Institute for Governance & Sustainable Development

The Need for Speed

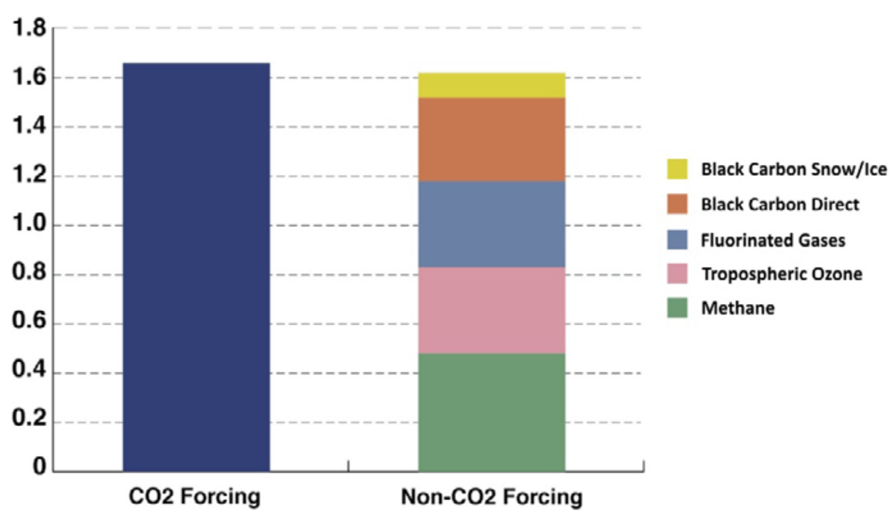
Reducing Short-Lived Climate Pollutants Has the Potential to Cut Rate of Global Warming by Half and Arctic Warming by Two-Thirds Over the Next 30 to 40 Years

SLCP mitigation promotes sustainable development, reduces near-term impacts on health, crops, and regional climate, along with sea-level rise and other near-term impacts on vulnerable people and places

Summary

14 Feb 2013. Carbon dioxide (CO_2) emissions are responsible for 55 to 60% of radiative forcing. S*ee* Fig. 1. Fast and aggressive CO_2 mitigation is essential to combat the resulting climate change. But this is not enough. CO_2 mitigation must be combined with fast and aggressive mitigation of the pollutants causing the other 40 to 45% of warming. These pollutants include black carbon aerosols, tropospheric ozone and its precursor, methane, and hydrofluorocarbons (HFCs). Because these pollutants have atmospheric lifetimes of days to decades, 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.

Figure 1. Changes in radiative forcing from anthropogenic emissions since the Industrial Revolution of 1750 (in W/m^2)



Based on IPCC, WG 1, Fig. 2.21, AR 4 (2007). (*Note graph does not include all non-CO_2 forcers.*)

While we have known about SLCPs for more than thirty-five years, the following scientific developments have catapulted them to the front lines of the battle against climate change.

- First is the recognition that we have already added enough climate pollutants to warm the planet by 2.4°C or more during this century. 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 to protect public health and ecosystems, but are contributing to near-term warming.
- Second is the recognition that without fast-action mitigation, warming may cross the 1.5° to

2°C threshold by the middle of this century even with strong CO_2 mitigation. Reducing SLCPs is the most effective strategy for constraining warming in the short-term, since most of their warming effect disappears within weeks to a decade and a half after emissions are reduced.

- Third is the recognition that in addition to being climate forcers, two of the three SLCPs are also harmful air pollutants and reducing them will prevent millions of premature deaths ever year and protect tens of millions of tonnes of crops, while promoting sustainable development.

- Fourth is the recognition that the health benefits and crop improvements will accrue primarily in the nations that mitigate these pollutants.

- Fifth is the recognition that there are practical and proven ways to reduce all four pollutants and readily available laws and institutions to support reductions in most cases.

Reducing three of the non-CO_2 short-lived climate pollutants—black carbon and tropospheric ozone and its precursor, methane—can avoid 0.5°C in warming by 2050 and 0.84°C in the Arctic by 2070. 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. *See* Fig. 7 & 11. It also will produce significant collateral benefits for health, crops, and local air quality valued at $5.9 trillion annually by 2030.

Avoiding growth in the other short-lived climate pollutant, HFCs, can increase by 20% the avoided warming from reductions in black carbon, tropospheric ozone, and methane, bringing the total prevented warming to 0.6°C by 2050. The combined reduction in rate of global warming from reducing these SLCPs will slow the rate of sea level rise and reduce other impacts. Reductions can be achieved quickly and in most cases by using existing technologies and existing laws and institutions.

The SLCP mitigation strategy may offer the best near-term protection for the countries that are most vulnerable to climate change, including island nations, countries with low-lying coastal areas, and agriculture-dependent countries in Asia and Africa already suffering droughts, floods, and shifting rainfall. Reducing SLCPs will:

- 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.

- 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.

All SLCPs are being addressed in the Climate and Clean Air Coalition (CCAC) to Reduce Short-lived Climate Pollutants, which was launched in early 2012 to pursue these reductions. The Coalition now has 55 partners, including 27 States and the European Commission, the World Bank, the United Nations Environment Programme, the United Nations Development Programme, the United Nations Industrial Development Organization and 23 NGOs. The G8 nations announced in their *Camp David Declaration* 19 May 2012 that their countries would join the Coalition; the G8 also requested the World Bank to conduct a study of how best to integrate SLCP reductions into the World Bank's programs. Select CCAC press coverage is here.

In addition to being included in the CCAC, HFCs are addressed in the Rio + 20 declaration, *The Future We Want*, where world leaders supported phasing down HFC production and use. Such a phase-down can be achieved through the Montreal Protocol, which has already phased out the production and use of nearly 100 similar chemicals, while simultaneously improving the energy efficiency of refrigerators, air conditioners, and other equipment and products that use HFCs, 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.). (Montreal Protocol 2012 & Montreal Protocol 2012). 108 Parties had expressed support to the *Bangkok Declaration* on the global transition away from HCFCs and HFCs, upon its closure to additional signatories in 2011. Through November 2012, 105 parties had provided written support to the *Bali Declaration* on Transitioning to Low Global Warming Potential Alternatives to Ozone Depleting Substances. 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, only about 25% of CO_2 emissions 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. *See* Fig. 2. CO_2's long lifetime combined with the thermal inertia of the heat stored in the ocean means that even if CO_2 emissions were to cease completely, 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 decreased warming from cuts to most SLCPs would be realized within a decade.

When combined with substantial CO_2 reductions that begin immediately, these fast actions 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, the agreed goal of the international community, for the next 60 to 90 years. *See* Fig. 6 & 7. It will also be necessary to deliberately remove previously emitted CO_2 from the atmosphere on a timescale of decades rather than the millennia of the natural cycle, in order to return to a safe and stable climate by the end of the century. This can be done using CO_2 removal strategies such as bio-sequestration, biochar, and chemical air capture and re-utilization, although many of these tools need to be further developed at scale.

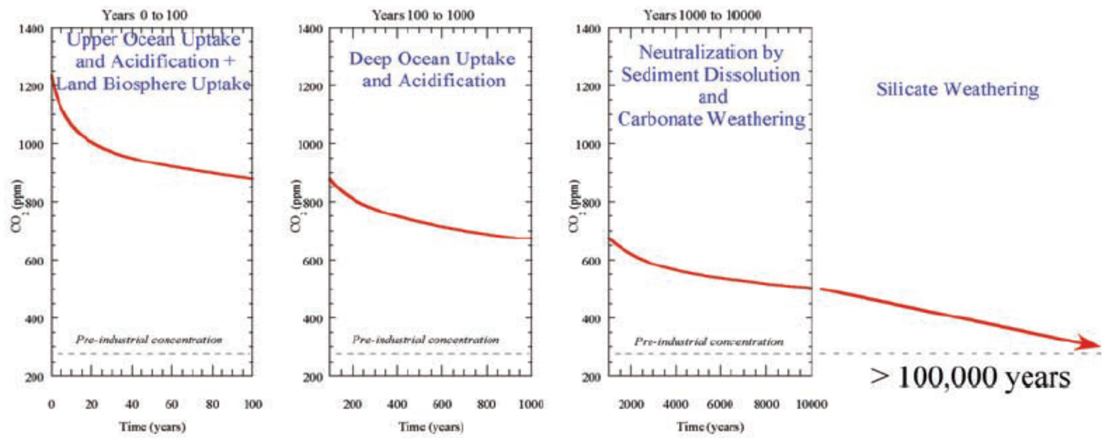
The following discussion elaborates these points, drawing on quotation from the relevant scientific publications and the relevant policy statements. (*See* here for summary of policy statements supporting SLCPs reductions from key international, regional, and bilateral policy meetings; and here for a list of top press stories. Additional resources on SLCP science and policy are below.)

