Primer on Short-Lived Climate Pollutants

Slowing the rate of global warming over the near term by cutting short-lived climate pollutants to complement carbon dioxide reductions for the long term

IGSD

Institute for Governance & Sustainable Development

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The Institute for Governance & Sustainable Development's mission is to promote just and sustainable societies and to protect the environment by advancing the understanding, development, and implementation of effective, accountable and democratic systems of governance for sustainable development.

Beginning in 2006, the Institute embarked on a "fast-action" climate mitigation campaign to promote non-CO_2 strategies that will result in significant reductions of emissions, temperature, and impacts in the near-term, to complement cuts in CO_2 which are essential for the long-term. These fast-action strategies include reducing emissions of short-lived climate pollutants—black carbon, methane, tropospheric ozone, and hydrofluorocarbons. IGSD's fast-action strategies also include measures to capture, reuse, and / or store CO_2 after it is omitted, including biosequestration and efforts to turn biomass into more stable forms of carbon for long-term storage.

Durwood Zaelke, President*

IGSD

Institute for Governance & Sustainable Development

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Executive Summary

Carbon dioxide (CO_2) emissions are responsible for 55-60% of anthropogenic radiative forcing.[1] Fast and aggressive CO_2 mitigation is therefore essential to combat the resulting climate change. But this is not enough. CO_2 mitigation must be combined with fast and aggressive reductions of the pollutants causing the other 40-45% of warming.[2] These pollutants include black carbon, tropospheric ozone, methane, and hydrofluorocarbons (HFCs). Because these pollutants have atmospheric lifetimes of only days to a decade and a half, they are referred to as short-lived climate pollutants (SLCPs). Reducing SLCPs is critical for slowing the rate of climate change over the next several decades and for protecting the people and regions most vulnerable to near-term climate impacts.

Although we have known about SLCPs for more than thirty-five years,[3] the following scientific developments have catapulted them to the front lines in the battle against climate change.

- *First* is the recognition that we have already added enough greenhouse gases to warm the planet by 2.4°C or more during this century.[4] Much of this warming has been offset by cooling aerosols, primarily sulfates, which are being reduced under current air pollution policies. These reductions are important, but will contribute to near-term warming. Without fast-action mitigation to cut SLCPs, warming may cross the 1.5° to 2°C threshold by mid-century. Reducing SLCPs is the most effective strategy for constraining warming in the near term, since most of their warming effect disappears within weeks to a decade and a half after reductions.

- *Second* is the recognition that in addition to being climate forcers, three of the four SLCPs are also harmful air pollutants. Reducing them will prevent millions of premature deaths every year, protect tens of millions of tonnes of crops, and contribute to sustainable development.
- *Third* is the recognition that the benefits for health, crops, and sustainable development will accrue primarily in the nations or regions that take action to mitigate these pollutants, due to the stronger impacts black carbon and tropospheric ozone have near their emissions sources.
- *Fourth* is the recognition that there are practical and proven ways to reduce all four of these pollutants and that existing laws and institutions are often available to support the reductions.

Reducing three of the SLCPs—black carbon, tropospheric ozone, and methane—has the potential to avoid ~0.5°C global average warming by 2050[5] and 0.84°C in the Arctic by 2070.[6] This would cut the current rate of global warming by half, the rate of warming in the Arctic by two-thirds, and the rate of warming over the elevated regions of the Himalayas and Tibet by at least half.[7]

Reducing SLCPs will in turn:

- Help stabilize regional climate systems and reduce heat waves, fires, droughts, floods and hurricanes in mid-latitudes, and slow shifts in monsoons, expansion of desertification, and increases in cyclones in the tropics.
- Slow the melting of glaciers and Arctic sea ice and the rate of sea-level rise.[8]
- Slow the pace of climate impacts and provide critical time to adapt to large climate changes.

The primary direct local benefits for developing countries from reducing SLCPs include:

- Saving millions of lives a year and significantly reducing other illnesses.
- Improving food security.
- Expanding energy access for the billion forced to depend on solid biomass.

Preventing growth in the other SLCP, HFCs, can avoid additional future warming of at least 0.1°C by 2050, adding 20% more avoided warming to the ~0.5°C warming avoided from reductions in black carbon and ozone. Reductions in these SLCPs can be achieved quickly, and in most cases by using existing technologies and existing laws and institutions.

Using existing technologies and institutions to reduce these non-CO_2 climate pollutants may offer the best near-term protection for the countries that are most vulnerable to climate change impacts, including island nations, countries with low-lying coastal areas, and agriculture-dependent countries in Asia and Africa already suffering droughts, floods, and shifting rainfall. Slowing the rate of climate change and reducing near-term impacts is a critical complement to adaptation strategies and to sustainable development, with the potential to provide global benefits for climate, crops, and health valued at $5.9 trillion annually, starting in 2030.

All of the SLCPs are being addressed in the Climate and Clean Air Coalition (CCAC) to Reduce Short-lived Climate Pollutants, comprised of developing and developed countries, along with UNEP, the European Commission, and the World Bank.[9] The G8 Leaders joined the Coalition and requested the World Bank to conduct a study of how best to integrate SLCP reductions in its programs.

In addition to being included in the CCAC, HFCs are addressed in the Rio + 20 declaration, *The Future We Want*, where leaders supported phasing down their production and use.[10] Such a phase down can be achieved through the Montreal Protocol, while simultaneously improving the energy efficiency of refrigerators, air conditioners, and other equipment and products that use these chemicals, thus reducing CO_2 emissions as well. The Federated States of Micronesia has made a formal proposal to amend the Montreal Protocol to do this, as have the North American Parties (Mexico, Canada, and the U.S.).[11] Through mid-2012, 108 Parties have expressed support.[12] Action at national and regional levels also can help reduce HFCs, as can voluntary efforts.

Although reducing SLCPs is essential for reducing near-term climate impacts, it is not sufficient. Aggressive reductions in CO_2 emissions also are essential for long-term climate stability. In contrast to the short lifetime of SLCPs, however, only about 25% of CO_2 emitted is removed from the atmosphere in the first fifty years, increasing to approximately 50% after one hundred years, with most of the remaining CO_2 lasting for a thousand years or more.[13] CO_2's long lifetime combined with the thermal inertia of the ocean means that if CO_2 emissions were to cease, more than 80% of the expected decrease in global mean temperature would not be realized for hundreds of years, whereas up to 90% of the decrease from cuts to SLCPs would be realized within a decade.[14]

If combined with substantial CO_2 reductions that begin quickly, fast action to reduce SLCPs have a high probability of keeping the increase in global temperature to less than 1.5°C above the pre-industrial temperature for the next 30 years and below the 2°C guardrail for the next 60 to 90 (*see* Fig. 3 & 4).

Introduction to Short-lived Climate Pollutants

CO_2 emissions account for 55-60% of current anthropogenic radiative forcing. Fast and aggressive CO_2 cuts are essential to combat the resulting climate change. But this is not enough. CO_2 cuts must be combined with fast and aggressive cuts to SLCPs, which are causing the other 40-45% of forcing.

Black carbon

Black carbon is a potent climate-forcing aerosol that remains in the atmosphere for only a few days or weeks.[15] Black carbon is a component of soot and is a product of the incomplete combustion of fossil fuels, biofuels, and biomass.[16] Black carbon contributes to climate change in several ways: It warms the atmosphere directly by absorbing solar radiation and emitting it as heat. It contributes to melting by darkening the surfaces of ice and snow when it is deposited on them. It can also affect the microphysical properties of clouds in a manner than can perturb precipitation patterns. Estimates of black carbon's radiative forcing indicate that it may be the second or third leading cause of global warming after CO_2 and methane.[17]

The main sources of black carbon are open burning of biomass, diesel engines, and the residential burning of solid fuels such as coal, wood, dung, and agricultural residues.[18] In 2000 global emissions of black carbon were estimated at approximately 8.4 million tons.[19] Thanks to modern pollution controls and fuel switching, black carbon emissions in North America and Europe were significantly curbed in the early 1900s. However, mobile sources, particularly diesel vehicles, continue to be a major source category for these regions.[20] Black carbon sources in developing countries are significantly different from those in North America and Europe. In developing countries, a much larger proportion of black carbon emissions comes from residential heating and cooking, and industry.[21] According to UNEP, global emissions of black carbon are expected to remain relatively stable through 2030, with continuing reductions in North America and Europe largely offset by continued growth in other parts of the world.[22]

Tropospheric ozone and methane

Ozone is a reactive gas which, when in the stratosphere, absorbs dangerous ultraviolet radiation; however, lower atmosphere (tropospheric) ozone is a major air and climate pollutant which is harmful to human health and crop production.[23] Its impacts on plant include not only lower crop yields but also a reduced ability to absorb CO_2.

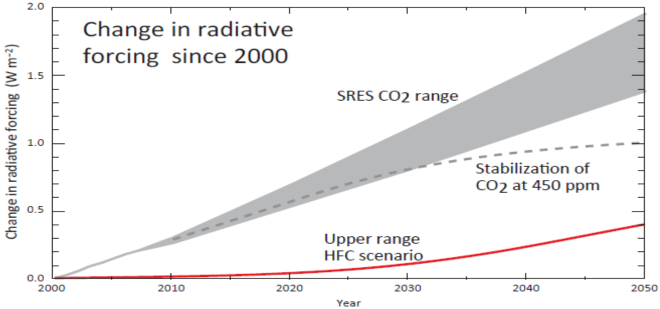
Tropospheric ozone is not emitted directly but instead forms from reactions between precursor gases, both human-produced and natural. These precursor gases include carbon monoxide, oxides of nitrogen (NOx), and volatile organic compounds (VOCs) which include methane. Globally increased methane emissions are responsible for approximately two-thirds of the rise in tropospheric ozone.[24] Reducing emissions of methane will lead to significant reductions in tropospheric ozone and its damaging effects.[25]

Methane is a powerful greenhouse gas with a 100-year global warming potential 21 times that of CO_2 and an atmospheric lifetime of approximately 12 years.[26] The main sources of anthropogenic methane emissions are oil and gas systems, enteric fermentation, landfills, manure management, wastewater treatment, rice cultivation, and emissions from coal mines. According to a recent UNEP assessment, anthropogenic methane emissions are expected to grow 25% over 2005 levels by 2030, driven by increased production from coal mining, oil and gas production, and growth in agricultural and municipal waste emissions.[27]

Hydrofluorocarbons (HFCs)

HFCs are factory-made chemicals used primarily in refrigeration and insulating foams. They have a warming effect hundreds to thousands of times more powerful than CO_2. The average lifetime of the mix of HFCs, weighted by usage, is 15 years.[28] HFCs are the fastest growing greenhouse gases in many countries, including the U.S., where emissions grew nearly 9% between 2009 and 2010 compared to 3.6% for CO_2.[29] Globally, HFC emissions are growing 10 to 15% per year and are expected to double by 2020. Without fast action to limit their growth, by 2050 the annual climate forcing of HFCs could equal nearly 20% of the forcing from CO_2 emissions in a BAU scenario, and up to 40% of the forcing from CO_2 emissions under a scenario where CO_2 concentrations have been limited to 450 parts per million (ppm) (*see* Fig. 1).[30] This is about the same as the forcing from present annual CO_2 emissions from the transportation sector.

