CLIMATE & CLEAN AIR COALITION
TO REDUCE SHORT-LIVED CLIMATE POLLUTANTS

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Prepared by CCAC Scientific Advisory Panel

ANNUAL SCIENCE UPDATE 2015

Several publications were released in 2015 and early 2016 that have provided insights and better understanding of SLCP science, including on their emissions, inventories, impacts as well as benefits of emissions mitigation. They have also provided stronger scientific basis for action on SLCPs. This Climate and Clean Air Coalition (CCAC) Scientific Advisory Panel (SAP) Annual Science Update 2015 presents a summary of some of the important new scientific findings relevant to CCAC's work.

MAIN FINDINGS

SLCP emissions and inventories

- Atmospheric observations suggest that methane in the atmosphere has started to increase rapidly again after a decade of hiatus that was followed by slower growth (Figure S.1). This increase is likely due to a number of factors, including increased emissions from agriculture activities, large increases in natural gas extraction and associate leaks (see Section 1.1).
- Comparison of recent estimates of methane emissions with existing inventories such as that of the USEPA shows that current inventories underestimates methane emissions due to inaccurate measurements in some emissions sectors (see Section 1.1).
- It is therefore important that causes of methane emissions increase are clearly identified and existing inventories updated. This will provide vital data and information needed for developing and evaluation of relevant policies and for taking actions geared towards preventing further increases, as well as decreasing emissions from known sources.

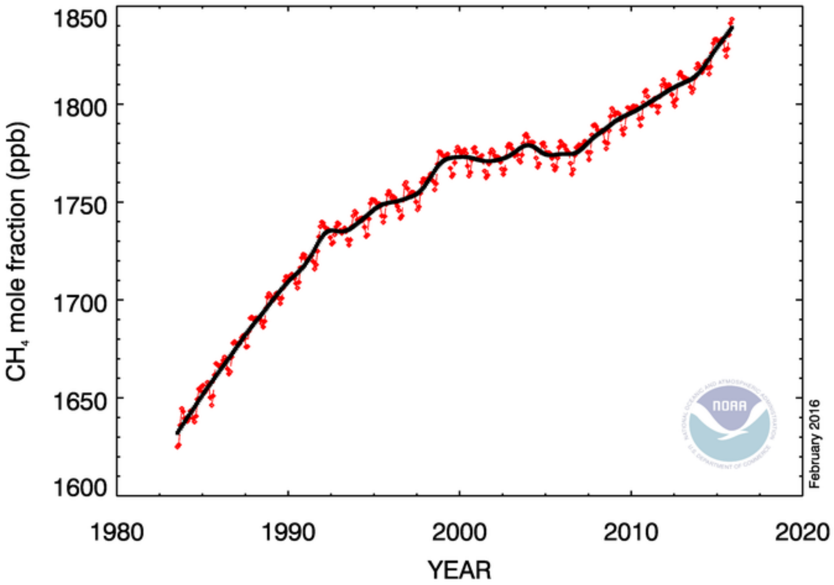

Figure S.1. Trend in the global mean of methane concentration *(Source: NOAA, February 2016).*

- Refinement of HFCs emissions inventories at the global and regional levels, to date and projected into the coming decades, points to a rise in emissions which are expected to grow steadily in coming years, mainly in developing countries. Particularly important is the growth in the production, consumption and emissions of high global warming HFCs. The findings highlight the importance of opportunities to mitigate emission growth in order to minimize their current and future climate forcing (see Section 1.2).
- Black carbon emissions are set to reduce somewhat under current policies. Asia remains the major emitter globally. In terms of emitting sector, recent results suggest that flaring of gases during oil and gas production is a major source of emissions that have been usually overlook, including in Russia (see Section 1.3).