Discussion

Fast reduction of CO_2 is essential for a safe climate. CO_2 is responsible for 55-60% of warming, a substantial portion remains in the atmosphere for millennia, and most of the warming and seal level rise it causes is irreversible for 1,000 years after emissions stop.

> *While more than half of the CO_2 emitted is currently removed from the atmosphere within a century … about 20% … remains … for many millennia.* (IPCC, AR4 2007.)
>
> *[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.* (Matthews & Caldeira, GRL 2008, citing Archer, JGR 2005.)
>
> *About one-quarter of fossil fuel CO_2 emissions will stay in the air "forever", i.e. more than 500 years…. Resulting climate changes would be … irreversible.* (Hansen *et al.*, PTRS 2007.)

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

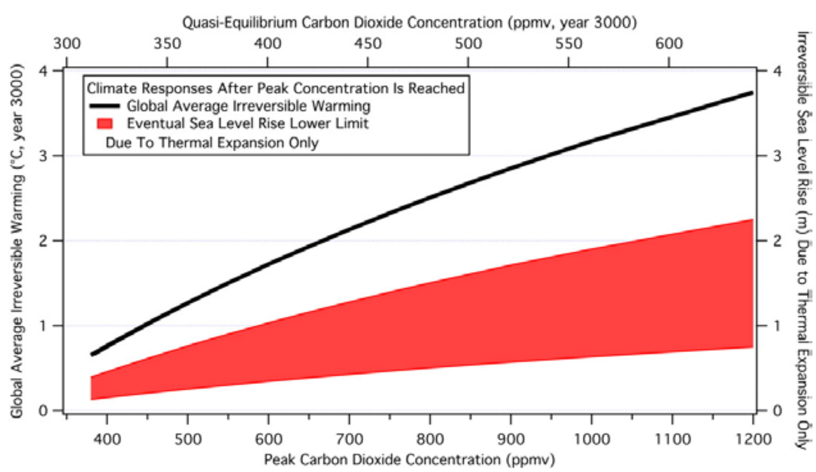


Model simulation of atmospheric CO_2 concentration for >100,000 years following a large CO_2 release from combustion of fossil fuels. Different fractions of the released gas recover on different timescales. (Solomon S. *et al.*, NAS 2011.)

[C]limate change that takes place due to increases in carbon dioxide concentrations is largely irreversible for 1,000 years after emissions stop. (Solomon *et al.*, PNAS 2009.)

Anthropogenic carbon dioxide will cause irrevocable sea level rise…. An assessed range of models suggests that the eventual contribution to sea level rise from thermal expansion of the ocean is expected to be 0.2–0.6 m per degree of global warming (5). Fig. [3] uses this range together with a best estimate for climate sensitivity of 3 °C (5) to estimate lower limits to eventual sea level rise due to thermal expansion alone. Fig. [3] shows that even with zero emissions after reaching a peak concentration, irreversible global average sea level rise of at least 0.4–1.0 m is expected if 21st century CO_2 concentrations exceed 600 ppmv and as much as 1.9 m for a peak CO_2 concentration exceeding 1,000 ppmv. (Solomon S. et al., PNAS 2009)

Figure 3: Irreversible Sea-Level Rise and Warming from CO_2



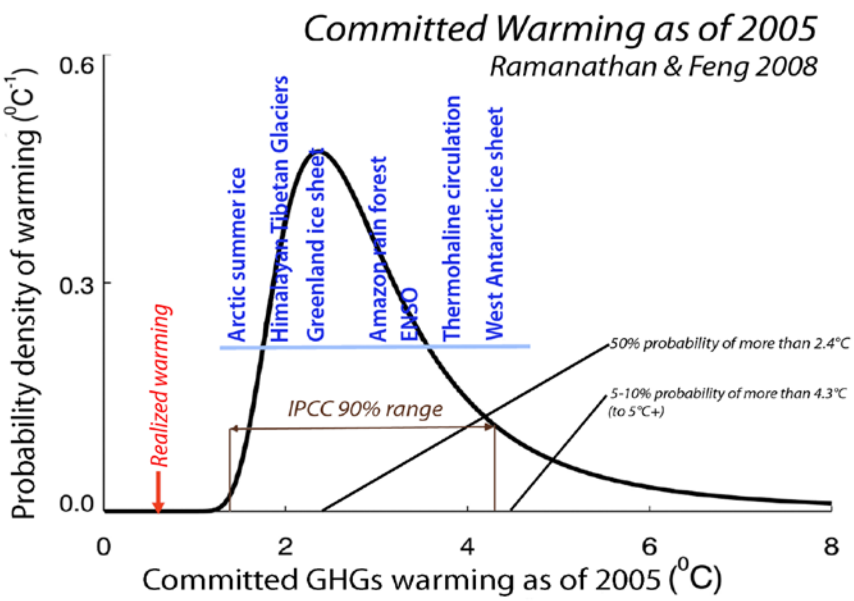
The black line shows irreversible global average surface warming based upon peak atmospheric CO_2 concentrations. The red band shows lower limit range of corresponding sea-level rise from thermal expansion only, due to peak atmospheric CO_2 concentrations. (Solomon S. et al., PNAS 2009)

[A] simplified way to view future warming persistence is that emissions of CO_2 and a handful of other extremely long-lived gases imply warming that is essentially irreversible on human timescales without geoengineering or active sequestration. (Solomon *et al.*, PNAS 2010.)

The greenhouse gases that have already been emitted into the atmosphere through 2005 have added about 3 Wm^{-2} heat energy (radiative forcing) to the planet and this is sufficient to warm the planet by about 2.4°C and to risk passing predicted tipping points (*see* Fig.4) (Ramanathan & Feng, 2008).

> *This article uses the greenhouse gases (GHGs) forcing of 3 (2.6 to 3.5) Wm^{-2} estimated by the IPCC-AR4 for the preindustrial to present (year 2005) period…. Using these data, this study infers that we have already committed the planet to a global warming of 2.4°C (1.4–4.3°C)….* (Ramanathan & Feng, 2008)

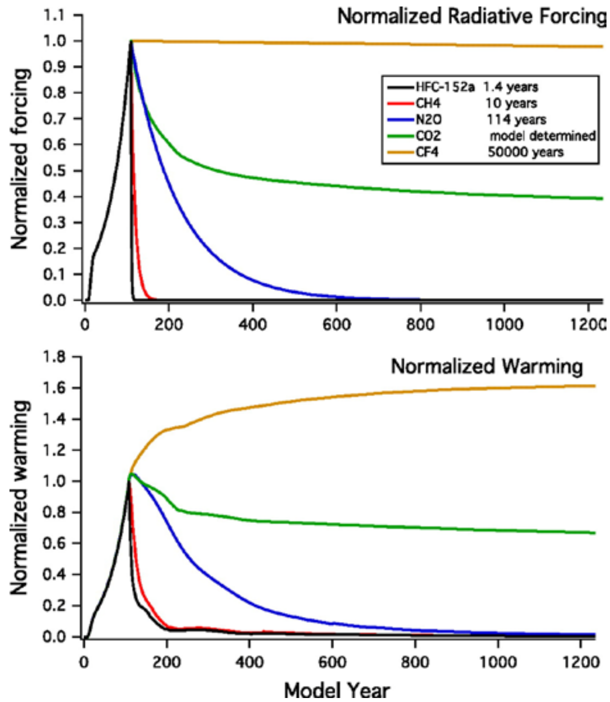
Figure 4. Committed Warming as of 2005 and Predicted Tipping Points



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. 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. (Ramanathan & Feng, 2008)

While reducing CO_2 is essential for limiting warming, reducing SLCPs also is essential for limiting warming in the next few decades; together, these two strategies provide the best chance to keep temperature below the 2°C guardrail through 2100 (Ramanathan & Xu, PNAS 2010). Due to its long lifetime in the atmosphere and the thermal inertia of the oceans, CO_2 reductions do little to constrain warming in the critical next 30-40 years, but the mitigation benefit grows quickly 50 years after significant reductions begin. For SLCPs, however, cuts can produce rapid benefits (*see* Fig. 6 & 7); up to 90% of the decrease in global mean temperatures would be realized in a few decades.

Figure 5. Persistence of Warming From Greenhouse Gases



Relative changes in radiative forcing (Upper) and warming (Lower) in the Bern 2.5CC model, for the same assumed profile of increasing radiative forcing over 100 y, followed by a stop of emissions as in Fig. 3, for a range of greenhouse gases of varying lifetimes. The gases considered are HFC-152a (1.4-y lifetime), methane (≈10-y lifetime), N2O (114-y lifetime), carbon dioxide (see text), and CF4 (50,000-y lifetime). All quantities are normalized to one when emissions stop, in order to examine relative changes. (Solomon *et al.*, PNAS 2010.)

[M]itigation of 0.15°C due to CO_2 measures takes place only around 2050 … 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. (UNEP-WMO 2011.)

