Fate of Mountain Glaciers in the Anthropocene
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A comprehensive approach for reducing anthropogenic climate impacts including risk of abrupt climate changes*

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Summary

Annual greenhouse gases emissions in 2010 were at their highest recorded level in spite of a global recession. The risk is growing that the climate system could pass tipping points that lead to abrupt and irreversible impacts on a continental scale, perhaps within decades. Successfully addressing climate change requires fast and aggressive action to reduce CO_2 emissions, which are responsible for up to 55% of radiative forcing since 1750. It also requires fast and aggressive action to reduce emissions of the pollutants causing the other 45% of warming – the non-CO_2 climate forcers, including hydrofluorocarbons (HFCs), black carbon, methane, and tropospheric ozone. Along with reducing CO_2, reducing emissions of these non-CO_2 climate forcers, which in most cases can be done using existing technologies and existing laws and institutions, can cut the rate of global warming in half for several decades and by two-thirds in the Arctic in the next 30 years. In addition, given the profoundly persistent nature of CO_2, it is necessary to explore and implement "carbon-negative" strategies to drawdown existing CO_2 on a timescale of decades rather than millennia, and ultimately produce a net drawdown of CO_2 when sinks exceed sources.

Dangerous anthropogenic interference

Increasing global temperature due to the increase in anthropogenic climate forcers has put human civilization and the Earth it depends upon in

*This paper draws on Molina, Zaelke, Sarma, Andersen, Ramanathan, & Kaniaru, (2009) Reducing abrupt climate change risk using the Montreal Protocol and other regulatory actions to complement cuts in CO_2 emissions, *Proc. National Academy of Sciences* 106:20616.

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danger. The climatic impacts of this human interference with the Earth system are expected to last for millennia, warranting the name Anthropocene for the new "man-made" geologic epoch we are living in.[3]

Concentrations of CO_2 are the highest in the last 800,000 years.[4] The Earth has already warmed by about 0.76°C[5] above preindustrial levels, and the committed warming is estimated to be 2.4 to 4.3°C.[6] The committed warming overlaps and surpasses the internationally agreed upon 2°C guardrail[7] for preventing dangerous anthropogenic interference with the climate system (DAI) that the United Nations Framework Convention on Climate Change (UNFCCC) was established to prevent.[8] Even warming of 2°C cannot be considered safe as impacts from current warming are appearing sooner and are often more damaging than predicted by the climate models.[9]

Current and anticipated near-term climate impacts

The year 2010 equalled the warmest year on record, and global temperatures from 2001 to 2010 were the highest ever recorded for a 10-year period.[10] The year 2010 also was the wettest on record.[11] Current and

[3] Crutzen J. & Stoermer E. (2000) The "Anthropocene", Global Change Newsletter 41:17-18. *See also* Crutzen J., (2002) Geology of Mankind, *Nature* 415.

[4] British Antarctic Survey (2010) Ice cores and climate change: slices of ice core, drilled from the depths of the Earth's ice sheets reveal details of the planet's past climate *available at* www.antarctica.ac.uk/press/journalists/resources/science/ice_cores_and_climate_change_briefing-sep10.pdf. *See also* Tripati A. *et al.* (2009) Coupling of CO_2 and Ice Sheet Stability Over Major Climate Transitions of the Last 20 Million Years, *Science* 326:1394.

[5] Solomon S. *et al.* (2007) Technical Summary, in IPCC, Climate Change 2007: The Physical Sciences Basis 19-92.

[6] Ramanathan V. & Feng Y., (2008) On avoiding dangerous anthropogenic interference with the climate system: Formidable challenges ahead, *Proc. of the Nat'l Acad. Sci.* 105:14245. *See also* Schellnhuber H.J. (2008) Global warming: Stop worrying, start panicking? *Proc. of the Nat'l Acad. Sci.* 105:1439.

[7] German Advisory Council on Global Change (WBGU) (2009) *Solving the climate dilemma: The budget approach: special report* 13-14.

[8] UNFCCC (1992) United Nations Framework on Climate Change Art. 2 (United Nations, NY).

