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Retreat of Tibetan Plateau Glaciers Caused by Global Warming Threatens Water Supply and Food Security

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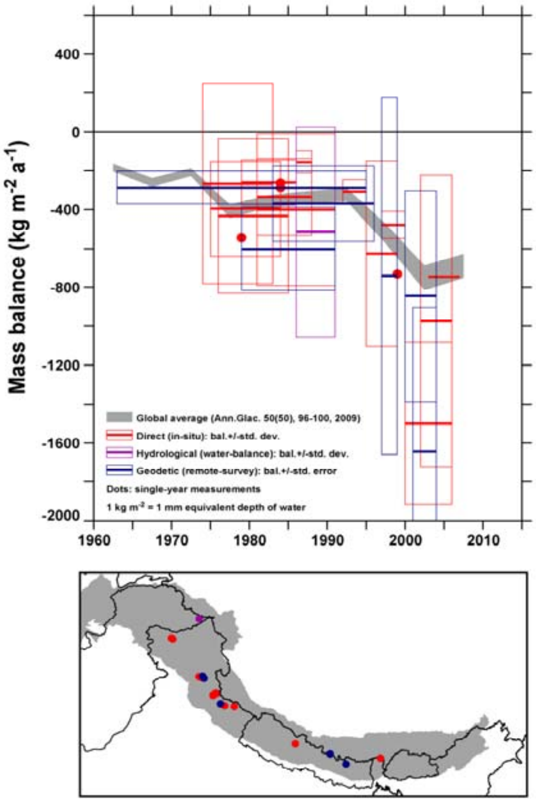
Summary

According to the IPCC, the global average surface temperature increase from 1850-1899 to 2001-2005 is 0.76°C ± 0.19°C. V. Ramanathan and Y. Feng from the Scripps Institution of Oceanography, University of California, San Diego, calculate that greenhouse gas emissions as of 2005 have committed the planet to warming of "2.4ºC (1.4º-4.3º) above the preindustrial surface temperatures." The Tibetan Plateau is warming about three times the global average. Since the 1950's, warming in excess of 1ºC on the Tibetan side of the Himalayas has contributed to retreat of more than 80% of the glaciers. Melting glaciers endangers the fresh water supply and food security of billions of people in Asia. The warming also contributes to the land use changes, especially melting of permafrost, which could result in significant carbon loss. Black carbon (soot) may have a significant effect on melting snow and glaciers equaling the impact of increased atmospheric CO_2. Therefore, in addition to a central reduction of CO_2, it is imperative to implement fast-action strategies to reduce non-CO_2 warming agents, including black carbon, hydrofluorocarbons, methane and tropospheric ozone precursors, as well as expand bio-sequestration and enhance urban albedo which together can reduce committed warming and associated abrupt climate changes on a decadal timescale.

Retreat of Tibetan Plateau Glaciers

According to the IPCC, the global average surface temperature increase from 1850-1899 to 2001-2005 is 0.76°C ± 0.19°C.[1] At high latitudes, temperatures are rising faster than the global average. Glaciers, including the Tibetan Plateau glaciers, are at particular risk.[2] The Tibetan Plateau—the planet's largest store of ice after the Arctic and Antarctic— is warming about three times the global average, with temperature increases of 0.3ºC or more per decade measured for the past half-century.[3] The significant impacts of this warming include "a major reduction of area and volume of Hindu-Kush-Himalaya-Tibetan (HKHT) glaciers, which provide the head-waters for most major river systems of Asia."[4]

In a study in the *Proceedings of the National Academy of Sciences*, V. Ramanathan and Y. Feng from the Scripps Institution of Oceanography, University of California, San Diego, calculate that greenhouse gas (GHG) emissions as of 2005 have committed the planet to warming of "2.4ºC (1.4º-4.3º) above the preindustrial surface temperatures."[5] Of the 2.4ºC committed warming, more than 50% is expected within 50 years, as heat stored in oceans is returned to the atmosphere, and as short-lived anthropogenic aerosols that are masking warming continue to be reduced to protect health and local environment resources.[6] By the end of the century, business-as-usual emissions could cause atmospheric concentrations of CO_2 and other long-lived GHGs to double, leading to an eventual global temperature increase of up to 6ºC.[7]



The graph shows all published Himalaya-Karakoram (HK) measurements; they are more negative after 1995 than before. The map shows where the measurement sites are.

Mass balance varies greatly year to year; these are series averages. Boxes suggest estimated uncertainty. The apparent trend is less uncertain than any one measurement. The data indicate either accelerating loss or stepwise increase in mass loss rate. This need not be true of every part of the region. For example there are suggestions of recent mass gain in the Karakoram.

Mass loss rate here is consistent with the global average.

The mass-balance rate required to remove all H-K ice during 2000-2035 would be about -11,000 kg m^{-2} a^{-1}. The oft-quoted 2035 disappearance date of Himalayan glaciers is not accurate (see slides 39-41).