The use of current infrastructure to build this new low-emission [energy] system [to phase out existing coal-fired power plants] 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 [over the next 40 years] can do little to diminish the climate impacts in the first half of this century. (Myhrvold & Caldeira, ERL 2012.)

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 few decades. 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. (UNEP-WMO 2011.)

Reducing SLCPs will have fast effects; cutting black carbon and methane can cut the rate of Arctic warming by two-thirds and the rate of global warming by up to half or more within decades. The UNEP-WMO (2011 & 2011 Summary for Decision Makers) assessment analyzed 1,650 possible control measures and selected 16 priority measures for black carbon, tropospheric ozone and its precursor, methane[1] which maximize warming mitigation while limiting reductions of cooling aerosols and gases; Shindell *et al.* (2012) consolidated these into 14 measures (*see* page 20 for list).

> *The selection criterion was that the [control] measure had to be likely to reduce global climate change and also provide air quality benefits, so-called win-win measures. Those measures that provided a benefit for air quality but increased warming were not included in the selected measures. For example, measures that primarily reduce emissions of* SO_2 *were not included…. [T]he top 16 have been selected that collectively achieve nearly 90 per cent of the overall mitigation potential according to the GWP100 metric…. When all measures are fully implemented, warming during the 2030s relative to the present day is only half as much as if no measures had been implemented. … 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.* (UNEP-WMO 2011.)

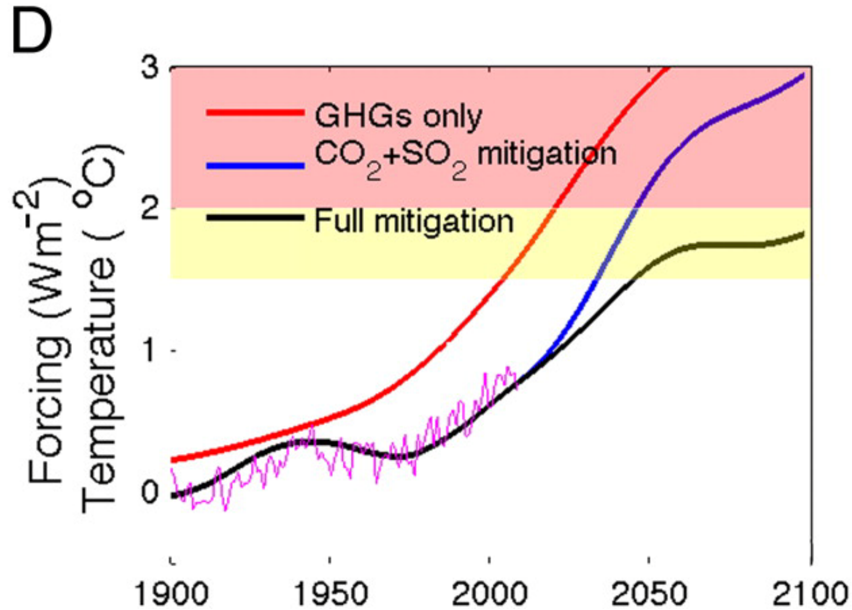
> *We identified 14 measures targeting methane and BC emissions that reduce projected global mean warming ~0.5°C by 2050.… BC albedo and direct forcings are large in the Himalayas, where there is an especially pronounced response in the Karakoram, and in the Arctic, where the measures reduce projected warming over the next three decades by approximately two thirds....* (Shindell *et al.*, SCI 2012.)

The combination of CO_2 **mitigation and SLCP mitigation provides the greatest chance of keeping global temperatures below 1.5°C until 2050 and below 2°C through 2100.** (Ramanathan & Xu, PNAS 2010, Fig. 6 below).

> *These actions [to reduce emissions of SLCPs including HFCs, methane, black carbon, and tropospheric 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]*. (Ramanathan & Xu, PNAS 2010.)

[1] Unlike other SLCPs, tropospheric ozone is not emitted directly but instead forms from interactions between sunlight and precursor gases both human and natural. These precursor gases include oxides of nitrogen (NOx), carbon monoxide (CO), and volatile organic compounds (which includes methane). Globally, increased methane emissions are responsible for approximately two-thirds of the rise in tropospheric ozone, therefore controlling methane will lead to significant reductions in tropospheric ozone and its damaging effects. Reducing other 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).

Figure 6. Warming Avoided Through Combined SLCP and CO_2 Mitigation



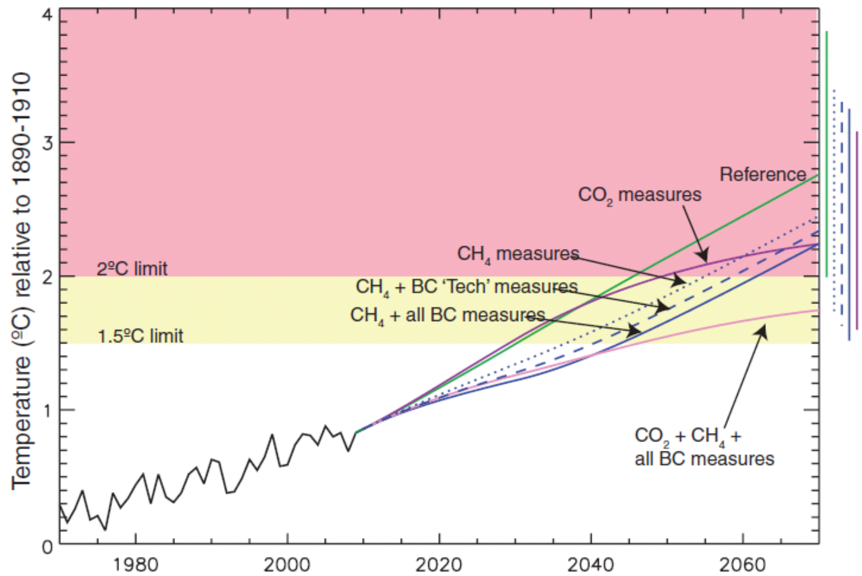
The red line depicts strong mitigation of CO_2 (peaking in 2015 and remaining at 2015 levels until 2100, reaching a concentration peak of 430 ppm by 2050), but no mitigation of non-CO_2 greenhouse gases, and does not account for forcing from aerosols or land use change; the blue line is the same as the 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. (Ramanathan & Xu, Fig 1D, PNAS 2010.)

Recent analysis by Shindell *et al.* (Sci 2012) and UNEP-WMO (2011 & 2011) confirm how much the rate of warming can be slowed for the next 30 to 60 years by cutting just black carbon and methane, provided progress also is made cutting CO_2. These results are show in Fig. 7 below.

> *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….* (Shindell *et al.*, Sci 2012.)

> *[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.)

Figure 7. Temperature Rise Predictions Under Various Mitigation Scenarios



Observed temperatures (42) 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 (7). 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 significant difference (Shindell *et al.*, SCI 2012 and UNEP-WMO 2011, based on Ramanathan & Xu, Fig 1D, PNAS 2010.[2]) (Note: HFC mitigation is not included in this graph, although it is included in Ramanathan & Xu, Fig. 1D, reproduced as Fig. 3, above.)

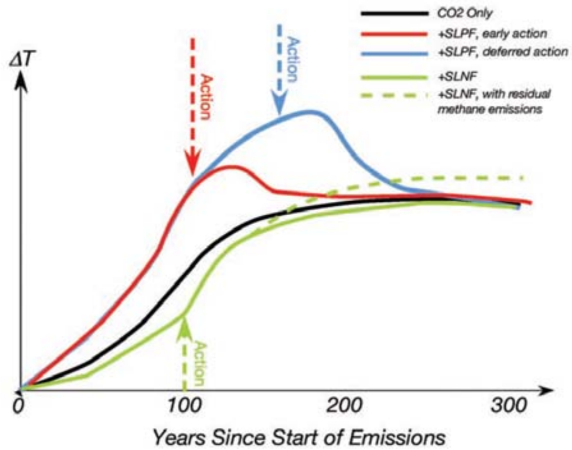
Mitigation of CO_2 and SLCPs is more effective if done sooner rather than later (Fig. 5 & 8). The heat stored in the deep ocean from any climate pollutant returns to the atmosphere on a time scale of centuries after that pollutant is removed from the atmosphere. Therefore, the best approach for reducing the heat that will be fed from the oceans back into the atmosphere over the next several centuries is to act quickly to prevent that heat from being absorbed by the ocean in the first place. In the case of CO_2, this is exacerbated by its millennial time scale for removal from the atmosphere, as well as the thermal inertia of the deep oceans (*see* Fig. 3 & 5). Reductions in CO_2 can do little to slow warming over the next thirty years, but mitigation benefits accrue quickly in the medium- to long-term.

> *[M]itigation of 0.15°C due to CO_2 measures [in the IEA 450 Scenario] takes place only around 2050 … 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 [the difference between the green reference line and the dark purple CO_2 mitigation line in Fig. 7, above].* (UNEP, 2011.)