SLCP impacts and mitigation benefits

Climate

- The continued increase in the production, consumption and emission of HFCs would lead to a substantial increase in the associated radiative forcing. If HFCs emissions are not abated, the radiative forcing could reach 0.22-0.25 Wm^{-2} in 2050. Under this business as usual scenario, HFCs contribution to global climate forcing between 2015 and 2050 will be equivalent to 12-24% of the total forcing expected from CO_2 in that same period under the RCP6 and RCP8.5 scenarios respectively (see Section 2.1.1).
- Knowledge of the global warming impact of black carbon continues to advance. New modelling result suggest that radiative forcing of black carbon have been underestimated by between 10 and 15% in many climate models that uses simplified modelling schemes instead of the more complex multi-stream schemes (see Section 2.1.1). New studies from the past two years also indicated that the lifetime of BC was likely overestimated in most models, biasing the forcing upwards. The net impacts accounting for both factors are unlikely to be markedly different (see Section 2.1.1).
- SLCP emissions, in particular from black carbon, led to a surface temperature response of 0.35°C (range 0.03-0.84) in the arctic region. Similarly, a net warming of 0.6°C across the Tibetan Plateau and the Himalayas was attributed to black carbon emissions, which consequently resulted in enhanced snow retreat. By mitigating SLCP emissions, warming in the arctic can be reduced by between 0.2 and 0.62°C (range of results from different studies). Overall, this highlights the importance and benefits of mitigating SLCP emissions especially in sensitive and vulnerable regions (see Section 2.1.1).
- Air pollution caused by absorbing aerosols, including black carbon, has been found to be linked to the 2013 flood in China. Similarly, black carbon related pollution was shown to be able to induce changes in precipitation patterns leading to both floods and drought. This emphasises the linkage between air pollution and extreme weather events and provide further incentives for tackling air pollution especially at the local and regional levels (see Section 2.1.2).

Health

- SLCP emission reductions are expected to yield health benefits while also providing long-term CO_2 mitigation benefits. Three key ways in which mitigating SLCPs would yield health benefits include by reducing the burden of disease due to air pollution, by reducing the impact of SLCP on extreme weather events such as floods and droughts and agriculture which consequently impacts human health, and by leading to improved human behaviour such as change in diet and active lifestyles, which promotes human health (see Section 2.2).
- Implementation of climate and clean air strategies focused mainly on CO_2, but also including methane, aerosols and ozone-related species, in the energy and transportation sectors, could help avoid 175,000 and

120,000 premature deaths respectively by 2030 in the US, while also providing a national economic value worth 250 billion dollars (see Section 2.2).

Ecosystems and agriculture

- Evidences continue to highlight the impacts of ozone on agriculture. Without significant reduction in ozone concentration, a 20% loss in yield of rice and maize by 2050 is expected in most part of the Middle East, India and China with a consequent need to expand agricultural land by 1.3 million km^2.
- More so, the use of different metrics is providing clearer insight into impacts of ozone on vegetation. It includes finding about higher uptake at low ozone concentration, with new results showing that trees in northern Europe with high uptake of ozone are more affected than those in the Mediterranean with higher concentration but lower uptake (see Section 2.3).

Energy efficiency

- Concurrent implementation of HFC refrigerant transition and energy efficiency improvement policies for room air conditioning could save between 340-790 gigawatts of peak power load globally. This action is also expected to lead to an avoided CO_2 emission of up to approximately 98 billion tonnes of CO_2 by 2050 (see Section 2.4).

Policies for SLCP abatement

The following highlights the main message from some recent influential publications discussing policies that can enhance SLCP actions:

- Climate change mitigation would require collective action happening on multiple fronts and not just within the UNFCCC. Such fronts could include partnerships like the CCAC, multilateral agreement actions, for example the Montreal Protocol and bilateral programmes such as that between the US and China or the US and Canada. International cooperation is therefore imperative for achieving success.
- Tackling climate change and its impacts could be the greatest global health opportunity of the 21st century; hence, a need for stronger emphasis of health issues in the climate change discourse. Furthermore, the incorporation of the full range of impacts attributable to emissions not just the climate-related damages could help in the identification of policies with the greatest overall benefits to the society.
- Carbon pricing could be one of the effective tools for reducing carbon emissions as it helps account for the health and other socio-economic impacts of emissions. More so, an estimated income worth 2.6% of global gross domestic product together with a 23% reduction in CO_2 emissions, as well as 63% avoided pollution-related premature mortality can accrue through carbon taxation. Broad metrics are needed in order to optimally use pricing to reduce SLCPs.