Negative mass balance is loss of a non-renewable water resource. We can only get it back from the ocean by desalination. In the meantime, it will raise the level of the sea, and the glaciers themselves (and thawed mountain slopes) in some cases become more hazardous as they shed mass.

The data are insufficient to make strong intraregional comparisons, and so inferences about regional transitions of behavior are drawn from other types of information, such as the pattern of glacier breakup into lakes and other morphological indicators of behavior.

More benchmark glacier data and satellite observations are needed.

The graphs above and the accompanying text are from Jeffrey S. Kargel et al., *Satellite-era Glacier Changes in High Asia*, Background support presentation for NASA "Black Carbon and Aerosols" press conference associated with Fall AGU, Dec. 14, 2009.

Glacier responses depend on a number of complicated parameters. However, the total Himalayan mass balance is distinctly negative, with some possible anomalies.[8] According to Chinese scientists, the majority of Tibetan glaciers are retreating, and across much of the plateau the retreat is accelerating.[9] Based on meteorological station data, reanalyses and remote sensing, the Tibetan Plateau has shown significant warming during the last decades and will continue to warm in the future.[10] Himalayan glacier retreat is well documented through remote sensing techniques and aerial photographs.[11] The warming was also confirmed by recent ice core samples from Naimona'nyi Glacier in the Himalaya (Tibet) that show "no net accumulation of mass (ice) since at least 1950. Naimona'nyi is the highest glacier (6050 masl) documented to be losing mass annually suggesting the possibility of similar mass loss on other high-elevation glaciers in low and mid-latitudes under a warmer Earth scenario."[12]

Since the 1950's, warming in excess of 1ºC on the Tibetan side of the Himalayas has contributed to retreat of more than 80% of the glaciers, and the degradation of 10% of its permafrost in the past ten years.[13] Under current trends, two-thirds of the glaciers will disappear by 2060, threatening water supply for a billion people, including critical dry-season irrigation.[14]

Water Shortages and Droughts

Rapidly melting alpine glaciers and ice caps will initially be a source of flooding until they melt completely, when the problem will become the lack of glacial run-off to regions dependent on it.[15] In the Himalayas there are approximately 15,000 glaciers (of 46,377 glaciers catalogued by the Chinese Glacier Inventory in western China), storing an estimated 12,000 km^3 of freshwater.[16] The 'greater Himalayan region' is the source of ten of the largest rivers in Asia. The basins of these rivers are inhabited by 1.3 billion people and contain seven megacities.[17] The Himalayan glaciers seasonally release meltwater into tributaries of the Indus, Ganges, and Brahmaputra Rivers with glacial melt contributing up to 45% of the total river flow.[18] Approximately 500 million people depend upon water from these three rivers for agriculture and other purposes.[19] This region and its water resources play an important role in global atmospheric circulation, biodiversity, rainfed and irrigated agriculture, and hydropower, as well as in the production of commodities exported to markets worldwide.[20]

These geographic regions where water supply is dominated by melting snow or ice are predicted to suffer severe consequences as a result of recent warming.[21] A projected increase in surface air temperature in north-western China is, by linear extrapolation of observed changes, expected to result in a 27% decline in glacier area, a 10–15% decline in frozen soil area, an increase in flood and debris flow, and more severe water shortages by 2050 compared with 1961–1990.[22] The duration of seasonal snow cover in alpine areas, namely the Tibet Plateau, Xinjiang and Inner Mongolia, is expected to shorten, leading to a decline in volume and resulting in severe spring droughts. Between 20% and 40% reductions in runoff per capita in Ningxia, Xinjiang and Qinghai Provinces are *likely* by the end of the 21st century.[23]

Food Insecurity

Widespread famine is the expected result of disappearing glaciers and reduced run-off to life-sustaining rivers and lakes. The greatest risks of climate change are faced by many of the world's poorest, especially those living in subtropical and tropical areas, and those dependent on agriculture and food production systems in semiarid and arid regions.[24] These regions include in sub-Saharan Africa, south, east and South-east Asia, tropical parts of Latin America and some Pacific island nations.[25]

At first, over-melting of glaciers may cause flooding, but eventually a cessation of glacial run-off could create even more serious agricultural problems.[26] "Climate change-related melting of glaciers could seriously affect half a billion people in the Himalaya-Hindu-Kush region and a quarter of a billion people in China who depend on glacial melt for their water supplies."[27] Over the next century, the maximum flow of the Mekong is estimated to increase significantly, while the minimum monthly flows are estimated to decline, meaning increased flooding risks during wet season and an increased possibility of water shortage in dry season.[28]

Increasing temperatures and water stress are expected to lead to a 30% decrease in crop yields in Central and South Asia by the mid-21st Century.[29] In addition, an increase in agricultural water demand by 6 to 10% or more is projected for every 1°C rise in temperature.[30] As a result, the net cereal production in South Asian countries is projected to decline by at least between 4 to 10% by the end of this century, under the most conservative climate production projections.[31]

Land Use Changes and Positive Feedbacks

Human activities have significantly impacted land use on the Tibetan Plateau during the last fifty years. Significant land cover changes on the Tibetan Plateau include permafrost and grassland degradation, urbanization, deforestation and desertification.[32] The land use changes can not only affect the local environment, but can also lead to positive feedbacks to climate change.