Figure 1. HFCs projected to be up to 20-40% of RF of CO_2 in 2050



Projected radiative forcing of climate by HFCs and CO_2 since 2000, when the in.uence of HFCs was essentially zero. The HFC climate forcing for an upper range scenario is compared with the CO_2 forcing for the range of scenarios from IPCC-SRES and the 450 ppm CO_2 stabilization scenario. Clearly, the contribution of HFCs to radiative forcing could be very signi.cant in the future; by 2050, it could be as much as a quarter of that due to CO_2 increases since 2000, if the upper range HFC scenario is compared to the median of the SRES scenario. Alternatively, the contribution of HFCs to radiative forcing could be one-.fth the radiative forcing due to CO_2 increases since 2000, if the upper range HFC scenario is compared to the upper range of the SRES scenario. The contribution of HFCs to radiative forcing could also be as much as 40% of the radiative forcing by CO_2 under the 450 ppm scenario.[31]

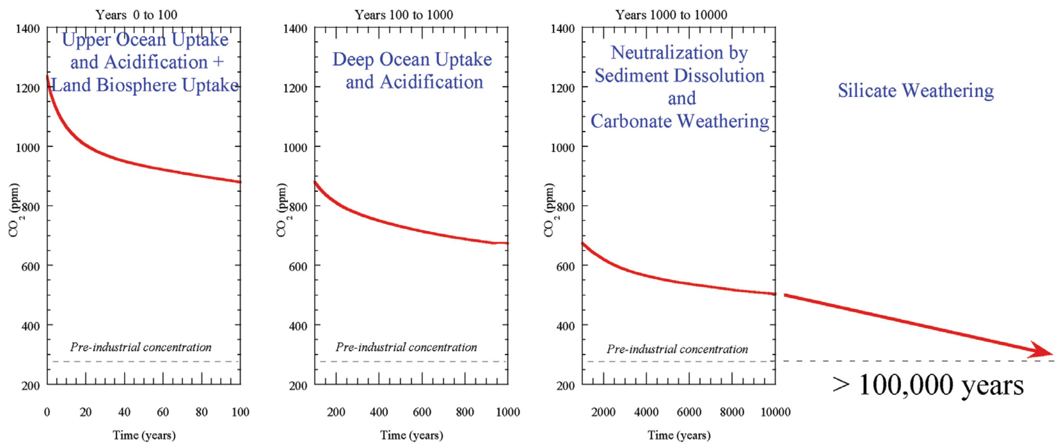
Both CO_2 mitigation and SLCP mitigation are critical for climate safety

Importance of immediate CO_2 mitigation

CO_2 is the single most significant climate forcer, accounting for 55-60% of present climate forcing. Substantial reductions in global CO_2 emissions are necessary to successfully combat long-term global warming, although they are less effective for limiting warming over the next 30 years.[32] Even after reductions in CO_2 emissions take place, resultant reductions in warming will be gradual, taking almost half a century.[33] For example, reducing CO_2 emissions to reach 450 ppm by 2100 is predicted to prevent approximately 0.15°C of business-as-usual warming in the first 30 years, but prevented warming will increase to 0.5°C fifty years after significant reductions begin (*see* Fig. 4).[34] This is due to the fact that while approximately 25% of emitted CO_2 leaves the atmosphere in the first 50 years, and 50% is drawn into the oceans and the biosphere within a century, a substantial portion of CO_2 emissions remains in the atmosphere for millennia (*see* Fig. 2).[35]

CO_2's long atmospheric lifetime combined with the thermal inertia of the ocean, which causes trapped heat to be released over long periods of time, means that if CO_2 emissions were to cease, more than 80% of the expected decrease in global mean temperatures would not be realized for hundreds of years.[36]

Figure 2. Time Scales for Removal of CO_2 from the Atmosphere



Model simulation of atmospheric CO_2 concentration for >100,000 years following a large CO_2 release from combustion of fossil fuels. Different fractions of the released gas recover on different timescales.[37]

In addition, building a new, cleaner energy infrastructure will require considerable energy from the present infrastructure. The very effort to put in place a sustainable energy system will likely require increased emissions over the short term. Therefore, the prevention of climate impacts from such an effort would likely be delayed for several decades.[38]

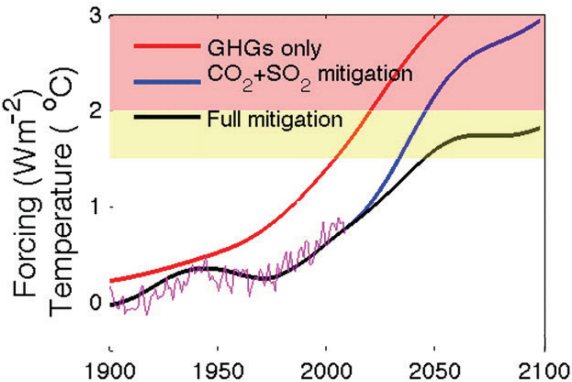
Importance of immediate SLCP mitigation

Cutting SLCPs is a critical climate strategy for reducing the near-term rate of global warming, particularly in regions most vulnerable to climate change, as well as for offsetting the near-term warming that will result from reductions of cooling aerosols such as sulfates, which are important to reduce to protect public health and ecosystems despite the warming this will cause.

SLCPs account for approximately 40-45% of present climate forcing.[39] In contrast to CO_2, the short atmospheric lifetimes of SLCPs means that reducing them will produce as much as 90% of predicted prevented warming within a decade. Reducing three of the non-CO_2 SLCPs—black carbon, tropospheric ozone, and methane—has the potential to avoid 0.5°C global warming by 2050[40] and 0.7°C in the Arctic by 2040,[41] which can cut the rate of global warming by half, the rate of Arctic warming by two-thirds, and can reduce warming in the high altitude Himalayan-Tibetan Plateau by at least half.[42] (During the past half century, the rate of global warming has been about 0.13°C per decade.[43] The rate of warming in the Arctic is currently at least twice the global average, and the rate in the Himalayas and Tibet is about three times the global average.[44]) Adding HFC reductions to these black carbon, tropospheric ozone and methane reductions can increase the reduction in the rate of global warming from 50% to about 60%.[45]

While the measured warming from climate pollutants is presently about 0.8°C above preindustrial levels, the total warming that is committed but yet not fully realized from historic emissions through 2005 is estimated to be 2.4 to 4.3°C.[46] Up to 1.15°C of this committed warming is currently being 'masked' by emissions of cooling aerosols, primarily sulfates, from fossil fuel and biomass combustion which are now being rapidly reduced to protect human health and ecosystems.[47] Un-masking this committed warming could push global temperatures over the 2°C guardrail by mid-century (*see* Fig. 3, blue line).[48] Reducing HFCs, black carbon, tropospheric ozone, and methane is essential for limiting this warming (*see* Fig. 3, black line).

Figure 3. Warming Avoided Through Combined SLCP and CO_2 Mitigation

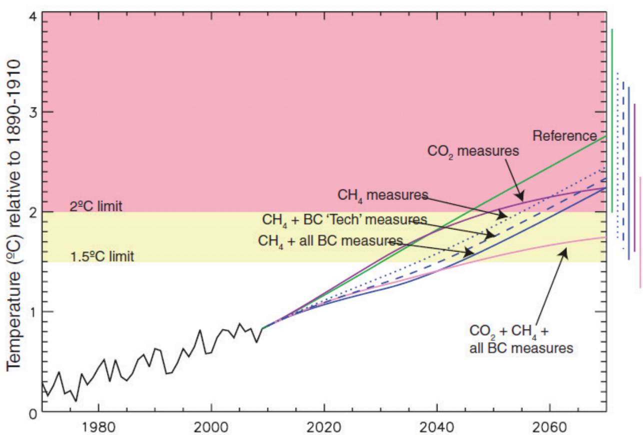


The red line depicts strong mitigation of CO_2 (peaking in 2015 and remaining at 2015 levels until 2100, reaching a concentration peak of 430 ppm by 2050), but no mitigation of non-CO_2 greenhouse gases, and does not account for forcing from aerosols or land use change; the blue line is the same as the red line except it includes warming and *cooling aerosol forcing and the mitigation of cooling sulfate aerosols; the black line is the same as the blue line except it includes mitigation of all SLCPs including HFCs; the pink and yellow backgrounds show zones beyond 2°C and 1.5°C.*[49]

Benefits of combined CO_2 and SLCP mitigation

CO_2 and SLCPs can be thought of as two separate control-knobs for temperature increase that operate independently and on different timescales.[50] Both must be turned down simultaneously and immediately as part of a comprehensive climate strategy to prevent possible near-term, abrupt climate change and long-term climate destabilization. The combination of CO_2 mitigation and SLCP mitigation provides the greatest chance of keeping global temperatures below 1.5°C for the next 30 to 40 years and provides the best chance to keep global temperatures below the 2°C guardrail through 2100.[51]

Figure 4. Temperature Rise Predictions Under Various Mitigation Scenarios



Observed temperatures through 2009 and projected temperatures thereafter under various scenarios, all relative to the 1890–1910 mean. Results for future scenarios are the central values from analytic equations estimating the response to forcings calculated from composition-climate modeling and literature assessments. The rightmost bars give 2070 ranges, including uncertainty in radiative forcing and climate sensitivity. A portion of the uncertainty is systematic, so that overlapping ranges do not mean there is no signi.cant difference.)[52] *(Note: HFC mitigation is not included in this graph, although it is included in Fig. 3, above.)*

Benefits for climate vulnerable regions

Global warming is expressed as a global average increase in surface temperature, but warming is experienced unevenly across different regions, with some of the world's most vulnerable regions warming much faster than the global average rate.[53] For example, Africa is warming about one and a half times faster than the average, and the Arctic and the Himalayan-Tibetan plateau are warming two to three times of the average global rate.[54] Therefore, it is particularly important that SLCP reductions may be able to rapidly reduce the rate of regional warming in places such as the Arctic, the high elevation regions of the Himalayas and Tibet, and other regions with vulnerable climates, including those where enhanced warming may trigger amplifying feedbacks and/or the passage of potential climate tipping points–the points at which a chain of events escalate such that it is impossible to return to former condition.

