

Target Atmospheric Greenhouse Gas Concentrations

Why Humanity Should Aim For 350 ppm CO_{2e}

TARIEL MÓRRÍGAN

Global Climate Change, Human Security, and Democracy

Global & International Studies
University of California
Social Sciences & Media Studies Building, Room 2006
Santa Barbara, CA 93106-7065

tmorrigan@bren.ucsb.edu

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March 07, 2010

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“If humanity wishes to preserve a planet similar to that on which civilization developed and to which life on Earth is adapted, paleoclimate evidence and ongoing climate change suggest that CO₂ will need to be reduced from its current 385 ppm to at most 350 ppm, but likely less than that.”

~ James Hansen et al. (2008)

Summary

- ***A 300 ppm CO₂ (350 ppm CO₂-eq) is likely the safe upper limit for atmospheric greenhouse gases.*** Global average temperatures may stabilize within a likely range of 0.6–1.4°C above pre-industrial values at or below 300 ppm CO₂ (350 ppm CO₂-eq).
- ***A concentration of 400 ppm CO₂ (450 ppm CO₂-eq) would only provide approximately a 50% chance of remaining below a dangerous global average temperature rise of 2.1°C above pre-industrial global average temperature*** with a "likely in the range" of 1.4–3.1°C rise. As CO₂ concentrations approach 441 ppm a corresponding committed warming of 3.1°C will occur by 2030 in the absence of strong countervailing mitigation.
- ***An atmospheric CO₂ concentration of 450+/-100 ppm (350–550 ppm) was the boundary condition between an ice-free planet and one in which large scale glaciation occurred 35 million years ago.***
- ***A CO₂ concentration of order 450 ppm or greater would push the Earth toward an ice-free state and that “such a CO₂ level likely would cause the passing of climate tipping points and initiate dynamic responses that could be out of humanity’s control”.***
- ***Humanity has already passed the threshold for “dangerous anthropogenic interference” with the natural climate system.*** The global climate system has not yet fully responded to the recent increase of anthropogenic climate forcings because of its inertia. The already occurring climate impacts indicate that ***the current 387 ppm CO₂ concentration is already deleterious and a unprecedented threat to the planet on which civilization developed and to which life on Earth is adapted.***
- ***As of 2005, when atmospheric CO₂ concentrations were already about 380 ppm, GHG emissions may have committed the planet to a warming of 2.4°C (1.4°–4.3°C) above the pre-industrial surface temperatures, which is within the range of predicted climate tipping points.***
- Limiting the atmospheric CO₂ concentration to no greater than 350 ppm might prevent committed global warming to no more than 2.4°C in the long-term, after the temporary delay by climate and ocean thermal inertia reach their peak potential climate forcing (i.e. warming). However, ***a CO₂ target as low as 300 ppm may be necessary to stabilize to prevent a dangerous warming of 2°C.***

- ***Approximately 20–30% of the plant and animal species assessed by the IPCC are likely to be at an increased risk of extinction, if global average temperature exceeds 1.5–2.5°C above pre-industrial value.*** For increases exceeding 1.5–2.5°C, the IPCC projects major changes in ecosystem structure and function, species' ecological interactions and shifts in species' geographical ranges, with predominantly negative consequences for biodiversity and ecosystem goods and services (e.g. water and food supply). ***At a 2°C temperature rise, approximately 1–3 billion people may experience increased water stress, sea level rise, hurricanes could displace millions from the world's coastlines, and global agricultural yields would likely decline.*** At lower latitudes, especially in seasonally dry and tropical regions, the IPCC projects that crop productivity will decrease for even small local temperature increases (1–2°C), which would increase the risk of hunger and malnutrition.
- In order to safely avoid passing a dangerous threshold for ocean acidification, the maximum concentration of atmospheric CO₂ should be limited to no greater than 450 ppm. However, given that additional stressors (e.g. increased temperatures from climate change, pollution) will also seriously impact fish and other marine organisms, especially the world's corals and their associated species, ***the maximum concentration of CO₂ may need to be lower than 450 ppm to avoid an unprecedented collapse of the world's marine ecosystems, and lower than 350 ppm for the long-term viability of coral reefs.***
- The populations of many small island states and low lying coastal nations are located below 2 meters above sea level, the results of a 2°C temperature rise from pre-industrial levels could displace millions of people from the world's coastlines, inundate a large area of the world's arable land, and submerge large areas of these low-lying nations. ***To prevent 0.75 meters or more sea level rise, it is likely that the global mean temperature should be kept from rising above 1.5°C, which would require a target of stabilizing greenhouse gas emissions at no greater than 300 ppm CO₂ (350 ppm CO₂-eq).***
- ***The paleoclimate records show that past climate changes included both steady, linear changes and abrupt, non-linear changes (i.e. tipping points).*** The catastrophic impacts from these events would include many meters of sea level rise, massive displacement of people and wildlife, severe loss of biodiversity, megadroughts, catastrophic water shortages, and massive famine that could result in political instability, resource wars, and human rights challenges. Passing climate tipping points would likely cause other severe impacts, such as additional runaway climate feedbacks.
- ***Temperature tipping points for abrupt climate changes could be passed within this century, or even in the next decade.*** For example, the disappearance of Arctic summer sea ice, which is the first predicted tipping point, is already occurring. The Arctic could be virtually ice-free in September of 2037, or even as early as September of 2028.
- Despite the certainty that climate changes have occurred abruptly in the past, and that abrupt climate changes could be triggered again in the near future, ***current climate policy does not account for abrupt climate change.*** Although policy must continue to address mid- and long-term mitigation strategies to reduce CO₂ emissions, societies also must begin fast-track mitigation strategies that can produce immediate climate mitigation and delay the onset of tipping points in order to avoid catastrophic climate changes. Major efforts in carbon sequestration combined with a substantial reduction of GHG emissions will be necessary to achieve this target.

Introduction

Pre-Industrial Revolution atmospheric CO₂ concentrations were 280 ppm. Paleoclimate evidence and observed and ongoing global environmental changes suggest that the current 387 ppm atmospheric CO₂ concentration is already too high to maintain the climate in which civilization developed and to which humanity and life on Earth is adapted. The best available scientific evidence now indicates that a warming of 2°C is not “safe” and would not prevent dangerous interference with the climate system. As of 2005, when atmospheric CO₂ concentrations were already about 380 ppm, GHG emissions may have committed the planet to a warming of 2.4°C above the pre-industrial surface temperatures, which is within the range of predicted abrupt, climate tipping points.

Leading climate scientists suggest an initial objective of reducing atmospheric CO₂ concentrations to 350 ppm or less, with the target to be adjusted as scientific understanding and empirical evidence of climate effects accumulate. Atmospheric CO₂ concentrations higher than 350 ppm would be dangerous, and may result in catastrophic global climate changes. Although a case already could be made from existing scientific understanding – and is made in this report – that the eventual atmospheric greenhouse gas concentration target probably needs to be lower than 350 ppm, the 350 ppm target may be sufficient to qualitatively change the policy discussion and drive critical changes in climate policy and social behavior. Paleoclimate evidence, current global environmental changes, and the delayed climate and ocean response times suggest that this target must be pursued on a timescale of years and decades since it would be irresponsible and perilous to allow GHG concentrations to remain in the dangerous zone for longer. Ultimately, the target atmospheric CO₂ concentration should be 300 ppm in order to avoid passing abrupt, catastrophic climate tipping points.