Specifically, the warming directly influences the permafrost, which could become a significant carbon source. Permafrost is defined as subsurface earth materials that remain frozen for two consecutive years.[33] Trapped inside some permafrost is organic matter which survived decomposition for thousands of years because of the freezing temperatures.[34] Embedded in the permafrost are CH_4 clathrates, which are stabilized CH_4 crystals that result from the breakdown of organic materials at marine depths, under pressure equivalent to that produced by 250 m of water.[35]

Melting permafrost generates other positive feedbacks, including loss of albedo, deeper water penetration, and fires, all of which can warm the soils and trigger more microbial activity.[36] Permafrost melt can also lead to negative feedbacks such as increased growth of shrubbery and more photosynthesis, but this greening is not nearly enough to offset soil carbon loss.[37]

Impacts of Black Carbon on Melting Glaciers

Deposition of black carbon ("BC") is a major driver of glacial retreat in the Hindu-Kush-Himalaya-Tibetan region.[38] Ramanathan and Carmichael report that the impact of BC on melting snow and glaciers may equal the impact of increased atmospheric CO_2. Their model calculations indicate that approximately 0.6°C of the 1°C warming in the Tibetan Himalayas since the 1950s is due to BC.[39] Similarly, S. Menon et al. found out that the contribution of the enhanced Indian BC to the decline of snow/ice cover over the Himalayas, from 1990 to 2000 is ~30%.[40] In addition, snow darkening is an important component of carbon aerosol climate forcing.[41]

The United Nations Environment Programme (UNEP) also issued a comprehensive report on the negative effects of atmospheric brown clouds (ABCs) over Asia, including the deposition by ABCs of black carbon on the HKHT glaciers.[42] The UNEP report also connects ABCs to a number of other trends that negatively impact crop yields, including decreases in Indian Summer Monsoon (ISM) rainfall, a north-south shift in rainfall over China, and increased surface ozone.[43] Despite the negative effects of ABCs, the report echoes Ramanathan and Feng, warning that ABCs must be eliminated carefully since they mask GHG warming of 0.3-2.2ºC.[44] Added to the already observed 0.76ºC global temperature increase, an unmasking of warming in the high end of the 0.3-2.2ºC range could easily push the climate system past the dangerous anthropogenic interference threshold (DAI).[45]

Fast-Action Strategies Are Urgently Needed

A suite of fast-action mitigation strategies are urgently needed to avoid passing tipping points for abrupt climate changes.

Black carbon may be the second largest contributor to climate warming, and because its atmospheric lifetime is days to weeks, reducing it may offer the fastest mitigation.[46] Globally, Cofala et al. estimate that BC can be reduced by approximately 50% with full application of existing technologies by 2030, primarily from reducing diesel emissions and improving cook stoves.[47] Wallack and Ramanathan estimate that it may be possible to offset the warming effect from one to two decades of CO_2 emissions by reducing BC by 50% using existing technologies.[48]

Other fast-action climate mitigation strategies include reducing other short-lived forcers such as methane and tropospheric ozone precursors.[49] The Royal Society estimates that rigorous global implementation of air pollution regulations and available technologies, including for shipping and aviation, can reduce NO_x and CO emissions by >50%[50], which would reduce the anthropogenic tropospheric ozone forcing from 20 to 10%.[51] That reduction in ozone forcing would delay by ≈10 years' time when the threshold for DAI would otherwise have been passed.[52]

The Montreal Protocol on Substances that Deplete the Ozone Layer can be applied to reduce HFCs and to collect and destroy ozone-depleting substance (ODS) "banks". Reducing HFC production and consumption, and hence the opportunity to reduce later emissions, can be done by regulating HFCs under the Montreal Protocol.[53] Velders et al. estimated scenarios for HFC emissions derived from gross domestic product and population growth and incorporating information on demand for HCFC products in developing countries, patterns of replacements of HCFCs by HFCs, and increases in HFC-134a use in mobile air conditioning.[54] Global HFC emissions in 2050 are projected to be 5.5–8.8 Gt CO_2-eq. per year, which is equivalent to 9–19% of projected global CO_2 emissions in business-as-usual scenarios. Global HFC emission projections increase strongly after 2013 and significantly exceed previous estimates after 2025. Without regulatory action, global radiative forcing from projected HFC emissions in 2050 will be equivalent to that from 6 to 13 years of CO_2 emissions. In addition, up to 6 Gt CO_2-eq. by 2015 and an additional 14 Gt CO_2-eq. thereafter can be avoided by collecting and destroying banks of ODSs that would otherwise be emitted from unwanted stockpiles and discarded refrigeration and air-conditioning equipment and insulating foam.[55]