Warming in the Arctic and Himalayan-Tibetan plateau in particular could lead to dangerous climate feedbacks that cause warming to accelerate past tipping points. One example of such a feedback is the melting of Arctic snow and sea-ice, which reached a record low September 2012.[55] As the reflective ice and snow is replaced with darker heat-absorbing land and ocean, warming can amplify,[56] which in turn further reduces ice and snow cover, creating the dangerous feedback loop.[57]

Black carbon is estimated to be responsible for 50% of the increase in Arctic warming, or almost 1°C of the total 1.9°C increase between 1890 and 2007.[58] Approximately 50% of the warming on the Himalayan-Tibetan plateau has also been attributed to black carbon.[59] Cutting black carbon, tropospheric ozone and methane can cut the rate of warming in the Arctic by two-thirds and the rate of warming over the elevated regions of the Himalayan-Tibetan plateau by at least half.[60] Reducing these pollutants is essential, though not sufficient for saving the Arctic and other vulnerable places in the short term.[61]

Benefits for human health and food security

In addition to climate benefits, reducing SLCPs provides strong benefits for public health and food security. Cutting these local air pollutants can save up to 4.7 million lives each year, increase global crop yields by up to 135 million metric tons and repair the ability of plants to sequester carbon, a function now being impaired by tropospheric ozone.[62] According to one study, the deaths avoided from technically possible reductions in black carbon and methane would represent "*1-8% of cardiopulmonary and lung cancer deaths among those age 30 years and older, and 1-7% of all deaths for all ages.*"[63] Improvements in crop production are estimated to be up to 4% of total annual global production of the four major staple grains: maize, rice, soybeans, and wheat.[64]

Due to the heightened effects of black carbon and tropospheric ozone near emissions sources, these benefits, including much of the climate mitigation benefits, are enjoyed largely by the regions making the cuts. For example, eliminating emissions of black carbon from traditional solid biomass stoves with improved cook stoves would have a major impact in reducing black carbon direct climate effects over South Asia (by about 60%).[65]

Mitigation measures for short-lived climate pollutants

Black carbon and methane mitigation

Recent studies have identified fourteen mitigation measures targeting emissions of black carbon and methane that can provide immediate benefits.[66] These measures are capable of reducing global methane emissions by ~38% and emissions of black carbon by ~77%, realizing "nearly 90% of the maximum reduction in net GWP," from these sources.[67]

Methane Control Measures

- Control fugitive emissions from oil and gas production
- Control emissions from coal mining
- Control fugitive emissions from long distance gas transmission
- Capture gas from municipal waste and landfills
- Capture gas from wastewater treatment facilities
- Capture gas from livestock manure
- Intermittent aeration of constantly flooded rice paddies

Black Carbon Control Measures

- Install particulate filters on diesel vehicles
- Replace traditions cooking stoves with clean burning biomass stoves
- Modernize brick kilns
- Modernize coke ovens
- Ban open burning of biomass
- Eliminate high emitting on and off-road diesel vehicles
- Provide global access to modern cooking and heating

Most of the control measures for reducing black carbon, and for reducing tropospheric ozone by reducing one of its precursors, methane, can be implemented today with existing technologies, and often with existing laws and institutions, including through enhancement and enforcement of existing air quality regulations.[68]

Half of the identified black carbon and methane measures can be implemented with a net cost savings averaged globally.[69] Recent analysis indicates that approximately 64% of predicted reductions in methane from the identified measures can be achieved for less than $250 per metric ton, well below the estimated ~$1000 per metric ton value gained from climate mitigation, improved health outcomes, and crop production.[70] For black carbon, improved efficiencies from modernizing brick kilns and replacing traditional wood burning stoves can lead to a net cost savings, and together account for approximately half of possible black carbon reductions.[71] Recent research indicates that a large portion of the remaining black carbon mitigation measures will likely cost substantially less than the value of the health, climate, and crop benefits achieved (*see* Table 1).[72] All of these mitigation measures are ultimately cost effective when the $5.9 trillion annual benefits that start in 2030 are taken into account, which can be achieved by linearly phasing in the identified fourteen targeted control measures from 2010 through 2030 (*see* Table 1).[73]

Table 1. Valuation of Global Benefits from full implementation of 14 SLCP Measures [74]

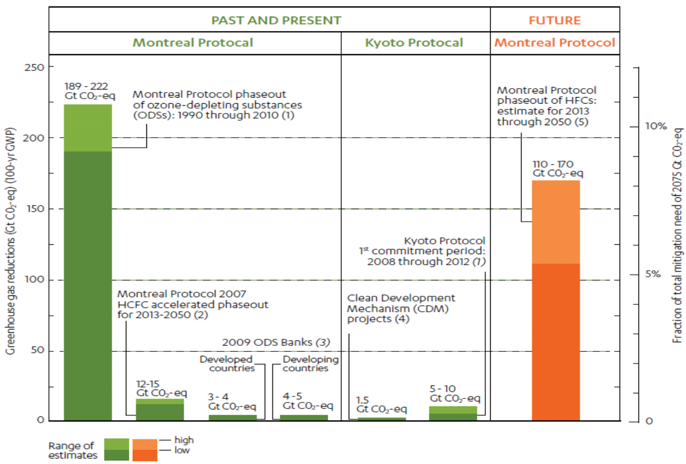
	Methane Measures	Black Carbon Measures	Total
Climate Benefit	*$331 (449 – 213)*	*$225 (343 – 13)*	*$556 (792 – 226)*
Crop Benefit	*$4.2 (5.4 – 3)*	*$4 (7.2 – 0.8)*	*$8.2 (12.6 – 3.8)*
Health Benefit	*$148 (247 – 49)*	*$5142 (9853 – 1564)*	*$5290 (10100 – 1613)*
Total	*$483.2 (701.4 – 265)*	*$5371 (10203.2 – 1577.8)*	*$5854.2 (10904.6 – 1845.2)*

HFC Mitigation

The mitigation approach for reducing HFCs is different from that for black carbon and methane. Because they are manmade, HFCs can be most effectively controlled through a phase-down of their production and consumption, which could take place under the Montreal Protocol. The successful phase-out of CFCs and the ongoing phase-out of HCFCs have made the Montreal Protocol the world's most effective climate treaty.[75] Between 1990 and 2010 the Montreal Protocol reduced CO_2-eq emissions nearly twenty times more than the initial commitment period of the Kyoto Protocol (*see* Fig. 5).[76]

There have been two proposals put forth to phase down high-GWP HFCs under the Montreal Protocol, one by the Federated States of Micronesia and the other by the North American countries, the U.S., Canada, and Mexico.[77] The proposals are similar, and each would reduce 85-90% of HFC production and use, providing climate mitigation equivalent to 100 billion tonnes of CO_2 emissions by 2050 (range of 87-146 billion tonnes) (*see* Fig. 6), at very low cost. The HFC amendments would substantially eliminate the global warming caused by one of the six Kyoto Protocol greenhouse gases by avoiding the production and use of high-GWP HFCs, providing up to 7% of the total CO_2-eq mitigation needed to have a 75% chance of staying below the 2˚C guardrail.[78]

Figure 5. Climate Protection of the Montreal Protocol and the Kyoto Protocol



UNEP, Climate Protection of the Montreal Protocol and the Kyoto Protocol (2012)[79]

HFCs are now the fastest growing GHG pollutant in the U.S. and in many other countries. This is due in part to their being used as replacements for HCFCs and in part to the growing global demand for air conditioning and refrigeration.[80] This demand is increasing as the world warms and as the population grows and gets richer. If left unchecked, by 2050 warming from annual emissions of HFCs could be equivalent to 20% of warming from annual CO_2 emissions under a BAU scenario, and up to 45% of the warming from annual CO_2 emissions under a 450 ppm CO_2 stabilization scenario.[81]

Many national governments have taken action to reduce HFCs. Such action includes: creating national databases of equipment containing HFCs in Hungary, Slovenia, and Estonia; mandatory refrigerant leakage checks for mobile equipment in Germany, Sweden, and the Netherlands; and producer responsibility schemes requiring producers and suppliers of HFCs to take back recovered bulk HFCs for further recycling, reclamation and destruction in Sweden and Germany.[82] California is reducing HFC use in mobile air conditioning systems through its Low Emission Vehicle (LEV III) regulation by requiring that all passenger cars, light duty trucks, and medium-duty passenger vehicles use refrigerants with a global warming potential less than or equal to 150, as of model year 2017.[83] The U.S. allows manufacturers of cars and light-trucks to generate credits towards their compliance with CO_2 emission standards and fuel economy CAFE standards by employing HFC alternative refrigerants in mobile air conditioning systems for model year 2012-2016 vehicles.[84] According to the new rules for model years 2017-2025, U.S. CAFE standards continue to provide HFC alternative credits and include credits for improvements in mobile air conditioner efficiency.[85]

Private companies are also taking voluntary action to limit HFCs. The Consumer Good Forum, a global network of over 650 retailers, manufactures, service providers, and other stakeholders from over seventy countries has pledged to begin pashing-out HFCs in new equipment beginning in 2015.[86]

Because the global weighted average lifetime of HFCs now in use is 15 years, HFCs are included in the CCAC.[87] In the Rio +20 declaration, *The Future We Want*, more than one hundred heads of State recognized the climate damage from HFCs and called for the gradual phase-down of their production and consumption.[88] In addition, 108 countries have joined the *Bangkok Declaration* calling for the use of low-GWP alternatives to CFCs and HCFCs.[89]

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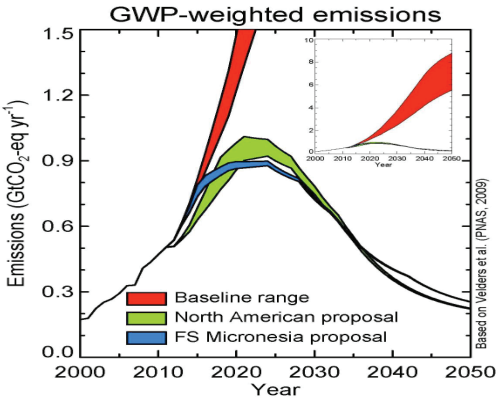
Figure 6. Projected HFC emission reductions from FSM and NA proposals



The North American proposal and the Micronesian proposal are similar; both decrease the cumulative (2013-2050) direct GWP-weighted emissions of HFCs to 22-24 $GtCO_2$-eq from 110-170 $GtCO_2$-eq, for a total of ~87 to 146 $GtCO_2$-eq in mitigation. This is equivalent to a reduction from projected annual emissions of 5.5 to 8.8 $GtCO_2$-eq/yr in 2050 to less than ~0.3 $GtCO_2$-eq/yr.[92]

Climate and Clean Air Coalition to Reduce SLCPs

The Climate and Clean Air Coalition to Reduce Short-Lived Climate Pollutants (CCAC) was launched in February, and now includes 20 state partners: Australia, Bangladesh, Canada, Colombia, Denmark, European Commission, Finland, France, Germany, Ghana, Israel, Italy, Japan, Jordan, Mexico, Nigeria, Norway, Sweden, the U.K., and the U.S.; and 16 non-state partners, the World Bank, UNEP, UNDP, Clean Air Task Force, ClimateWorks Foundation, International Council on Clean

Transportation, International Cryosphere Climate Initiative, Institute for Governance and Sustainable Development (IGSD), the Stockholm Environment Institute, Global Alliance for Clean Cookstoves, Clean Air Initiative for Asian Cities, Earthjustice, International Union of Air Pollution Prevention and Environmental Protection Associations, Bellona Foundation, Environmental Defense Fund and the Molina Center for Strategic Studies in Energy and the Envrionment.[93] IGSD was elected to be the initial NGO representative on the Coalition's Steering Committee. UNEP is representing the Inter-Governmental Organizations.

In conjunction with the Rio+20 summit in June, the Coalition and the World Bank joined New York City Mayor Michael R. Bloomberg, Chair of the C40 Cities Climate Leadership Group, former U.S. President Bill Clinton, and Rio de Janeiro Mayor Eduardo Paes to announce the launch of the *Solid Waste Network* to help cities reduce methane emissions through solid waste management.[94]

The CCAC is the first-ever global effort specifically dedicated to reducing emissions of SLCPs as a collective challenge. The CCAC seeks to reduce SLCPs by supporting and coordinating existing programs such as the Clean Cookstove Initiative and the Global Methane Initiative, while "driving development of national action plans and the adoption of policy priorities; building capacity among developing countries; mobilizing public and private action; raising awareness globally; fostering regional and international cooperation, and; improving scientific understanding of the pollutant impacts and mitigation."[95]

Five targeted initiatives have been approved by the CCAC for rapid implementation:[96]

- Reducing black carbon emissions from heavy duty diesel vehicles and engines;
- Mitigating black carbon and other pollutants from brick production;

- Mitigating short-lived climate pollutants from the municipal solid waste sector;
- Promoting HFC alternative technologies and standards; and
- Accelerating methane reductions from oil and natural gas production.

