

1 Cumulative carbon as a policy framework for achieving climate stabilization

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Abstract

9 The primary objective of The United Nations Framework Convention on Climate
10 Change is to stabilize greenhouse gas concentrations at level that will avoid dangerous
11 climate impacts. However, greenhouse gas concentration stabilization is an awkward
12 framework within which to assess dangerous climate change on account of the signifi-
13 cant lag between a given concentration level, and the eventual equilibrium temperature
14 change. By contrast, recent research has shown that global temperature change can
15 be well described by a given cumulative carbon emissions budget. Here, we propose
16 that cumulative carbon emissions represent an alternate framework that is applicable
17 both as a tool for climate mitigation as well as for the assessment of potential cli-
18 mate impacts. We show first that both atmospheric CO₂ concentration at a given year
19 and the associated temperature change are generally associated with a unique cumu-
20 lative carbon emissions budget that is largely independent of the emissions scenario.
21 The rate of global temperature change can therefore be related to first order to the
22 rate of increase of cumulative carbon emissions. However, transient warming over the
23 next century will also be strongly affected by emissions of shorter lived forcing agents
24 such as aerosols and methane. Non-CO₂ emissions therefore contribute to uncertainty
25 in the cumulative carbon budget associated with near-term temperature targets, and
26 may suggest the need for a mitigation approach that considers separately short- and
27 long-lived gas emissions. By contrast, long-term temperature change remains primarily
28 associated with total cumulative carbon emissions due to the much longer atmospheric
29 residence time of CO₂ relative to other major climate forcing agents.

1 Introduction: Beyond Greenhouse Gas Stabilization

2 For the past two decades, efforts to mitigate emissions of carbon dioxide and other greenhouse
3 gases have centered around the goal of stabilizing atmospheric concentrations of these gases.
4 This focus on atmospheric stabilization is historically rooted in text of Article 2 of the United
5 Nations Framework Convention on Climate Change, in which is written:

6 The ultimate objective of this Convention ... is to achieve ... stabilization of
7 greenhouse gas concentrations in the atmosphere at a level that would prevent
8 dangerous anthropogenic interference with the climate system. (*United Nations*,
9 1992)

10 Following this objective, a considerable body of literature has evolved to attempt to first
11 quantify what could be considered to be a “dangerous” level of climate change, and second
12 to determine what levels of greenhouse gas stabilization are consistent with avoiding said
13 climate changes (e.g. *Schneider and Mastrandrea*, 2005, *Smith et al.*, 2009, *Knutti and Hegerl*,
14 2008).

15 There are several inherent difficulties with this approach, which have posed a consider-
16 able challenge to the progress of climate mitigation. Defining “dangerous” levels of climate
17 change is clearly a subjective exercise, which is difficult to incorporate in a compelling man-
18 ner to the process of policy decision making. There has been a recent convergence in policy
19 discussions towards a stated goal of limiting global warming to 2 degrees above pre-industrial
20 temperatures (*UNFCCC*, 2009); while there is evidence that 2 degrees of global warming
21 would avoid a number of important and potentially dangerous climate impacts (see *Solomon*
22 *et al.*, 2011, for a review of climate impacts associated with various levels of global tem-
23 perature change), there is little by way of quantitative evidence that this represents a ‘safe’
24 policy target, and some climate scientists argue that 2 degrees would result in unacceptably
25 severe impacts (e.g. *Rockström et al.*, 2009, *Hansen et al.*, 2008).

1 Even given some chosen target for global temperature change, however, it is extremely
2 difficult within the paradigm of greenhouse gas *concentration* stabilization to define an appro-
3 priate policy target for greenhouse gas *emissions*. The reasons for this are threefold. First,
4 the relationship between emissions and atmospheric concentrations is complex; achieving sta-
5 bilized concentrations over time would clearly require large emissions reductions, but would
6 also imply continued emissions at a changing level consistent with the level of natural sinks
7 that evolve over time in a manner difficult to quantify (*Matthews, 2006, Meehl et al., 2007*).
8 Second, the relationship between greenhouse gas concentrations and temperature change is
9 an elusive quantity that has preoccupied climate scientists for several decades. This “cli-
10 mate sensitivity” has been estimated many times, but remains subject to at least a three-
11 fold likely uncertainty range which has not narrowed appreciably in thirty years of research
12 (*Meehl et al., 2007*). Third, even given some known instantaneous temperature response to
13 increased greenhouse gas concentrations, there is still a considerable lag between the point
14 of atmospheric concentration stabilization and the eventual “equilibrium” climate change.
15 This lag results from the slow adjustment of the ocean and other slowly responding climate
16 system components to the relatively rapidly increasing atmospheric forcing; consequently,
17 the eventual temperature change associated with a given greenhouse gas stabilization level
18 will not be fully realized for many centuries (*Wigley, 2005, Meehl et al., 2005*).

19 Taken together, these difficulties present no clear mechanism by which to estimate by
20 how much emissions must be decreased to avoid a given level of global temperature change,
21 which may or may not be sufficient to avoid dangerous anthropogenic interference in the
22 climate system. Many attempts have been made, and current policy discussions revolving
23 around numbers like 50% reductions in greenhouse gas emissions by 2050 followed by 80%
24 reductions at the end of the century (see *UNFCCC (2009)*, and analysis by *Ramanathan*
25 *and Xu (2010)*) do have some basis in climate science. For example, at least an 80% re-
26 duction in carbon dioxide emissions is consistent with short-term concentration stabilization

1 (*Solomon et al.*, 2011), and if enacted quickly enough as to stabilize concentrations below
2 450 parts per million, this would give even odds of avoiding a long-term warming of 2 degrees
3 (*Knutti and Hegerl*, 2008). But there are many possible emissions pathways leading to an
4 80% reduction, which could lead to considerably different atmospheric concentrations and
5 temperature change, and what happens to emissions after an 80% decrease is achieved will
6 have an equally large bearing on the eventual climate change that occurs.