[9] Arctic Monitoring and Assessment Programme (2011) Snow, Water, Ice and Permafrost in the Arctic, Executive Summary and Key Message, *available at* www.documentcloud.org/documents/88367-arctic-ice-melt-2011-executivesummary.html.

[10] World Meteorological Organization, 2010 Equals Record for World's Warmest Year (20 January 2011), *available at* www.wmo.int/pages/mediacentre/press_releases/pr_906_en.html.

[11] National Oceanic and Atmospheric Administration, NOAA: 2010 Tied For Warmest Year on Record (January 12, 2011), *available at* www.noaanews.noaa.gov/stories2011/20110112_globalstats.html.

anticipated near-term climate impacts include loss of vulnerable coral reefs, forests, and other ecosystems, with an increasing rate of species extinction 100 to 1,000 times above the historic average.[12] Ocean acidification from CO_2 concentrations could cause coral growth to stop by 2030 and possibly begin dissolving by 2050.[13] By the end of the 21st century, climate change is projected to radically shift the geographical distribution of species and vegetation types with ranges moving from hundreds to thousands of kilometres towards the poles.[14] By mid-century production of five major grains in Africa could decrease by 8% to 22%.[15] From 1980 to 2008 global production of maize and wheat had already decreased by 3.8% and 5.5% respectively, compared to models without temperature increases.[16]

A clear correlation is beginning to emerge between global temperature increases and increased instances of extreme weather events.[17] Weather-related disasters and floods have increased nearly three-fold in the past thirty years, with the number of catastrophic wind storms doubling during the same period.[18] Climate models predict that warming could increase the severity of tropical storms, potentially doubling the frequency of category 4 and 5 storms in the Atlantic by 2100.[19] Recent climate model analyses also indicate that

[12] IPCC (2007) Climate Change 2007: The Physical Science Basis, 129, 132, *available at* www.ipcc.ch/publications_and_data/ar4/wg2/en/contents.html.

[13] Veron J.E.N. *et al.* (2009) The coral reef crisis: The critical importance of <350 ppm CO2, *Marine Pollution Bulletin* 58:1428J. *See also* Silverman, *et al.* (2009) Coral reefs may start dissolving when atmospheric CO_2 doubles, *Geophys. Res. Lett.* 36, *available at* www.stanford.edu/~longcao/Silverman%282009%29.pdf.

[14] The Convention on Biological Diversity (2010) Global Biodiversity Outlook 3, *available at* www.cbd.int/doc/publications/gbo/gbo3-final-en.pdf.

[15] Schlenker W. & Lobell D. (2010) Robust negative impacts of climate change on African agriculture, *Environmental Research Letters* 5:014010.

[16] Lobell D. *et al.* (2011) Climate Trends and Global Crop Production Since 1980, *Sciencexpress.*

[17] IPCC (2007) Climate Change 2007: Synthesis Report 30, *available at* www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4_syr.pdf. *See also* U.S. Climate Change Science Program (CCSP), (2008) *Weather and Climate Extremes in a Changing Climate* 35 *available at* www.climatescience.gov/Library/sap/sap3-3/final-report/sap3-3-final-Chapter2.pdf.

[18] Munich RE (2010) Topics GEO: Natural catastrophes 2010 Analyses, assessments, positions, *available at* www.munichre.com/publications/302-06735_en.pdf. *See also* EM-DAT: The OFDA/CRED International Disaster Database – www.emdat.be, Université Catholique de Louvain, Brussels (Belgium).

[19] Bender M. (2010) Modeled Impact of Anthropogenic Warming on the Frequency of Intense Atlantic Hurricanes, *Science* 327:454. *See also* Knutson T. *et al.*, Tropical cyclones and climate change, *Nature Geoscience* 3:157.

warming has contributed to observed intensification of heavy precipitation in the Northern Hemisphere.[20] Sea-level rise and increased storm surges threaten vulnerable ecosystems and peoples, with sea level rise projections now up to 1.6 meters by end of the century, more than double the Intergovernmental Panel on Climate Change fourth Assessment Report (IPCC AR4) scenarios.[21] These and other climate impacts are expected to increase in number and severity without fast and aggressive mitigation.