The Coalition is developing additional proposals including one addressing open burning of biomass by Ghana and another on cookstoves from Bangladesh.

The CCAC Secretariat is hosted by UNEP's Paris office, and will manage a dedicated Trust Fund, with an initial contribution of $16.7 million from the U.S., Canada, Sweden, and Norway.[97] The World Bank indicated that it has $12 billion of its portfolio contributing to the CCAC's goals.[98] Also, the G8 leaders commissioned the World Bank to prepare a report on ways to integrate reductions of SLCPs into their activities and to assess funding options for methane reductions.[99]

Other regional and global SLCP mitigation initiatives

In addition to the CCAC there are a number of other global and regional initiatives that target SLCPs. For example, the Executive Body of the Long-Range Transboundary Air Pollution (CLRTAP) recently approved an amendment to the Gothenburg Protocol adopting new PM requirements and including specific language on black carbon, making it the first international treaty to act on the link between air pollution and climate change.[100] The Arctic Council is addressing SLCPs through its Task Force on Short-Lived Climate Forcers.[101] The Global Alliance for Clean Cookstoves and the Global Methane Initiative are both specifically targeting some of the largest global sources of black carbon and methane emissions.[102] UNEP's Atmospheric Brown

Cloud program is also addressing black carbon and tropospheric ozone, with a focus on Asia and plans to expand to Latin America and Africa.[103] Finally, the International Maritime Organization (IMO) is currently considering whether to control black carbon emissions from ships.[104]

Conclusion

Reducing SLCPs will reduce near-term climate impacts, slow dangerous feedbacks, allow more time to adapt, and reduce the risk of passing tipping points that could lead to irreversible climate damage. In addition to providing near-term climate benefits, cutting SLCPs would also provide major benefits for human health and food security and would contribute to sustainable development goals. Cutting SLCPs to achieve near-term climate benefits is an important complement to reducing CO_2 emissions, but SLCP reductions are not a substitute for the immediate action urgently needed to reduce CO_2. Reducing both CO_2 and SLCPs provides the best chance of limiting global temperature rise to below 2°C through 2100. As highlighted by Nobel Laureate Mario Molina and co-authors, regulatory measures in dedicated venues are often the preferred way to reduce SLCPs.[105]

Endnotes

[1] Forster P. *et al.* (2007) Changes in Atmospheric Constituents and in Radiative Forcing, in Climate Change 2007: The Physical Science Basis, at Figure 2.21, *available at* http://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-chapter2.pdf

[2] Forster P. *et al.* (2007), Changes in Atmospheric Constituents and in Radiative Forcing, in Climate Change 2007: The Physical Science Basis, at Figure 2.21, *available at* http://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-chapter2.pdf.

[3] The science of SLCPs dates back to the 1970s (Ramanathan V. (1975) Greenhouse effect due to chlorofluorocarbons: climatic implications, *Sci.* 190:50, *available at* http://www.jstor.org/discover/10.2307/1740877?uid=3739584&uid=2&uid=4&uid=3739256&sid=21101110887503; Wang et al. (1976) Greenhouse effects due to man-made perturbations of trace gases, *Sci.* 194:685), *available at* http://pubs.giss.nasa.gov/docs/1976/1976_Wang_etal.pdf. A major WMO-UNEP-NASA-NOAA report in 1985 concluded that non-CO_2 greenhouse gases in the atmosphere are adding to the greenhouse effect by an amount comparable to the effect of CO_2.(Ramanathan *et al.* (1985) Trace gas trends and their potential role in climate change, *J. Geophys Res.* 90:5547, *available at* http://ramanathan.ucsd.edu/files/pr35.pdf.) This finding has been confirmed and strengthened in the following decades by hundreds of studies culminating in IPCC reports (IPCC (1990) Overview Chapter, in IPCC First Assessment Report 1990, *available at* http://www.ipcc.ch/ipccreports/1992%20IPCC%20Supplement/IPCC_1990_and_1992_Assessments/English/ipcc_90_92_assessments_far_overview.pdf; IPCC (1995) IPCC Second Assessment Report: Climate Change 1995, *available at* http://www.ipcc.ch/pdf/climate-changes-1995/ipcc-2nd-assessment/2nd-ass essment-en.pdf; IPCC (2001) IPCC Third Assessment Report: Climate Change 2001, *available at* http://www.grida.no/publications/other/ipcc_tar/; *and* IPCC

(2007) Climate Change 2007: Synthesis Report, *available at* http://www.ipcc.ch/publications_and_data/ar4/syr/en/contents.html.) In short, researchers have had at least 25 years to carefully develop the science of SLCPs and assess the findings.

[4] Ramanathan V. & Xu Y. (2010) The Copenhagen Accord for limiting global warming: Criteria, constraints, and available avenues, *Proc. Nat'l Acad. Sci. USA* 107:8055, 8056, *available at* http://www.pnas.org/content/107/18/8055.full ("CO_2 (1.65 Wm^{-2}) and the non-CO_2 GHGs (1.35 Wm^{-2}) have added 3 (range: 2.6–3.5) Wm^{-2} of radiant energy since preindustrial times.…. The 3-Wm^{-2} energy should have led to a warming of 2.4 °C (14). The observed warming trend (as of 2005) is only about 0.75 °C (15), or 30% of the expected warming. Observations of trends in ocean heat capacity (16) as well as coupled ocean–atmosphere models suggest that about 20% (0.5 °C warming) is still stored in the oceans (17). The rest of the 50% involves aerosols or particles added by air pollution.")

[5] Shindell D. *et al.* (2012) Simultaneously mitigating near-term climate change and improving human health and food security, *Sci.* 335:183, 183, *available at* http://www.sciencemag.org/content/335/6065/183 ("We identified 14 measures targeting methane and BC emissions that reduce projected global mean warming ~0.5°C by 2050.").

[6] UNEP/WMO (2011) Integrated Assessment of Black Carbon and Tropospheric Ozone, *available at* http://www.unep.org/dewa/Portals/67/pdf/BlackCarbon_report.pdf, at Table 5.2.

[7] During the past half century, the rate of global warming has been about 0.13°C per decade. IPCC (2007) Technical Summary, in Climate Change 2007: The Physical Science Basis, 36, *available at* http://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-ts.pdf. The rate of warming in the Arctic is currently at least twice the global average and in the Himalayas and Tibet three times the average. Arctic Monitoring and Assessment Programme (2011) Snow, Water, Ice and Permafrost in the Arctic, Executive Summary and Key Message, 4, *available at* https://www.documentcloud.org/documents/88367-arctic-ice-melt-2011-executivesummary.html; *and* Arctic Monitoring and Assessment Programme (2011) Snow, Water, Ice and Permafrost in the Arctic, Executive Summary and Key Message, 4, *available at* https://

www.documentcloud.org/documents/88367-arctic-ice-melt-2011-executivesummary.html. Average global surface temperatures have increased by 0.8°C, over the 1880–1920 average, and under business-as-usual it could increase by an additional 2°C by 2070. Hansen J. *et al*. (2010) Global surface temperature change, *Rev. Geophys*. 48:4004, *available at* http://pubs.giss.nasa.gov/docs/2010/2010_Hansen_etal.pdf; IPCC (2007) Technical Summary, in Climate Change 2007: The Physical Science Basis, 36, *available at* http://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-ts.pdf; *and* UNEP/WMO (2011) Integrated Assessment of Black Carbon and Tropospheric Ozone, *available at* http://www.unep.org/dewa/Portals/67/pdf/BlackCarbon_report.pdf.

[8] Schneider, S.H., *et al.*, 2007: Assessing key vulnerabilities and the risk from climate change, in Climate Change 2007: Impacts, Adaptation and Vulnerability. 779-810 *available at* http://www.ipcc.ch/publications_and_data/ar4/wg2/en/ch19.html; and IPCC (2012): Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change, *available at* http://www.ipcc-wg2.gov/SREX/images/uploads/SREX-All_FINAL.pdf.

[9] Climate and Clean Air Coalition to Reduce Short Lived Climate Pollutants, http://www.unep.org/ccac/ (last visited 2 October 2012).

[10] United Nations (2012) Resolution adopted by the General Assembly: The future we want, A/RES/66/288, *available at* http://daccess-dds-ny.un.org/doc/UNDOC/GEN/N11/476/10/PDF/N1147610.pdf?OpenElement.

[11] Proposed Amendment to the Montreal Protocol (submitted by the Federated States of Micronesia), (11 May 2012) *available at* http://conf.montreal-protocol.org/meeting/oewg/oewg-32/presession/PreSession%20Documents/OEWG-32-5E.pdf. *See also* Proposed Amendment to the Montreal Protocol (submitted by the United States, Canada, and Mexico), (9 May 2012) *available at* http://conf.montreal-protocol.org/meeting/oewg/oewg-32/presession/PreSession%20Documents/OEWG-32-5E.pdf.

[12] UNEP (2010) Declaration on the global transition away from hydrochlorofluorocarbons (HCFCs) and clholrofluorocarbons (CFCs), *available at* http://ozone.unep.org/new_site/en/Treaties/treaties_decisions-hb.php?nav_id=2030. *See also* UNEP (2011) Report of the

combined ninth meeting of the Conference of the Parties to the Vienna Convention on the Protection of the Ozone Layer and the Twenty-Third Meeting of the Parties to the Montreal Protocol on Substances that Deplete the Ozone Layer, *available at* http://conf.montreal-protocol.org/meeting/mop23-cop9/draft-reports/default.aspx.

[13] *See* Solomon S. *et al.* (2011) Climate Stabilization Targets: Emissions, Concentrations, and Impacts over Decades to Millennia, National Research Council, *available at* http://www.nap.edu/catalog.php?record_id=12877.

[14] *See* United Nations Environment Programme & World Meteorological Organization (herein after UNEP/WMO) (2011) Integrated Assessment of Black Carbon and Tropospheric Ozone, 6, *available at* http://www.unep.org/dewa/Portals/67/pdf/BlackCarbon_report.pdf ("In the case of an SLCF this means that, when its concentration and hence its radiative forcing is reduced by emission controls, the global mean temperature will achieve most of its decrease towards a new equilibrium value in about a decade. About 10 per cent of the full decrease will not be realized for hundreds of years, since the redistribution of heat stored in the deep ocean while the SLCF was active, and hence its upwards transport, will continue for hundreds of years …. In the case of CO_2, more than 80 per cent of the expected decrease in global mean temperature after emission reductions will not be realized for hundreds of years. This is because the drawing down of atmospheric CO_2 into the deep ocean, and hence the decrease in its radiative forcing, is roughly offset by the upward transport of heat to the surface, since both phenomena are achieved by the same physics of deep-ocean mixing….") *citing* Solomon S. *et al.* (2010) Persistence of climate changes due to a range of greenhouse gases, *Proc. Natl. Acad. Sci. USA* 107:18354, *available at* http://www.pnas.org/content/early/2009/01/28/0812721106.full.pdf+html ("Fig. 2 illustrates the factors influencing the warming contributions of each gas for the test case in Fig. 1 in more detail, by showing normalized values (relative to one at their peaks) of the warming along with the radiative forcings and concentrations of CO_2, N_2O, and CH_4. For example, about two-thirds of the calculated warming due to N_2O is still present 114 y (one atmospheric lifetime) after emissions are halted, despite the fact that its excess concentration and associated radiative forcing at that time has dropped to about one-third of the peak value. Two factors contribute

to the differences between decreases in concentrations of greenhouse gases and persistence of the resulting warming, discussed further below: (i) Radiative forcing may not simply follow concentration because of optical depth effects (for CO_2 and CH_4), and (ii) warming may not match decreases in radiative forcing because of climate inertia, particularly due to the ocean."); *and* Matthews D & Weaver J. (2010) Committed climate warming, *Nat. Geosci.* 3:142, *available at* http://www.nature.com/ngeo/journal/v3/n3/full/ngeo813.html.