7 This preoccupation with atmospheric concentration stabilization—while cumbersome
8 when applied to mitigation policy—is nevertheless consistent with the historical develop-
9 ment of global climate models, which until recently have required the use of prescribed
10 atmospheric greenhouse gas concentrations. However, the development of coupled climate-
11 carbon models over the past decade has allowed for the investigation of the climate response
12 to *emissions*, rather than *concentrations*, of carbon dioxide. With respect to carbon dioxide
13 emissions—we will return to other gases later in the paper—this analysis has revealed several
14 important conclusions:

- 15 1. Global temperature change is approximately linearly related to a given amount of
16 cumulative carbon dioxide emissions (*Matthews et al.*, 2009, *Zickfeld et al.*, 2009, *Allen*
17 *et al.*, 2009, *Meinshausen et al.*, 2009);
- 18 2. This temperature change is independent of the specific pathway of carbon dioxide
19 emissions, and depends only on the total carbon emitted over time (*Matthews et al.*,
20 2009, *Zickfeld et al.*, 2009, *Allen et al.*, 2009);
- 21 3. If carbon emissions are subsequently eliminated, global temperature changes will re-
22 main at near-constant levels for many centuries (*Matthews and Caldeira*, 2008, *Solomon*
23 *et al.*, 2009, *Lowe et al.*, 2009, *Matthews and Weaver*, 2010, *Plattner et al.*, 2008, *Meehl*
24 *et al.*, 2007);
- 25 4. The relationship between cumulative carbon and temperature change is remarkably

1 constant and robust for cumulative emission up to about 2000 PgC, and on timescales
2 from a decade to several centuries. This constancy holds within a given model (as well
3 as for observations), though varies between models as a result of physical climate and
4 carbon cycle uncertainty (*Matthews et al.*, 2009).

5 The policy implication of this body of literature is that a given level of cumulative carbon
6 emissions can be uniquely associated with a given global temperature change. Consequently,
7 the climate mitigation challenge can be simplified to the task of selecting an allowable cu-
8 mulative emissions budget that is consistent with a given amount of global warming.

9 Cumulative Carbon and Global Warming

10 The allowable carbon dioxide emissions associated with a given CO₂ stabilization scenario
11 can be estimated with any coupled climate-carbon model when driven by prescribed CO₂
12 concentrations; the requirement of global carbon conservation allows simulated carbon sink
13 changes to be used to calculate the emissions profile that is required to drive the prescribed
14 CO₂ concentration changes (*Matthews*, 2006). Such simulations have been performed by
15 several models (e.g *Meehl et al.*, 2007), and have also been adopted as a primary methodology
16 for simulations carried out in preparation for the upcoming Fifth Assessment Report of the
17 Intergovernmental Panel on Climate Change (*Hibbard et al.*, 2007).

18 Figure 1 shows a series of such prescribed-CO₂ stabilization simulations carried out using
19 an intermediate complexity coupled climate-carbon model¹. The scenarios shown here have
20 atmospheric CO₂ stabilizing at the year 2100 at levels between 350 and 650 ppm (panel A.).
21 Annual emissions (panel B.) were diagnosed from annual changes in atmosphere, land and
22 ocean carbon pools, and represent total CO₂ emissions from both fossil fuels and land-use

¹For the model simulations shown here, I have used the University of Victoria Earth-System Climate Model, a coupled global climate and carbon cycle model with interactive representations of 3-dimensional ocean circulation, atmospheric energy and moisture balance, sea ice dynamics/thermodynamics, vegetation dynamics, and land, ocean and sedimentary carbon cycles (*Weaver et al.*, 2001, *Meissner et al.*, 2003, *Schmittner et al.*, 2008, *Eby et al.*, 2009).

1 change. In all cases, allowable annual emissions decreased dramatically as global carbon
2 sinks quickly saturated under stable atmospheric CO₂ concentrations. Stabilizing CO₂ be-
3 low 400 ppm this century required prolonged periods of net negative emissions, though all
4 stabilization targets allowed small amounts of continued emissions for several centuries after
5 the point of atmospheric stabilization. Cumulative emissions (panel D.) are equivalent to
6 accumulated changes in simulated global carbon pools, and represent the total historical an-
7 thropogenic CO₂ emitted to date in each simulation. Global temperature changes (panel C.)
8 responded to CO₂ concentration such that there was substantial continued warming beyond
9 the point of atmospheric concentration stabilization; this continued warming is consistent
10 with the continued low-level emissions, leading to increasing cumulative carbon emissions
11 over time which closely tracked the changes in global temperature.