[2] The science of SLCPs dates back to the 1970s (Ramanathan, 1975; Wang *et al.*, 1976). 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.) This finding has been confirmed and strengthened in the following decades by hundreds of studies culminating in IPCC reports (IPCC 1990; IPCC 1995; IPCC 2001; IPCC 2007). In January 2013, an international team of 31 scientists concluded after a four-year assessment of black carbon that it was the second most damaging climate pollutant, after CO_2 (Bond *et al.*, 2013). The 2013 black carbon assessment confirmed the earlier calculations of Ramanathan & Carmichael (Ramanathan & Carmichael, 2008) and Jacobson (Jacobson, 2001). In short, researchers have had at least 25 years to carefully develop the science of SLCPs and assess the findings.

[M]ultiple centuries are required to warm or cool the deep ocean…. Maintaining a forcing for a longer period of time transfers more heat to the deep … ocean, with a correspondingly longer timescale for release of energy if emissions were to be halted…. [T]he slow timescales of the ocean imply that actions to mitigate the climate impacts of these warming agents [SLCPs] would be most effective if undertaken sooner; conversely such actions would become less effective the longer the radiative forcing is maintained. (Solomon *et al.*, PNAS 2010.)

Figure 8. Cooling from SLCP Mitigation in a Carbon Constrained Scenario



Qualitative sketch of the time-course of future temperature under various scenarios for control of emissions of short-lived radiative forcing agents…. The time course of warming produced by CO_2 emissions alone is given schematically by the black line. If one adds short-lived radiative forcing agents with an aggregate warming effect into the mix, the effect will be to add to the temperature increase until such time as the emissions are brought under control, where after the temperature will quickly drop back to the CO_2-only curve (the blue and red solid lines on the curve, representing early or delayed mitigation of shortlived forcing agents). (Solomon S. *et al.*, NAS 2011.)

In addition, some SLCPs damage ecosystems and their ability to sequester carbon, which causes more CO_2 to remain in the atmosphere increasing long-term warming.

O_3 pollution is also known to damage ecosystem health by reducing plant productivity. Gross primary production (GPP) is a measure of the total amount of CO_2 removed from the atmosphere every year to fuel photosynthesis…. Of great significance is that the O_3 climate impact through perturbation of the carbon cycle operates on longer timescales than the O_3 atmospheric lifetime itself of only a few weeks…. 30% of the maximum global warming due to the total ozone effect is essentially irreversible. (Unger & Pan, AE 2012.)

Many vulnerable regions are warming faster than the global average rate of warming. Global warming is expressed as an average increase in surface temperature but is experienced unevenly in different regions, with some of the world's most vulnerable regions warming much faster than the global average.

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. (AMAP 2011.)

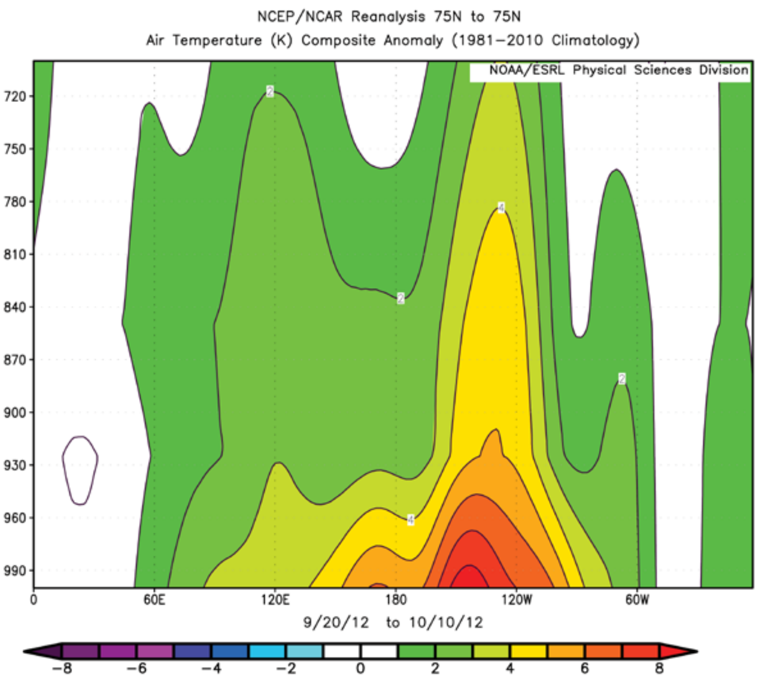
The proximate cause of the changes now being felt on the [Tibetan] plateau is a rise in temperature of up to 0.3 °C a decade that has been going on for fifty years — approximately three times the global warming rate. (Qiu, NAT 2008.)

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. (IPCC 2007.)

Warming in the Arctic could lead to dangerous climate feedbacks that cause warming to accelerate past tipping points. The term 'tipping element' on a basic level is a chain of events that escalate to a point where it is impossible to return to former conditions. Some examples include Arctic sea-ice melt, permafrost melt, and Himalayan glacial melt.

> *The word tipping element suggests the existence of a self-amplification process at the heart of the tipping dynamics. *** A prominent example of such self-amplification is the ice-albedo feedback … in the Arctic sea-ice region and on mountain glaciers such as the Alps and the Himalayas: An initial warming of snow- or ice-covered area induces regional melting. This uncovers darker ground, either brownish land or blue ocean, beneath the white snow- or ice-cover. Darker surfaces reflect less sunlight inducing increased regional warming, the effect self-amplifies.* (Levermann *et al.*, CC 2012.)

Figure 9. Open Water Warms the Lower Atmosphere



This figure shows air temperatures as a function of height and longitude at 75 degrees north latitude. Temperatures are for the period September 20 to October 10, 2012 compared to averages for the years 1981 to 2010. Between longitudes 120 degrees west to 150 degrees west, temperatures more than 4 degrees Celsius (7 degrees Fahrenheit) above normal are found up to the 850 hPa level (roughly 4500 feet above the surface), with temperatures near the surface, in closer proximity to the warming effects of the ocean, more than 6 degrees Celsius (11 degrees Fahrenheit) above normal. (NSIDC 2012.)

> *A variety of tipping elements could reach their critical point within this century under anthropogenic climate change. The greatest threats are tipping the Arctic sea-ice and the Greenland ice sheet, and at least five other elements could surprise us by exhibiting a nearby tipping point*. (Lenton *et al.*, PNAS 2008.)

> *Permafrost–permanently frozen ground–underlies most of the Arctic land area and extends under parts of the Arctic Ocean. Temperatures in the permafrost have risen by up to 2˚C over the past two to three decades.... The southern limit of the permafrost retreated northward by 30 to 80 km in Russia between 1970 and 2005, and by 130 km during the past 50 years in Quebec.* (AMAP 2011.)

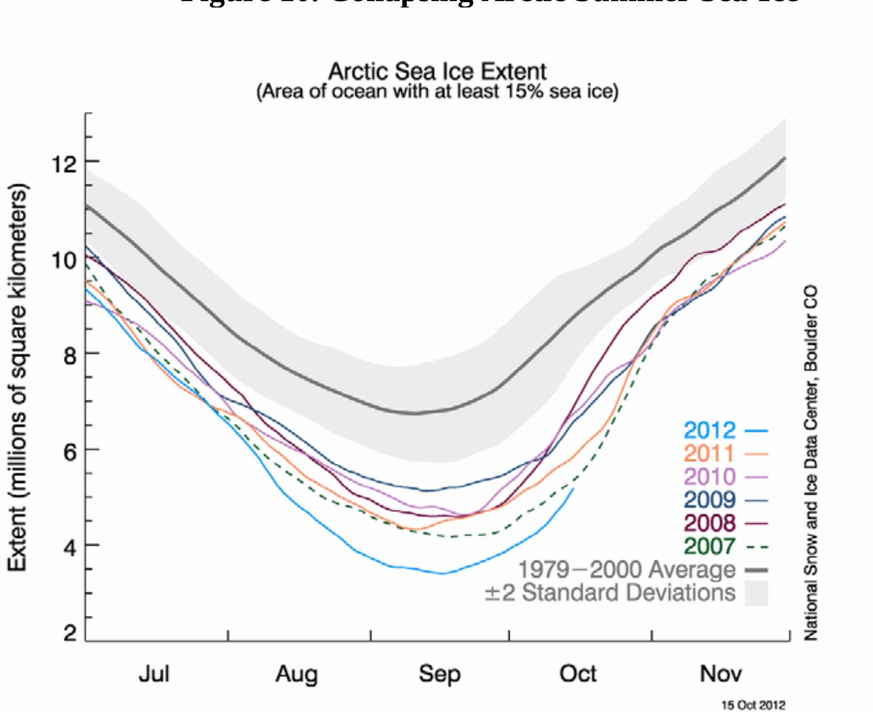
> *The thaw and release of carbon currently frozen in permafrost will increase atmospheric CO_2 concentrations and amplify surface warming to initiate a positive permafrost carbon feedback (PCF) on climate.* (Schaefer *et al.*, TELLUS B 2011.)