Other fast-action mitigation efforts include bio-sequestration in forests and soils. McKinsey & Company estimate reducing emissions from deforestation and degradation can provide mitigation up to 5.1 Gt CO_2-eq. per year by 2030.[56] In addition, biochar removes carbon from the carbon cycle by drawing down atmospheric concentrations of CO_2 in a carbon-negative process and provides near permanent carbon storage while also improving soil productivity and reducing the need for fossil fuel-based fertilizer.[57] The International Biochar Initiative estimates that biochar production has the potential to provide 1 Gt carbon per year in climate mitigation by 2040, or 3.67 Gt CO_2 per year, using only waste biomass.[58] Under an aggressive scenario, where all projected demand for renewable biomass fuel is met through pyrolysis, Lehmann et al. estimate that biochar may be able to sequester 5.5–9.5 Gt C per year, or ≈20–35 Gt CO_2, per year by 2100.[59]

Improving energy efficiency[60] and expanding renewables, especially wind, also can produce fast mitigation,[61] as can improving urban albedo.[62] A 25% and 15% increase in the albedo of roofs and pavements, respectively, for all global urban areas, could lead to an offset of approximately 57

Gt CO_2.[63] Increasing surface albedo does not fix the underlying problem of greenhouse gas accumulation,[64] but "cool roofs" can help address the key symptom, while also reducing energy needs and associated emissions,[65] and decreasing building cooling costs more than 20%.[66]

Most of these fast-action strategies have strong co-benefits, such as public health benefits from black carbon reductions, earlier recovery of the ozone layer from faster ODS phase-outs and from collecting and destroying ODSs in discarded products and equipment, soil enhancement and reduced fertilizer and water use from biochar, and increased energy security and green jobs from efficiency and renewables. These co-benefits provide further incentives to act now to forestall temperature tipping points visible on the horizon.

The G8 has committed to take rapid action to reduce hydrofluorocarbons, black carbon, and other significant short-term climate forcing agents, in addition to ambitious and urgent cuts in emissions from CO_2 and other more long-lasting, greenhouse gases.[67] Many countries may have some existing legal authority to begin addressing some of these strategies. Where this is the case, improving compliance can help promote near-term climate mitigation.[68] The International Network for Environmental Compliance & Enforcement recently issued *Climate Compliance Alerts* on black carbon[69] and illegally harvested timber.[70]

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Endnotes

1 Solomon S et al., *Technical summary*, in Climate Change 2007: The Physical Sciences Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, pp 19–92 (2007).

2 Lenton TM, et al., *Tipping elements in the Earth's climate system,* 105 Proc Natl Acad Sci USA 1786 1788 (2008) ("Transient warming is generally greater toward the poles and greater on the land than in the ocean."); *see also* Jane Qiu, *The Third Pole*, 454 NATURE 393 (2008).

3 Qiu, *id,* at 393. *Also see* Cruz, R. V., H. Harasawa, M. Lal, S. Wu, Y. Anokhin, B. Punsalmaa, Y. Honda, M. Jafari, C. Li, and N. Huu Ninh (2007), *Asia*, in Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, edited by M. L. Parry et al., pp. 475, Cambridge Univ. Press, Cambridge, U. K ("0.16 and 0.32°C per decade increase in annual and winter temperatures, respectively").

4 V. Ramanathan & Y. Feng, *On avoiding dangerous anthropogenic interference with the climate system: Formidable challenges ahead*, 105 Proc. of the Nat'l Acad. of Sci. 14245, 14245 (2008).

5 *Id*.

6 *Id*, at 14247.

7 International Energy Agency [IEA], *World Energy Outlook* 45-46 (2008) ("The projected rise in emissions of greenhouse gases in the Reference Scenario puts us on a course of doubling the concentration of those gases in the atmosphere by the end of this century, entailing an eventual global average temperature increase of up to 6°C. The Reference Scenario trends point to continuing growth in emissions of CO_2 and other greenhouse gases. Global energy-related CO_2 emissions rise from 28 Gt in 2006 to 41 Gt in 2030 - an increase of 45%. The 2030 projection is only 1 Gt lower than that projected in last year's *Outlook*, even though we assume much higher prices and slightly lower world GDP growth. World greenhouse-gas emissions, including non-energy CO_2 and all other gases, are projected to grow from 44 Gt CO_2-equivalent in 2005 to 60 Gt CO_2-eq in 2030, an increase of 35% over 2005.").

8 *Id*.

9 Yao, T., J. Pu, A. Lu, Y. Wang, and W. Yu, 39 *Recent glacial retreat and its impact on the hydrological processes on the Tibetan Plateau, China, and surrounding regions*, Arct. Antarct. Alp. Res., 642– 650(2007b).