Uneven regional warming, positive climate feedbacks, and tipping points for abrupt climate change

Global warming is expressed as an average but is experienced unevenly in different regions, with some of the world's most vulnerable regions warming faster than the global average.[22] The annual average temperature over the Arctic has increased twice as fast as the rest of the world since 1980,[23] and the Tibetan Plateau – the planet's largest store of ice after the Arctic and Antarctic – is warming about three times the global average.[24] Warming in these regions threaten to push critical ecosystems past predicted climate thresholds or "tipping points" even before the critical global 2°C guardrail is reached.[25]

The greatest danger of near-term regional warming may be the threat that it could set off positive feedbacks triggering large scale warming effects.[26]

[20] Min S. *et al.* (2011) Human contribution to more–intense precipitation extremes, *Nature* 470:378.

[21] Arctic Monitoring and Assessment Programme (2011) Snow, Water, Ice and Permafrost in the Arctic, Executive Summary and Key Message, *available at* www.documentcloud.org/documents/88367-arctic-ice-melt-2011-executivesummary.html. *See also* Vermeer M. & S. Rahmstorf (2009) Global sea level linked to global temperature, *Proc. Natl. Acad. Sci* 106:21527-21532.

[22] Lenton TM *et al.*, Tipping elements in the Earth's climate system, *Proc. Nat'l Acad. Sci. USA* 105:1786, 1788 (2008) ("Transient warming is generally greater toward the poles and greater on the land than in the ocean"). *See also* Qiu J. (2008) The Third Pole, *Nature* 454:393.

[23] World Metrological Organization (2011) 2010 Equals Record for World's Warmest Year, *available at* www.wmo.int/pages/mediacentre/press_releases/pr_906_en.html. *See also* A.P. Ballantyne *et al.* (2010) Significantly warmer Arctic surface temperatures during the Pliocene indicated by multiple independent proxies, *Geology* 38:603-606.

[24] Qiu J. (2008) The Third Pole, *Nature* 454:393. *See also* R.V. Cruz *et al.* (2007) Asia, in IPCC (2007) Climate Change 2007: Impacts, Adaptation and Vulnerability 475 (Cambridge Univ. Press, Cambridge, U.K.).

[25] Lenton TM (2011) 2C or not 2C? That is the climate question, *Nature* 473:7.

[26] Schellnhuber H.J. (2010) Tragic triumph, *Climatic Change* 100:299, 233. *See also* Allison I. *et al.* (2011) The Copenhagen Diagnosis, 55-61.

Observed evidence shows that current melting of Arctic snow and sea ice is accelerating warming, as darker sea water and ground revealed by receding sea-ice and snow absorb more heat than the reflective ice and snow that once covered it.[27] This amplifies local warming that in turn further reduces ice and snow cover, creating a warming feedback loop.[28] The Arctic Ocean is likely to be nearly free of summer sea ice within the next thirty to forty years.[29]

Another positive feedback is the thawing of near-surface permafrost, which could mobilize billions of tons of stored carbon.[30] Warming has already caused the southern limit of permafrost in Russia to shift northward by up to 80 kilometers (50 miles) during 1970-2005 and by 130 kilometers (81 miles) in Canada. The release of carbon stores in permafrost could push the climate past predicted tipping points, triggering abrupt and irreversible climate changes that may overwhelm society's ability to adapt, with potentially catastrophic ramifications for humanity and the global climate system.[31] Predicted impacts of passing climate tipping points include disintegration of the Greenland Ice Sheet, disappearance of the Hindu-Kush-Himalayan-Tibetan glaciers

[27] M.G. Flanner *et al.*, (2011) Radiative Forcing and Albedo Feedback from the Northern Hemisphere Cryosphere between 1979 and 2008, *Nature Geoscience* 4:151-155. *See also* Arctic Monitoring and Assessment Programme (2011) Snow, Water, Ice and Permafrost in the Arctic, Executive Summary and Key Message, *available at* www.documentcloud.org/documents/88367-arctic-ice-melt-2011-executivesummary.html; *and* Stroeve, J. *et al.* (2007) Arctic sea ice decline: Faster than forecast, *Geophys. Res. Lett.* 34:L09501.