[15] U.S. Envtl. Prot. Agency (2012) Report to Congress on Black Carbon, *available at* http://www.epa.gov/airquality/blackcarbon/2012report/fullreport.pdf; UNEP/WMO (2011) Integrated Assessment of Black Carbon and Tropospheric Ozone, *available at* http://www.unep.org/dewa/Portals/67/pdf/BlackCarbon_report.pdf.

[16] U.S. Envtl. Prot. Agency (2012) Report to Congress on Black Carbon, *available at* http://www.epa.gov/airquality/blackcarbon/2012report/fullreport.pdf.

[17] U.S. Envtl. Prot. Agency (2012) Report to Congress on Black Carbon, 4, 18, *available at* http://www.epa.gov/airquality/blackcarbon/2012report/fullreport.pdf ("The sum of the direct and snow/ice albedo effects of BC on the global scale is likely comparable to or larger than the forcing effect from methane, but less than the effect of carbon dioxide; however, there is more uncertainty in the forcing estimates for BC…. There is significant controversy regarding the use of metrics for direct comparisons between the long-lived GHGs and the short-lived particles for policy purposes; however, these comparisons are less controversial when used for illustrative purposes.").

[18] U.S. Envtl. Prot. Agency (2012) Report to Congress on Black Carbon, *available at* http://www.epa.gov/airquality/blackcarbon/2012report/fullreport.pdf.

[19] U.S. Envtl. Prot. Agency (2012) Report to Congress on Black Carbon, *available at* http://www.epa.gov/airquality/blackcarbon/2012report/fullreport.pdf.

[20] U.S. Envtl. Prot. Agency (2012) Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 – 2010, *available at* http://www.epa.gov/climatechange/emissions/downloads11/US-GHG-Inventory-2011-Complete_Report.pdf.

[21] U.S. Envtl Prot. Agency (2012) Report to Congress on Black Carbon, *available at* http://www.epa.gov/airquality/blackcarbon/2012report/fullreport.pdf.

[22] UNEP/WMO (2011) Integrated Assessment of Black Carbon and Tropospheric Ozone, *available at* http://www.unep.org/dewa/Portals/67/pdf/BlackCarbon_report.pdf.

[23] UNEP/WMO (2011) Integrated Assessment of Black Carbon and Tropospheric Ozone, *available at* http://www.unep.org/dewa/Portals/67/pdf/BlackCarbon_report.pdf.

[24] Reducing other ozone precursors can have varying effects on the climate, for example cutting non-methane VOCs can provide some additional cooling but reducing NOx is predicted to produce warming due to its importance for removing methane from the atmosphere. UNEP/WMO (2011) Integrated Assessment of Black Carbon and Tropospheric Ozone, 57, *available at* http://www.unep.org/dewa/Portals/67/pdf/BlackCarbon_report.pdf ("Two-thirds of the O_3 radiative forcing to date may be attributed to the increase in atmospheric CH_4 over the last century, and hence CH_4 emissions are responsible for a large part of the increase.").

[25] UNEP/WMO (2011) Integrated Assessment of Black Carbon and Tropospheric Ozone, *available at* http://www.unep.org/dewa/Portals/67/pdf/BlackCarbon_report.pdf.

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

[27] UNEP/WMO (2011) Integrated Assessment of Black Carbon and Tropospheric Ozone, 12, *available at* http://www.unep.org/dewa/Portals/67/pdf/BlackCarbon_report.pdf ("Without implementation of measures beyond current and planned regulations, methane (CH_4) emissions are expected to increase in the future. Increased coal mining and oil and gas production, coupled with growth in agricultural activities and municipal waste generation, are likely to lead to more than 25 per cent higher global athropogenic CH_4 emissions by 2030 relative to 2005. The projected increase in fossil fuel production is the main driving force behind this growth.").

[28] UNEP (2011) HFCs: A Critical Link in Protecting Climate and the Ozone Layer, *available at* http://www.unep.org/dewa/Portals/67/pdf/HFC_report.pdf.

[29] U.S. Envtl. Prot. Agency (2012) Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 – 2010, *available at* http://www.epa.gov/climatechange/emissions/downloads11/US-GHG-Inventory-2011-Complete_Report.pdf.

[30] UNEP (2011) HFCs: A Critical Link in Protecting Climate and the Ozone Layer, 11, *available at* http://www.unep.org/dewa/Portals/67/pdf/HFC_report.pdf.

[31] UNEP (2011) HFCs: A Critical Link in Protecting Climate and the Ozone Layer, *available at* http://www.unep.org/dewa/Portals/67/pdf/HFC_report.pdf.

[32] Archer D. *et al.* (2005) Fate of fossil fuel CO_2 in geologic time, *J. of Geophys. Res.* 110:C09S05, *available at* http://www.agu.org/pubs/crossref/2005/2004JC002625.shtml ("[W]hile approximately half of the carbon emitted is removed by the natural carbon cycle within a century, a substantial fraction of anthropogenic CO_2 will persist in the atmosphere for several millennia."). *See also* UNEP/WMO (2011) Integrated Assessment of Black Carbon and Tropospheric Ozone, 241, *available at* http://www.unep.org/dewa/Portals/67/pdf/BlackCarbon_report.pdf. ("For example, mitigation of 0.15°C due to CO_2 measures takes place only around 2050 (Figure 6.1) under the CO_2 measures scenario; 30 years after emissions begin to decline rapidly.")

[33] Myhrvold N. P. & Caldeira K. (2012) Greenhouse gases, climate change and the transition from coal to low-carbon electricity, *Environ. Res. Let.* 7:014019, *available at* http://iopscience.iop.org/1748-9326/7/1/014019, at 4-5 ("Conservation is thus equivalent to phasing out 1 TWe of coal power over 40 yr without any replacement technology. Even in this case, GHGs (particularly CO_2) emitted by coal during the phaseout linger in the atmosphere for many years; in addition, ocean thermal inertia causes temperature changes to lag radiative forcing changes. Consequently, conservation takes 20 yr to achieve a 25% reduction in HGE [high-GHG-emission scenario] warming and 40 yr to achieve a 50% reduction…. Natural gas plants emit about half the GHGs emitted by coal plants of the same capacity, yet a transition to natural gas would require a century or longer to attain even a 25% reduction in HGE warming…. Carbon capture and storage (CCS) also slows HGE warming only very gradually. Although CCS systems are estimated to have raw GHG emissions of 17%–27% that of unmodified coal plants,

replacement of a fleet of conventional coal plants by coal-fired CCS plants reduces HGE warming by 25% only after 26–110 yr.”).

[34]UNEP/WMO (2011) Integrated Assessment of Black Carbon and Tropospheric Ozone, 241, *available at* http://www.unep.org/dewa/Portals/67/pdf/BlackCarbon_report.pdf (“For example, mitigation of 0.15°C due to CO_2 measures takes place only around 2050 (Figure 6.1) under the CO_2 measures scenario; 30 years after emissions begin to decline rapidly. The influence of the CO_2 reductions grows rapidly, however, so that they mitigate roughly 0.5°C by 2070. Hence a delay of 20 years in implementation of those CO_2 reductions would mean that only ~0.15°C of warming mitigation relative to the reference scenario would be achieved within the 2070 timeframe examined here. Thus delayed CO_2 measures plus all the near-term measures examined here would lead to warming of about 2.1°C in 2070 rather than the 1.75°C shown in Figure 6.1. Conversely, a delay in reducing emissions of short-lived species would have a large impact on near-term warming rates, but little effect on 2070 temperatures (see Figure 5.12).”)

[35] Solomon S. *et al.* (2011) Climate Stabilization Targets: Emissions, Concentrations, and Impacts over Decades to Millennia, National Research Council, *available at* http://www.nap.edu/catalog.php?record_id=12877.

[36] UNEP/WMO (2011) Integrated Assessment of Black Carbon and Tropospheric Ozone, 6, *available at* http://www.unep.org/dewa/Portals/67/pdf/BlackCarbon_report.pdf (“In the case of an SLCF this means that, when its concentration and hence its radiative forcing is reduced by emission controls, the global mean temperature will achieve most of its decrease towards a new equilibrium value in about a decade. About 10 per cent of the full decrease will not be realized for hundreds of years, since the redistribution of heat stored in the deep ocean while the SLCF was active, and hence its upwards transport, will continue for hundreds of years …. In the case of CO_2, more than 80 per cent of the expected decrease in global mean temperature after emission reductions will not be realized for hundreds of years. This is because the drawing down of atmospheric CO_2 into the deep ocean, and hence the decrease in its radiative forcing, is roughly offset by the upward transport of heat to the surface, since both phenomena are achieved by the same physics of deep-ocean mixing….”) *citing* Solomon S. *et al.* (2009) Irreversible

climate change due to carbon dioxide emissions*, Proc. Natl. Acad. Sci. USA* 106:1704, 1704, *available at* http://www.pnas.org/content/early/2009/01/28/0812721106.full.pdf+html ("[C]limate change that takes place due to increases in carbon dioxide concentration is largely irreversible for 1,000 years after emissions stop. Following cessation of emissions, removal of atmospheric carbon dioxide decreases radiative forcing, but is largely compensated by slower loss of heat to the ocean, so that atmospheric temperatures do not drop significantly for at least 1,000 years."); *and* Matthews D & Weaver J. (2010) Committed climate warming, *Nat. Geosci.* 3:142, *available at* http://www.nature.com/ngeo/journal/v3/n3/full/ngeo813.html.

[37] Solomon S. *et al.* (2011) Climate Stabilization Targets: Emissions, Concentrations, and Impacts over Decades to Millennia, National Research Council, *available at* http://www.nap.edu/catalog.php?record_id=12877.

[38] Myhrvold N. P. & Caldeira K. (2012) Greenhouse gases, climate change and the transition from coal to low-carbon electricity, *Environ. Res. Let.* 7:014019, *available at* http://iopscience.iop.org/1748-9326/7/1/014019, at 1 ("The use of current infrastructure to build this new low-emission system necessitates additional emissions of greenhouse gases, and the coal-based infrastructure will continue to emit substantial amounts of greenhouse gases as it is phased out. Furthermore, ocean thermal inertia delays the climate benefits of emissions reductions.... We show that rapid deployment of low-emission energy systems can do little to diminish the climate impacts in the first half of this century*.")*.

