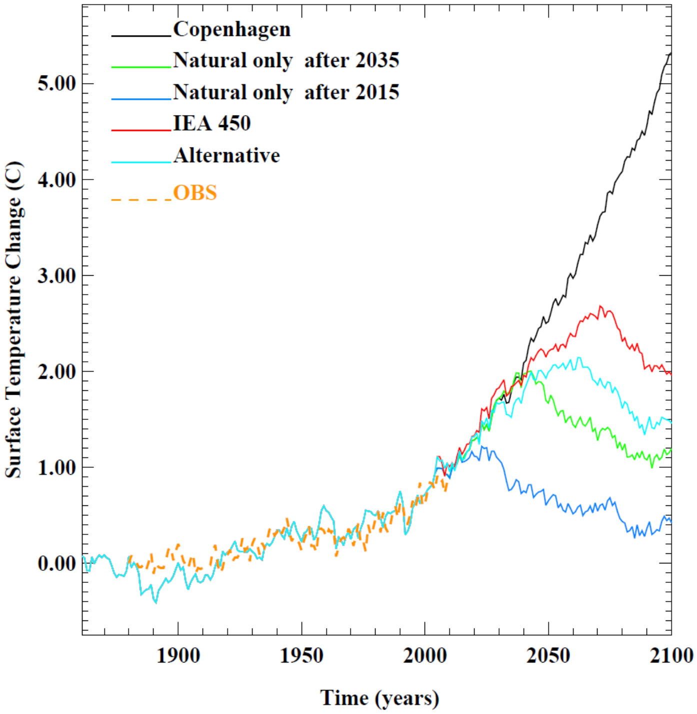


Figure 5. Mean surface air temperature for five scenarios. OBS—observations from 1850 to 2010; blue line from 1850 to 2010 represents MIT IGSM reproduction of historic temperature.

5. CONCLUSIONS

As noted at the outset, some have called for CO_2 concentration targets well below the nearly 400 ppm level we have already reached. We have shown here that even if anthropogenic emissions were to drop immediately to zero, levels would still remain above 350 ppm through at least the end of the century. Since CO_2 is not destroyed but rather reallocated among reservoirs—the oceans, atmosphere, and vegetation—our addition to these pools through the combustion of fossil fuels results in, for practical purposes, a permanent increase in the CO_2 that is cycling among these pools. That said, equilibrium with the deep ocean is a very slow process and so over hundreds or thousands of years atmospheric concentrations would continue to slowly decline if we were to reduce emissions to zero. Of course, it is not possible to transform our energy and industrial systems overnight—extremely aggressive policies might imagine such a transformation over 50 years. Of course, we have not considered negative CO_2 emissions technologies, from the simple, such as planting more trees, to the more complex and costly, such as using biomass for energy and capturing and storing carbon when biomass is burned. Somewhat surprisingly we find a 350 CO_2-eq target possibly within range but this depends on eliminating all human influence on methane (and nitrous oxide). Rice agriculture is the biggest human contributor to methane and nitrogen fertilizer use to nitrous oxide. Thus, to achieve these levels requires not only transformation of the world's energy sector but also its agricultural sector.

Acknowledgments

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