Some tipping points are already approaching much faster than worst case scenarios in IPCC AR4 in 2007. On September 16, 2012 Arctic summer sea-ice reached a new record minimum, nearly

50% less than the 1979-2000 average (*see* Fig. 10). Scientists now predict that the Arctic could be free of summer sea-ice by mid-century if not significantly sooner.

> *[C]ontraction of snow cover area, increases in thaw depth over most permafrost regions and decrease in sea ice extent; in some projections using SRES scenarios, Arctic late-summer sea ice disappears almost entirely by the latter part of the 21st century.* (IPCC AR4, 2007)

Figure 10. Collapsing Arctic Summer Sea-Ice



The graph above shows Arctic sea ice extent as of October 15, 2012, along with daily ice extent data for the previous five years. 2012 is shown in blue, 2011 in orange, 2010 in pink, 2009 in navy, 2008 in purple, and 2007 in green. The gray area around the average line shows the two standard deviation range of the data (NSIDC 2012.)

> *[T]he observed downward trend in sea-ice cover suggests that summer sea ice could disappear completely as early as 2030, something that none of the models used for the next report by the Intergovernmental Panel on Climate Change comes close to forecasting.* (Schiermeier, Nat 2012.)

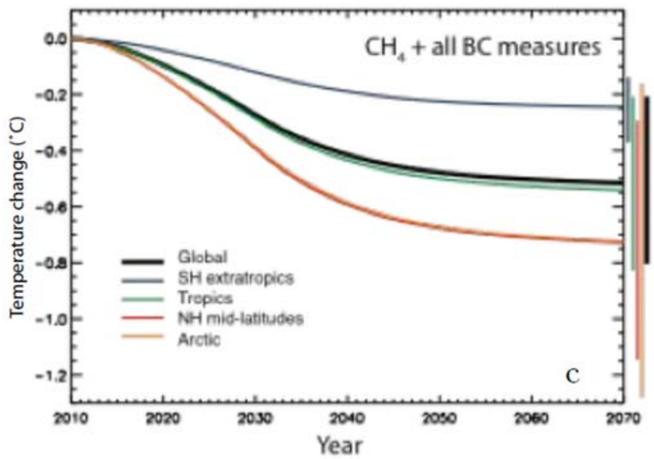
Reducing black carbon, tropospheric ozone, and its precursor, methane is critical for reducing warming and associated impacts in the Arctic and other vulnerable places in the near term. Black carbon is estimated to be responsible for 50% of the increase in Arctic warming, or almost 1°C of the total 1.9°C increase from 1890 to 2007. (Jacobson, JGR 2010; Shindell & Faluvegi, NG 2009.) Roughly 50% of the warming in the elevated Himalayan region has been attributed to the direct black carbon heating of the atmosphere and the surface. (Ramanathan *et al.*, JGR 2007; Flanner *et al.*, ACPD 2009; Xu *et al.*, CB 2009; Menon *et al.*, ACP 2010) Thus, reducing black carbon and other SLCPs is critical for slowing down the warming and glacier melting in the Arctic, the Himalayan-Tibetan region, and other vulnerable places (Menon *et al.*, ACP 2010; Ramanathan & Xu, PNAS 2010).

> *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.* (Shindell *et al.*, SCI 2012.)

Controlling FS [fossil-fuel soot] and BSG [solid-biofuel soot and gases] may be a faster method of reducing Arctic ice loss and global warming than other options, including controlling CH_4 or CO_2, although all controls are needed. (Jacobson, JGR 2010.)

Implementation of the [16 mitigation] measures would substantially slow, but not halt, the current rapid pace of temperature rise and other changes already occurring at the poles and high-altitude glacier regions. This is in part because particles co-emitted with BC, which are reflecting and therefore cooling over other regions, are still dark and absorb heat over ice and snow, leading to greater warming impacts…. the CH_4, BC Group 1 and Group 2 measures may reduce Arctic warming in 2070 by 0.37°C, 0.21°C and 0.14°C, respectively. The two additional Group 1 measures (pellet stoves and coal briquettes) drive the highest ratio of Arctic/global climate benefit in 2070, reducing Arctic warming by an additional 0.12°C [for a total of 0.84°C in avoided Arctic warming]. (UNEP-WMO 2011.)

Figure 11. Regional Temperature Benefits From SLCP Mitigation



Global and regional temperature benefits relative to business-as-usual (BAU) warming from deployment of 16 SLCP mitigation measures. In 2070 additional temperature rise in the Arctic, compared to 2010 temperatures, could be 0.84°C lower than BAU, 0.25°C in the Southern Hemisphere extratropics, 0.59°C in the tropics, and 0.83°C lower in the Northern Hemisphere mid-latitudes. Global average temperatures are expected to be 0.54°C lower over the same period. (UNEP-WMO 2011.)

Reducing the current rate of warming and returning to a safer climate requires *fast-action mitigation for both CO_2 and SLCPs*, along with deliberate CO_2 removal from the atmosphere on a timescale of decades, starting with bio-sequestration, including biochar.

We define ''fast-action'' to include regulatory measures that can begin within 2–3 years, be substantially implemented in 5–10 years, and produce a climate response within decades. We discuss strategies for short-lived non-CO2 GHGs and particles, where existing agreements can be used to accomplish mitigation objectives. Policy makers can amend the Montreal Protocol to phase down the production and consumption of hydrofluorocarbons (HFCs) with high global warming potential. Other fast-action strategies can reduce emissions of black carbon particles and precursor gases that lead to ozone formation in the lower atmosphere, and increase biosequestration, including through biochar. These and other fast-action strategies may reduce the risk of abrupt climate change in the next few decades by complementing cuts in CO_2 emissions. (Molina *et al.*, PNAS 2009.)

Mitigation of SLCPs is not a substitute for CO_2 mitigation; both are required to keep the warming below the 2°C guardrail this century:

Therefore, efforts to reduce emissions of black carbon and ozone precursors should be presented not as substitutes for commitments to reducing carbon dioxide emissions but as wasys to quickly achieve local environmental and economic benefits.

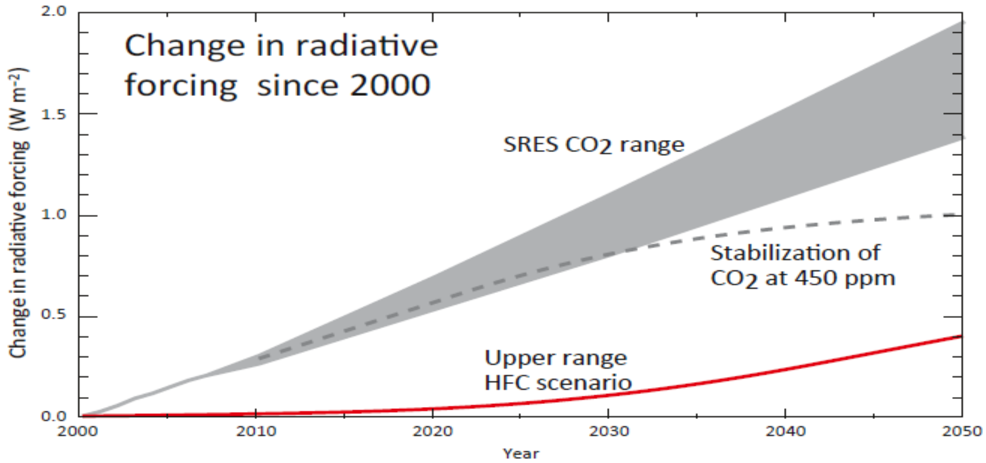
At the current rate of global warming the earth's temperature stands to careen out of control. Now is the time to look carefully at all the possible brakes that can be applied to slow climate change, hedge against near-term climate disasters, and buy time for technological innovations. Of the available strategies, focusing on reducing emissions of black carbon and ozone precursors is the low-hanging fruit: the costs are relatively low, the implementation is feasible, and the benefits would be numerous and immediate. (Wallack & Ramanathan, FA 2009.)

One promising fast-action strategy is to strengthen climate protection under the Montreal Protocol stratospheric ozone treaty by phasing down high GWP HFCs. The Montreal Protocol has successfully phased out 98% of nearly 100 ozone-depleting and climate-warming chemicals. This has provided mitigation of up to 222 billion tonnes of CO_2-eq. and delayed warming by up to 12 years worth of CO_2 emissions (Velders *et al.*, PNAS 2007.) The 197 Parties to the treaty are now phasing out ozone-depleting and climate-damaging HCFCs, which will provide an additional 15 billion tonnes of CO_2-eq. in climate mitigation by 2040 (Velders *et al.*, PNAS 2009.) Unfortunately, high-GWP HFCs are growing 10 to 15% per year as they are used as substitutes for HCFCs in an increasing number of applications. Phasing down production and use of high GWP HFCs would substantially reduce one of the six Kyoto gases and achieve mitigation of over 100 billion tonnes of CO_2-eq. by 2050 through a treaty that has always succeeded, and at a cost that could be pennies of public funding per tonne of CO_2-eq. Historically, such transitions under the Montreal Protocol have also significantly improved the energy efficiency of the refrigerators, air conditioners, and other products and equipment using refrigerants, reducing CO_2 emissions (TEAP 2010.) Unless high-GWP HFCs are phased down, the rapid growth of HFCs will cancel the climate mitigation already achieved by the Montreal Protocol (Velders *et al.*, SCI 2012; UNEP 2011.)