[39] UNEP/WMO (2011) Integrated Assessment of Black Carbon and Tropospheric Ozone, 6, 159, *available at* http://www.unep.org/dewa/Portals/67/pdf/BlackCarbon_report.pdf ("In the case of an SLCF this means that, when its concentration and hence its radiative forcing is reduced by emission controls, the global mean temperature will achieve most of its decrease towards a new equilibrium value in about a decade. About 10 per cent of the full decrease will not be realized for hundreds of years, since the redistribution of heat stored in the deep ocean while the SLCF was active, and hence its upwards transport, will continue for hundreds of years…. Over the longer term, from 2070 onwards, there is still a reduction in warming in the early measures case, but the

value becomes quite small. This reinforces the conclusions drawn from previous analyses that reducing emissions of O_3 precursors and BC can have substantial benefits in the near term, but that long-term climate change is much more dependent on emissions of long-lived GHGs such as CO_2.")

[40] Shindell D. *et al.* (2012) Simultaneously mitigating near-term climate change and improving human health and food security, *Sci.* 335:183, 183, *available at* http://www.sciencemag.org/content/335/6065/183. ("We identified 14 measures targeting methane and BC emissions that reduce projected global mean warming ~0.5°C by 2050.").

[41] UNEP/WMO (2011) Integrated Assessment of Black Carbon and Tropospheric Ozone, 246, *available at* http://www.unep.org/dewa/Portals/67/pdf/BlackCarbon_report.pdf ("The 16 measures examined here, including the measures on pellet stoves and coal briquettes, reduce warming in the Arctic by 0.7°C (range 0.2 to 1.3°C) at 2040. This is a large portion of the 1.1°C (range 0.7 to 1.7°C) warming projected under the reference scenario for the Arctic…")

[42] Shindell D. *et al.* (2012) Simultaneously mitigating near-term climate change and improving human health and food security, *Sci.* 335:183, 183, 185, *available at* http://www.sciencemag.org/content/335/6065/183 ("We identified 14 measures targeting methane and BC emissions that reduce projected global mean warming ~0.5°C by 2050. *** BC albedo and direct forcings are large in the Himalayas, where there is an especially pronounced response in the Karakoram, and in the Arctic, where the measures reduce projected warming over the next three decades by approximately two thirds and where regional temperature response patterns correspond fairly closely to albedo forcing…"). *See also* UNEP/WMO (2011) Integrated Assessment of Black Carbon and Tropospheric Ozone: Summary for Decisions Makers, 3, *available at* http://www.unep.org/dewa/Portals/67/pdf/BlackCarbon_SDM.pdf ("If the measures were to be implemented by 2030, they could halve the potential increase in global temperature projected for 2050 compared to the Assessment's reference scenario based on current policies and energy and fuel projections. *** This could reduce warming in the Arctic in the next 30 years by about two-thirds compared to the projections of the Assessment's reference scenario").

[43] IPCC (2007) Technical Summary, in Climate Change 2007: The Physical Science Basis, 36, *available at* http://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-ts.pdf ("The rate of warming averaged over the last 50 years (0.13°C ± 0.03°C per decade) is nearly twice that for the last 100 years.")

[44] Arctic Monitoring and Assessment Programme (2011) Snow, Water, Ice and Permafrost in the Arctic, Executive Summary and Key Message, 4, *available at* https://www.documentcloud.org/documents/88367-arctic-ice-melt-2011-execu tivesummary.html ("The increase in annual average temperature since 1980 has been twice as high over the Arctic as it has been over the rest of the world."); Qiu J. (2008) China: The third pole, *Nature* 454:393, 393, *available at* http://www.nature.com/news/2008/080723/full/454393a.html ("The proximate cause of the changes now being felt on the [Tibetan] plateau is a rise in temperature of up to 0.3 °C a decade that has been going on for fifty years — approximately three times the global warming rate.").

[45] Institute for Advanced Sustainability Studies (2012) Short Lived Climate Forcers: Pathways to Action – Workshop Summary, *available at* http://igsd.org/climate/documents/SLCP_Workshop_March_2012_summary.pdf ("… inclusion of HFCs mitigation would further reduce the warming by another 20% (about 0.1°C), thus increasing the total reduction of warming between now and 2050 to about 0.6°C" (citing Ramanathan V. & Xu Y. (2010)). *See also* Ramanathan V & Xu Y. (2010) The Copenhagen Accord for limiting global warming: Criteria, constraints, and available avenues, *Proc. Nat'l Acad. Sci. USA* 107:8055, 8055, *available at* http://www.pnas.org/content/107/18/8055.full ("These actions [to reduce emissions of SLCPs including HFCs, methane, black carbon, and ground-level ozone], even if we are restricted to available technologies … can reduce the probability of exceeding the 2°C barrier before 2050 to less than 10% and before 2100 to less than 50% [when CO_2 concentrations are stabilized below 441 ppm during this century]").

[46] Ramanathan V. & Feng Y. (2008) On Avoiding Dangerous Anthropogenic Interference with the Climate System: Formidable Challenges Ahead, *Proc. Nat'l Acad. Sci. USA* 105:14245, *available at* http://www.pnas.org/content/early/2008/09/16/0803838105.full.pdf+html. *See also* Schellnhuber H.J. (2008) Global Warming: Stop Worrying, Start Panicking?, *Proc. Nat'l Acad. Sci. USA* 105:14239,

available at http://www.pnas.org/content/105/38/14239.full.pdf+html.

[47] Ramanathan V. & Xu Y. (2010) The Copenhagen Accord for limiting global warming: Criteria, constraints, and available avenues, *Proc. Nat'l Acad. Sci. USA* 107:8055, at Fig. 1D, *available at* http://www.pnas.org/content/107/18/8055.full.

[48] Ramanathan V. & Xu Y. (2010) The Copenhagen Accord for limiting global warming: Criteria, constraints, and available avenues, *Proc. Nat'l Acad. Sci. USA* 107:8055, at Fig. 1D, *available at* http://www.pnas.org/content/107/18/8055.full.

[49] Ramanathan V. & Xu Y. (2010) The Copenhagen Accord for limiting global warming: Criteria, constraints, and available avenues, *Proc. Nat'l Acad. Sci. USA* 107:8055, at Fig. 1D, *available at* http://www.pnas.org/content/107/18/8055.full.

[50] National Research Council of the National Academies (2011) Climate Stabilization Targets: Emissions, Concentrations, and Impacts over Decades to Millennia 3, *available at* http://books.nap.edu/openbook.php?record_id=12877&page=R1. *See also* UNEP/WMO (2011) Integrated Assessment of Black Carbon and Tropospheric Ozone: Summary for Decisions Makers, *available at* http://www.unep.org/dewa/Portals/67/pdf/BlackCarbon_SDM.pdf; *and* United Nations Environment Program (2011) Near-term Climate Protection and Clean Air Benefits: Actions for Controlling Short-Lived Climate Forcers, *available at* http://www.unep.org/pdf/Near_Term_Climate_Protection_&_Air_Benefits.pdf.

[51] Ramanathan V. & Xu Y. (2010) The Copenhagen Accord for limiting global warming: Criteria, constraints, and available avenues, *Proc. Nat'l Acad. Sci. USA* 107:8055, 8055, *available at* http://www.pnas.org/content/107/18/8055.full ("These actions [to reduce emissions of SLCPs including HFCs, methane, black carbon, and ground-level ozone], even if we are restricted to available technologies … can reduce the probability of exceeding the 2°C barrier before 2050 to less than 10% and before 2100 to less than 50% [when CO_2 concentrations are stabilized below 441 ppm during this century]"*)*. *See also* UNEP/WMO (2011) Integrated Assessment of Black Carbon and Tropospheric Ozone: Summary for Decisions Makers, 12, *available at* http://www.unep.org/dewa/Portals/67/pdf/BlackCarbon_SDM.pdf ("[T]he combination of CO_2, CH_4, and BC measures holds the temperature increase below 2°C until

around 2070… [and] adoption of the Assessment's near-term measures (CH_4 + BC) along with the CO_2 reductions would provide a substantial chance of keeping the Earth's temperature increase below 1.5˚C for the next 30 years."); UNEP/WMO (2011) Integrated Assessment of Black Carbon and Tropospheric Ozone, 240, *available at* http://www.unep.org/dewa/Portals/67/pdf/BlackCarbon_report.pdf ("Hence adoption of the near-term measures analyzed in this Assessment would increase the chances for society to keep the Earth's temperature increase below 1.5°C for the next 40 years if these measures were phased in along with CO_2 reductions."); *and* Shindell D. *et al.* (2012) Simultaneously mitigating near-term climate change and improving human health and food security, *Sci.* 335:183, 184, *available at* http://www.sciencemag.org/content/335/6065/183.short ("The combination of CH_4 and BC measures along with substantial CO_2 emissions reductions [under a 450 parts per million (ppm) scenario] has a high probability of limiting global mean warming to <2°C during the next 60 years, something that neither set of emissions reductions achieves on its own….")

[52] Shindell D. *et al.* (2012) Simultaneously mitigating near-term climate change and improving human health and food security, *Sci.* 335:183, *available at* http://www.sciencemag.org/content/335/6065/183; *and* UNEP/WMO (2011) Integrated Assessment of Black Carbon and Tropospheric Ozone, *available at* http://www.unep.org/dewa/Portals/67/pdf/BlackCarbon_report.pdf; based on Ramanathan V. & Xu Y. (2010) The Copenhagen Accord for limiting global warming: Criteria, constraints, and available avenues, *Proc. Nat'l Acad. Sci. USA* 107: 8055, *available at* http://www.pnas.org/content/107/18/8055.full.

[53] UNEP/WMO (2011) Integrated Assessment of Black Carbon and Tropospheric Ozone, at 99, *available at* http://www.unep.org/dewa/Portals/67/pdf/BlackCarbon_report.pdf ("While global mean temperatures provide some indication of climate impacts and their simplicity makes them widely used indicators, temperature changes can vary dramatically from place to place…. In the case of the short-lived climate forcing by aerosols and O_3, the forcing itself is also very unevenly distributed, and hence can cause even greater regional contrasts in the temperature response. "); *and* Christensen, J.H. *et al.* (2007) Regional Climate Projections, in Climate Change 2007: The Physical Science

Basis, *available at* http://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-chapter11.pdf.

[54] Qiu J. (2008) China: The Third Pole, *Nat.* 454:393, 393, *available at* http://www.nature.com/news/2008/080723/full/454393a.html ("The proximate cause of the changes now being felt on the [Tibetan] plateau is a rise in temperature of up to 0.3 °C a decade that has been going on for fifty years — approximately three times the global warming rate"). *See also* Arctic Monitoring and Assessment Programme (2011) Snow, Water, Ice and Permafrost in the Arctic, Executive Summary and Key Message, 4, *available at* https://www.documentcloud.org/documents/88367-arctic-ice-melt-2011-executivesummary.html ("The increase in annual average temperature since 1980 has been twice as high over the Arctic as it has been over the rest of the world"); and Cruz R. V. *et al.* (2007) Asia, in Climate Change 2007: Impacts, Adaptation and Vulnerability, 475, *available at* http://www.ipcc.ch/pdf/assessment-report/ar4/wg2/ar4-wg2-chapter10.pdf ("In all four regions [of Africa] and in all seasons, the median temperature increase [between 1980 and 2099] lies between 3°C and 4°C, roughly 1.5 times the global mean response.").

[55] According to passive microwave data analyzed by the National Snow and Ice Data Center and NASA, on 16 September 2012 the Arctic reached a new record minimum of 1.32 million square miles, 18% less than the previous record minimum set in 2007 and nearly 50% less than the 1979 to 2000 average. National Snow & Ice Data Center, Arctic sea ice extent settles a record seasonal minimum, (16 September 2012), *available at* http://nsidc.org/arcticseaicenews/; *and* Derksen C. & Brown R. (2012) Spring snow cover extent reductions in the 2008-2012 period exceeding climate model projections', *Geophys. Res Lett.* (in press).