The following seven converging lines of scientific evidence argue strongly for the need to reduce atmospheric greenhouse gas concentrations to less than 350 parts-per-million carbon dioxide equivalent (400 ppm CO₂-eq), and likely to no greater than 300 ppm CO₂ (350 ppm CO₂-eq):

1. Risk of Passing a Threshold at 400 ppm CO₂
2. Threshold to an Ice-Free Planet: Paleoclimate at 350–550 ppm CO₂
3. Warning from Current Climate Changes: 387 ppm CO₂
4. Tipping Points
5. Ecosystems and Human Security
6. Ocean Acidification
7. Sea Level Rise

1. Risk of Passing a Threshold at 400 ppm CO₂

In order to stabilize atmospheric concentrations of greenhouse gases to 450 ppm CO₂-eq (400 ppm CO₂)*, the Intergovernmental Panel on Climate Change (IPCC) climate models indicate that developed countries need to reduce emissions to 25-40% below 1990 levels by 2020, and 80-95% below 1990 levels by 2050 (IPCC, 2007b). However, the IPCC claims that a concentration of 450 ppm CO₂-eq would only provide approximately a 50% chance (within a probability distribution of 26–78%) of remaining below a dangerous global average temperature rise of 2.1°C above pre-industrial global average temperature with a "likely in the range" of 1.4–3.1°C rise (IPCC, 2007c; Meinshausen, 2006). Achieving a 2°C target with at least a likely chance (>66%) would require a long-term stabilization below 400ppm CO₂-eq (Moss, 2008). At 400 ppm CO₂-eq, the mean probability of exceeding 2°C is 28 percent (Meinshausen, 2006). A target of stabilizing greenhouse gas emissions at 350 ppm CO₂-eq (approximately 300 ppm CO₂) would reduce the mean probability of exceeding a 2°C temperature rise to 7 percent (Meinshausen, 2006).

However, caution should be used when interpreting the 2007 IPCC report findings since they tended to ignore various critical climate forcing mechanisms (e.g. Arctic and Greenland ice sheet melt), assumed linear responses in the climate system, and inadequately consider non-linear climate responses (i.e. abrupt climate change) (IPCC, 2007c). Consequently, the 2007 IPCC estimates are considered very conservative and under-estimate climate sensitivity and climate forcing mechanisms and feedback cycles. In December 2008, the Copenhagen Climate Science Congress concluded "the worst-case IPCC scenario trajectories (or even worse) are being realized (University of Copenhagen, 2009)". In addition, the 2007 IPCC report did not include the many new scientific findings published after its release. Therefore, these concerns about the findings and recommendations of the 2007 IPCC report suggest that the recommended 450 ppm stabilization target should be accepted as an upper limit – but not necessarily a safe limit – to atmospheric GHG concentrations. Given that as of 2005, when atmospheric CO₂ concentrations were already about 380 ppm (~422 ppm CO₂-eq), GHG emissions may have committed the planet to a warming of 2.4°C (within a range of 1.4°–4.3°C) above the pre-industrial surface temperatures (Ramanathan and Feng, 2008), the climate system may have already passed the 2°C threshold.

* see Appendix 1 for conversion rule

2. Threshold to an Ice-Free Planet: Paleoclimate at 350–550 ppm CO₂

Pre-Industrial Revolution atmospheric CO₂ concentrations were 280 ppm (IPCC, 2007c). Hansen et al. (2008) found that an atmospheric CO₂ concentration of 450±100 ppm (350–550 ppm CO₂) was the boundary condition between an ice-free planet and one in which large scale glaciation occurred 35 million years ago. Studies indicate that 350 ppm CO₂-eq (approximately 300 ppm CO₂) is likely the safe upper limit for atmospheric greenhouse gases (Hansen et al, 2008; Ramanathan and Feng, 2008). Stabilization at or below 350 ppm CO₂-eq provides a 93% probability of staying below 2°C above pre-industrial values (IPCC, 2007c; Meinshausen, 2006). Global average temperatures may stabilize within a likely range of 0.6–1.4°C above pre-industrial values at or below 350 ppm CO₂-eq (IPCC, 2007c; Meinshausen, 2006). The greatest uncertainty in the target concentration is due to the possible changes of non-CO₂ forcings (Hansen et al, 2008).

Based on an estimated history of CO₂ through the Cenozoic Era (the period from 65.5 million years ago to the present), Hansen et al. suggest that a CO₂ concentration of order 450 ppm or greater, if long maintained, would push the Earth toward an ice-free state and that “such a CO₂ level likely would cause the passing of climate tipping points and initiate dynamic responses that could be out of humanity’s control (Hansen et al, 2008)”.

It is important to note that atmospheric CO₂ concentration oscillated periodically during the past 800,000 years as a result of positive feedback responses to the Earth's orbital changes. These oscillations in atmospheric CO₂ concentrations led to the temperature swings of the glacial/interglacial cycles. At the peak of interglacial warmth of each cycle – which corresponded to the peaks of CO₂ concentration – atmospheric CO₂ concentrations never exceeded 300 ppm (Hansen et al, 2008, IPCC, 2007c). This maximum CO₂ concentration of 300 ppm does not include the concentrations of other greenhouse gases. Due to the lack of sufficient understanding of climate feedback mechanisms, it may be very risky to allow CO₂ concentrations to exceed the historic levels associated to human evolutionary history.

3. Warning from Current Climate Changes: 387 ppm CO₂

The global climate system has not yet fully responded to the recent increase of anthropogenic climate forcings because of its inertia (i.e. climate inertia) (Hansen et al., 2007). Nevertheless, climate impacts are already occurring that allow scientists to make an initial estimate for target atmospheric GHG concentrations. Although GHG targets will need to be adjusted as climate data and knowledge improve, the urgency and challenge of reducing anthropogenic forcings will be less, and more likely manageable, if excess forcing is limited soon. Pre-Industrial Revolution atmospheric CO₂ concentrations were 280 ppm (IPCC, 2007c). The already occurring climate impacts indicate that the current 387 ppm CO₂ concentration is already deleterious and a unprecedented threat to the planet on which civilization developed and to which life on Earth is adapted.

Civilization is adapted to climate zones of the Holocene – human civilization dates entirely within the Holocene which started around 10,000 BC. Although theory and models indicate that subtropical regions expand poleward with a warming global climate (IPCC, 2007c; Hansen et al., 2008), data already reveal a 4-degree latitudinal shift (Hansen et al., 2008), which is greater than model predictions. The results of this climate shift are increased aridity in the southern United States, the Mediterranean region, Australia, and parts of Africa (Hansen et al., 2008). The impacts of this climate shift (IPCC, 2007a) suggest that the current 387 ppm CO₂ concentration is already dangerous.

Alpine glaciers are in near-global retreat (IPCC, 2007a; Barnett et al., 2005). Glacier demise will result in summers and autumns of frequently dry rivers in many regions, including the rivers that originate in the Andes, Himalayas and Rocky Mountains, which currently supply water to billions of people. Therefore, the current glacier retreat, and predicted future warming (i.e. warming that is in the 'pipeline'), suggest that the current 387 ppm CO₂ concentration is already a dangerous threat.

In order to stabilize the Arctic sea ice cover, atmospheric CO₂ concentrations must be reduced to 325-355 ppm, if other forcings are unchanged. However, in order to restore sea ice to its area of 25 years ago, CO₂ concentrations must be reduced to approximately 300–325 ppm (Hansen et al., 2008).

Ocean acidification, ocean warming, and other stressors are damaging the world's coral reefs, which support over 25% of the world's fish biodiversity, 9–12% of the world's total fisheries, and billions of dollars of commercial activity (Stone, 2007). The findings of IPCC suggest that a increase of 1°C in mean global temperatures above pre-industrial levels is the maximum target temperature rise in order to protect coral reefs (IPCC, 2007a). Given additional warming in the pipeline, the current 387 ppm CO₂ concentration is already dangerous.