12 This close association between cumulative emissions and global temperature change can
13 be seen clearly in Figure 2, which shows the temperature change per unit carbon emitted as a
14 function of time in each model simulation. For all model simulations, temperatures increased
15 by an approximately constant value of 1.8 degrees per 1000 PgC emitted; this linear response
16 of global warming to cumulative emissions is a striking model property that is independent
17 of both time and atmospheric CO₂ concentration (*Matthews et al., 2009*). *Matthews et al.*
18 (2009) defined this as the *carbon-climate response* (CCR) and showed that a constant CCR
19 is a robust feature of the current generation of coupled climate-carbon models—though with
20 different models exhibiting different CCR values as a result of uncertainty in both climate
21 and carbon cycle response to emissions. Further, they showed that the observational record
22 (overlaid on Figure 2 as the thick solid and dashed lines) showed a similar constancy of the
23 temperature response to cumulative emissions, with a mean value of 1.5 °C per 1000 PgC
24 emitted, and a 5-95% range of 1 to 2.1 °C/1000 PgC.

25 The importance of the temperature response to cumulative emissions was highlighted
26 concurrently by *Allen et al. (2009)*, who used a simple climate model and a wide range of

1 climate sensitivity values to calculate the *peak* temperature response to cumulative emissions
2 of 1000 PgC. They defined this quantity as the *cumulative warming commitment* (CWC),
3 and estimated a 5-95% confidence interval of 1.3 – 3.9 °C/1000 PgC. They further estimated
4 the *instantaneous* temperature response to cumulative emissions (which is consistent with
5 the *climate-carbon response* of (Matthews et al., 2009)) to fall between 1.4 and 2.5 °C/1000
6 PgC. Both Matthews et al. (2009) and Allen et al. (2009) concluded that the temperature
7 response to cumulative emissions is remarkably constant over time, and over a wide range of
8 CO₂ concentrations. Based on the uncertainty ranges estimated in these two studies, we have
9 adopted a *very likely* (5-95%) uncertainty range of 1 to 2.5 °C of global temperature increase
10 per 1000 PgC of cumulative carbon emitted; this range is indicated by the red vertical bar
11 to the right of Figure 2.

12 This uncertainty in the temperature response to cumulative emissions stems from fun-
13 damental model uncertainties in: (1) the carbon cycle response to CO₂ emissions (*carbon*
14 *cycle sensitivity*); (2) the climate response to changes in CO₂ concentration (*climate sen-*
15 *sitivity*); and (3) the feedbacks between climate change and carbon sinks (*climate-carbon*
16 *feedbacks*). When estimated from historical observations, the primary contributors to the
17 total uncertainty are uncertainty in aerosol forcing (leading to uncertainty in climate sen-
18 sitivity, or more specifically, the transient climate response) in addition to uncertainty in
19 historical CO₂ emissions from land-use change (which reflects uncertainty in the carbon cy-
20 cle sensitivity) (Matthews et al., 2009). As with climate sensitivity, it is difficult to exclude
21 the possibility of much higher values of the carbon-climate response, which would be con-
22 sistent with either strong negative aerosol forcing or low emissions from land-use change in
23 the historical record (Matthews et al., 2009).

24 Despite uncertainty in its absolute value, the temperature response to cumulative emis-
25 sions does not depend on the specific transient nature of a given emissions scenario. This
26 scenario-independence is shown in Figure 3, which shows the simulated model response to

1 three CO₂ emissions scenarios which all have cumulative emissions of 1000 PgC (panel A.).
2 All three scenarios have CO₂ emissions that peak and decline at rates between 1.5 and 4.5
3 % per year (relative to the peak emission value), and reach zero at the year 2100. Despite
4 the different emissions rates over the 21st century, both year-2100 CO₂ concentration (panel
5 B.) and temperature changes (panel C.) are the same for all three simulations. While the
6 transient changes in CO₂ and global temperature do depend on the emission scenario, the
7 final climate state depends only on the total cumulative emissions.

8 This dependence of transient climate change on the emissions scenario can be seen clearly
9 in Figure 4, which plots the annual temperature increase as a function of annual emissions
10 for each of the three scenarios shown in Figure 3. All points fall approximately on a line
11 corresponding to 0.018 °C per 10 PgC emitted (1.8 °C per 1000 PgC)—which characterizes
12 this model’s temperature response to cumulative emissions—with some variation from the
13 line as a result of natural interannual variability in the model. The annual rate of tempera-
14 ture increase is therefore linearly related to the rate of increase of cumulative emissions; this
15 relationship appears to be surprisingly constant over the range of emissions shown here. A
16 key reason for this behaviour was emphasized by *Caldeira and Kasting* (1993) who noted
17 the compensation between increased retention of atmospheric carbon as emissions accumu-
18 late (linked to a slowdown in the ocean sink) and decreased radiative efficiency as stronger
19 absorption bands saturate at higher CO₂ concentrations. Whereas long-term temperature
20 changes (and associated impacts) will be determined primarily by total cumulative emis-
21 sions, short-term impacts that depend on the rate of climate warming will likely be more
22 sensitive to the rate at which emissions increase or decrease over the next century.

23 In summary, cumulative carbon dioxide provides a powerful tool with which to assess the
24 climate impacts of various levels of anthropogenic CO₂ emissions. The following are robust
25 conclusions that emerge from this framework of analysis:

- 26 1. A given emission of carbon will lead to an approximately constant increment to global

1 temperature, regardless of when or over how long this emission occurs;

2 2. Uncertainty in the climate and carbon cycle response to emissions results in uncertainty
3 in the temperature response to cumulative emissions;

4 3. We can define a *very likely* (5-95%) range for the temperature response to cumulative
5 emissions of 1 to 2.5 °C per 1000 PgC emitted;

6 4. At a given year, the global temperature change which occurs due to cumulative emis-
7 sions to that date can be associated also with a unique atmospheric CO₂ concentration
8 (assuming reasonably similar CO₂ emission scenarios);

9 5. Stabilizing atmospheric CO₂ concentrations at this level would allow continued emissions—
10 and would correspondingly lead to continued climate warming—though if emissions are
11 subsequently eliminated, CO₂ concentrations would decrease over time and global tem-
12 peratures would stabilize;

13 6. The long-term temperature change depends only on cumulative emissions, and not on
14 the rate of change of emissions over the next century;

15 7. The transient rate of warming does depend on the emissions scenario, with faster
16 increases in cumulative emissions leading to faster rates of warming over the next few
17 decades.