[56] Flanner M. G. *et al.* (2011) Radiative forcing and albedo feedback from the Northern Hemisphere cryosphere between 1979 and 2008, *Nat. Geosci.* 4:151, *available at* http://www.nature.com/ngeo/journal/v4/n3/abs/ngeo1062.html. *See also* Arctic Monitoring and Assessment Programme (2011) Snow, Water, Ice and Permafrost in the Arctic, Executive Summary and Key Message, *available at* https://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, *available at* http://www.agu.org/pubs/crossref/2007/2007GL029703.shtml.

[57] Lenton T. M. (2011) 2°C or not 2°C? That is the climate question, *Nat.* 473:7, *available at* http://www.nature.com/news/2011/110504/full/473007a.html.

[58] 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, *available at* http://www.agu.org/pubs/crossref/2010/2009JD013795.shtml.

[59] Menon S. *et al.* (2010) Black carbon aerosols and the third polar ice cap, *Atmos. Chem. Phys.*, 10:4559, *available at* http://www.atmos-chem-phys.net/10/4559/2010/acp-10-4559-2010.pdf. *See also* Ramanathan V. *et al.* (2007) Atmospheric brown clouds: Hemispherical and regional variations in long range transport, absorption, and radiative forcing, *J. of Geophys. Res.*, 12:D22S21, *available at* http://www.agu.org/pubs/crossref/2007/2006JD008124.shtml; *and* UNEP/WMO (2011) Integrated Assessment of Black Carbon and Tropospheric Ozone, *available at* http://www.unep.org/dewa/Portals/67/pdf/BlackCarbon_report.pdf.

[60] Shindell D. *et al.* (2012) Simultaneously mitigating near-term climate change and improving human health and food security, *Sci.* 335:183, 183, 185, *available at* http://www.sciencemag.org/content/335/6065/183/ ("We identified 14 measures targeting methane and BC emissions that reduce projected global mean warming ~0.5°C by 2050. *** BC albedo and direct forcings are large in the Himalayas, where there is an especially pronounced response in the Karakoram, and in the Arctic, where the measures reduce projected warming over the next three decades by approximately two thirds and where regional temperature response patterns correspond fairly closely to albedo forcing…"). *See also* UNEP/WMO (2011) Integrated Assessment of Black Carbon and Tropospheric Ozone: Summary for Decisions Makers, 3, *available at* http://www.unep.org/dewa/Portals/67/pdf/BlackCarbon_SDM.pdf ("If the measures were to be implemented by 2030, they could halve the potential increase in global temperature projected for 2050 compared to the Assessment's reference scenario based on current policies and energy and fuel projections. *** This could reduce warming in the Arctic in the next 30 years by about two-thirds compared to the projections of the Assessment's reference scenario").

[61] Menon S. *et al.* (2010) Black carbon aerosols and the third polar ice cap, *Atmos. Chem. Phys.*, 10:4559, *available at* http://www.atmos-chem-phys.net/10/4559/2010/acp-10-4559-2010.pdf.

[62] Shindell D. *et al.* (2012) Simultaneously mitigating near-term climate change and improving human health and food security, *Sci.* 335:183, 183, *available at* http://www.sciencemag.org/content/335/6065/183.short ("This strategy avoids 0.7 to 4.7 million annual premature deaths from outdoor air pollution and increases annual crop yields by 30 to 135 million metric tons due to ozone reductions in 2030 and beyond."). *See also* UNEP/WMO (2011) Integrated Assessment of Black Carbon and Tropospheric Ozone: Summary for Decisions Makers, *available at* http://www.unep.org/dewa/Portals/67/pdf/BlackCarbon_SDM.pdf; *and* UNEP (2011) Near-term Climate Protection and Clean Air Benefits: Actions for Controlling Short-Lived Climate Forcers, *available at* http://www.unep.org/pdf/Near_Term_Climate_Protection_&_Air_Benefits.pdf.

[63] Anenberg *et al.* (2012) Global air quality and health co-benefits of mitigating near-term climate change through methane and black carbon emission controls, *Envtl. Health Perspectives*, 120:831, 831, 838, *available at* http://www-ramanathan.ucsd.edu/files/pr189.pdf ("We estimate that, for $PM_{2.5}$ [black carbon] and ozone respectively, fully implementing these [14] measures could reduce global population-weighted average surface concentrations by 23-34% and 7-17% and avoid 0.6-4.4 and 0.04-0.52 million annual premature deaths globally in 2030. More than 80% of the health benefits are estimated to occur in Asia…. Based on our estimates, avoided deaths would represent 1-8% of cardiopulmonary and lung cancer deaths among those age 30 years and older, and 1-7% of all deaths for all ages, assuming constant baseline mortality rates.").

[64] UNEP/WMO (2011) Integrated Assessment of Black Carbon and Tropospheric Ozone: Summary for Decisions Makers, 3, *available at* http://www.unep.org/dewa/Portals/67/pdf/BlackCarbon_SDM.pdf ("Full implementation of the identified measures could avoid … the loss of 52 million tonnes (within a range of 30–140 million tonnes), 1–4 per cent, of the global production of maize, rice, soybean and wheat each year.").

[65] Ramanathan V. & Carmichael G. (2008) Global and regional climate changes due to black carbon, *Nat. Geosci.* 1:221, *available at* http://www.nature.com/ngeo/journal/v1/n4/full/ngeo156.html.

[66] The UNEP/WMO and Shindell *et al.* studies analyzed the 1650 individual control measures in the technology and emission databases of the IIASA Greenhouse gas: Air pollution Interactions and Synergies (GAINS) climate model. These were grouped into 400 categories which were then analyzed for their impacts on emissions of methane, carbon monoxide, black carbon, organic carbon, sulfur dioxide (SO_2), nitrogen oxides (NOx), volatile organic compounds (VOCs) and carbon dioxide. The measures were further analyzed to determine the net effect of the changes in global radiative forcing (RF) due to changes in emissions of the studied gases and aerosols, and ranked according to their efficacy at reducing global RF. 130 measures were shown to reduce global RF and the top 16 of those measures were shown to produce almost 90% of the total mitigation potential. Shindell *et al.* combined four measures into two larger categories of measures, reducing to 14 the original 16 measures. *See* Shindell D. *et al.* (2012) Simultaneously mitigating near-term climate change and improving human health and food security, *Sci.* 335:183, *available at* http://www.sciencemag.org/content/335/6065/183.short; *and* UNEP/WMO (2011) Integrated Assessment of Black Carbon and Tropospheric Ozone: Summary for Decision Makers, *available at* http://www.unep.org/dewa/Portals/67/pdf/BlackCarbon_SDM.pdf.

[67] UNEP (2011) Near-term Climate Protection and Clean Air Benefits: Actions for Controlling Short-Lived Climate Forcers, xii *available at* http://www.unep.org/pdf/Near_Term_Climate_Protection_&_Air_Benefits.pdf ("These measures can accomplish about 38 per cent reduction of global methane emissions and around 77 per cent of black carbon emissions, if implemented between now and 2030, relative to a 2030 'reference' emission scenario."). *See also* Shindell D. *et al.* (2012) Simultaneously mitigating near-term climate change and improving human health and food security, *Sci.* 335:183, *available at* http://www.sciencemag.org/content/335/6065/183.short.

[68] Molina, M., Zaelke, D., Sarma, K. M., Andersen, S. O., Ramanathan, V., and Kaniaru, D. (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. USA*, *available at* http://www.pnas.org/content/early/2009/10/09/0902568106.full.pdf+html ("BC can be reduced by approximately 50% with full application of existing technologies by 2030…. Strategies to reduce BC could borrow existing management and

institutions at the international and regional levels, including existing treaty systems regulating shipping and regional air quality."). *See also* UNEP (2011) Near-term Climate Protection and Clean Air Benefits: Actions for Controlling Short-Lived Climate Forcers, x *available at* http://www.unep.org/pdf/Near_Term_Climate_Protection_&_Air_Benefits.pdf ("National efforts to reduce SLCFs can build upon existing institutions, policy and regulatory frameworks related to air quality management, and, where applicable, climate change. *** Regional air pollution agreements, organizations and initiatives may be effective mechanisms to build awareness, promote the implementation of SLCF mitigation measures, share good practices and enhance capacity. *** Global actions can help enable and encourage national and regional initiatives and support the widespread implementation of SLCF measures. A coordinated approach to combating SLCFs can build on existing institutional arrangements, ensure adequate financial support, enhance capacity and provide technical assistance at the national level."); *and* Shindell D. *et al.* (2012) Simultaneously mitigating near-term climate change and improving human health and food security, *Sci.* 335:183, 188, *available at* http://www.sciencemag.org/content/335/6065/183.short ("Many other policy alternatives exist to implement the CH_4 [methane] and BC measures, including enhancement of current air quality regulations.").

[69] UNEP (2011) Near-term Climate Protection and Clean Air Benefits: Actions for Controlling Short-Lived Climate Forcers, x, *available at* http://www.unep.org/pdf/Near_Term_Climate_Protection_&_Air_Benefits.pdf ("About 50 per cent of both methane and black carbon emissions reductions can be achieved through measures that result in net cost savings (as a global average) over their technical lifetime. The savings occur when initial investments are offset by subsequent cost savings from, for example, reduced fuel use or utilization of recovered methane. A further third of the total methane emissions reduction could be addressed at relatively moderate costs.").

[70] Shindell D. *et al.* (2012) Simultaneously mitigating near-term climate change and improving human health and food security, *Sci.* 335:183, 186, *available at* http://www.sciencemag.org/content/335/6065/183.short ("using $430 for climate and discounted health and agricultural values, gives a total benefit of ~$1100 per metric ton of CH_4 (~$700 to $5000 per metric ton, using the above analyses). IEA estimates (37)

indicate roughly 100 Tg/year of CH_4 emissions can be abated at marginal costs below $1100, with more than 50 Tg/year costing less than 1/10 this valuation (including the value of CH_4 captured for resale). Analysis using more recent cost information in the GAINS model (38, 39) finds that the measures analyzed here could reduce 2030 CH_4 emissions by ~110 Tg at marginal costs below $1500 per metric ton, with 90 Tg below $250. The full set of measures reduce emissions by ~140 Tg, indicating that most would produce benefits greater than—and for approximately two-thirds of reductions far greater than—the abatement costs. Of course, the benefits would not necessarily accrue to those incurring costs.").

[71] Shindell D. *et al.* (2012) Simultaneously mitigating near-term climate change and improving human health and food security, *Sci.* 335:183, 186, *available at* http://www.sciencemag.org/content/335/6065/183.short ("GAINS estimates show that improved efficiencies lead to a net cost savings for the brick kiln and clean-burning stove BC measures. These account for ~50% of the BC measures' impact.").

[72] Shindell D. *et al.* (2012) Simultaneously mitigating near-term climate change and improving human health and food security, *Sci.* 335:183, 186, *available at* http://www.sciencemag.org/content/335/6065/183.short ("The regulatory measures on high-emitting vehicles and banning of agricultural waste burning, which require primarily political rather than economic investment, account for another 25%. Hence, the bulk of the BC measures could probably be implemented with costs substantially less than the benefits given the large valuation of the health impacts.").