4. Tipping Points

The paleoclimate records show that past climate changes included both steady, linear changes and abrupt, non-linear changes. The abrupt, non-linear changes were caused by small increases in global climate change that resulted in large and irreversible environmental changes once temperature and biogeochemical (e.g. ocean acidification) tipping points were passed. Anthropogenic GHG emissions are driving the global climate system toward such temperature and biogeochemical tipping points earlier than previously predicted. The potential impacts of passing such climate tipping points would be catastrophic, and include (Lenton et al., 2008):

- the disappearance of Arctic summer sea ice,
- a major reduction of area and volume of Hindu-Kush-Himalaya-Tibetan glaciers, which provide the head-waters for most major river systems of Asia including the Indus, Ganges, Irrawady, Mekong, Red, Yangtze, and Yellow rivers (almost half of the world's population lives in the watersheds of these rivers),
- the deglaciation of Greenland Ice Sheet,
- the dieback of Amazonian and boreal forests,
- the shutdown of the Atlantic Thermohaline Circulation, and
- the collapse of West Antarctic Ice Sheet.

The catastrophic impacts from these events would include many meters of sea level rise, massive displacement of people and wildlife, severe loss of biodiversity, megadroughts, catastrophic water shortages, and massive famine that could result in political instability, resource wars, and human rights challenges (Lenton et al., 2008). Furthermore, passing climate tipping points would likely cause other severe impacts, such as the release of methane and other GHGs from permafrost and ocean hydrates that could cause additional runaway climate feedbacks.

Temperature tipping points for abrupt climate changes could be passed within this century, or even in the next decade (Lenton et al., 2008). Under a “business-as-usual” scenario, where atmospheric CO₂ concentrations are increasing approximately 2 ppm per year, the question is not whether abrupt climate change will occur, but rather how soon (Hansen et al., 2008).

The gravity of the threat of passing climate tipping points cannot be understated. Areas at high latitudes and altitudes are already experiencing major rapid changes. For example, the disappearance of Arctic summer sea ice, which is the first predicted tipping point, is already occurring. The Arctic could be virtually ice-free in September of 2037, or even as early as September of 2028 (Wang and Overland 2009). Furthermore, temperatures are rising faster than the global average at high latitudes and altitudes. The Arctic, Greenland, and the Tibetan Plateau are at particular risk (Lenton et al., 2008). Arctic temperatures increased at least 2 times as rapidly as global averages during the period between 1965 and 2005 (IGSD, 2008). The temperature of the Greenland Ice Sheet is increasing 2.2 times faster than global averages (IGSD, 2008). The temperature of the Tibetan Plateau temperature increased by about 3 times

the global average for the past half-century (IGSD, 2008), which has contributed to glacial retreat (Ramanathan and Carmichael, 2008).

The melting of the Arctic, Greenland, and Tibetan Plateau would also cause additional runaway climate feedbacks. For instance, melting of ice sheets produces positive feedbacks by reducing surface albedo (i.e. surface reflectivity) that leads to more absorption of heat by the exposed underlying surface, which then accelerates the melting of the remaining ice. For example, melting Arctic sea ice reduces albedo which leads to more absorption of heat by exposed Arctic waters (Lenton et al., 2008). This reduction of albedo is further accelerated by the additional darkening of polar surfaces caused when atmospheric anthropogenic black carbon (i.e. impure carbon particles resulting from the incomplete combustion of organic matter, such as wood or fossil fuels), or black soot, deposits on snow and ice (Ramanathan and Carmichael, 2008). Black carbon is also a heat-absorbing component of 'atmospheric brown clouds' (see below). The deposition of black carbon is also a significant driver of glacial retreat in the Hindu-Kush-Himalayan-Tibetan region (Ramanathan et al., 2008).

James Hansen, Director of NASA's Goddard Institute for Space Studies, and other climate scientists believe that humanity has already passed the threshold for "dangerous anthropogenic interference" with the natural climate system (Hansen et al., 2008). Ramanathan and Feng project that as CO₂ concentrations approach 441 ppm a corresponding committed warming of 3.1°C will occur by 2030 in the absence of strong countervailing mitigation (Ramanathan and Feng, 2008).

As of 2005, when atmospheric CO₂ concentrations were already about 380 ppm (~422 ppm CO₂-eq), GHG emissions may have committed the planet to a warming of 2.4°C (within a range of 1.4°-4.3°C) above the pre-industrial surface temperatures (Ramanathan and Feng, 2008), which is within the range of predicted tipping points (See Figure 1). If the total committed warming is at least 2.4°C, the present observed temperature increase of 0.76°C (Ramanathan and Feng, 2008) is misleading. Warming of at least another 1°C is currently masked by 'atmospheric brown clouds' that contain cooling particulates released with GHG emissions and other pollution (Ramanathan and Feng, 2008). As societies continue to reduce the pollution that create these clouds (mainly for health reasons) temperature increases of 1°C or greater temperature that are already committed from current emissions are being unmasked (Ramanathan and Feng, 2008). A further 0.6°C warming is temporarily delayed by ocean thermal inertia.⁸ More than 50% of this total committed warming of 2.4°C is expected to occur within decades (Ramanathan and Feng, 2008).

If the total committed global warming is at least 2.4°C, as of 2005 when atmospheric CO₂ concentrations were already about 380 ppm, then clearly an atmospheric CO₂ concentration of 450 ppm would very likely be deleterious and threatening. Indeed, a CO₂ concentration of 380 ppm would very likely be dangerous, as well. In the absence of 'atmospheric brown clouds', the amount of which could be reduced by pollution controls, global temperatures could have increased by 0.76°–1.76°C as of 2005.

Limiting the atmospheric CO₂ concentration to no greater than 350 ppm might prevent committed global warming to no more than 2.4°C in the long-term, after the temporary delay by climate and ocean thermal inertia reach their peak potential climate forcing (i.e. warming). Stabilization at or below 350 ppm CO₂-eq provides a 93% probability of staying below 2°C above pre-industrial values (IPCC, 2007c; Meinshausen, 2006). Therefore, a CO₂ target as low as 300 ppm may be necessary to stabilize to prevent a dangerous warming of 2°C. Global average temperatures may stabilize within a likely range of 0.6–1.4°C above pre-industrial values at or below 350 ppm CO₂-eq (300 ppm CO₂) (IPCC, 2007c; Meinshausen, 2006).