Total avoided net annual ODS emissions [under the Montreal Protocol] are estimated to be equivalent to about 10 Gt CO_2/ year in 2010, which is about five times the annual reduction target of the Kyoto Protocol for 2008–2012. This climate benefit of the Montreal Protocol may be reduced or lost completely in the future if emissions of ODS substitutes with high GWPs, such as long- lived HFCs, continue to increase. (Velders *et al.*, SCI 2012.)

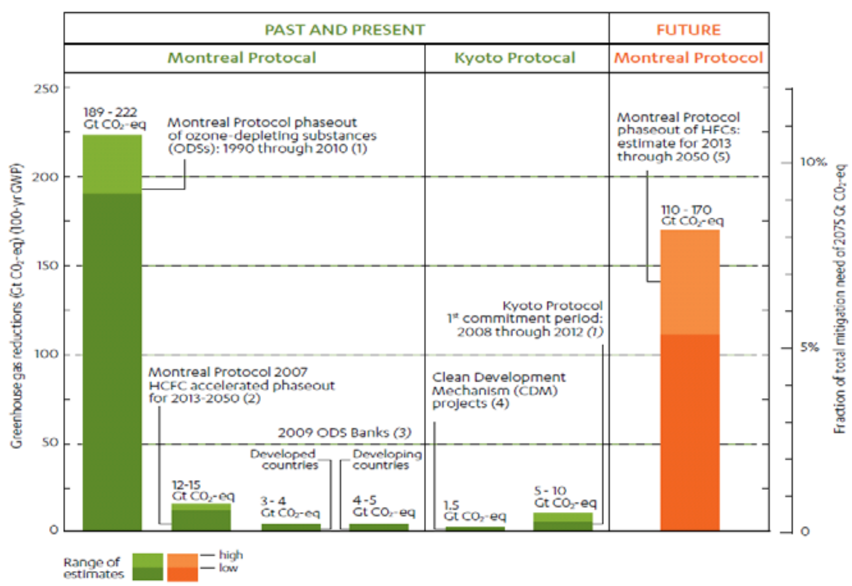
The atmospheric abundances of major HFCs used as ODS substitutes are increasing 10 to 15% per year in recent years…. In an upper-range scenario, global radiative forcing from HFCs increases from about 0.012 W/m^{-2} in 2010 to 0.25 to 0.40 W/m^{-2} in 2050. This corresponds to 14 to 27% of the increase in CO_2 forcing under the range of Intergovernmental Panel on Climate Change (IPCC) business-as-usual scenarios from 2010 to 2050…. If the current mix of HFCs with an average lifetime of 15 years (average GWP of 1600) were replaced by HFCs with life- times less than 1 month (GWP less than ~20), the total HFC radiative-forcing contribution in 2050, even under the high-emission scenario, would be less than the current forcing from HFCs (see the graph). Such choices are currently available. (Velders *et al.*, SCI 2012.)

Figure 12. 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 influence 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 significant 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-fifth 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. (UNEP 2011)

Figure 13. Climate Protection of the Montreal Protocol and the Kyoto Protocol



(UNEP, 2012)

The study by Molina et al. (2009) reports that in the twenty years up to 2010, the phase-out of production and consumption of ODSs has reduced GHG emissions by a net 135 billion tonnes of CO_2 equivalent or about 11 billion tones CO_2 equivalent per year. This is about five times more than the Kyoto Protocol annual emissions reduction target for the period 2008–2012 (WMO, 2010). . . . The value attached to the cumulative reduction in GHG emissions from the Montreal Protocol would then be estimated at US$ 3,262 billion over a period of 20 years. This amounts to about 6 per cent of the world's current GDP or put another way, the average annual reduction over the period is valued at 0.3 per cent of current GDP. (UNEP, 2012)

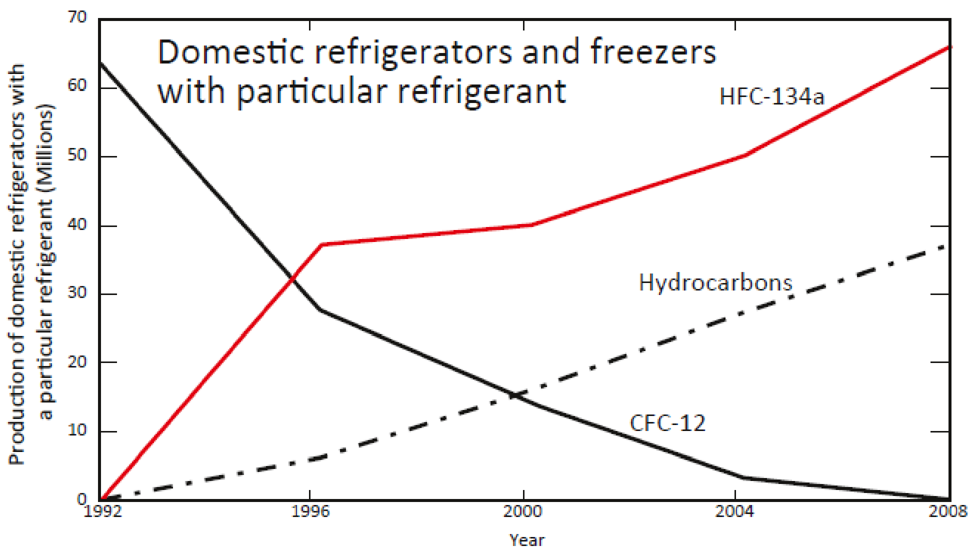
Substitutes for HFCs already exist for many uses and others are expected soon, according to TEAP and other authorities. In addition, a coalition of 650 companies in the Consumer Goods Forum has already pledged to avoid HFCs beginning in 2015.

> *Approaches to reduce climate forcing from future HFC use and to preserve climate benefits provided by the Montreal Protocol include…: (i) replacing high-GWP HFCs with substances that have low impact on climate (e.g., hydrocarbons, CO_2 or certain HFCs) and alternative technologies (e.g., fiber insulation materials) and (ii) reducing HFC emissions (e.g., by changing the design of equipment and capturing and destroying HFCs when equipment reaches the end of its useful life)…. Low-climate-impact substitutes are already in commercial use in several sectors.* (Velders *et al.*, SCI 2012.)

> *Technology is available to leapfrog high-GWP HFCs in some applications, which would avoid a second transition out of HFCs and complications of an increasingly large inventory of HFC equipment requiring servicing with HFCs that may be expensive or not easily available.* (TEAP 2010.)

> *As the Board of the Consumer Goods Forum, we recognise the major and increasing contribution to total greenhouse gas emissions of HFCs and derivative chemical refrigerants. We are therefore taking action to mobilize resources within our respective businesses to begin phasing-out HFC refrigerants as of 2015 and replace them with non-HFC refrigerants (natural refrigerant alternatives) where these are legally allowed and available for new purchases of point-of-sale units and large refrigeration installations.* (TCGF 2010.)

Figure 14. Annual global production of domestic refrigerators and freezers, showing changes in the refrigerants used from 1992 to 2008 (RTOC 2011).



About 104 million domestic refrigerators and freezers are produced annually. Each unit can contain 50 - 250 grams of HFC refrigerant, and up to 1kg of HFC blowing agent in the insulating foam. When CFCs were being phased out in the 1990s, hydrocarbon technology was developed for domestic refrigerators to provide a low-GWP alternative to ODSs and HFCs. The use of hydrocarbons has grown to about 36% of the global market for new domestic refrigerators and freezers (Figure 4.1), and is expected to reach about 75% of global production by 2020 (TEAP 2010a). Energy efficient hydrocarbon systems are now used by refrigerator manufacturing companies in many countries, including: Argentina, China, Denmark, France, Germany, Hungary, India, Indonesia, Italy, Japan, South Korea, Mexico, Russia, Swaziland, Turkey, Brazil and recently in USA (Maté 2010; TEAP 2010a). (UNEP 2011.)