[28] Lenton T.M. (2011) 2C or not 2C? That is the climate question, *Nature* 473:7.

[29] Wang, M. & J.E. Overland (2009) A sea ice free summer Arctic within 30 years? *Geophys. Res. Lett. 36:* L07502. *See also* Holland, M.M. *et al.* (2006) Future abrupt reductions in the summer Arctic sea ice, *Geophys. Res. Lett.,* 33:L23503; Arctic Monitoring and Assessment Programme (2011) Snow, Water, Ice and Permafrost in the Arctic, Executive Summary and Key Message, *available at* www.documentcloud.org/documents/88367-arctic-ice-melt-2011-executivesummary.html; *and* Stroeve, J. *et al.* (2007) Arctic sea ice decline: Faster than forecast *Geophys. Res. Lett.* 34:L09501.

[30] Koven C. *et al.* (2011) Permafrost carbon-climate feedbacks accelerate global warming, *Proc. Natl. Acad. Sci.* 1103910108v1-6. *See also* Schaefer K. *et al.* (2011) Amount and Timing of Permafrost Carbon Release in Response to Climate Warming, *Tellus B.* 63:165-180; *and* National Research Council (2011) Climate Stabilization Targets 223 (The National Academies Press, Washington D.C.).

[31] Arctic Monitoring and Assessment Programme (2011) *Snow, Water, Ice and Permafrost in the Arctic, Executive Summary and Key Message*, *available at* www.documentcloud.org/documents/88367-arctic-ice-melt-2011-executivesummary.html. *See also* Schaefer K. *et al.* (2011) Amount and Timing of Permafrost Carbon Release in Response to Climate Warming, *Tellus B.* 63:165-180; *and* National Research Council (2011) Climate Stabilization Targets 223 (The National Academies Press, Washington D.C.).

that supply water to most of Asia's major rivers, dieback of Amazonian and boreal forests, shutdown of the Atlantic Thermohaline Circulation, and collapse of the West Antarctic Ice Sheet (see Figure 1).[32]

Predicted Warming Under CO_2 and SLCF Mitigation Scenarios

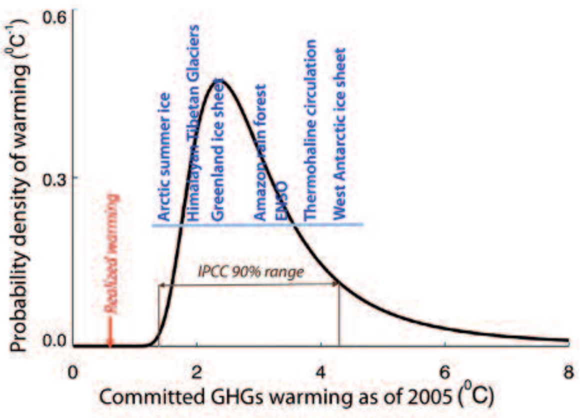

Figure 3. Observed deviation of temperature to 2009 and projections under various scenarios. Immediate implementation of the identified BC and CH_4 measures, together with measures to reduce CO_2 emissions, would greatly improve the chances of keeping Earth's temperature increase to less than 2°C relative to pre-industrial levels. The bulk of the benefits of CH_4 and BC measure are realized by 2040 (dashed line). (Source: UNEP/WMO [2011] *Integrated Assessment of Black Carbon and Tropospheric Ozone* available at www.unep.org/dewa/Portals/67/pdf/Black-Carbon_SDM.pdf).