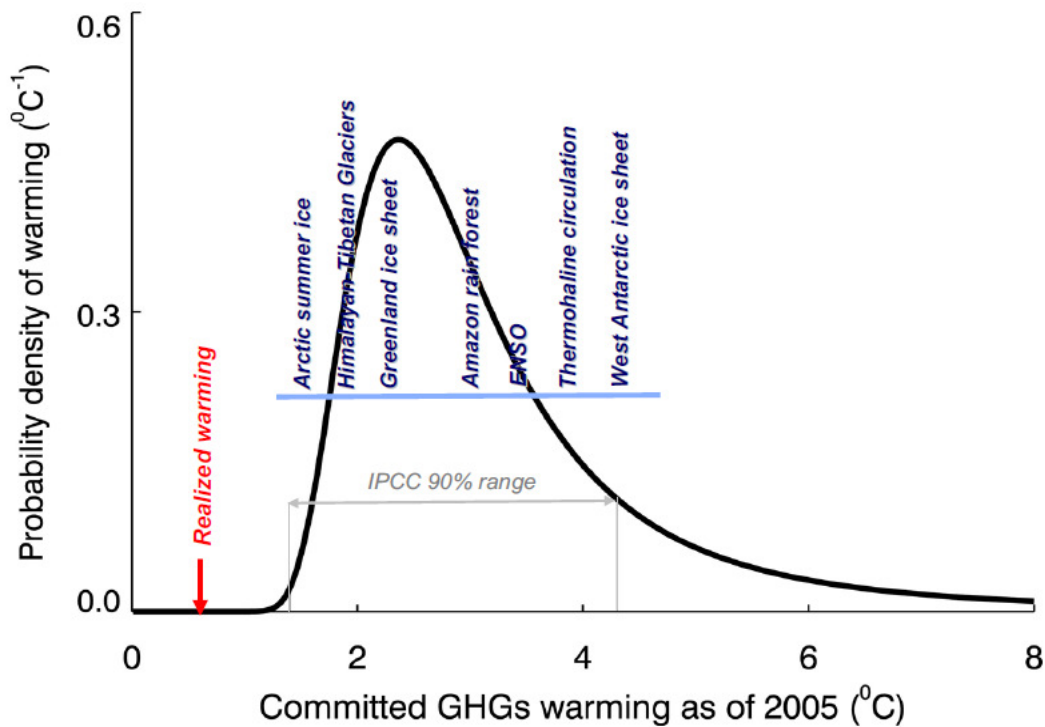


Figure 1: “Probability distribution for the committed warming by GHGs between 1750 and 2005... Shown are the climate-tipping elements and the temperature threshold range that initiates the tipping... (Ramanathan and Feng, 2008)”.

Despite the certainty that climate changes have occurred abruptly in the past, and that abrupt climate changes could be triggered again in the near future, current climate policy does not account for abrupt climate change (IGSD, 2008). Remarkably, abrupt climate change is not considered in the projections of the IPCC, which is still regarded as one of the most authoritative sources of information on climate science.

Although policy must continue to address mid- and long-term mitigation strategies to reduce CO₂ emissions, societies also must begin fast-track mitigation strategies that can produce immediate climate mitigation and delay the onset of tipping points in order to avoid catastrophic climate changes. As the climate passes the first tipping point, the disappearance of Arctic summer sea ice, it is apparent that a CO₂ concentration of 450 ppm could be disastrous. A target atmospheric concentration of CO₂ of no greater than 350 ppm will likely be needed to prevent the world from passing climate tipping points. However, a target concentration of CO₂ of 300 ppm may be needed to ensure that the climate does not pass the 2°C threshold. Obviously, major efforts in carbon sequestration combined with a substantial reduction of GHG emissions will be necessary to achieve this target.

5. Ecosystems and Human Security: 1.5°C vs. 2°C

Since the consequences of overshooting a 2°C threshold could be dangerous, if not catastrophic, the risk tolerance for exceeding a 2°C temperature rise should be extremely low. Approximately 20–30% of the plant and animal species assessed by the IPCC are likely to be at an increased risk of extinction, if global average temperature exceeds 1.5–2.5°C above pre-industrial value, which poses significant risks to many unique and threatened systems including many biodiversity hotspots (IPCC, 2007a). For increases in global average temperature exceeding 1.5–2.5°C, the IPCC projects major changes in ecosystem structure and function, species' ecological interactions and shifts in species' geographical ranges, with predominantly negative consequences for biodiversity and ecosystem goods and services (e.g. water and food supply) (IPCC, 2007a). At a 2°C temperature rise, approximately 1–3 billion people may experience increased water stress, sea level rise, hurricanes could displace millions from the world's coastlines, and global agricultural yields would likely decline (Vespa, 2009). At lower latitudes, especially in seasonally dry and tropical regions, the IPCC projects that crop productivity will decrease for even small local temperature increases (1–2°C), which would increase the risk of hunger and malnutrition (IPCC, 2007d).

Furthermore, corals are vulnerable to thermal stress and have low adaptive capacity. Increases in sea surface temperature of about 1 to 3°C are projected to result in more frequent coral bleaching events and widespread mortality, unless corals can undergo thermal adaptation or acclimatisation (IPCC, 2007a), which would have substantial impacts on marine biodiversity and fisheries. For instance, an assessment of the impacts of climate change on tropical fisheries determined that at 2°C warming, tropical coral cover is expected to decrease by 75%, as compared with 30–40% under a 1.5°C scenario (Simpson, 2009). Besides the threat to biodiversity, the loss of tropical coral reef habitat is projected to lead to declines in abundance of up to 65% for virtually all tropical reef-associated fish, which means that there is a moderate likelihood that declines in tropical coastal fisheries production of 20–50% could also occur (Simpson, 2009).

The table in Appendix 2 (Table 4.1 from IPCC (2007a)) indicates the projected impacts of climate change on ecosystems and population systems for different levels of global mean annual temperature rise, ΔT_g , relative to pre-industrial climate. In particular, one can see that even at an increase of 1.5°C there will likely be very serious climate change impacts throughout the world. Although this table focuses on ecosystems and selected species, it is very important to note that people are highly dependent on these biological and ecological systems for the provision of various ecosystem services (e.g. water, food, materials, flood management, storm protection). The second column in Table 4.1 shows the mean temperature change, ΔT_g , above pre-industrial levels. The third column shows the range of temperature change, ΔT_g , which represents the uncertainty arising from the use of different global climate models (GCM) to calculate global temperature change.

Since it will likely be challenging to keep the global average temperature at exactly the target value (e.g. 1°C, 1.5°C, or 2°C), it is important to consider the impacts of temperatures up to approximately 0.5°C above the target to account for the uncertainty in the IPCC's conservative projections and for the uncertainty in being able to keep global temperatures consistently at the target value. Therefore, one should look at the projected impacts for at least 0.5°C above a given target temperature in Table 4.1. Additionally, one should look at the range of temperature change in the third column in Table 4.1, and not just the second column showing the mean temperature. In the third column, one can see that the low end of some of these temperature ranges include both the 1.5°C and 2°C targets.

Given the climate impacts and temperature ranges in Table 4.1, it is likely that a 2°C global temperature increase will be deleterious; and that even a 1.5°C temperature increase will likely threaten the stability and security of global society as climate change impacts the planet's biophysical and ecological systems. The safest target atmospheric GHG concentration may be at or below 350 ppm CO₂-eq (300 ppm CO₂) since global average temperatures may stabilize within a likely range of 0.6–1.4°C above pre-industrial values (IPCC, 2007c; Meinshausen, 2006).

6. Ocean Acidification

The ocean is one of the planet's largest natural reservoirs of carbon. The ocean absorbs approximately 26–29% of anthropogenic carbon emissions each year (Sabine et al., 2004; SCBD, 2009). In the absence of anthropogenic CO₂ uptake by the oceans, atmospheric CO₂ levels would be approximately 55 ppm higher than present, and the effects of global climate change more severe (IPCC, 2007c). Although the uptake of CO₂ by the oceans buffers the rate of global climate change, the rate of change of ocean chemistry due to anthropogenic carbon emissions is rapid and unprecedented (SCBD, 2009).

Ocean acidity affects marine carbonate chemistry. Ocean acidification is predicted to have major negative impacts on corals, shellfish, plankton, and other marine organisms that build calcium carbonate (CaCO₃) skeletons and shells, and whose success is significantly controlled by marine carbonate chemistry. Many calcifying species occupy the bottom or middle of global ocean food webs. Consequently, the loss of these calcifying organisms to ocean acidification will alter predator–prey relationships, the structure of food webs and ecosystems (SCBD, 2009). Additionally, a loss or change in biodiversity as a result of ocean acidification will likely have significant ecological consequences (SCBD, 2009).

Ocean acidification will also negatively affect other organisms besides calcifying organisms. Some fish species are sensitive to anomalous environmental pH levels, which can be toxic and cause stress and reproductive problems (SCBD, 2009). Fisheries will likely be affected as affected fish species migrate to more suitable habitat.