[10] Shichang Kang et al., *Review of climate and cryospheric change in the Tibetan Plateau*, 5 Environ. Res. Lett. (2010).
[11] Ding, Y., S. Liu, J. Li, and D. Shangguan, 43(1) *The retreat of glaciers in response to recent climate warming in western China*, Ann. Glaciol., 97–105 (2006).
[12] Kehrwald, N. M., L. G. Thompson, Y. Tandong, E. Mosley-Thompson, U. Schotterer, V. Alfimov, J. Beer, J. Eikenberg, and M. E. Davis, 35 *Mass loss on Himalayan glacier endangers water resources*, Geophys. Res. Lett. (2008).
[13] V. Ramanathan & G. Carmichael, *Global and regional climate changes due to black carbon*, 1 NATURE GEOSCIENCE 221, 224 (2008); *see also* Qiu, *supra* note 2, at 393 ("The Tibetan plateau gets a lot less attention than the Arctic or Antarctic, but after them it is Earth's largest store of ice. And the store is melting fast. In the past half-century, 82% of the plateau's glaciers have retreated. In the past decade, 10% of its permafrost has degraded. As the changes continue, or even accelerate, their effects will resonate far beyond the isolated plateau, changing the water supply for billions of people and altering the atmospheric circulation over half the planet . . . . The melting seasons on the plateau now begin earlier and last longer . . . . If current trends hold, two thirds of the plateau glaciers could be gone by 2050."). In the Tibetan Plateau Steppe, where the headwaters of the Yangtze, Mekong, and Indus are located, there is concern both for short-term flood and long-term reductions in water supplies. *See*, *e.g.*, *id.* at 395 ("The risk of floods, though, is but a short-term danger far exceeded by long-term issues with water supplies atop the [Tibetan plateau].").
[14] Lester R. Brown, *Plan B 3.0: Mobilizing to Save Civilization* 54 (2008) ("Yao Tandong, a leading Chinese glaciologist, predicts that two thirds of China's glaciers could be gone by 2060. 'The fullscale glacier shrinkage in the plateau region,' Yao says, 'will eventually lead to an ecological catastrophe.'")
[15] *See*, *e.g.*, Qiu, *supra* note 2, at 395 ("The risk of floods, though, is but a short-term danger far exceeded by long-term issues with water supplies atop the [Tibetan plateau]."); Cruz et al., *supra* note 3, at 483 ("As glaciers melt, river runoff will initially increase in winter or spring but eventually will decrease as a result of loss of ice resources.").
[16] Ding *et al*, *supra* note 12; Cruz, et al., *supra* note 3, pp. 469–506.
[17] Mats Eriksson, Xu Jianchu, Arun Bhakta Shrestha, Ramesh Ananda Vaidya, Santosh Nepal, Klas Sandström, *The Changing Himalayas: Impact of Climate Change on Water Resources and Livelihoods in the Greater Himalayas*, 1 The International Centre for Integrated Mountain Development (2009).
[18] World Resources Institute (2003), *Watersheds of the World* [CD-ROM], World Resour. Inst., New York.
[19] Cruz et al., *supra* note 3.
[20] Eriksson et al., *supra* note 18.
[21] Barnett, T. P., J. C. Adam, and D. P. Lettenmaier, *Potential impacts of a warming climate on water availability in snow-dominated regions*, 438 Nature, 303–309 (2005).
[22] Qin, D.H., *Assessment of Environment Change in Western China*, 2 Prediction of Environment Change in Western China *(*2002).
[23] Tao, F.L., M. Yokozawa, Y. Hayashi and E. Lin, *A perspective on water resources in China: interactions between climate change and soil degradation*, 68(1–2) Climatic Change 169 – 197 (2005).
[24] Natural Resources Mgmt. and Environment Dep't, Food and Agriculture Org. of the United Nations, *Climate and Food Security* (1996) [hereinafter FAO], *available at* http://www.fao.org/DOCREP/x0262e/x0262e15.htm ("Many of the world's poorest people are most at risk, especially those living in subtropical and tropical areas, and dependent on food production systems in semiarid and arid regions. These areas are found in sub-Saharan Africa, south, east and south-east Asia, tropical parts of Latin America and in some Pacific island nations."); *see also* Josef Schmidhuber & Francesco N. Tubiello, *Global food security under climate change*, 104 Proc. of the Nat'l Acad. of Sci. 19703, 19705 (2007), *available at* http://www.pnas.org/content/104/50/19703.full.pdf ("In semiarid areas, droughts can dramatically reduce crop yields and livestock numbers and productivity….[M]ost of this land is in sub-Saharan Africa and parts of South Asia, meaning that the poorest regions with the highest level of chronic undernourishment will also be exposed to the highest degree of instability in food production.").
[25] *Id*, FAO.
[26] Cruz et al., *supra* note 3 ("As glaciers melt, river runoff will initially increase in winter or spring but eventually will decrease as a result of loss of ice resources.").
[27] *Id.*
[28] *Id.* ("The maximum monthly flow of the Mekong is estimated to increase by 35 to 41% in the basin and by 16 to 19% in the delta, with lower value estimated for years 2010 to 38 and higher value for years 2070 to 99, compared with 1961 to 90 levels. In contrast, the minimum monthly flows are estimated to decline by 17 to 24% in the basin and 26 to 29% in the delta suggesting that there could be increased flooding risks during wet season and an increased possibility of water shortage in dry season.") (citation omitted).