International climate policy

Historically, much of international climate policy has focused on CO_2 because it is the long-term determinate of warming. Until the 1970s, it was generally thought that CO_2 was the only manmade greenhouse gas. This changed in 1975 when a study identified the greenhouse effect of chlorofl orocarbon-11 (CFC-11), chlorflorocarbon-12 (CFC-12) and other CFCs, showing that addition of one molecule of CFCs can have the same warning

[32] Molina M. *et al.* (2009) Reducing abrupt climate change risk using the Montreal Protocol and other regulatory actions to complement cuts in CO_2 emissions, *Proc. Natl. Acad. Sci.* 106:20616. *See also* Schellnhuber H.J., (2008) Global warming: Stop worrying, start panicking? 105 *Proc. of the Nat'l Acad. of Sci.* 1439.

effect of more than 10,000 molecules of CO_2[33] Other non-CO_2 greenhouse gases (methane, nitrous oxide, and tropospheric ozone among numerous others) were identified by the mid 1980s.[34] Many non-CO_2 climate forcers have short atmospheric lifetimes of a few hours to a few decades, and are collectively referred to as short-lived climate forcers (SLCFs).

Emissions of CO_2 account for up to 55% of global temperature rise since 1750, making CO_2 the single largest force influencing long-term global climate change.[35] CO_2 is unique among the well-mixed greenhouse gases and does not break down in the atmosphere. Instead some fraction remains until drawn out through slow natural processes on a timescale of millennia (see Figure 2).[36] Within the first century after being emitted, more than half of CO_2 equilibrates temporarily in ocean and terrestrial sinks, with the remainder residing in the atmosphere contributing to warming until removed over the course of thousands of years.[37] Thus, an approximation of the life-

[33] Molina M. *et al.* (2009) Reducing abrupt climate change risk using the Montreal Protocol and other regulatory actions to complement cuts in CO2 emissions, *Proc. Natl. Acad. Sci.* 106:20616. *See also* Lenton T. *et al.* (2008) Tipping Points in the Earth climate system, *Proc. Nat. Acad. Sci.* 105:1786; Arctic Monitoring and Assessment Programme (2011) Snow, Water, Ice and Permafrost in the Arctic, Executive Summary and Key Message, *available at* www.documentcloud.org/documents/88367-arctic-ice-melt-2011-executivesummary.html; Pollard D. & DeConto R.M. (2009) Modelling West Antarctic ice sheet growth and collapse through the past five million years, *Nature* 458:329-332; Allison I. *et al.* (2009) The Copenhagen Diagnosis, 2009: Updating the World on the Latest Climate Science. (SOS Print + Media, Sydney, Australia); Matsuo K. & Heki K. (2010) Time-variable ice loss in Asian high mountains from satellite gravimetry, *Earth and Planetary Science Letters* 290:30-36; Yao T. *et al.* (2009) Recent glacial retreat in the Chinese part of High Asia and its impact on water resources in Northwest China, in: Assessment of Snow, Glacier, and Water Resources in Asia, Table 1, *available at* www.indiaenvironmentportal.org.in/files/Glacier%20in%20Asia_lowres.pdf; The World Bank (2010) Assessment of the Risk of Amazon Dieback, *available at* www.bicusa.org/en/Document.101982.aspx; *and* National Research Council (2011) Climate Stabilization Targets 218 (The National Academies Press, Washington D.C.).

[34] Ramanathan V. (1975) Greenhouse Effect Due to Chlorofluorocarbons: Climatic Implications, *Science* 190:50.

[35] Ramanathan V. *et al.* (1985) Trace Gas Trends and Their Potential Role in Climate Change, *J. Geophys. Res. Atmos.* 90:5547-5566. *See also* Ramanathan, V. *et al.* (1987) Climate-Chemical Interactions and Effects of Changing Atmospheric Trace Gases, *Rev. of Geophy.* 25:1441-1482.

[36] National Research Council (2011) Climate Stabilization Targets 61 (The National Academies Press, Washington D.C.).

[37] National Research Council (2011) Climate Stabilization Targets 73 (The National Academies Press, Washington D.C.).

time of fossil fuel CO_2 might be 300 years, plus 25% that lasts millennia.[38] Its long lifetime means that even cutting CO_2 emissions to zero today is not expected to produce significant cooling for centuries.[39]