Additionally, as the oceans become more acidic, sound will travel farther underwater. Ilyina et al. (2010) predict that by 2050, under conservative projections of ocean acidification, sound could travel as much as 70 percent farther in some ocean areas. This could dramatically improve the ability of marine mammals to communicate over long distances, but it could also increase the amount of background noise that they have to live with. For some marine species, this background noise may negatively affect health and interfere with their ability to perceive, communicate, navigate, and reproduce (Ilyina et al., 2010).

The CO₂ Reaction

Ocean acidification is a direct consequence of increasing atmospheric CO₂ concentrations (SCBD, 2009). CO₂ dissolves in seawater to form carbonic acid. The Intergovernmental Panel on Climate Change (IPCC) defines 'ocean acidification' as “A decrease in the pH of sea water due to the uptake of anthropogenic carbon dioxide (IPCC, 2007c).” Additionally, freshwater will also experience a decrease in the pH of sea water due to the uptake of anthropogenic carbon dioxide, which also makes freshwater bodies, such as lakes and rivers, and the organisms living in them susceptible to anthropogenic acidification.

The acidity of a solution is measured in pH units. On this logarithmic scale, a decrease of 1 unit corresponds to a 10-fold increase in the concentration of hydrogen ions, which represents significant acidification. The surface waters of the oceans are currently slightly alkaline, with a mean pH of about 8.16, which is approximately 0.1 pH units less than the estimated pre-industrial values (Feely et al., 2009). Note, the pH of the oceans is currently greater than pH=7 (neutral pH), and therefore, the term “ocean acidification” refers to the oceans becoming progressively less basic along the pH scale.

The dissolution of CO₂ into the oceans increases the concentration of hydrogen ions (H⁺), which reduces

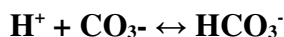
pH, and makes the oceans more acidic. CO₂ reacts with water to form a weak carbonic acid (H₂CO₃) when it dissolves in surface seawater (or freshwater). This reaction can be described as follows (SCBD, 2009):



Subsequently, carbonic acid dissociates into bicarbonate ions (HCO₃⁻) and hydrogen ions (H⁺). The release of hydrogen ions decreases the pH (i.e. increases the acidity) of surrounding waters.



The excess hydrogen ions (H⁺) react with carbonate ions (CO₃⁻) to form more bicarbonate ions.



Bicarbonate (HCO₃⁻) is the most abundant form of CO₂ dissolved in seawater under current ocean conditions. Increased CO₂ absorption in the surface ocean will increase both hydrogen ion (H⁺) and bicarbonate (HCO₃⁻) concentrations, while reducing the availability of carbonate ions (CO₃⁻) (ACE CRC, 2008) that are necessary for calcium carbonate (CaCO₃) skeleton and shell formation in marine organisms such as corals, shellfish and marine plankton (Feely et al., 2008). In other words, increasing ocean acidification reduces the availability of carbonate minerals (aragonite and calcite) in seawater, which are important building blocks for marine plants and animals. Oceanic carbonate ion concentrations are currently lower than at any other time during the last 800,000 years (SCBD, 2009).

Experimental evidence has demonstrated that increasing CO₂ concentrations to 560 ppm negatively effects the calcification of marine organisms by causing a decrease in calcification rates of between 5 – 60% in corals, and foraminifera and coccolithophores (both are types of plankton) (SCBD, 2009). Ocean acidification will also reduce the available habitat for important calcifying organisms (Feely et al., 2004). Seawater becomes more corrosive as it becomes under-saturated with respect to these minerals, which makes the shells of calcifying organisms increasingly vulnerable to dissolution. As these organisms dissolve and lose habitat, the ecosystem services and economic value they provide are also lost.

In particular, coral reefs are critical for maintaining ocean ecosystems, food security, and commercial activities. More than 25% of the world's fish biodiversity, and 9–12% of the world's total fisheries, are associated with coral reefs (SCBD, 2009). For instance, tropical coral reefs provide over US\$ 30 billion annually in global goods and services, such as shoreline protection, food security, and tourism (SCBD, 2009). Coral reefs produce 10–12% of the fish caught in the tropics and 20–25% of the fish caught by developing nations (SCBD, 2009). Cold-water coral reef ecosystems also provide habitat, feeding grounds, and nursery areas for many marine organisms, and support commercially important fauna several times as biodiverse as that found on the surrounding seabed (Turley et al., 2007). Combined with the impacts of global climate change and increasing temperatures, coral reef acidification and bleaching enhance dangerous ecosystem feedbacks, which will drive coral ecosystems toward domination by macroalgae and non-coral communities (Hoegh-Guldberg et al., 2007).

Marine ecosystems are also likely to become less robust as a result of predicted changes to ocean chemistry, which would increase their vulnerability to other environmental impacts, such as large-scale

fishing and increasing sea-surface temperatures. Overall impacts on ecosystem services will be a result of the combined effects of several pressures, such as ocean exploitation and pollution (Jackson, 2008). For example, decreasing rates of reef accretion, increasing rates of bio-erosion, rising sea levels, and intensifying storms due to the influence of future climate change negatively impact the coastal protection function of coral reefs. People, infrastructure, and coastal and estuarine ecosystems will become increasingly vulnerable to growing wave and storm impacts (Hoegh-Guldberg et al., 2007).

Ocean acidification will slow or reverse marine plant and animal carbonate shell and skeleton growth, with a corresponding decrease in fishing revenues, which will significantly impact communities that depend on these marine resources for income and livelihoods (SCBD, 2009). The economic consequences will depend on both the adaptation of marine ecosystems and human resource management efforts. The economic impacts resulting from fishery losses on a local scale could alter the dominant economic activities and demographics of a given area, which could increase the proportion of the population living in poverty in dependent communities that have little economic resilience or few alternatives (Cooley and Doney, 2009). For example, coastal and marine related industries contribute to approximately 25% of Indonesia's gross domestic product and employ almost 15% of the nation's workforce (Kite-Powell, 2009).

Approximately 50% of all food fish comes from aquaculture industries that depend heavily on carbonate-forming organisms like crustaceans and shellfish as a source of broodstock for hatcheries (Kite-Powell, 2009). Most aquaculture facilities are located in coastal areas that will likely experience ocean acidification (Cooley and Doney, 2009). Reduced calcification and reproduction success in calcifying organisms will cause significant losses of economic and livelihood opportunities in aquaculture and commercial fisheries sectors, which will likely affect developing countries that are more reliant on aquaculture sources for the provision of protein and revenue.

Warnings From The Past

The increase in the atmospheric concentration of CO₂ during the past 250 years has caused the average sea surface pH to decrease by about 0.1 pH units, which is equivalent to a 30% increase in hydrogen ions (i.e. acidity) (SCBD, 2009). This rate of change is 100 times faster than any change in ocean acidity that has occurred for the last 20 million years, which represents a rare geological event in the Earth's history (SCBD, 2009). This rapid change in ocean acidity is significantly changing the chemistry of the seas and altering the ability of the marine system to adjust to changes in CO₂ that naturally occur over thousands of years. The impacts of this change on marine plants and animals, ecosystems, food security, human health, and world economies are predicted to be profound and far-reaching, and include the disruption of fundamental biogeochemical processes, regulatory ocean cycles, ecosystem structure and function, and marine food webs and productivity (SCBD, 2009).

The magnitude of ocean acidification can be predicted with a high level of certainty based on the complicated but predictable marine carbonate chemistry reactions and cycles of CO₂ as it dissolves in seawater (SCBD, 2009). Increasing ocean acidification follows directly (albeit with a time lag) the accelerating rate of global CO₂ emissions, which could result in a 150–185% increase in acidity by 2100 under current emission rates (i.e. a decrease of 0.4–0.45 pH units) (SCBD, 2009), and a 60% decrease in the concentration of ocean calcium carbonate that is the basic building block for the skeletons and shells of many marine organisms (SCBD, 2009).