DETAILED UPDATE

1. SLCPs emissions and inventories

Several publications on SLCP emissions and inventories were produced in the past one year which has help expand our knowledge of SLCPs and their impacts. This section present the findings from some of these publications.

1.1. Methane emissions and inventories

A recent study[1] on methane emissions from the 2015 Aliso Canyon blowout in California, US, indicates that the incident resulted in an unprecedented methane release into the atmosphere. According to the analysis, which employed pollution-detecting aircraft to collect data on emissions from dozens of plume between 7 Nov 2015 and 13 Feb 2016, a total of 97,100 metric tonnes (0.1Tg) of methane was released into the atmosphere. The emissions, which represents the largest methane leak in US history, is expected to substantially impact the State of California greenhouse gas (GHG) emission targets and equates to the yearly energy sector methane emissions from a medium-sized European Union country. The study further suggest that the radiative forcing[2] from the released gas, when integrated over the next 100 years, equals that from the annual GHG emissions from 572,000 passenger cars. Overall, the incident represents a warning about the important role of fugitive emissions and the need for preventative measures in the effort to reduce methane emissions into the atmosphere and therefore calls for increased action to reduce emission in order to counter the unfortunate situation.

A number of new studies have attempted to quantify methane emissions from diverse sources and at different geographical scale. One study[3] put the total global methane emissions between 2009 and 2011 at approximately 540 Tg/yr with human induced emission accounting for about 360 Tg/yr. The study further found discrepancies between the US EPA inventory and their results which estimated US anthropogenic emissions at about 40 Tg/yr compared to US EPA inventory of 27 Tg/yr. Similarly, another publication[4], using satellite retrieval and surface observations suggested that US methane emissions have increased by more than 30% between 2002 and 2014 contrary to national inventory estimates which indicates no significant trend. Another study,[5] focused on East Asia, indicated that total emission from countries in this region increased from 43 to 59 Tg/yr between 2000 and 2011 largely due to increased emissions in China (39 to 54 Tg/yr.). The study however indicated that China's emissions were 29% lower than previous estimates.

From the sectorial perspective, findings[6] from both top-down and bottom-up estimates of methane emissions from oil and gas operations indicates that emissions from these operations have been underestimated. Results from a

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[1] Conley et al. 2016. Methane emissions from the 2015 Aliso Canyon blowout in Los Angeles, CA. Science, DOI: 10.1126/science.aaf2348

[2] Radiative forcing is a measure of how a climate forcing agent influences the energy balance of Earth, thereby contributing to climate change. A positive value indicates a net heat gain to the lower atmosphere, which leads to a globally average surface temperature increase, and a negative value indicating a net heat loss.

[3] Turner et al. 2015. Estimating global and North American methane emissions with high spatial resolution using GOSAT satellite data. Atmos. Chem. Phys., 15, 7049-7069.

[4] Turner et al. 2016. A large increase in US methane emissions over the past decade inferred from satellite data and surface observations. Geophysical Research Letters. DOI: 10.1002/2016GL067987

[5] Thompson et al. 2015. Methane emissions in East Asia for 2000–2011 estimated using an atmospheric Bayesian inversion. J. Geophysical Research, Atmosphere, 120, 4352–4369

[6] For example Harriss et al. 2015. Using Multi-Scale Measurements to Improve Methane Emission Estimates from Oil and Gas Operations in the Barnett Shale Region, Texas. Environ. Sci. Technol. 2015, 49, 7524−7526; Lan et al. 2015. Characterizing Fugitive Methane Emissions in the Barnett Shale Area Using a Mobile Laboratory. Environ. Sci. Technol., 49, 8139-8146. Zavala-Araiza et al. 2015. Reconciling divergent estimates of oil and gas methane emissions. PNAS, 112, 15597–15602, doi: 10.1073/pnas.1522126112; Karion et al. 2015. Aircraft-Based Estimate of Total Methane Emissions from the Barnett Shale Region.