Timescales for Removal of CO_2 from the Atmosphere

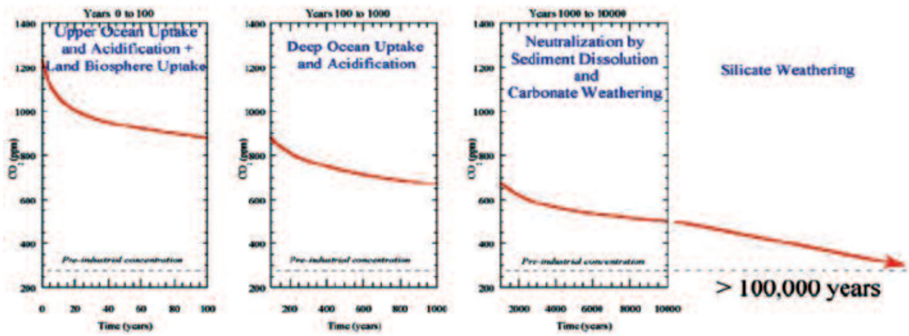

Figure 2. Model simulation of atmospheric CO_2 concentration for >100,000 years following after a large CO_2 release from combustion of fossil fuels. Different fractions of the released gas recover on different timescales. (Source: Research Council [2011] *Climate Stabilization Targets* 75 [The National Academies Press, Washington D.C.]).

The benefits of a comprehensive mitigation approach

Successfully addressing long-term climate change requires fast and aggressive cuts in CO_2 emissions, but that is not enough. In the face of uneven regional warming and increasing climate impacts that are already occurring and that may be accelerating, fast and aggressive cuts in SLCFs also are essential.[40] The short atmospheric lifetimes of the SLCFs and their enhanced

[38] Archer D. *et al.* (2005) Fate of Fossil Fuel CO_2 in Geologic Time, *J. of Geophysical Research* 110:C09S05. *See also* Hansen J. *et al.* (2007) Climate Change and Trace Gasses, *Phil. Trans. R. Soc. A.* 365:1925, 1938.

[39] Archer D. *et al.* (2005) Fate of Fossil Fuel $C0_2$ in Geologic Time, *J. of Geophysical Research* 110:C09S05.

[40] Solomon S. *et al.* (2009) Irreversible climate change due to carbon dioxide emissions, *Proc. Nat. Acad. Sci.* 106:1704, 1708.

regional effects means that cutting them will produce cooling within decades, often in regions most vulnerable to climate change.[41] In essence, CO_2 and the SLCFs are two separate control-knobs for climate mitigation that operate independently and on different timescales.[42] Both must be turned down simultaneously as part of a comprehensive climate strategy to prevent possible near-term abrupt climate change and long-term climate destabilization. Finally, given the profoundly persistent nature of CO_2, it is necessary to perfect and implement strategies that can draw down CO_2 from the atmosphere on a timescale of decades.

Fast reduction of SLCFs and CO_2 to reduce the risk of DAI

Cutting SLCFs including black carbon, tropospheric ozone and its precursor methane will have immediate climate impacts while significantly improving human and environmental health.[43] A recent joint study by the United Nations Environment Program (UNEP) and the World Meteorological Organization (WMO) identified 16 out of 2,000 possible emissions reduction measures that use existing technologies and often existing laws, and that if fully implemented by 2030 could cut the global rate of warming in half by 2050 and by two-thirds in the Arctic in the next 30 years (see Figure 3).[44]

Cutting these local air pollutants can also save more than 2 million lives each year, increase crop productivity, and repair the ability of plants to sequester carbon, a function now being impaired by tropospheric ozone.[45]

[41] *See generally* Molina M. *et al.* (2009) Reducing Abrupt Climate Change Risk Using the Montreal Protocol and Other Regulatory Actions to Complement Cuts in CO_2 Emissions, *Proc. Nat'l. Acad. Sci.* 106:20618. *See also* Solomon S. *et al.* (2009) Irreversible climate change due to carbon dioxide emissions, *Proc. Nat. Acad. Sci.* 106:1704, 1708; *and* National Research Council (2011) Climate Stabilization Targets 75 (The National Academies Press, Washington D.C.).

[42] United Nations Environment Programme & World Meteorological Organization (herein after UNEP/WMO) (2011) Integrated Assessment of Black Carbon and Tropospheric Ozone: Summary for Decisions Makers 3.