During the past 300 million years, global mean ocean pH values have probably never been more than 0.6 units below current values (SCBD, 2009). Therefore, ocean ecosystems have evolved over this time in a pH environment of relative stability. It is unknown if they can adapt to such large and rapid changes. Since the end of the Ordovician period (434 million years ago), five mass extinction events have significantly influenced the paths of evolution of life on Earth. Perturbations of the carbon cycle in general, and changes in ocean chemistry in particular, with clear association to atmospheric CO₂ levels, have been the primary causes of each extinction event (Vernon, 2008).

During the early Triassic period (250 million years ago), atmospheric CO₂ concentrations increased significantly to five times higher than present day (Hoegh-Guldberg, 2007). The fossil record from this period for benthic (i.e. bottom-dwelling organisms) calcified organisms, including reef-building corals and calcareous algae, shows a significant gap (Hoegh-Guldberg, 2007), and the recovery lasted hundreds of thousands of years (SCBD, 2009). By 2050, ocean pH is predicted to be lower than it has been for around 20 million years (see Figure 2) (Turley et al., 2007). The records from the Earth's past are a disquieting cause for concern that ocean acidification could trigger a sixth mass extinction event, independently of the anthropogenic extinctions that are currently happening (Vernon, 2008).

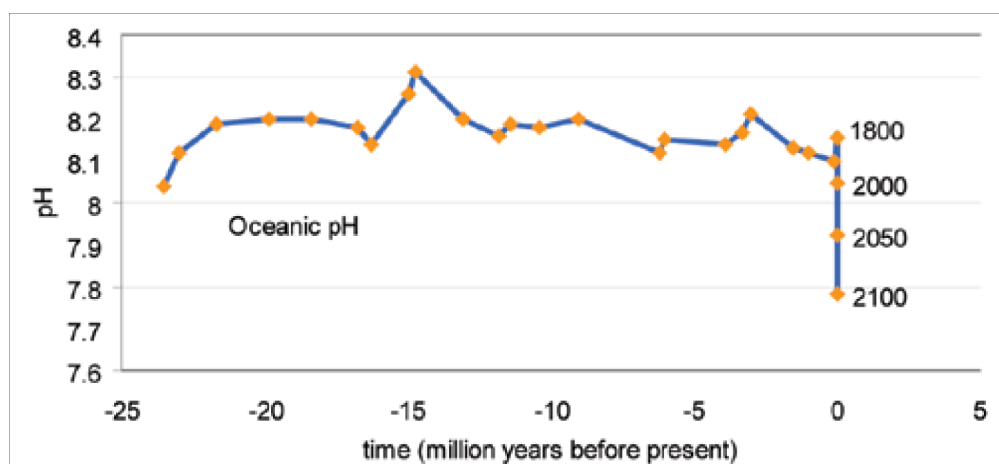


Figure 2: Past and present variability of marine pH. Future predictions for years shown on the right-hand side in the figure are model-derived values based on IPCC mean scenarios. From Pearson and Palmer (2000), adapted by Turley et al. (2006) and from the Eur-Oceans Fact Sheet (2007).

Although ocean acidification is a global issue, the pH of the ocean is not uniform throughout the world. Regional and seasonal influences, and biological, chemical and physical factors (e.g. temperature effects on CO₂ solubility, carbonate chemistry, biological productivity) influence the influx of CO₂ resulting in a variable mixed surface layer pH. In particular, cold water naturally has the capacity to hold more CO₂ and is more acidic than warmer waters because CO₂ is more soluble in cold water (SCBD, 2009). With increasing atmospheric CO₂ concentrations the surface waters of high latitude oceans, such as the Arctic Ocean, will likely be the first to experience under-saturated with respect to calcium carbonate (SCBD, 2009).

For instance, models of atmospheric CO₂ indicate that the cold Southern Ocean is particularly vulnerable to changes in carbonate saturation state (SCBD, 2009). However, the largest pH changes during this century will likely occur in the surface waters of the Arctic Ocean, where hydrogen ion concentration may increase by up to 185% (a decrease in pH of 0.45 units), if the emission of anthropogenic CO₂ continues along current trends (SCBD, 2009). Research suggests that Arctic ocean waters will be corrosive to Arctic calcifiers, such as shelled plankton and bivalves (e.g. clams), that are very important to Arctic marine food webs (IAP, 2009). Further, the projected impacts of climate change (e.g. sea ice retreat and seawater freshening from ice melt) during this century will likely amplify the decrease in Arctic surface mean pH and CaCO₃ saturation by more than 20% (SCBD, 2009).

Ocean Acidification and Target CO₂

Ocean acidification is irreversible on short-term timeframes (IAP, 2009). Substantial damage to ocean ecosystems can only be avoided through urgent and rapid reductions in global emissions of CO₂ by at least 50% by 2050, followed by further reductions in emissions thereafter (IAP, 2009). Ocean acidification is an already observable and predictable consequence of increasing atmospheric CO₂ concentrations, with biological impacts, and should be recognized and integrated into the global climate change debate.

In order to prevent changes that would lead to under-saturation of aragonite and threaten the integrity of marine ecosystems, the average pH of surface waters should be prevented from decreasing by more than 0.2 pH units below the pre-industrial value. Stabilization of atmospheric CO₂ concentrations at 450 ppm by the year 2100 would likely lead to a pH decrease of about 0.17; stabilization at 540 ppm by the year 2100 would likely lead to a decrease of 0.23 pH units. However, even with stabilization at 450 ppm CO₂, about 7% of the Southern Ocean would likely still become under-saturated with respect to aragonite. At 550 ppm, about half of the Southern Ocean could become under-saturated (Schubert et al., 2006).

Therefore, in order to safely avoid passing a dangerous threshold for ocean acidification, the maximum concentration of atmospheric CO₂ should be limited to no greater than 450 ppm. However, given that additional stressors (e.g. increased temperatures from climate change, pollution) will also seriously impact fish and other marine organisms, especially the world's corals and their associated species whose resilience will be compromised by ocean acidification, the maximum concentration of CO₂ may need to be lower in order to avoid an unprecedented collapse of the world's marine ecosystems. Nevertheless, the scientific consensus is that atmospheric CO₂ concentrations need to be “significantly below 350 ppm” for the long-term viability of coral reefs (Royal Society, 2009).

7. Sea Level Rise: 1.5°C vs. 2°C

The IPCC indicates a sea-level rise at equilibrium of approximately 0.4–1.4 meters above the pre-industrial level for a 2–2.4°C (350–400 ppm CO₂) warming for water thermal expansion only, but it did not provide a total estimate that would include the melting of glaciers and small ice caps, and the melting of the Greenland and Antarctic ice sheets (IPCC, 2007d). For 440–485 ppm CO₂, sea level is projected to rise by 0.6–1.9 meters global average sea level rise above pre-industrial at equilibrium from thermal expansion only. Already melting glaciers and small ice caps contain the potential of 15–37 cm of sea-level increase. (Vespa, 2009) One study estimates that a mean global temperature increase of 1.5°C above pre-industrial levels could potentially trigger irreversible melting of the Greenland ice sheet, which could result in an additional sea level rise of 0.75 meters as early as 2100 (Vespa, 2009). Adding the potential sea level rise from thermal expansion and from glacier and ice cap melt, a temperature increase of 2°C could result in a sea level rise of at least 0.45–1.77 meters (an average of about 1.1 meters), plus the sea level rise resulting from the melting Greenland and Antarctic ice sheets. Based on these projections, a temperature increase of 2°C above pre-industrial levels could result in a sea level rise of at least 1.2–2.52 meters (an average of about 1.65 meters) as early as 2100. In addition to inundating land in low-elevation coastal areas, sea level rise results in saltwater contamination of coastal freshwater aquifers, raises the water level of rivers near its headwaters, increases coastal erosion, and increases the vulnerability of coastal areas to storm surges.