18 **Cumulative Carbon, Aerosols and Other Greenhouse Gases**

19 The use of cumulative carbon emissions provides a simple and versatile approach to the
20 problem of climate change mitigation. This is particularly true for long-term temperature
21 targets; because of the very long lifetime of anthropogenic CO₂ in the atmosphere relative to
22 most other climate-relevant gases (e.g. *Archer et al.*, 2009, *Solomon et al.*, 2010), the climate
23 warming signal will become increasingly CO₂-dominated as we move into the latter half

1 of this century and beyond. When considering nearer-term climate targets, however, and
2 particularly if we are to restrict the overall rate of climate warming over the next several
3 decades, it is not possible to ignore the effect of other greenhouse gases and aerosols.

4 The current balance of positive and negative forcings is such that the best estimate of
5 the net anthropogenic forcing is very close to the forcing from CO₂ alone. This can be seen
6 in Figure 5, which shows the estimate from *Forster et al.* (2007) of the radiative forcing
7 for 2005 from all radiatively active gases and aerosols, expressed in terms of equivalent CO₂
8 concentration (panel A). When considering only positive forcings (CO₂ and other greenhouse
9 gases), the year-2005 CO₂-equivalent concentration is approaching 450 ppm (panel B). How-
10 ever, when negative forcings are included also, the CO₂-equivalent concentration at 2005 is
11 close to that of CO₂ alone (panel B.). This result has important policy implications: when
12 aerosol forcing is included, it is clear that we have not yet reached the 450-ppm atmospheric
13 CO₂-equivalent concentration level that is generally associated with a long-term warming of
14 2 degrees above pre-industrial temperature.

15 Atmospheric lifetimes of non-CO₂ greenhouse gases and aerosols vary considerably, from
16 a few days (aerosols and tropospheric ozone) to a decade (methane) to a century and longer
17 (nitrous oxide and halocarbons) (*Forster et al.*, 2007). If emissions of all gases (including CO₂
18 were to be eliminated, one would expect an immediate warming (of uncertain magnitude,
19 given the current large uncertainty associated with aerosol forcing), followed by a multi-
20 decadal cooling due to the decreases in atmospheric concentrations of methane and nitrous
21 oxide (*Armour and Roe*, 2011, *Hare and Meinshausen*, 2006, *Frölicher and Joos*, 2010); on
22 timescales of a century or so, the climate change signal would likely converge with that due
23 to CO₂ alone. This suggests that one approach to mitigation could be a two-basket method
24 in which CO₂ (and perhaps nitrous oxide and perfluorocarbons) would be dealt with in one
25 basket to provide a multi-century constraint, while aerosols, methane and ozone precursors
26 were dealt with in another basket constraining shorter-term changes.

1 In a more realistic scenario where emissions of all gases change more slowly, it is less clear
2 how the relative balance of positive and negative non-CO₂ forcings would change over time.
3 For some guidance on this question, we have drawn on the recent RCP scenarios (*Moss et al.*,
4 2010), which provide information on changes in greenhouse gas and aerosol forcing over a
5 range of mitigation scenarios. The scenarios RCP 2.6 and RCP 4.5 closely approximate our
6 400–450 and 550 stabilization scenarios, respectively. From these, we calculated the year-
7 2100 CO₂-equivalent with all anthropogenic forcings included in the same manner as for the
8 year-2005 values shown in Figure 5. In all three cases, the fraction of radiative forcing due
9 to CO₂ alone increased relative to the total due to all greenhouse gases (i.e. CO₂ became
10 more dominant among positive radiative forcing agents by the end of the century than it is
11 today). CO₂-equivalent concentrations, compared to the CO₂-only concentrations, were 415
12 ppm versus 400, 465 ppm versus 450, and 580 ppm versus 550 (plotted as the ‘x’ symbols in
13 panel C of Figure 5). In all cases, the uncertainty ranges (assumed to be equivalent to the
14 uncertainty range at the year 2005, but decreased in proportion to the magnitude of the net
15 aerosol forcing) overlapped the CO₂-only concentrations.

16 From this analysis, we can conclude that the current close balance of positive (non-CO₂
17 greenhouse gas) forcing and negative (aerosol) forcing is unlikely to persist throughout this
18 century, though it is also unlikely to shift enough to result in dramatic deviations from the
19 CO₂-only results. For the range of RCP scenarios that we have analyzed, there is some
20 continued cancellation of these two sets of forcing, though the balance of forcings does move
21 somewhat towards smaller aerosol relative to non-CO₂ gas forcing. As a result, the CO₂-
22 equivalent concentration increases by 15–30 ppm relative to the CO₂-only concentration.
23 This clearly introduces some additional uncertainty into the climate response to cumula-
24 tive carbon emissions, though in all cases, the CO₂-only result falls within the uncertainty
25 range of possible CO₂-equivalent concentration when all forcings are included; consequently,
26 the temperature response to cumulative carbon emissions remains a close approximation

1 of the temperature response to cumulative carbon in combination with emissions of other
2 greenhouse gases and aerosols.