[43] National Research Council (2011) Climate Stabilization Targets 3 (The National Academies Press, Washington D.C.). *See also* UNEP/WMO (2011) Integrated Assessment of Black Carbon and Tropospheric Ozone: Summary for Decisions Makers 3.

[44] UNEP/WMO (2011) Integrated Assessment of Black Carbon and Tropospheric Ozone: Summary for Decisions Makers 3. *See also* IPCC (2007) Climate Change 2007: The Physical Science Basis, *available at* www.ipcc.ch/publications_and_data/ar4/wg2/en/contents.html.

[45] UNEP/WMO (2011) Integrated Assessment of Black Carbon and Tropospheric Ozone: Summary for Decisions Makers 3.

Probability of Warming & Predicted Impacts of Passing Climate Tipping Points

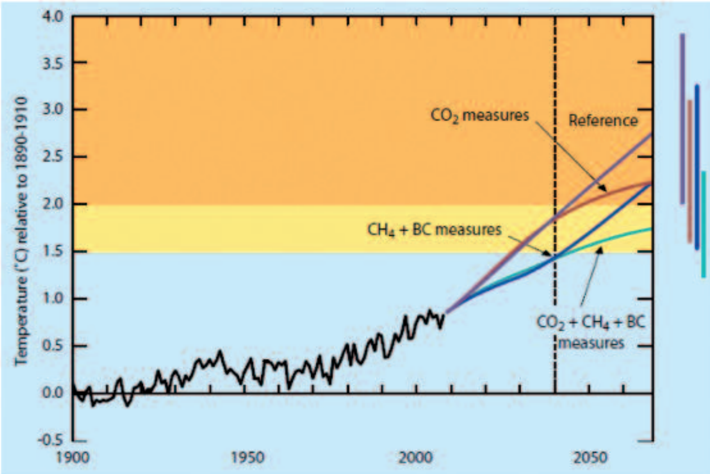

Figure 1. "Probability distribution for the committed warming by GHGs between 1750 and 2005. … Shown are the tipping elements [large-scale components of the Earth's system] and the temperature threshold range that initiates the tipping…." (Source: Ramanathan V. & Feng Y., [2008] On avoiding dangerous anthropogenic interference with the climate system: Formidable challenges ahead, *Proc. of the Nat'l Acad. Sci.* 105:14245).

Fast mitigation through cuts in these two SLCFs is likely to keep warming from increasing above 1.5°C for 30 years and below 2°C for 60 years by cutting black carbon and tropospheric ozone, and even longer when HFCs are also cut.[46] Cutting BC, which is responsible for 50%, or almost 1°C of the total 1.9°C increase in Arctic warming from 1890 to 2007, may be the best way to reduce Arctic ice loss.[47]

Non-CO_2 climate forcers include hydrofluorocarbons (HFCs), synthetic gases that are the fastest growing climate forcers in the U.S. and many other countries.[48] The production and use of HFCs can be cut by including these

[46] UNEP/WMO (2011) Integrated Assessment of Black Carbon and Tropospheric Ozone: Summary for Decisions Makers 3.

[47] UNEP/WMO (2011) Integrated Assessment of Black Carbon and Tropospheric Ozone: Summary for Decisions Makers 3.

[48] Jacobson M. (2010) Short-term effects of controlling fossil-fuel soot, biofuel soot and gases, and methane on climate, Arctic ice, and air pollution health, *J. Geophys Res.* 115:3795.

climate-forcing gases in the Montreal Protocol on Substance that Destroy the Ozone Layer, while leaving their downstream emissions in the Kyoto Protocol. An amendment to do this has been proposed by island States that are vulnerable to increasing sea level rise and storm surges.[49] A similar proposal was made jointly by Mexico, Canada, and the United States. The Montreal Protocol is widely considered the world's best environmental treaty having already phased out 96 similar chemicals by 98% and produced climate mitigation of 11 $GtCO_2$-eq per year from 1990 to 2010, for a net of 135 $GtCO_2$-eq.[50] Phasing out production and use of HFCs with high global warming potential would nearly eliminate one of the six Kyoto gases and achieve mitigation of over 100 billion tons of CO_2-eq. by 2050 through a treaty that has always succeeded, and at a very low cost.[51]