coordinated field campaign of oil and gas facilities in north Texas, US shows that estimates were approximately 1.5 times higher than expected from the US EPA Greenhouse Gas Inventory (GHGI). Two reasons for this is because of higher emissions factor and more importantly, because old estimates do not include all gathering compressor stations which have emissions that are comparable to mainline transmission compressor stations. Results from another study[7], indicate that estimates of methane emissions from natural gas infrastructures have been underestimated due to failure of the only commercially available, US EPA approved and therefore widely deployed Bacharach Hi-Flow Sampler (BHFS), used for quantifying leakages from natural gas transmission, storage and processing facilities. The findings suggest that natural gas concentrations reported by the BHFS can be more than an order of magnitude lower which would consequently result in erroneous low emission estimate since the concentrations from the BHFS is employed in calculating emissions rate. This finding could be an explanation for the discrepancies in results from top-down and bottom-up estimates from natural gas infrastructures and have implication for emissions estimates across this sector as well as safety.

Another important finding with significant implication for future methane emission and the need for urgent mitigation action is the recent observed decline in the use of coal as the major energy source in high energy consuming countries including China and the US. According to a recent commentary in Nature Climate Change[8], speedy growth in global CO_2 emissions from fossil fuel and industry stopped between year 2013 and 2014 despite continued economic growth due to a stall in the growth rate of energy consumption from coal. While this is a welcomed development in terms of CO_2 emission reduction, it is of concern for methane emission. This is because the stall in the growth rate of coal consumption has been accompanied by an increased growth rate for energy consumption from oil and especially gas (see figure 1.1)[9]. For example, the paper reported a 24% increase in consumption of natural gas for energy needs during the period of declined coal consumption resulting in a growth rate of approximately 3% for coal and 13% for natural gas in China. A similar trend is seen in the transition from conventional oil and gas to shale gas in the US in relation to CO_2 and methane emissions. According to one publication[10], the total greenhouse gas emissions from fossil fuel use in the USA increased between 2009 and 2013 due to increased methane emission from shale gas production lifecycle even though total CO_2 emissions within this period declined. The paper indicates that this trend is set to continue until 2040 unless mitigation effort are put in place.

While, the above suggest that the recent increase in methane emissions can be attributed to increased natural gas production, a more recent publication[11] seems to suggest the contrary. By investigating historical methane emissions from several measuring stations spanning between 1984 and 2015, the new study suggested that the post-2006 increases in methane concentrations are predominantly from biological sources rather than from fossil fuels. The study indicates that agricultural activities including rice farming and livestock production are the main source of recent methane emissions, with ruminants such as cows and sheep contributing a significant portion.

Environ. Sci. Technol., 49, 8124–8131; Lavoie et al. 2015. Aircraft-Based Measurements of Point Source Methane Emissions in the Barnett Shale Basin. Environ. Sci. Technol., 49, 7904−7913; McKain et al (2015). Methane emissions from natural gas infrastructure and use in the urban region of Boston, Massachusetts. PNAS, 112, 1941–1946, doi: 10.1073/pnas.1416261112

[7] Howard et al (2015). Sensor transition failure in the high flow sampler: Implications for methane emission inventories of natural gas infrastructure. Journal of the Air & Waste Management Association, 65, 856–862 and Howard 2015. University of Texas study underestimates national methane emissions at natural gas production sites due to instrument sensor failure. Energy Science & Engineering, 3, 443–455.

[8] Jackson et al. 2015. Reaching peak emissions. Nature Climate Change, 6, 7–10.

[9] It must be noted however that growth rate for energy consumption from nuclear and other renewable energy sources in China within the same period were higher than from natural gas at 13.3%/yr and 34.3%/yr respectively. Growth rate for hydro within this period was 10.5%/yr

[10] Howart 2015. Methane emissions and climatic warming risk from hydraulic fracturing and shale gas development: implications for policy

[11] Schaefer et al. 2016. A 21st century shift from fossil-fuel to biogenic methane emissions indicated by $^{13}CH_4$. Science. DOI: 10.1126/science.aad2705

Overall, these new insights provide vital data and information and highlight the need to develop relevant policies and for taking actions geared towards preventing further increases as well as decreasing emissions from known sources.