[29] United Nations Development Programme, *Human Development Report: Beyond Scarcity: Power, Poverty and the Global Water Crisis,* New York (2006); Cruz et al., *supra* note 3, at 479.
[30] Cruz et al, *supra* note 3, at 481.
[31] Cruz et al, *supra* note 3, at 480-481.
[32] Xuefeng Cui, Hans-F. Graf, *Recent land cover changes on the Tibetan Plateau: a review*, Climatic Change (2009) doi: 10.1007/s10584-009-9556-8.
[33] Edward A.G. Schuur et al., *Vulnerability of Permafrost Carbon to Climate Change: Implications for the Global Carbon Cycle*, BIOSCIENCE, Sept. 2008, at 702, *available at* http://www.bioone.org/doi/pdf/10.1641/B580807 ("Permafrost, defined as subsurface earth materials remaining below 0°C for two consecutive years, is widespread in the Arctic and boreal regions of the Northern Hemisphere, where permafrost regions occupy 22% of the exposed land surface area.").
[34] David Archer, *Methane hydrate stability and anthropogenic climate change*, 4 BIOGEOSCIENCES 521, 531 (2007), *available at* http://geosci.uchicago.edu/~archer/reprints/archer.2007.hydrate_rev.pdf ("Permafrost soils contain relict organic matter that survived decomposition due to the freezing temperatures. Fossil mammoths, still edible after all these years, are examples of this phenomenon. Peat deposits are a substantial reservoir of carbon, are estimated to be 350–450 Gton C. With a thaw will come accelerated decomposition of this organic matter, increasing the flux of CO_2 and CH_4. Soil that has been frozen for thousands of years still contains viable populations of methanotrophic bacteria") (citations omitted).
[35] Martin Kennedy, David Mrofka & Chris von der Boch, *Snowball Earth termination by destabilization of equatorial permafrost methane clathrate*, 453 NATURE 642, 644 (2008) ("Methane clathrates form when methane produced by thermogenic or biogenic breakdown of organic matter at depth migrates upwards to stabilize more than 200m below the sea floor or land surface in a narrow range of pressure and temperature. To be stable, marine clathrates require both sea water at 0ºC and the additional pressure derived from more than 250m of water. Because the Reynella Member consists of intertidal deposits within a deepening succession midway between the preceding glacial sealevel lowstand and the shelfal deposits of the Seacliff sandstone/Nuccaleena dolomite, the water could not have been deep enough to stabilize clathrates. The stabilization thus must have resulted either from the pressure of a shelf-borne ice sheet or from the permafrost conditions (<0ºC) indicated by local evidence of frost wedging. Permafrost clathrates that accumulated beneath the broad exposed shelves of the Arctic during the Pleistocene are now destabilizing as a result of post-glacial flooding and global warming.") (footnotes omitted).
[36] Schuur et al., supra note 34, at 710 ("In combination with dry conditions or increased water infiltration, thawing and fires could, given the right set of circumstances, act together to expose and transfer permafrost C to the atmosphere very rapidly."); *see also id.* at 711 ("Changes in albedo brought about by changes in plant species composition, length of the snow season, lake area, or fire frequency can have positive or negative effects on climate warming.").
[37] Edward A. G. Schuur, Jason G. Vogel1, Kathryn G. Crummer, Hanna Lee, James O. Sickman & T. E. Osterkamp, *The effect of permafrost thaw on old carbon release and net carbon exchange from tundra*, 459 NATURE 556, 556 (2009) ("We find that areas that thawed over the past 15 years had 40 per cent more annual losses of old carbon than minimally thawed areas, but had overall net ecosystem carbon uptake as increased plant growth offset these losses. In contrast, areas that thawed decades earlier lost even more old carbon, a 78 per cent increase over minimally thawed areas; this old carbon loss contributed to overall net ecosystem carbon release despite increased plant growth. Our data document significant losses of soil carbon with permafrost thaw that, over decadal timescales, overwhelms increased plant carbon uptake at rates that could make permafrost a large biospheric carbon source in a warmer world.")(footnotes omitted); *see also* Schuur et al., supra note 34, at 711 ("One important offset to permafrost C losses is an increase in C uptake from the atmosphere by photo synthesis and plant growth (figure 6). Higher temperatures can stimulate photosynthetic rates directly, and can also lengthen the growing season (Myneni et al. 1997). This can increase C storage in plant biomass and in new soil organic matter.").
[38] V. Ramanathan et al., United Nations Environment Programme, *Atmospheric Brown Clouds: Regional Assessment Report with Focus on Asia* 6 (2008), *available at* http://www.unep.org/pdf/ABCSummaryFinal.pdf ("The present report adds that soot in [atmospheric brown clouds] is another major cause of the retreat of [Hindu-Kush-Himalayan-Tibetan] glaciers and snow packs. The warming of the elevated atmospheric layers due to greenhouse warming is amplified by the solar heating by soot at elevated levels and an increase in solar absorption by snow and ice contaminated by the deposition of soot."); *see also id.* at 25 ("Decreased reflection of solar radiation by snow and ice due to black carbon deposition is emerging as another major contributor to the melting of snow packs and glaciers."); *see also* Ramanathan & Carmichael, *supra* note 14, at 224; Baiqing Xu et al., *Black soot and the survival of Tibetan glaciers*, 106 Proc Natl Acad Sci USA 22114-22118 (2009).
[39] Ramanathan & Carmichael, *supra* note 14, at 224.