Expanding sinks through biosequestration

The final piece of an integrated mitigation strategy is to expand actions and technologies that remove excess CO_2 from the atmosphere on a time scale of decades, rather than the millennia required by the natural cycle.[52] This can be done quickly and stably by protecting and expanding biological sinks such as forests, wetlands, grassland, and other sources of biomass, and by producing biochar, which turns biomass into a more stable form of carbon,[53] as well as by perfecting carbon capture and storage. When CO_2 re-

[49] United States Department of State (2010) U.S. Climate Action Report: Fifth National Communication of the United States of America Under the United Nations Framework Convention on Climate Change 6, *available at* www.state.gov/documents/organization/140636.pdf. *See also* Velders G. *et al.* (2009) The Large Contribution of Projected HFC Emissions to Future Climate Forcing, *Proc. Nat'l Acad. Sci.* 106:10952-10953.

[50] Proposed Amendment to the Montreal Protocol (submitted by the Federated States of Micronesia), Open-Ended Working Group of the Parties to the Montreal Protocol on Substances that Deplete the Ozone Layer, UNEP/OzL.Pro.W.G.1/31/4 (May 9, 2011).

[51] Velders G., *et al.* (2007) The importance of the Montreal Protocol in protecting climate, *Proc Natl Acad Sci USA* 104:4814-4819.

[52] Velders G. *et al.* (2009) The large contribution of projected HFC emissions to future climate forcing, *Proc Natl Acad Sci.* 106:10949; Velders G. *et al.* (2009) The Large Contribution of Projected HFC Emissions to Future Climate Forcing, Supporting Information, *Proc Natl Acad Sci* 106:3, www.pnas.org/content/suppl/2009/06/22/0902817106.DCSupplemental/0902817106SI.pdf; and Proposed Amendment to the Montreal Protocol (submitted by the Federated States of Micronesia), 28 Apr. 2011 at 4-6 and 9, ozone.unep.org/Meeting_Documents/oewg/31oewg/FSM-Proposed-Amendment.pdf.

[53] Lenton T.M. & Vaughan N. (2009) The radiative forcing potential of difference climate geoengineering options, *Atmos. Chem. & Phys. Disc.* 9:2559.

moval through natural and enhanced approaches exceeds emissions, it will result in net negative emissions, i.e., drawdown, of CO_2.[54] Recent analysis calculates that enhanced removal of CO_2 from the atmosphere could match emissions and stabilize CO_2 concentrations by mid-century and possibly achieve carbon negative status by the end of the century.[55]

Conclusion

Faced with serious and largely irreversible changes to large components of the Earth's climate system, a comprehensive climate policy can benefit from considering all sources of warming and all mitigation options. The scale and speed of climate change impacts requires comprehensive fast-action mitigation strategies, including strategies to reduce both CO_2 and non-CO_2 climate forcers, and to protect and expand existing and new carbon sinks. These strategies can in large part use existing national, regional, and international laws and institutions. They can be implemented rapidly and strengthened over time, including through technology transfer, innovative financing, good practices, capacity building, and improved compliance and enforcement. Fast-action mitigation reduces the near-term impacts of climate impacts the world is already experiencing. It also reduces the risk of reaching tipping points for abrupt and irreversible climate changes. It is critical for helping the most vulnerable peoples and places avoid unmanageable climate impacts in the next several decades, including extreme droughts and floods, shifting monsoons, water shortages, famine, and other threats. Pursuing all mitigation strategies simultaneously will give humanity the greatest chance of stepping back from DAI.

Acknowledgments. We thank Nathan Borgford-Parnell and Xiaopu Sun for their assistance.

[54] Lenton T.M. (2010) The potential for land-based biological CO_2 removal to lower future atmospheric CO_2 concentration, *Carbon Management* 1:1.

[55] Lenton T.M. (2010) The potential for land-based biological CO_2 removal to lower future atmospheric CO_2 concentration, *Carbon Management* 1:1.

[56] Lenton T.M. (2010) The potential for land-based biological CO_2 removal to lower future atmospheric CO_2 concentration, *Carbon Management* 1:1.