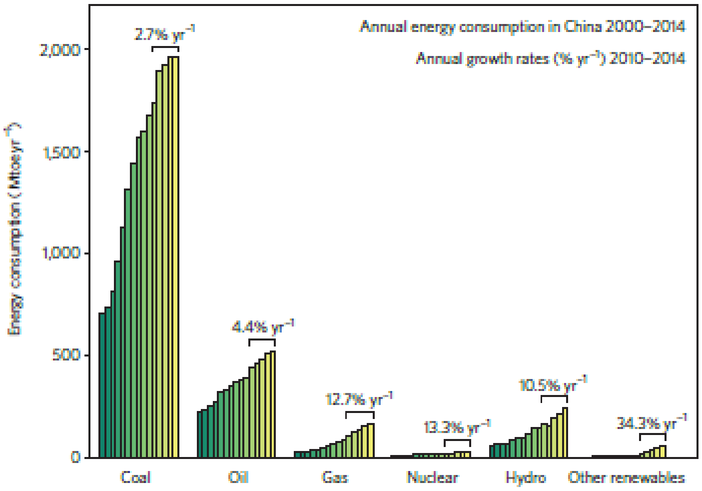

Figure 1.1. Energy consumption by fuel source from 2000 to 2014, with growth rates for period between 2010 and 2014.
(Source: Jackson et al. 2015. See footnote 8)

1.2. Hydrofluorocarbons emissions and inventories

Results from modelling efforts in 2015 provided insight into trends in the emissions of HFCs at the regional and global scales, as well as contributions from various emitting sectors. One study[12] indicates a continued dramatic rise in global emissions of five major HFCs from 0.30 (0.28–0.32) $TgCO_2$-eq/yr in 2007 to 0.47 (0.44–0.50) $TgCO_2$-eq/yr in 2012, representing an average increase of 0.03 (0.02–0.04) $TgCO_2$-eq/yr. In another study[13], under business as usual conditions[14], the use and emissions of HFCs is expected to grow steadily in the coming years (Fig 1.2A) with emissions projected to be in the range of 4.0-5.3 $GtCO_2$-eq/yr. globally by 2050, that is, 0.8-1.0 $GtCO_2$-eq/yr. from developed countries and 3.2-4.4 $GtCO_2$-eq/yr. from developing countries (Fig 1.2B). Their results also show that China, India and the rest of Asia, the Middle East and northern Africa and the US will be the main source of HFCs emissions globally by 2050 with values of 31%, 23%, 11% and 10% respectively. Broken down into sectors, they further show that industrial/commercial refrigeration and stationary air conditioning will be the major sources of emissions by 2050 with 54% (range 40-58) and 27% (range 21-40) of total emissions respectively. This business as usual situation is expected to consequently result in a radiative forcing of 0.22-0.25 Wm^{-2} by 2050 with developing countries responsible for 0.16-0.19 Wm^{-2} and developed countries responsible for 0.06-0.07 Wm^{-2} (Figure 1.2C).

Another publication[15] focused on historical and projected HFCs emission trajectories in China revealed a rapid increase in HFC production, consumption and emissions between 2005 and 2013 in the country. Equivalent CO_2 emissions of HFCs in 2013 were estimated to have increased from 8.1 CO_2eq to 113 Tg CO_2eq/yr between 2005 and 2013 and are projected to increase to between 2000 and 2800 Tg CO_2eq/yr by 2050 under business as usual

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[12] Lunt et al. 2015. Reconciling reported and unreported HFC emissions with atmospheric observations. PNAS, 112. 5927–5931, doi: 10.1073/pnas.1420247112

[13] Velders et al. 2015. Future atmospheric abundances and climate forcings from scenarios of global and regional hydrofluorocarbon (HFC) emissions. Atmospheric Environment, 123, 200–209.