3 **Summary**

4 Cumulative carbon represents a new framework within which to assess the question of how
5 to mitigate emissions so as to avoid dangerous anthropogenic climate impacts. The advan-
6 tages of using cumulative carbon are clear. There appears to be a robust linear relationship
7 between temperature change and cumulative carbon emissions, which greatly simplifies the
8 very complex relationship between emissions, concentrations and temperature change. Fur-
9 thermore, this framework allows an estimate of the instantaneous temperature response to
10 cumulative emissions, which is approximately consistent with the long-term temperature in
11 the absence of additional emissions; this avoids the difficulties inherent in the greenhouse gas
12 stabilization framework associated with the large difference between transient and equivalent
13 warming at a given atmospheric concentration. There remains a significant uncertainty on
14 the magnitude of the temperature response to cumulative emissions, which emerges as a re-
15 sult of fundamental uncertainties in the carbon cycle response to emissions, the temperature
16 response to changes in atmospheric concentrations, and the feedbacks between tempera-
17 ture change and carbon sinks. There is also additional uncertainty that reflects the relative
18 balance of non-CO₂ greenhouse gas and aerosol forcing over the next century, which is partic-
19 ularly relevant to near-term climate targets, and is of comparable magnitude to the climate
20 and carbon cycle uncertainties.

21 The cumulative carbon framework is summarized in Figure 6. Read sequentially from left
22 to right, this figure connects cumulative carbon emissions at the year 2100, with CO₂ concen-
23 trations and temperature changes at that date. Uncertainties in temperature changes (red
24 bars) reflect our estimate of the *very likely* (5–95%) range of temperature responses to the
25 associated level of cumulative carbon emissions, based on carbon cycle and climate feedback

1 uncertainties (*Solomon et al.*, 2011, *Matthews et al.*, 2009, *Allen et al.*, 2009). The uncer-
2 tainty associated with the carbon cycle alone is indicated by the purple shaded region around
3 the 550 ppm CO₂ scenario at the year 2100, reflecting inter-model differences in the carbon
4 cycle response to emissions and climate changes (*Friedlingstein et al.*, 2006).² The CO₂-
5 equivalent of all greenhouse gases and aerosols, along with the uncertainty on this estimate,
6 is plotted on the CO₂ concentration profiles with green ‘x’ symbols and error bars at year
7 2005, and at year 2100 for the three intermediate CO₂ scenarios. For these scenarios (400,
8 450 and 550 ppm CO₂ concentrations at 2100), we have also given a modified temperature
9 response, which reflects the slight increase in the year-2100 CO₂-equivalent concentration
10 (relative to the CO₂-only concentration) associated with a given level of cumulative carbon
11 emissions (thin green vertical bars).

12 The shaded region at the bottom of Figure 6 shows total historical cumulative emissions
13 (about 530 PgC at the end of 2009 (*Boden et al.*, 2010, *Houghton*, 2008)). Areas within this
14 shaded region represent CO₂ and temperature targets that are likely inaccessible this century,
15 assuming positive future emissions (though see *Matthews* (2010) for a review of proposals
16 for carbon cycle geoengineering aimed at achieving net negative CO₂ emissions). Even
17 when the negative forcing due to aerosols is considered, we have probably already exceeded
18 the total cumulative emissions that are consistent with achieving CO₂ concentrations of 350
19 ppm within this century. Similarly, we are fast approaching the level of cumulative emissions
20 consistent with 1 degree of global temperature change above pre-industrial (about 550 PgC),
21 though there is a 5% chance that this target could still be met with emissions up to about
22 1000 PgC. The most likely level of emissions for 2 degrees of global temperature change is
23 about 1100 PgC, though it may be possible (5% likelihood) that 2 degrees will be reached
24 with cumulative emissions as low as 800 PgC, or as high as 2000 PgC (Figure 6; calculations

²We estimated the carbon cycle uncertainty based on the range of cumulative emissions at the time when atmospheric CO₂ reached 550 ppm in the “coupled” simulations from models participating in the C4MIP project; we discarded one model in this group as a clear outlier.

1 based on a 5-95% range of 1 to 2.5 °C per 1000 PgC).

2 According to this analysis, the year-2100 CO₂ concentration most consistent with 2 de-
3 grees is 500 ppm, though this is predicated on the assumption of zero CO₂ emissions after
4 the year 2100. The temperature change values shown here are only consistent with cumula-
5 tive emissions over the entire span of time during which humans emit CO₂; in order for the
6 temperature changes shown here at the year 2100 to remain at that level further into the
7 future, human emissions of CO₂ must have reached zero by the year 2100.

8 Despite exceeding the cumulative emissions threshold for 350 ppm this century, as well
9 as that for 1 degree of global warming, we have almost certainly not yet reached a level of
10 cumulative emissions that could result in 2 degrees of global temperature change. Meet-
11 ing the stated international goal of 2 degrees over pre-industrial temperatures is clearly a
12 difficult task that would require dramatic reductions and likely the eventual elimination of
13 CO₂ emissions this century. This may well be daunting, but it depends entirely on choices
14 regarding future energy sources, and is far from an impossible objective.