Since the populations of many small island states and low-elevation coastal nations are located below 2 meters above sea level, the impacts of a 2°C temperature rise from pre-industrial levels could submerge large areas of these low-elevation nations, displace millions of people from the world's coastlines, and inundate large areas of the world's arable land. For instance, the average elevation of the Maldives is 1.5 meters above sea level, and its highest point is at 2.4 meters elevation (CIA, 2010). For Bangladesh, a rise of 1.0 and 1.5 meters would inundate 10% and nearly 16% of the country, respectively, and the height of storm surges could increase by at least a meter (Ali, 1996).

In order to prevent 0.75 meters or more sea level rise, it is likely that the global mean temperature should be kept from rising above 1.5°C, which would require a target of stabilizing greenhouse gas emissions at no greater than 350 ppm CO₂-eq (approximately 300 ppm CO₂) would likely be necessary.

Appendix 1

CO₂ to CO₂-eq Conversion

Although CO₂ is a major GHG, other GHGs (e.g. methane, ozone depleting gases) also contribute to climate change. Equivalent CO₂ (CO₂-eq) is the concentration of CO₂ that would cause the same value of radiative forcing as a given type and concentration of greenhouse gas. The following is one method to convert between CO₂ concentrations and CO₂-eq.

Meinshausen (2006) estimates that:

- 550 CO₂-eq is approximately equivalent to 475 ppm CO₂ stabilization,
- 500 CO₂-eq is approximately equivalent to 450 ppm CO₂ stabilization,
- 450 CO₂-eq is approximately equivalent to 400 ppm CO₂ stabilization,
- 400 CO₂-eq is approximately equivalent to 350–375 ppm CO₂ stabilization,
- 350 CO₂-eq is approximately equivalent to 300–315 ppm CO₂ stabilization.*

* Meinshausen does not state the CO₂ level equivalent to a 350 ppm CO₂-eq stabilization level. However, based on the ratios used for the other CO₂-eq levels, a 350 ppm CO₂eq would equate to approximately 300–315 ppm CO₂.

[Appendix 2 follows this page as supplementary material]

References

Ali, A (1996). *Vulnerability of Bangladesh to climate change and sea level rise through tropical cyclones and storm surges*. Water, Air, & Soil Pollution 92 (1–2): 171–179.

Antarctic Climate and Ecosystems Cooperative Research Centre. (ACE CRC) (2008). *Position Analysis: CO₂ and climate change: ocean impacts and adaptation issues*.
http://www.acecrc.org.au/uploaded/117/797619_20pa02_acidification_0805.pdf

Barnett, T.P. Adam, J.C. Lettenmaler, D.P. (2005). *Potential impacts of a warming climate on water availability in snowdominated regions*. Nature, 438: 303-309.

CIA Factbook (2010). *Maldives*.

<https://www.cia.gov/library/publications/the-world-factbook/geos/mv.html> (accessed Jan. 16, 2010).

Cooley, S. R., Doney, S. C. (2009). *Ocean Acidification's impact on Fisheries and Societies: A U.S. Perspective*. Journal of Marine Education, 25(1):15–19.

Eur-Oceans Fact Sheet No. 7 (2007), *Ocean Acidification - the other half of the CO₂ problem*.
<http://www.eur-oceans.org/KTU>.

Feely, R. A., Sabine, C. L., Lee, K., Berelson, W., Kleypas, J., Fabry, V. J., Millero, F. J. (2004). *Impact of anthropogenic CO₂ on the CaCO₃ system in the oceans*. Science 305:362–365.

Feely, R. A., Sabine, C. L., Hernandez-Ayon, J. M., Lanson, D., Hales, B. (2008). *Evidence for Upwelling of Corrosive “Acidified” Water onto the Continental Shelf*. Science, Vol320:1490 -1492.

Feely, R.A., Doney, S.C., Cooley, S.R., (2009). *Ocean acidification: present conditions and future changes in a high-CO₂ world*. Oceanography 22(4): 36-47.

Hansen, J. Sato, M. Kharecha, P. Beerling, D. Berner, R. Masson-Delmotte, V. Pagani, M. Raymo, M. Royer, D. L. Zachos, J. C. (2008). *Target atmospheric CO₂: Where should humanity aim?* Open Atmos. Sci. J., 2, 217-231.

Hansen, J. Sato, M., Ruedy, R. Kharecha, P. Lacis, A. Miller, R. Nazarenko, L. Lo, K. Schmidt, G. A. Russell, G. Aleinov, I. Bauer, S. Baum, E. Cairns, B. Canuto, V. Chandler, M. Cheng, Y. Cohen, A. Del Genio, A. Faluvegi, G. Fleming, E. Friend, A. Hall, T. Jackman, C. Jonas, J. Kelley, M. Kiang, N. Y. Koch, D. Labow, G. Lerner, J. Menon, S. Novakov, T. Oinas, V. Perlwitz, Ja. Perlwitz, Ju. Rind, D. Romanou, A. Schmunk, R. Shindell, D. Stone, P. Sun, S. Streets, D. Tausnev, N. Thresher, D. Unger, N. Yao, M. Zhang. *Dangerous human-made interference with climate: a GISS modelE study*. Atmos Chem Phys 2007; 7: 2287-2312.

Hoegh-Guldberg, O., Mumby, P. J., Hooten, A. J., Steneck, R. S., Green eld, P., Gomez, E., Harvell, C. D., Sale, P. F., Edwards, A. J., Caldeira, K., Knowlton, N., Eakin, C. M., Iglesias-Prieto, R., Muthiga, N., Bradbury, R. H., Dubi, A., and Hatziolos, M. E. (2007). *Coral reefs under rapid climate change and ocean acidification*. Science 318, 1737–1742.

Ilyina, T., Zeebe, E., Brewer, P. G. (2010). *Future ocean increasingly transparent to low-frequency sound owing to carbon dioxide emissions*. *Nature Geoscience* 3, 18–22.

Institute for Governance and Sustainable Development (IGSD) (2008). *Abrupt Climate Changes Approaching Faster than Previously Predicted Fast-Track Climate Mitigation Strategies Needed*. Institute for Governance and Sustainable Development. Washington D.C., USA.

Inter-Academy Panel on International Issues (IAP) (2009). *Statement on Ocean Acidification*. www.interacademies.net/CMS/9075.aspx

Intergovernmental Panel on Climate Change (IPCC) (2007a). Parry, Martin. Canziani, Osvaldo. Palutikof, Jean. van der Linden, Paul. Hanson, Clair (Eds.). *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, UK.

Intergovernmental Panel on Climate Change (IPCC) (2007b). Metz, Bert. Davidson, Ogunlade. Bosch, Peter. Dave, Rutu. Meyer, Leo (Eds.). *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Intergovernmental Panel on Climate Change (IPCC) (2007c). Solomon, Susan. Qin, Dahe. Manning, Martin. Chen, Zhenlin. Marquis, Melinda. Averyt, Kristen. Tignor, Melinda. Miller, Henry (Eds.). *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Intergovernmental Panel on Climate Change (IPCC) (2007d). Bernstein, Lenny. Bosch, Peter. Canziani, Osvaldo. Chen, Zhenlin. Christ, Renate. Davidson, Ogunlade. Hare, William. Huq, Saleemul. Karoly, David. Kattsov, Vladimir. Kundzewicz, Zbigniew. Liu, Jian. Lohmann, Ulrike. Manning, Martin. Matsuno, Taroh. Menne, Bettina. Metz, Bert. Mirza, Monirul. Nicholls, Neville. Nurse, Leonard. Pachauri, Rajendra. Palutikof, Jean. Parry, Martin. Qin, Dahe. Ravindranath, Nijavalli. Reisinger, Andy. Ren, Jiawen. Riahi, Keywan. Rosenzweig, Cynthia. Rusticucci, Matilde. Schneider, Stephen. Sokona, Youba. Solomon, Susan. Stott, Peter. Stouffer, Ronald. Sugiyama, Taishi. Swart, Rob. Tirpak, Dennis. Vogel, Coleen. Yohe, Gary. *Climate Change 2007: Synthesis Report*.