[14] The business as usual condition assumes that current uses (substances and technologies) of HFCs for specific sectors continue as it is presently and that developing countries follow the same transitions from HCFCs to HFCs as has occurred in developed countries.

[15] Fang et al. 2016. Hydrofluorocarbon (HFC) Emissions in China: An Inventory for 2005–2013 and Projections to 2050. Environ. Sci. Technol., 50, 2027–2034

situation. Of particular interest and concern is the fact that HFCs with high relative global warming potential (GWP)[16] including HFC-143a (GWP$_{100}$ = 5080) and HFC-125 (GWP$_{100}$ = 3450) dominate the emissions and have been growing at 100% and 83% respectively between 2005 and 2013. Under business as usual situation, the cumulative emissions of China between 2014 and 2050 was estimated at 59,000 (51,000-67,000) Tg CO$_2$eq, and is projected to offset the global climate benefit of the Montreal Protocol by a factor of 5 to 7.

Another study[17] highlighted an increase in the emissions of HFC-134a between 1995 and 2010 from about 19 Gg/yr to 167 Gg/yr with a slowdown in developed countries and a 20% increase in China since 2005. This is of particular concern and interest given that HFC-134a has high GWP of over 1500 over a 100 year period and there are already available low GWP products replacement for use in refrigeration and air-conditioning systems.

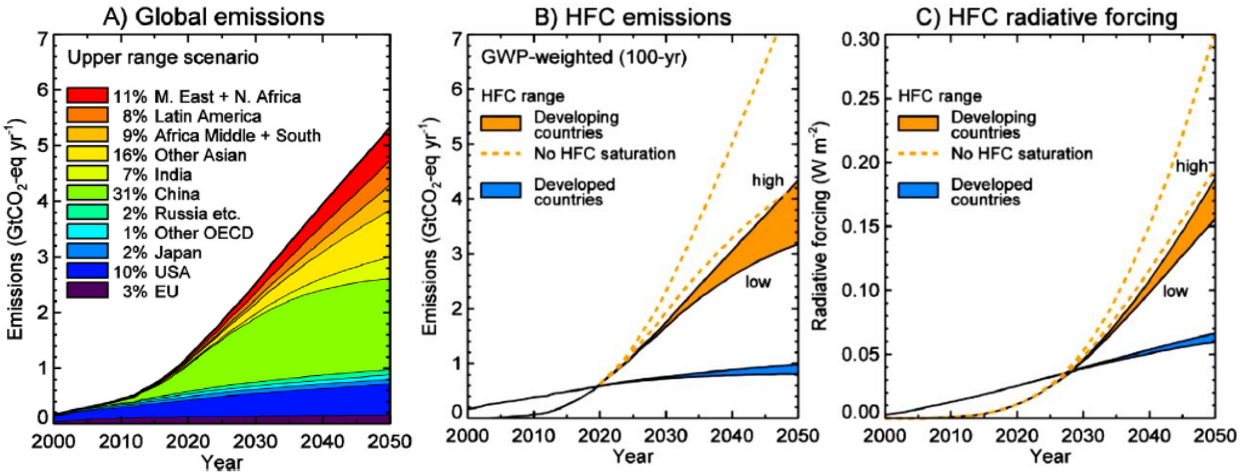

Figure 1.2. Global HFC emissions and associated radiative forcing from year 2000 projected up to 2050 under business as usual situation. *(Source: Velders et al. 2015. See footnote 13)*

1.3. Black carbon emissions and inventories

The 2015 AMAP assessment[18] put the total global emission of black carbon in 2010 at about 7 Tg/yr and projected a decrease to about 6 Tg/yr. in 2030 which will then remain constant until 2050 under business as usual conditions. The assessment show that Asia[19] is responsible for more than 50% of emissions between 2010 and 2050 with the Arctic nations[20] contributing about 10% of the total global emissions. In terms of specific emissions source, the AMAP assessment indicates that, although laden with much uncertainties due to inadequate knowledge of flaring volumes and emission factors, flaring of gas associated with oil production has potentially a very large impact on the concentrations of black carbon in the Arctic. This is further supported by a study[21] focused on black carbon emissions in the Russian Federation - the largest country by land area in the Arctic Council. The study estimated total

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[16] The global warming potential (GWP) is a relative index that enables comparison of the climate effect of the emissions of various greenhouse gases (and other climate changing agents). It measures how much energy the emissions of one ton of a gas will trap in the atmosphere over a given period of time, relative to the emissions of one ton of carbon dioxide, which is chosen as the reference gas and has a GWP of 1.