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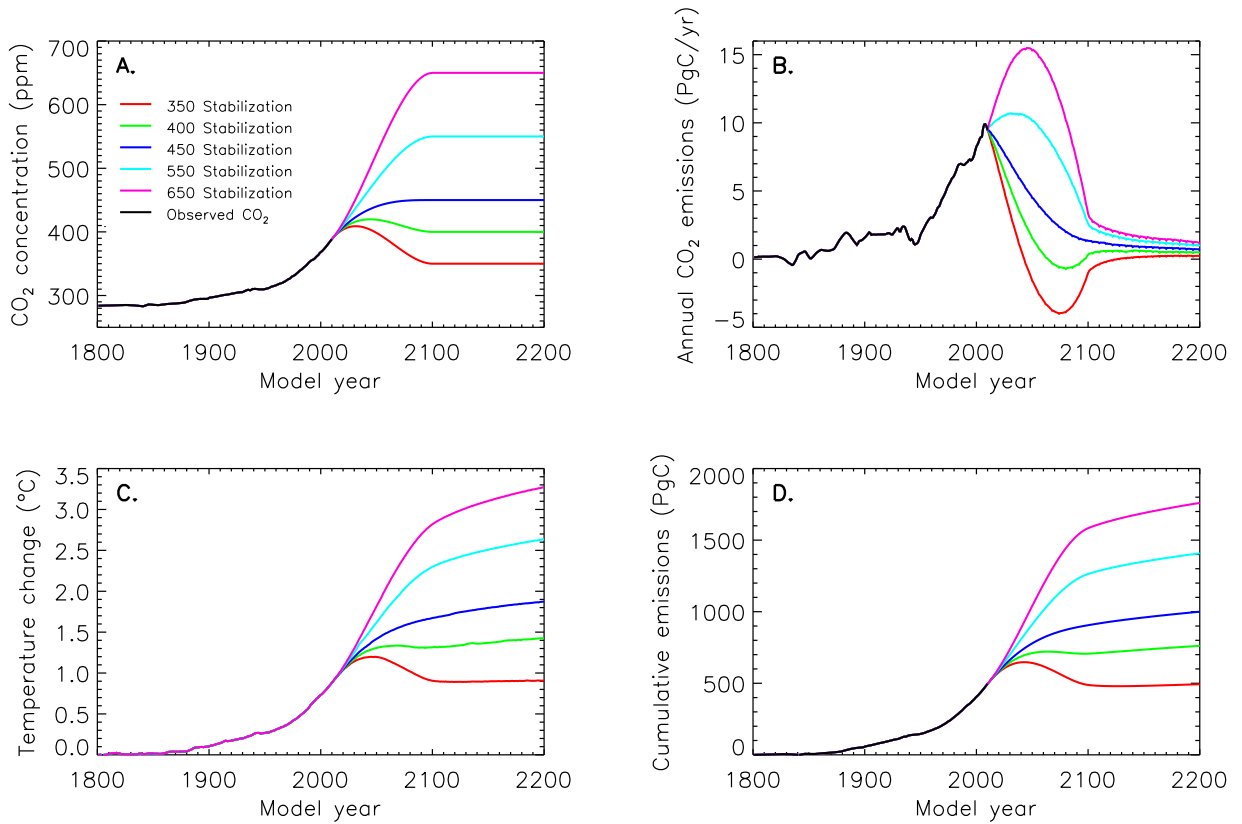


Figure 1: Climate and carbon cycle response to prescribed CO₂ stabilization scenarios. **A.** Prescribed atmospheric CO₂ concentration (ppm); **B.** Simulated allowable annual CO₂ emissions (PgC/year), based on global carbon balance; **C.** Simulated globally averaged temperature change relative to pre-industrial (°C); **D.** Cumulative carbon emissions (PgC).

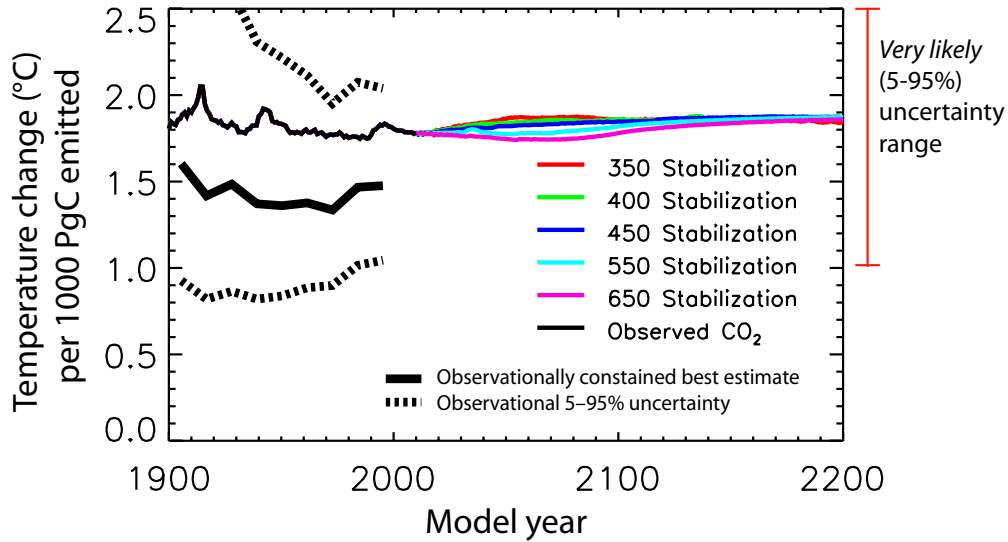


Figure 2: Simulated temperature change per 1000 PgC cumulative carbon emitted. Observational constraints for the twentieth century are given by the thick solid and dashed lines, as in *Matthews et al. (2009)*. The *very likely* (5-95%) uncertainty range is indicated by the red error bar, based on a combination of estimates given by *Matthews et al. (2009)* and *Allen et al. (2009)*.