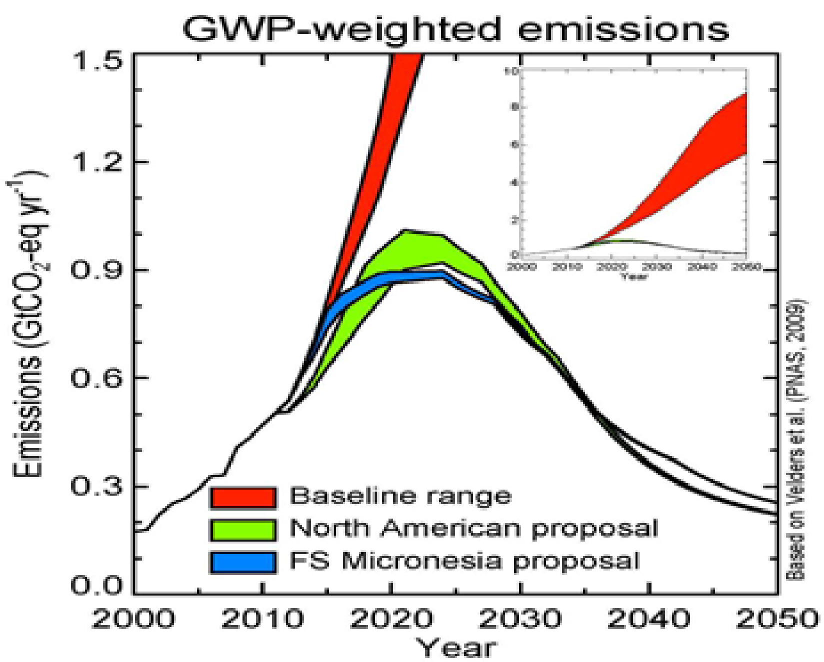
Vulnerable island states, led by the Federated States of Micronesia (FSM), have proposed phasing down production and use of high-GWP HFCs under the Montreal Protocol, leaving control of emissions of HFCs in the Kyoto Protocol. (Montreal Protocol 2012.) The US, Mexico, and

Canada made a similar proposal (Montreal Protocol 2012). 108 Parties had expressed support to the Bangkok Declaration on the global transition away from HCFCs and HFCs, upon its closure to additional signatories in 2011 (Montreal Protocol 2011). By November 2012, 105 parties had provided written support to the Bali Declaration on Transitioning to Low Global Warming Potential Alternatives to Ozone Depleting Substances, with a few more verbal supports (Montreal Protocol 2012).

The FSM's 2012 Proposed Amendment will strengthen climate protection under the Montreal Protocol by phasing down the production and consumption of HFCs, a group of super-greenhouse gases. Phasing down HFCs is essential to fulfilling obligations under the Vienna Convention to limit the adverse environmental effects, including effects on the climate system, of actions taken to protect the ozone layer. The resulting benefit will be up to 100 billion tonnes of CO_2-eq. mitigation by 2050 under a treaty that has successfully phased out nearly 100 other chemicals. (Montreal Protocol 2012.)

Cumulative benefits of the HFC phasedown estimated by the U.S. Government amount to reductions of 2,200 million metric tons of carbon dioxide equivalent (MMT CO2eq) through 2020, and about 85,000 $MMTCO_2eq$ through 2050…. Cumulative benefits from HFC-23 byproduct emissions controls as estimated by the U.S. Government amount to an additional 11,300 $MMTCO_2eq$ through 2050…. The proposal leaves unchanged the provisions of the UNFCCC/Kyoto Protocol that govern HFC emissions. Parties could follow Montreal Protocol obligations to meet certain UNFCCC obligations (Montreal Protocol 2012.)

Figure 15. Cumulative Decrease of Direct GWP-Weighted Emissions of HFCs under the Proposed Micronesian and North American Amendments to the Montreal Protocol



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. Prepared Dr. Guus Velders, based on Velders G. et al., The large contribution of projects HFC emissions to future climate forcing, PNAS (2009).

[Bali] Declaration on the global transition away from hydrochlorofluorocarbons (HCFCs) and chlorofluorocarbons (CFCs)…. [The 108 Party signatories] Encourage all Parties to promote policies and measures aimed at selecting low-GWP alternatives to HCFCs and other ozone-depleting

substances;… Declare our intent to pursue further action under the Montreal Protocol aimed at transitioning the world to environmentally sound alternatives to HCFCs and CFCs. (Montreal Protocol 2010 & 2011.)

The Rio+20 declaration, *The Future We Want*, provides universal support for phasing down consumption and production of HFCs.

222. We recognize that the phase-out of ozone-depleting substances is resulting in a rapid increase in the use and release of high global-warming potential hydrofluorocarbons to the environment. We support a gradual phase-down in the consumption and production of hydrofluorocarbons. (*The Future We Want* 2012)

A second fast-action strategy is to cut black carbon and tropospheric ozone and its precursor, methane—local air pollutants that harm public health, crops, ecosystems, and carbon sinks, and that also cause climate change. Unlike CO_2, black carbon, tropospheric ozone and its precursor, methane, disappear quickly from the atmosphere once emissions are cut. Reducing these local air pollutants can cut the rate of global warming by up to half and the rate of Arctic warming by up to two-thirds over the next thirty years. In addition to producing fast climate results, reducing these local air pollutants would also deliver strong collateral benefits for public health, food security, and ecosystems, including carbon sinks, providing independent justification for fast action. These benefits, including much of the climate mitigation benefit, would be 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% (Ramanathan & Carmichael, NG 2008).

Reducing black carbon, methane and tropospheric ozone now will slow the rate of climate change within the first half of this century…. A small number of emission reduction measures targeting black carbon and ozone precursors could immediately begin to protect climate, public health, water and food security, and ecosystems. (UNEP-WMO 2011.)

The selection criterion [for a mitigation measure] was that the measure had to be likely to reduce global climate change and also provide air quality benefits, so-called win-win measures. Those measures that provided a benefit for air quality but increased warming were not included in the selected measures. (UNEP-WMO, 2011)

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. (UNEP 2011.)

Mitigation of diesel-engine sources appears to offer the most confidence in reducing near-term climate forcing. Mitigating emissions from residential solid fuels also may yield a reduction in net positive forcing. The net effect of other sources, such as small industrial coal boilers and ships, depends on the sulfur content, and net climate benefits are possible by mitigating some individual source types. (Bond *et al.*, 2013)

Annual average BC concentrations in California have decreased by about 50% from 0.46 $\mu g\ m^{-3}$ in 1989 to 0.24 $\mu\ gm^{-3}$ in 2008 compared to the corresponding reductions in diesel BC emissions (also about 50%) from a peak of 0.013 Tg Yr^{-1} in 1990 to 0.006 Tg Yr^{-1} by 2008. We attribute the observed negative trends to the reduction in vehicular emissions due to stringent statewide regulations. Our conclusion that the reduction in diesel emissions is a primary cause of the observed BC reduction is also substantiated by a significant decrease in the ratio of BC to non-BC aerosols. (Bahadur *et al.*, 2011)

This small number of mitigation measures is capable of realizing "nearly 90% of the maximum reduction in net GWP." (Shindell *et al.*, SCI 2012.) They include the 14 measures listed below. Eliminating kerosene-fueled wick lamps is an additional mitigation measure. (Lam *et al.*, ES&T).

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

(Shindell *et al.*, SCI 2012.)

Full implementation of the [14] identified measures [by 2030] would reduce future global warming by 0.5˚C (within a range of 0.2–0.7˚C)… by 2050…. Full implementation of the identified measures… 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, [in addition to providing substantial benefits in] the Himalayas and other glaciated and snow-covered regions. (UNEP-WMO 2011.)

Kerosene-fueled wick lamps used in millions of developing-country households are a significant but overlooked source of black carbon (BC) emissions…. Kerosene lamps have affordable alternatives that pose few clear adoption barriers and would provide immediate benefit to user welfare…. No other major BC source has such readily available alternatives, definitive climate forcing effects, and cobenefits. Replacement of kerosene-fueled wick lamps deserves strong consideration for programs that target short-lived climate forcers. (Lam *et al.*, ES&T)

In addition to climate benefits, reducing SLCPs provides strong collateral benefits for public health and food security.

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. Over 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. (Anenberg *et al.*, EHP 2012.)

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. (Shindell *et al.*, SCI 2012.)

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. (UNEP-WMO 2011.)

Air pollution is set to become the world's top environmental cause of premature mortality, overtaking dirty water and lack of sanitation. Air pollution concentrations in some cities, particularly in Asia, already far *exceed World Health Organization safe levels, and they are projected to deteriorate further to 2050…. The number of premature deaths from exposure to particulate matter … is projected to more than double worldwide, from just over 1 million today to nearly 3.6 million per year in 2050, with most deaths occurring in China and India…. The absolute number of premature deaths from exposure to ground-level ozone is to more than double worldwide (from 385 000 to nearly 800 000) between 2010 and 2050. Most of these deaths are expected to occur in Asia, where the ground-level ozone concentrations as well as the size of the exposed population are likely to be highest.* (OECD 2012.)

The regions making reductions in black carbon and tropospheric ozone get most of the benefits.