[17] Fortems-Cheiney et al 2015. Increase in HFC-134a emissions in response to the success of the Montreal Protocol. J. Geophysical Research, Atmosphere. 120, 11,728–11,742

[18] AMAP ASSESSMENT 2015: Black Carbon and Ozone as Arctic Climate Forcers. http://www.amap.no/documents/doc/AMAP-Assessment-2015-Black-carbon-and-ozone-as-Arctic-climate-forcers/1299

[19] Asia countries include China, India, Japan, Singapore, and South Korea (without Central Asian countries).

[20] Including Canada, Denmark, Finland, Iceland, Norway, Russia, Sweden, and United States

[21] Huang et al. 2015. Russian anthropogenic black carbon: emission reconstruction and Arctic black carbon simulation, J. Geophys. Res. Atmos., 120, 11,306–11,333, doi:10.1002/ 2015JD023358

anthropogenic emissions of black carbon in the country at 0.2Tg, with gas flaring, a usually overlooked emission source, significantly making the highest contribution compared to other sectors at about 36% of total.

2. SLCP impacts and mitigation benefits

Some new studies that further broaden our knowledge on the diverse impacts of SLCPs and potential climate, air quality, human health, agriculture and energy use benefits were published in the past few months. This section provides a review and highlights of important findings from some of these studies.

2.1. Climate impacts/benefits

2.1.1. Warming impacts

Research on future atmospheric abundance and climate forcing due to HFCs[22] shows that the continued drastic increase in HFCs production, consumption and consequently emissions would lead to substantial increase of radiative forcing. As mentioned earlier (see Section 1.2), results indicates that under business as usual situation, the radiative forcing from HFCs could reach 0.22-0.25 Wm^{-2} by 2050 with developing countries responsible for 0.16-0.19 Wm^{-2} and developed countries responsible for 0.06-0.07 Wm^{-2}. This increase in radiative forcing of HFCs between 2015 and 2050 was shown to be equivalent to 12-24% of the increase in the radiative forcing of CO_2 in that same period under the RCP6 and RCP8.5 scenarios respectively.

Recent studies are also providing new insights on the climate impact of black carbon. One study[23] used a new satellite with much higher sensitivity to aerosol microphysical properties in comparison to other previous measurements. It was found that most models significantly underestimate aerosol absorption properties, especially in the tropics, suggesting that many 'raw' model results for the impact of black carbon may be biasedly very low. The paper concluded that aerosols have a potentially stronger direct and semi-direct impact within the atmosphere than currently estimated. Another study[24] shows that the global mean of the radiative forcing of black carbon has been underestimated by between 10 and 15%, depending on the sky condition, in many standard climate models which uses simplified radiation schemes instead of the more complex multi-stream schemes, which are computationally more demanding when applied for global simulations. One consequence of underestimating black carbon radiative forcing is the likely reduction of its climate warming effect at the regional and global scales.

A few new studies in 2015 provided further insight into the warming effect of black carbon and other SLCPs as well as the benefits associated with reducing their emissions. Note, however, that as noted in the previous paragraph, results from ‘raw’ model simulations (i.e. not adjusting for biases relative to observations) may lead many of these to underestimate the warming impact of BC. For example, the AMAP assessment provided new information on the impact of black carbon and ozone in the Arctic as well as the climate benefits of taking action to reduce their emission. It was estimated, based on four models, that the direct effect of current global combustion derived black carbon, organic carbon, and sulphur emissions would lead to a temperature increase of +0.35K (range +0.03 - 0.84K) across the Arctic equilibrium surface with +0.40K (0.28 to 0.56K), +0.22K (+0.15 to 0.29K), -0.04 K (-0.14 to 0.06K) and -0.23K (-0.37 to 0.07K) coming from black carbon in the atmosphere, black carbon in snow, organic carbon and