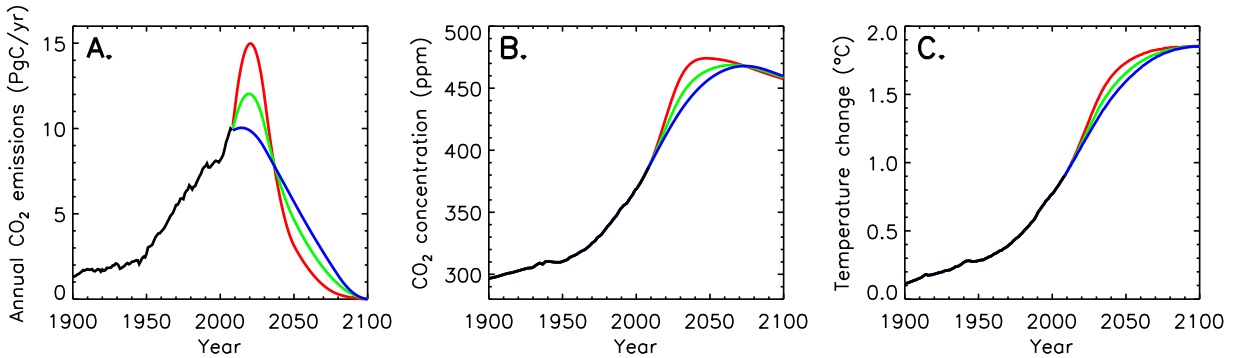


Figure 3: Climate response to three emission scenarios, each with cumulative emissions equal to 1000 PgC. The transient rate of temperature change differs between scenarios, but both CO₂ concentration and temperature change at the year 2100 are independent of scenario and depend only on the cumulative emissions. (Figure adapted from Figure 3.7 of *Solomon et al. (2011)*.)

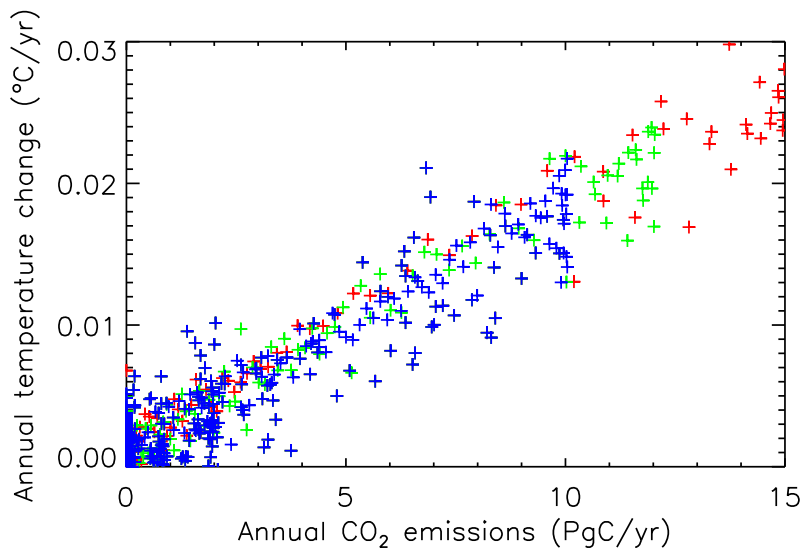


Figure 4: Response of annual temperature change to annual emissions for the simulations shown in Figure 3. The *rate* of warming depends linearly on the rate of increase of cumulative emissions, whereas the total warming to date depends on the total cumulative emissions to date.