The health benefits from implementing black carbon mitigation measures would be realized immediately and almost entirely in the regions that reduce their emissions. Regions taking action on black carbon would also benefit significantly from reduced regional warming, reduced disruption of regional weather patterns, as well as a substantial reduction in crop-yield losses.... Nearly all of the health benefit, 87-99 per cent, would be realized within the same regions that implement the measures, which is worth considering when deciding on national actions to reduce SLCFs. (UNEP 2011.)

Most of the control measures for reducing black carbon and tropospheric ozone and its precursor, methane, can be implemented immediately with existing technologies and often with existing laws and institutions.

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. (Molina *et al.*, PNAS 2009.)

*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.* (UNEP 2011.)

Many other policy alternatives exist to implement the CH4 [methane] and BC measures, including enhancement of current air quality regulations. (Shindell *et al.*, SCI 2012.)

Regulatory policies and forums exist to reduce non-CO2 warming agents. The Montreal Protocol with modifications for HFC regulations can be an effective tool for reducing watts attributable to HFCs. National policies exist to limit CO and other ozone-producing gases. (Ramanathan & Xu, PNAS 2010.)

These measurements … provide a direct link between regulatory control policies and the long-term impact of anthropogenic emissions. Our model calculation indicates that the decrease in BC in California has lead to a cooling of 1.4Wm^{-2} (±60%). The regulation of diesel fuel emissions in California therefore has proven to be a viable control strategy for climate change in addition to mitigating adverse human health effects. (Bahadur *et al.*, AE 2011.)

Half of the identified measures can be implemented with a net cost savings for those making the investment, and all are ultimately cost-effective when the $5.9 trillion annual benefits that start in 2030 are taken into account.

About 50 per cent of both methane and black carbon emission 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 emission reduction could be addressed at relatively moderate costs.* (UNEP 2011.)

*Benefits of methane emissions reductions are valued at $700 to $5000 per metric ton, which is well above typical marginal abatement costs (less than $250). *** … [T]he bulk of the BC measures could probably be implemented with costs substantially less than the benefits given the large valuation of the health impacts.* (Shindell *et al.*, SCI 2012.)

While many measures can provide a net cost savings, new policies and financing measures will likely be required to overcome implementation barriers.

[A]bout half of the temperature reduction would emerge from Group 1 measures [low cost methane and black carbon measures], which result in net cost savings to society over their full technical lifetime. However, the required up-front investments over an assumed 20 years implementation period do constitute a considerable barrier to implementation. Prevailing short-term profit expectations of private investors make these measures less attractive to the market…. For all Group 1 measures, targeted interventions or appropriate financing mechanisms could help to overcome implementation barriers. In comparison, measures of Group 2, which could potentially be competitive on a carbon market, require much lower up-front investments, especially for methane recovery in coal mines. Some of the more costly measures for controlling SLCFs are often/usually implemented for other development related objectives. (UNEP 2011.)

The Climate & Clean Air Coalition is pursing mitigation strategies for black carbon, tropospheric ozone, and methane, as well as HFCs. (CCAC 2012.) The World Bank, a member of the Coalition, wants to increase its initial portfolio of SLCP-relevant mitigation from its current 12 percent to 15 percent by 2015 and 20 percent by 2020. The Bank estimates that its current investment in mitigation of black carbon and methane is $12 billion.

At the Bank, we want to expand the SLCP-relevant part of our IDA/IBRD portfolio from 12 percent in 2012 to 15 percent by 2015 and 20 percent by 2020, and will work on payment for results for methane reduction. We also plan to increase impact on SLCPs through our GEF, Carbon Finance, Global Gas Flaring, and Montreal Protocol portfolios. (Kyte, 12 Dec 2012.)

The World Bank Group has numerous projects that we implement that help reduce SLCPs. For example, a back of the envelope analysis for methane and black carbon showed about $12 billion of investments, or 140 projects, approved between 2006-11 support SLCP reductions. These include investment in everything from cleaner fuels, better urban landfill management and cleaner cookstoves. We also support important partnerships to reduce SLCPs, such as the Global Gas Flaring Reduction Partnership (GGFR) which works with governments and companies in reducing the flaring and venting of associated gas. The Montreal Protocol, for which the World Bank serves as an implementing agency, is now actively promoting alternatives to HFCs where available. HFCs are human-created gases used to replace ozone depleting substances but which are strong, short-lived global warmers by themselves. (Barton-Dock, 9 July 2012.)

A final fast-action strategy is to deliberately remove excess CO_2 from the atmosphere on a timescale of decades rather than the natural timescale of millennia in order to return to a safe and stable climate as soon as possible. Reducing CO_2 concentrations to a level consistent with a safe and stable climate requires that carbon sinks ultimately exceed emissions sources. Strategies for enhancing sinks include protecting and expanding forests, wetlands, grasslands, and other sources of biomass that are removing CO_2 from the atmosphere, as well as pyrolysis of waste biomass (cooking it with limited oxygen) to produce a permanent form of carbon called biochar that can safely return carbon to permanent storage for hundreds to thousands of years. Bio-sequestration of CO_2, including biochar, can match and ultimately exceed CO_2 emissions to achieve a net drawdown of CO_2 on a timescale of decades rather than the millennia timescale of the natural cycle, assuming aggressive CO_2 mitigation as well.

> *A combined approach of deliberate CO_2 removal (CDR) from the atmosphere alongside reducing CO_2 emissions is the best way to minimize the future rise in atmospheric CO_2 concentration, and the only timely way to bring the atmospheric CO_2 concentration back down if it overshoots safe levels.... By mid-century, the CDR flux together with natural sinks could match current total CO_2 emissions, thus stabilizing atmospheric CO_2 concentrations. By the end of the century, CDR could exceed CO_2 emissions, thus lowering atmospheric CO_2 concentration and global temperature.* (Lenton, CM 2010.)

> *In the most optimistic scenarios, air capture and storage by BECS [bioenergy and carbon sequestration], combined with afforestation and bio-char production appears to have the potential to remove ≈100 ppm of CO_2 from the atmosphere…on the 2050 timescale.* (Lenton & Vaughan, ACP 2009.)

> *Strong mitigation, i.e. large reductions in CO_2 emissions, combined with global-scale air capture and storage, afforestation, and bio-char production, i.e. enhanced CO_2 sinks, might be able to bring CO_2 back to its pre-industrial level by 2100, thus removing the need for other geoengineering.* (Lenton & Vaughan, ACP 2009.)

Other CO_2 removal strategies include direct air capture and capture at smokestacks. The CO_2 captured from smokestacks then requires re-utilization or other storage, for example as calcium carbonate, which can be used as a substitute for a portion of ordinary Portland cement or of aggregate.

> *While about half of the anthropogenic CO_2 emissions are the result of large industrial sources such as power plants and cement factories, the other half originate from small distributed sources such as cars, home heating, and cooking. For those, CO_2 capture at the emission source is not practical and/or economical. A possible pathway to deal with these emissions is to capture CO_2 directly from the air. One of the advantages of CO_2 capture from the atmosphere is that the needed infrastructure can be placed anywhere, preferably where it has the least impact on the environment and human activities or close to CO_2 recycling centers.* (Goeppert *et al.*, JACS 2011.)

> *DAC [Direct Air Capture] is one of a small number of strategies that might allow the world someday to lower the atmospheric concentration of CO_2.* (APS 2011.)

> *Calera … can capture up to 90% of CO_2 from power plants…and can convert the CO_2 into stable calcareous material and bicarbonate solution with an energy penalty ranging from about 10% to 40%.... The … calcareous material … [can] replace a portion of either the product called "Ordinary Portland Cement" (OPC) or to replace or reduce OPC ingredients in blended cement, and thus potentially avoiding CO_2 emissions from cement manufacture… In some cases, the combined reductions in greenhouse gas emissions from power plant CCS and avoided cement production are potentially greater than the total emissions of either process alone….* (Zaelke *et al.*, 2011.)

> *Blue Planet, Ltd. (Blue Planet), a Cayman Islands company with offices in Moss Landing, California . . . commercialize[s] its patented method for converting the CO_2 captured from the flu gas of coal and gas-fired power plants, cement plants, or any other source, into solid building materials: cement or aggregate. The resulting cement or aggregate can be combined to form concrete for use in roads, bridges, dams or buildings. The CO_2 is permanently chemically bonded as carbonate inside the cement or aggregate without leaching into ground water or releasing into the air.*

Conclusion

All of these strategies are necessary to reduce current climate impacts, to slow dangerous feedbacks, and to reduce the risk of passing tipping points that could lead to irreversible climate impacts. Reducing CO_2 remains the top priority, but we also need to simultaneously reduce SLCPs in order to achieve near-term benefits that will keep us from losing the climate battle while CO_2 emission reductions are carried out. We also need to perfect and implement strategies to deliberately reduce excess CO_2 from the atmosphere on a time scale of decades. The take-away message from the science and the growing impacts is *the need for speed* and the importance of fast-action mitigation to address all causes of climate change.

Select press coverage of SLCPs

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