Jackson, J. B. C. (2008). *Ecological extinction and evolution in the brave new ocean*. *Proceedings of the National Academy of Sciences of the United States of America* 105, 11458–11465.

Kite-Powell, H. L. (2009). *A Global Perspective on the Economics of Ocean Acidification*. *Journal of Marine Education*, 25:1, pp.25 – 29.

Lenton, Timothy. Held, H., Kriegler, E., Hall, J., Lucht, W., Rahmstorf, S., Schellnhuber, H.J. (2008). *Tipping elements in the Earth's climate system*. 105 *Proc. of the Nat'l Acad. of Sci.* 1786.

Meinshausen, Malte (2006). *What Does a 2°C Target Mean for Greenhouse Gas Concentrations? A Brief Analysis Based on Multi-Gas Emission Pathways and Several Climate Sensitivity Uncertainty Estimates*. in *Avoiding Dangerous Climate Change* 268. H.J. Schellnhuber et al. (eds.), Cambridge:

Cambridge University Press.

Moss, Richard. Babiker, Mustafa. Brinkman, Sander. Calvo, Eduardo. Carter, Tim. Edmonds, Jae. Elgizouli, Ismail. Emori, Seita. Erda, Lin. Hibbard, Kathy. Jones, Roger. Kainuma, Mikiko. Kelleher, Jessica. Lamarque, Jean Francois. Manning, Martin. Matthews, Ben. Meehl, Jerry. Meyer, Leo. Mitchell, John. Nakicenovic, Nebojsa. O'Neill, Brian. Pichs, Ramon. Riahi, Keywan. Rose, Steven. Runci, Paul. Stouffer, Ron. Vuuren, Detlef van. Weyant, John. Wilbanks, Tom. Ypersele, Jean Pascal van. Zurek, Monika (2008). *Towards New Scenarios for Analysis of Emissions, Climate Change, Impacts, and Response Strategies*. Intergovernmental Panel on Climate Change, Geneva. Suisse.

Pearson, P., Palmer, M. (2000), *Atmospheric carbon dioxide concentrations over the past 60 million years*. Nature, 406, pp. 695 – 699.

Ramanathan, V., Carmichael, G. (2008). *Global and regional climate changes due to black carbon*. Nature Geoscience 221, 224.

Ramanathan, V., M. Agrawal, H. Akimoto, M. Aufhammer, S. Devotta, L. Emberson, S.I. Hasnain, M. Iyengararasan, A. Jayaraman, M. Lawrance, T. Nakajima, T. Oki, H. Rodhe, M. Ruchirawat, S.K. Tan, J. Vincent, J.Y. Wang, D. Yang, Y.H. Zhang, H. Autrup, L. Barregard, P. Bonasoni, M. Brauer, B. Brunekreef, G. Carmichael, C.E. Chung, J. Dahe, Y. Feng, S. Fuzzi, T. Gordon, A.K. Gosain, N. Htun, J. Kim, S. Mourato, L. Naeher, P. Navasumrit, B. Ostro, T. Panwar, M.R. Rahman, M.V. Ramana, M. Rupakheti, D. Settachan, A. K. Singh, G. St. Helen, P. V. Tan, P.H. Viet, J. Yinlong, S.C. Yoon, W.-C. Chang, X. Wang, J. Zelikoff and A. Zhu (2008). *Atmospheric Brown Clouds: Regional Assessment Report with Focus on Asia*. United Nations Environment Programme, Nairobi, Kenya.

Ramanathan, V. Feng, Y. (2008). *On avoiding dangerous anthropogenic interference with the climate system: Formidable challenges ahead*. Proc. Natl. Acad. Sci., 105, 14245-14250.

Royal Society (2009). *The Coral Reef Crisis: Scientific Justification For Critical CO₂ Threshold Levels Of < 350ppm*. Output of the technical working group meeting at the Royal Society. London, 6th July 2009.

Sabine, C. L., Feely, R., Gruber, N., Key, R. M., Lee, K., Bullister, J. L., Wanninkhof, R., Wong, C. S., Wallace, D. W. R., Tilbrook, B., Millero, F. J., Peng, T., Kozyr, A., Ono, T., Rios, A. F. (2004). *The Oceanic Sink for Anthropogenic CO₂*. Science 16, 305:5682, pp. 367 - 371.

Secretariat of the Convention on Biological Diversity (SCBD) (2009). *Scientific Synthesis of the Impacts of Ocean Acidification on Marine Biodiversity*. Montreal, Technical Series No. 46.

Schubert, R., Schellnhuber, H.J., Buchmann, N., Epiney, A., Griebhammer, R., Kulesa, M., Messner, D., Rahmstorf, S., Schmid, J. (2006). *The Future Oceans - Warming up, Rising High, Turning Sour: Special Report*. Wissenschaftlicher Beirat der Bundesregierung Globale Umweltveränderungen (WBGU): German Advisory Council on Global Change. Berlin.

Simpson, M.C., Scott, D., New, M., Sim, R., Smith, D., Harrison, M., Eakin, C.M., Warrick, R., Strong, A.E., Kouwenhoven, P., Harrison, S., Wilson, M., Nelson, G.C., Donner, S., Kay, R., Geldhill, D.K., Liu, G., Morgan, J.A., Kleypas, J.A., Mumby, P.J., Palazzo, A., Christensen, T.R.L., Baskett, M.L., Skirving,

W.J., Elrick, C., Taylor, M., Magalhaes, M., Bell, J., Burnett, J.B., Rutt, M.K., Overmas, M., Robertson, R. (2009). *An Overview of Modelling Climate Change Impacts in the Caribbean Region with contribution from the Pacific Islands*. United Nations Development Programme (UNDP), Barbados, West Indies.

Stone, Richard (2007). *A world without corals?* Science. 316: 678-681.

Turley, C., Blackford, J. C., Widdicombe, S., Lowe, D., Nightingale, P. D., and Rees, A. P. (2006). *Reviewing the Impact of Increased Atmospheric CO₂ on Oceanic Ph and the Marine Ecosystem*. In: *Avoiding Dangerous Climate Change*. (H. J. Schellnhuber, W. Cramer, N. Nakicenovic, T. Wigley, and G. Yohe, Eds.) Cambridge University Press: Cambridge, UK. pp. 65–70.

Turley, C. M., Roberts, J. M., Guinotte, J. M. (2007). *Corals in deepwater: will the unseen hand of ocean acidification destroy coldwater ecosystems*. Coral Reefs 26:445–448.

University of Copenhagen Climate Office (2009). *Key Messages from the Congress*. March 12, 2009 . http://climatecongress.ku.dk/newsroom/congress_key_messages/ (accessed: Jan. 14, 2010).

Veron, J. E. N. (2008) *Mass extinctions and ocean acidification: biological constraints on geological dilemmas*. Coral Reefs 27:459–472.

Vespa, Matt (2009). *Why 350? Climate Policy Must Aim to Stabilize Greenhouse Gases at the Level Necessary to Minimize the Risk of Catastrophic Outcomes*. Ecology Law Currents, 36:185. 185-194.

Wang, M. and Overland, J.E. (2009). *A sea ice free summer Arctic within 30 years?* Geophysical Research Letters 36, L07502