[40] Menon, S., Koch, D., Beig, G., Sahu, S., Fasullo, J., and Orlikowski, D., *Black carbon aerosols and the third polar ice cap*, 9 Atmos. Chem. Phys. Discuss. 26593-26625 (2009).
[41] Flanner, M. G., C. S. Zender, J. T. Randerson, and P. J. Rasch, 112 *Present-day climate forcing and response from black carbon in snow*, J. Geophys. Res. (2007).
[42] Ramanathan et al., *supra* note 39, at 2 ("[I]ncreasing amount of soot, sulphates and other aerosol components in atmospheric brown clouds (ABCs) are causing major threats to the water and food security of Asia and have resulted in surface dimming, atmospheric solar heating and soot deposition in the Hindu Kush-Himalayan-Tibetan (HKHT) glaciers and snow packs."); *id.* at 24 ("The observed retreat of the Hindu Kush- Himalayan-Tibetan (HKHT) glaciers is one of the most serious environmental problems facing Asia, since these glaciers and snow packs provide the head-waters for the major Asian river systems, including the Ganges, the Brahmaputra, the Mekong and the Yangtze.").
[43] *Id.* at 2 ("These have given rise to major areas of concern, some of the most critical being observed decreases in the Indian summer monsoon rainfall, a north-south shift in rainfall patterns in eastern China, the accelerated retreat of the HKHT glaciers and decrease in snow packs, and the increase in surface ozone. All these have led to negative effects on water resources and crop yields.").
[44] *Id.* at 11-12 ("Thus, air pollution regulations can have large amplifying effects on global warming. For example, using climate sensitivity recommended in IPCC-AR4, elimination of aerosols in ABCs can lead to an additional warming of 0.3 - 2.2ºC.").
[45] *Id.* at 12 ("The upper value of 2.2ºC, when added to the 20th century warming of 0.75ºC, could likely push the climate system over the 2ºC threshold value for the so-called dangerous climate change.").
[46] Ramanathan & Carmichael, *supra* note 14, at 222 ("The BC forcing of 0.9 W m^{-2} (with a range of 0.4 to 1.2 W m^{-2}) . . . is as much as 55% of the CO_2 forcing and is larger than the forcing due to the other GHGs such as CH_4, CFCs, N_2O or tropospheric ozone."); *see also* Mark Jacobson, *Control of Fossil-Fuel Particulate Black Carbon and Organic Matter, Possibly the Most Effective Method of Slowing Global Warming,* 107 J. Geophys. Res. D19 (2002); and Qiu, *supra* note 2, at 396 ("Reducing emissions of greenhouse gases and black carbon should be the top priority," according to Xu Baiqing of the Institute of Tibetan Plateau Research.).
[47] Cofala J, Amman M, Klimont Z, Kupiainen K, Hoeglund-Isaksson L, *Scenarios of global anthropogenic emissions of air pollutants and methane until 2030*, 41 Atmos Env 8486–8499 (2007).
[48] Wallack V & Ramanathan V, *The other climate changers: Why black carbon and ozone also matter*, 88 Foreign Affairs 105–113 (2009).
[49] *Role of Black Carbon on Global and Regional Climate Change: Hearing on the role of black carbon as a factor in climate change Before H. Comm. on Oversight and Gov't Reform*, 110th Cong. 4 (2007) (testimony of V. Ramanathan).
[50] Royal Society, *Ground-level ozone in the 21st century: Future trends, impacts and policy implications* (2008), *available at* http://royalsociety.org/displaypagedoc.asp?id_31506.
[51] Forster P, et al., *Changes in atmospheric constituents and in radiative forcing*, in Climate Change 2007: The Physical Sciences Basis, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, pp 129–234 (2007).
[52] Wallack & Ramanathan, *supra* note 49.
[53] Mario Molina, Durwood Zaelke, K. Madhava Sarma, Stephen O. Andersen, Veerabhadran Ramanathan, and Donald Kaniaru, *Reducing abrupt climate change risk using the Montreal Protocol and other regulatory actions to complement cuts in CO2 emissions*, Special Issue, Proc. of the Nat'l Acad. of Sci., USA (2009), *available at* http://www.pnas.org/content/early/2009/10/09/0902568106.full.pdf+html.
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[55] IPCC/Technology and Economic Assessment Panel, *Special Report*: *Safeguarding the Ozone Layer and the Global Climate System*: *Issues Related to Hydrofluorocarbons and Perfluorocarbons* (2005); TEAP, *Response to Decision XVIII/12*, *Report of the Task Force on HCFC Issues (with Particular Focus on the Impact of the Clean Development Mechanism) and Emissions Reductions Benefits Arising from Earlier HCFC Phase-Out and Other Practical Measures* (2007).
[56] McKinsey & Company, *Pathways to a Low-Carbon Economy, Version 2 of the Global Greenhouse Gas Abatement Cost Curve* (2009).
[57] Johannes Lehmann, John Gaunt & Marco Rondon, *Bio-char Sequestration In Terrestrial Ecosystems – A Review*, 11 Mitigation and Adaptation Strategies for Global Change 403, 404 (2006).
[58] International Biochar Initiative, *How much carbon can biochar systems offset - and when?* (2008), *available at* http://www.biochar-international.org/images/ final_carbon_wpver2.0.pdf.
[59] Lehmann et al., *supra* note 58.