[73] Shindell D. *et al.* (2012) Simultaneously mitigating near-term climate change and improving human health and food security, *Sci.* 335:183, *available at* http://www.sciencemag.org/content/335/6065/183.short.

[74] Numbers based on Shindell D. *et al.* (2012) Simultaneously mitigating near-term climate change and improving human health and food security, *Sci.* 335:183, *available at* http://www.sciencemag.org/content/335/6065/183.short: all numbers in billions $US annually starting in 2030.

[75] Velders G.J.M. *et al.* (2007) The importance of the Montreal Protocol in protecting climate, *Proc. Nat'l. Acad. Sci. USA* 104:4814, *available at* http://www.pnas.org/content/104/12/4814.

[76] UNEP (2012) The Montreal Protocol and the Green Economy: Assessing the contributions and co-benefits of a Multilateral Environmental

Agreement, *available at* http://www.unep.org/ozonaction/Portals/105/documents/publications/green-economy-report.pdf.

[77] Proposed Amendment to the Montreal Protocol (submitted by the Federated States of Micronesia), (11 May 2012) *available at* http://conf.montreal-protocol.org/meeting/oewg/oewg-32/presession/PreSession%20Documents/OEWG-32-5E.pdf. *See also* Proposed Amendment to the Montreal Protocol (submitted by the United States, Canada, and Mexico), (9 May 2012) *available at* http://conf.montreal-protocol.org/meeting/oewg/oewg-32/presession/PreSession%20Documents/OEWG-32-5E.pdf.

[78] The cumulative BAU emission from the 6 Kyoto gases from 2000-50 is about 975 GtC-eq (=650 x 1.5, Fig. 1, Scenario 6 (England *et al.*)), which is equivalent to approximately 3575 Gt CO_2-eq. The cumulative Kyoto-gas emission budget for 2000-50 is 1500 $GtCO_2$-eq. if the probability of exceeding 2˚C is to be limited to approximately 25% (Meinshausen *et al.*, pg. 1160). Therefore, the total mitigation needed by 2050 is approximately 2075 $GtCO_2$-eq. The 87-147 $GtCO_2$-eq. from the proposed HFC phase-down represents 4-7% of the total mitigation needed by 2050, and up to 8% if all HFCs are replaced by low-GWP substitutes. England M. H. *et al*. (2009) Constraining future greenhouse gas emissions by a cumulative target, *Proc. Nat'l. Acad. Sci. USA* 106:16539, *available at* http://www.pnas.org/content/106/39/16539.full.pdf+html; Meinshausen M. *et al.* (2009) Greenhouse-gas emission targets for limiting global warming to 2°C, *Nat.* 458:1158, *available at* http://www.nature.com/nature/journal/v458/n7242/full/nature08017.html; *and* Velders G.J.M. *et al.* (2009) The large contribution of projected HFC emissions to future climate forcing, *Proc. Nat'l. Acad. Sci. USA* 106:10949, *available at* http://www.pnas.org/content/early/2009/06/19/0902817106.full.pdf+html?with-ds=yes.

[79] UNEP (2012) The Montreal Protocol and the Green Economy: Assessing the contributions and co-benefits of a Multilateral Environmental Agreement, *available at* http://www.unep.org/ozonaction/Portals/105/documents/publications/green-economy-report.pdf; *citing* the following sources listed as they are cited in the figure *(1)* Velders G.J.M. *et al.* (2007) The importance of the Montreal Protocol in protecting climate, *Proc. Nat'l. Acad. Sci. USA* 104:4814, *available at* http://www.pnas.org/content/104/12/4814; *(2)* Velders *et al*. (2007) The Montreal Protocol, Celebrating 20 years of environmental progress, ed. Kaniaru D (Cameron

May, London, UK); *(3)* Montreal Protocol Technology and Economic Assessment Panel (2009) Task Force Decision XX/8 Interim Report: Environmentally Sound Management of Banks of Ozone-Depleting Substances, *available at* http://ozone.unep.org/teap/Reports/TEAP_Reports/teap-june-2009-decisionXX-7-task-force-report.pdf; *(4)* UNEP Riso (2009) A Primer on CDM Programme of Activities, November, *available at* http://cd4cdm.org/Publications/PrimerCMDPoA.pdf; *(5)* Velders G.J.M. *et al.* (2007) The importance of the Montreal Protocol in protecting climate, *Proc. Nat'l. Acad. Sci. USA* 104:4814, *available at* http://www.pnas.org/content/104/12/4814; *(6)* Velders G.J.M. *et al.* (2009) The large contribution of projected HFC emissions to future climate forcing, *Proc. Nat'l. Acad. Sci. USA* 106:10949, *available at* http://www.pnas.org/content/early/2009/06/19/0902817106.full.pdf+html?with-ds=yes. Note: Estimates are for direct emissions, and do not include CO_2 reductions from energy efficiency improvements.

[80] Montreal Protocol Technology and Economic Assessment Panel (2009) Task Force Decision XX/8 Report: Assessment of Alternatives to HCFCs and HFCs and Update of the TEAP 2005 Supplement Report Data, *available at* http://ozone.unep.org/teap/Reports/TEAP_Reports/teap-may-2009-decisionXX-8-task-force-report.pdf.

[81] Velders G.J.M. *et al.* (2009) The large contribution of projected HFC emissions to future climate forcing, *Proc. Nat'l. Acad. Sci. USA* 106:10949, 10949, *available at* http://www.pnas.org/content/early/2009/06/19/0902817106.full.pdf+html?with-ds=yes ("Global HFC emissions significantly exceed previous estimates after 2025 with developing country emissions as much as 800% greater than in developed countries in 2050. Global HFC emissions in 2050 are equivalent to 9–19% (CO_2-eq. basis) of projected global CO_2 emissions in business-as-usual scenarios and contribute a radiative forcing equivalent to that from 6–13 years of CO_2 emissions near 2050. This percentage increases to 28–45% compared with projected CO_2 emissions in a 450-ppm CO_2 stabilization scenario business-as usual scenarios from 2010 to 2050").

[82] Schwarz W. *et al.* (2011) Preparatory Study for a Review of Regulation (EC) No 842/2006 on Certain Fluorinated Greenhouse Gases: Final Report, *available at* http://ec.europa.eu/clima/policies/f-gas/docs/2011_study_en.pdf.

[83] California Air Resources Board, Amendments to the Low-Emission Vehicle Program – LEV III, *available at* http://www.arb.ca.gov/msprog/levprog/leviii/leviii.htm (last reviewed 12 July 2012).

[84] US EPA (2011) EPA and NHTSA Finalize Historic National Program to Reduce Greenhouse Gases and Improve Fuel Economy for Cars and Trucks, *available at* http://www.epa.gov/oms/climate/regulations/420f10014.pdf.

[85] US EPA (2012) 2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards, 40 CFR Parts 85, 86 and 600 ("In addition to the grams-per-mile CO_2-equivalent credits, for the first time the agencies are establishing provisions in the CAFE program that would account for improvements in air conditioner efficiency. Improving A/C efficiency leads to real-world fuel economy benefits, because as explained above, A/C operation represents an additional load on the engine. Thus, more efficient A/C operation imposes less of a load and allows the vehicle to go farther on a gallon of gas.")

[86] Consumer Goods Forum, Better Lives Through Better Business, (29 March 2012), *available at* http://www.theconsumergoodsforum.com/pfiles/publications/brochure/The-Forum-Brochure-ENG.pdf.

[87] Velders G.J.M. *et al.* (2009) The large contribution of projected HFC emissions to future climate forcing, *Proc. Nat'l. Acad. Sci. USA* 106:10949, *available at* http://www.pnas.org/content/early/2009/06/19/0902817106.full.pdf+html?with-ds=yes.

[88] United Nations (2012) Resolution adopted by the General Assembly: The future we want, A/RES/66/288, *available at* http://daccess-dds-ny.un.org/doc/UNDOC/GEN/N11/476/10/PDF/N1147610.pdf?OpenElement.

[89] UNEP (2010) Declaration on the global transition away from hydrochlorofluorocarbons (HCFCs) and clholrofluorocarbons (CFCs), *available at* http://ozone.unep.org/new_site/en/Treaties/treaties_decisions-hb.php?nav_id=2030. *See also* UNEP (2011) Report of the combined ninth meeting of the Conference of the Parties to the Vienna Convention on the Protection of the Ozone Layer and the Twenty-Third Meeting of the Parties to the Montreal Protocol on Substances that Deplete the Ozone Layer, *available at* http://conf.montreal-protocol.org/meeting/mop23-cop9/draft-reports/default.aspx.

[90] Proposed Amendment to the Montreal Protocol (submitted by the Federated States of Micronesia), (11 May 2012) *available at* http://conf.montreal-protocol.org/meeting/oewg/oewg-32/presession/PreSession%20Documents/OEWG-32-5E.pdf. *See also* Proposed Amendment to the Montreal Protocol (submitted by the United States, Canada, and Mexico), (9 May 2012) *available at* http://conf.montreal-protocol.org/meeting/oewg/oewg-32/presession/PreSession%20Documents/OEWG-32-5E.pdf.

[91] The cumulative BAU emission from the 6 Kyoto gases from 2000-50 is about 975 GtC-eq (=650 x 1.5, Fig. 1, Scenario 6 (England *et al*.)), which is equivalent to approximately 3575 Gt CO_2-eq. The cumulative Kyoto-gas emission budget for 2000-50 is 1500 $GtCO_2$-eq. if the probability of exceeding 2˚C is to be limited to approximately 25% (Meinshausen *et al*., pg. 1160). Therefore, the total mitigation need by 2050 is approximately 2075 $GtCO_2$-eq. The 87-147 $GtCO_2$-eq. from the proposed HFC phase-down represents 4-7% of the total mitigation needed by 2050, and up to 8% if all HFCs are replaced by low-GWP substitutes. England M. H. *et al*. (2009) Constraining future greenhouse gas emissions by a cumulative target, *Proc. Nat'l. Acad. Sci. USA* 106:16539, *available at* http://www.pnas.org/content/106/39/16539.full.pdf+html; Meinshausen M. *et al.* (2009) Greenhouse-gas emission targets for limiting global warming to 2°C, *Nat.* 458:1158, *available at* http://www.nature.com/nature/journal/v458/n7242/full/nature08017.html; *and* Velders G.J.M. *et al.* (2009) The large contribution of projected HFC emissions to future climate forcing, *Proc. Nat'l. Acad. Sci. USA* 106:10949, *available at* http://www.pnas.org/content/early/2009/06/19/0902817106.full.pdf+html?with-ds=yes.

[92] Prepared for IGSD by Dr. Guus Velders, based on Velders G.J.M. *et al.* (2009) The large contribution of projected HFC emissions to future climate forcing, *Proc. Nat'l. Acad. Sci. USA* 106:10949, *available at* http://www.pnas.org/content/early/2009/06/19/0902817106.full.pdf+html?with-ds=yes. *See also* Velders G.J.M., *et al.* (2007) The importance of the Montreal Protocol in protecting climate, *Proc. Nat'l. Acad. Sci. USA* 104:4814, *available at* http://www.pnas.org/content/suppl/2009/06/22/0902817106.DCSupplemental/0902817106SI.pdf; Proposed Amendment to the Montreal Protocol (submitted by the Federated States of Micronesia), (28 Apr. 2011 at 4-6 and 9), *available at* http://ozone.unep.org/Meeting_Documents/oewg/31oewg/FSM-Pro

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