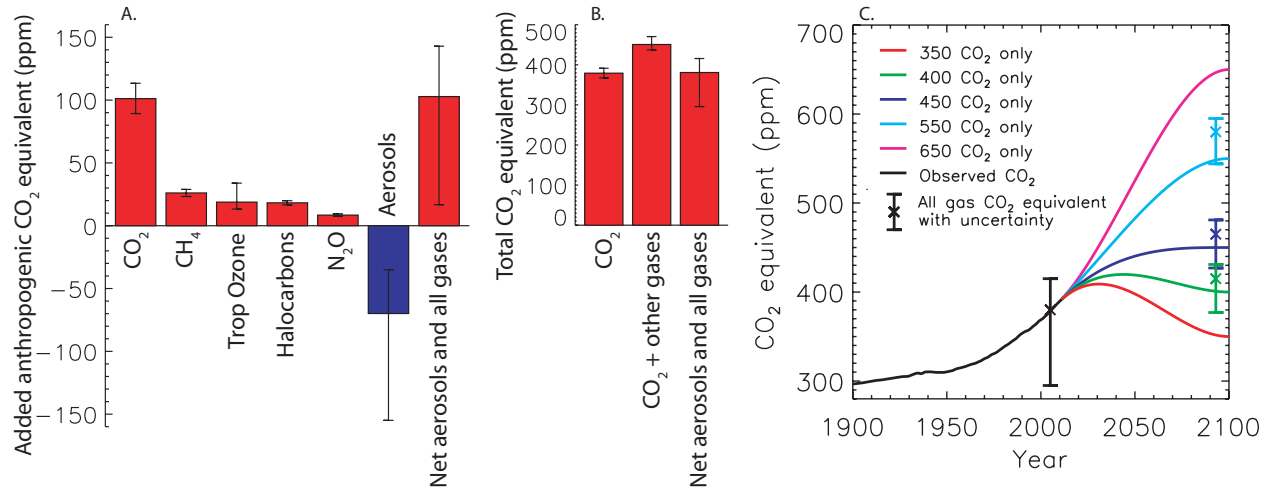


Figure 5: CO₂-equivalent concentrations of other gases and aerosols. **A.** Year-2005 CO₂-equivalent of anthropogenic aerosols and all greenhouse gases, based on forcings given in *Forster et al.* (2007). Halocarbons (including chlorofluorocarbons, hydrocarbons, hydrofluorocarbons and perfluorocarbons) have been grouped, as have the direct and indirect effect of aerosols. **B.** Year-2005 atmospheric CO₂ concentration, the equivalent CO₂ concentration including other greenhouse gases, and the equivalent CO₂ including other greenhouse gases and aerosols. The balance of negative forcing from aerosols and positive forcing from other greenhouse gases shown here is such that the equivalent CO₂ atmospheric concentration is very close to the current CO₂-only atmospheric concentration. **C.** Idealized CO₂ concentration scenarios with the year-2005 CO₂-equivalent range added, as well as year 2100 CO₂-equivalent ranges for the 400, 450 and 550 stabilization scenarios. Year 2100 central values for CO₂-equivalent (X symbols) were taken from the RCP 2.6 (400 and 450 ppm) and RCP 4.5 (550 ppm) scenarios (*Moss et al.*, 2010). We assumed a year 2100 uncertainty range that was equivalent to that at year 2005, but decreased in proportion with the magnitude of the net aerosol forcing. (Panels A and B adapted from Figure 2.1 of *Solomon et al.* (2011))

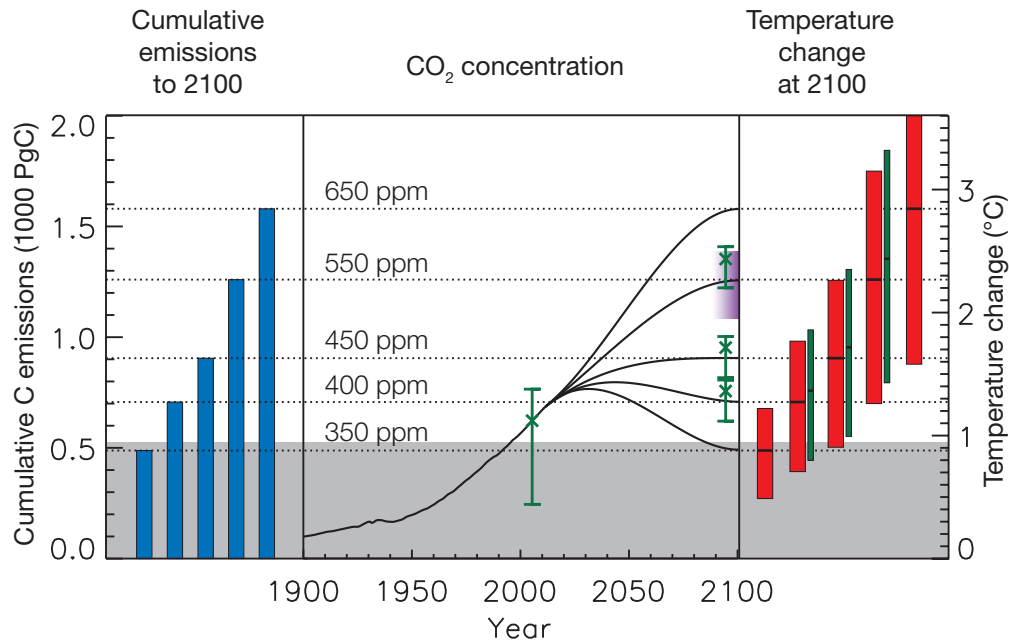


Figure 6: Summary figure showing the relationship between cumulative emissions, CO₂ concentrations and temperature change. Cumulative emission values (left panel), CO₂ scenarios (middle panel) and the central value for the year-2100 temperature changes (right panel) correspond to the UVic ESCM model simulations as shown in Figure 1. The red-bar temperature range represents the 5-95% uncertainty range for the temperature response to cumulative emissions (*Matthews et al.*, 2009, *Allen et al.*, 2009). In the middle panel, the purple shaded region represents an estimate (for 550 CO₂ scenario) of the uncertainty in the carbon cycle response to cumulative emissions, based on the C4MIP model simulations (*Friedlingstein et al.*, 2006)². Also shown in the middle panel, for the year 2005 as well as for the year 2100 of the 400, 450 and 550 scenarios, are additional ranges corresponding to the CO₂-equivalent values of CO₂ plus non-CO₂ greenhouse gases and aerosols (green 'x' symbols and uncertainty ranges, as plotted in Figure 5C). Finally, for the scenarios where we included an estimate of the CO₂-equivalent, we have included an additional range for the temperature response to cumulative emissions (thin green bars), shifted upward to match to the best estimate of the CO₂-equivalent concentration for each of the 400, 450 and 550 ppm scenarios. The gray shaded region at the bottom of the plot shows total cumulative emissions to date, and the correspondingly inaccessible climate targets, assuming positive future cumulative emissions. (Figure adapted from Figure 3-8 of *Solomon et al.* (2011))