[60] Group of Eight Summit, Heiligendamm, Ger., June 6-8, 2007, *Growth and Responsibility in the World Economy: Summit Declaration*, ¶ 46 (June 7, 2007) ("Improving energy efficiency worldwide is the fastest, the most sustainable and the cheapest way to reduce greenhouse gas emissions and enhance energy security.").

[61] The IPCC has predicted that renewable energy sources, which have "a positive effect on energy security, employment and on air quality," will be able to provide 30-35% of the world's electricity by 2030. IPCC, *Summary for Policymakers*, *in* Climate Change 2007: Mitigation 13 (B. Metz et al. eds., 2007). The IPCC has also found that "wind is the fastest growing energy supply sector." IPCC, *IPCC Scoping Meeting on Renewable Energy Sources* 4 (Olav Hohmeyer & Tom Trittin eds., 2008); *see also* Greenpeace & Global Wind Energy Council, *Global Wind Energy Outlook 2006*, at 38 (2006) ("Under the Advanced wind energy growth projection, coupled with ambitious energy saving, wind power could be supplying 29.1% of the world's electricity by 2030 and 34.2% by 2050."). In its most recent report, the International Energy Agency concludes "[p]reventing catastrophic and irreversible damage to the global climate ultimately requires a major decarbonisation of the world energy sources . . . . The energy sector will have to play the central role in curbing emissions – through major improvements in efficiency and rapid switching to renewable and other low-carbon technologies . . . ." *See* IEA, *supra* note 7, at 37-38.

[62] *See* Hashem Akbari, Surabi Menon & Arthur Rosenfeld, *Global Cooling: Increasing Worldwide Urban Albedos to Offset* CO_2, 94 Climatic Change 275-286 (2009). In California, which sets strict energy budgets for new construction, residential and some non-residential buildings can receive energy credits toward their energy budgets for installing "cool roofs." Cool roofs can lower roof temperatures up to 100 degrees Fahrenheit, reducing energy use for air conditioning and associated urban heat islands and smog. CAL. CODE REGS. tit. 24 § 118 (2007). Cool roof and reflective pavement are two of California's early action measures implementing California Assembly Bill Number 32, the Global Warming Solutions Act. *See* Air Resources Board, California Environmental Protection Agency, *Expanded List of Early Action Measures to Reduce Greenhouse Gas Emissions in California Recommended for Board Consideration*, at C-14 (2007).

[63] Surabi Menon, Hashem Akbari, Sarith Mahanama, Igor Sednev and Ronnen Levinson (2010) Radiative forcing and temperature response to changes in urban albedos and associated CO2 offsets, Environmental Research Letters doi:10.1088/1748-9326/5/1/014005.

[64] Akbari et al., supra note 63.

[65] Akbari et al., supra note 63.

[66] Akbari et al., supra note 63.

[67] G8 Summit, *Responsible Leadership for a Sustainable Future* (2009).

[68] See Eighth International Conference on Environmental Compliance and Enforcement, Cape Town, S. Afr., Apr. 5-11, 2008, *Cape Town Statement*, for an affirmation of the benefits of environmental compliance and enforcement.

[69] Int'l Network for Environmental Compliance and Enforcement [INECE], *Jump-Starting Climate Protection: INECE Targets Compliance with Laws Controlling Black Carbon* (June 12, 2008), *available at* http://inece.org/climate/INECEClimateComplianceAlert_BlackCarbon.pdf.

[70] INECE, *Recent Amendments to U.S. Lacey Act Should Help Protect Forests Worldwide*, *available at* http://www.inece.org/climate/ClimateComplianceAlert_LaceyAct.pdf.