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[22] Velders et al. 2015. Future atmospheric abundances and climate forcings from scenarios of global and regional hydrofluorocarbon (HFC) emissions. Atmospheric Environment, 123, 200–209

[23] Lacagnina et al. 2015. Aerosol single-scattering albedo over the global oceans: Comparing PARASOL retrievals with AERONET, OMI, and AeroCom models estimates, J. Geophys. Res. Atmos., 120, 9814–9836,

[24] Myhre and Samset (2015). Standard climate models radiation codes underestimate black carbon radiative forcing. Atmos. Chem. Phys., 15, 2883-2888

sulphate, respectively. Another study[25] found that mitigating SLCPs would reduce warming in the Arctic region by 0.44(0.39 to 0.49) °C by 2050 with the reduced warming peaking at 0.62(0.37-0.84) °C during the autumn. However, one study[26] reported a lesser warming reduction in the Arctic by 2050 of 0.2 (+/-0.17) K by implementing stringent but technically feasible mitigation scenario for SLCPs between 2015 and 2030. Overall, the findings highlight the importance and benefits of mitigating black carbon emissions to the Arctic region.

For other regions, one study focused on the Tibetan Plateau and the Himalayas[27], used a high-resolution ocean–atmosphere global climate model and observationally constrained black carbon (BC) aerosol forcing, to show that the emission of aerosols resulted in a warming of 1.3°C from black carbon and 0.7°C cooling from cooling agents, resulting in a net warming effect. Consequently, this has enhanced the snow cover retreat over the Tibet and the Himalayas. Another study[28], using a global climate model showed that a reduction in black carbon emissions could yield a decrease in mean summer surface temperature by up to 1°C in central parts of North America and 0.3°C in northern India respectively.

2.1.2. Impacts on weather and precipitation patterns

On the impact of black carbon on weather and precipitation patterns, a recent publication[29] indicated that the 2013 catastrophic flood in the mountainous area of the Sichuan Basin in China was due to enhanced extremely heavy rainfall caused by polluted air, laden with absorbing aerosols mainly black carbon (Figure 2.1). A more recent publication[30] by the same set of authors, also show that black carbon-laden polluted air could also lead to reduced precipitation. By using the Weather Research and Forecasting model with online coupled chemistry to carrying out simulations, they found that absorbing aerosols, mainly black carbon, through aerosol-radiation interactions, weakens valley breeze through induced warming aloft and cooling near the surface resulting in significant reduction in precipitation (Figure 2.2). Another publication[31] analysed the interaction between anthropogenic aerosols and the East Asian summer monsoon and concluded that black carbon-induced enhancement of atmospheric circulations can increase floods in south China, while increasing drought in north China due to local warming effect. Furthermore, another study[32] show that abating SLCP emissions could result in increased rainfall by 15mm/year (range 6-21), corresponding to 4% (range 2-6%) of total precipitation in Southern Europe. This is of particular interest given that a scenario without SLCPs mitigation has been shown to lead to drought and water shortage in the Mediterranean region during future summers.

2.2. Health impacts/benefits

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[25] Stohl et al. 2015. Evaluating the climate and air quality impacts of short-lived pollutants. Atmos. Chem. Phys., 15, 10529-10566

[26] Sand et al (2015). Response of Arctic temperature to changes in emissions of short-lived climate forcers. Nature Climate Change. 6, 286–289, doi:10.1038/nclimate2880

[27] Xu et al. 2015. Observed high-altitude warming and snow cover retreat over Tibet and the Himalayas enhanced by black carbon aerosols. Atmos. Chem. Phys., 16, 1303-1315

[28] Chuwah et al. 2015. Global and regional climate impacts of future aerosol mitigation in an RCP6.0-like scenario in EC-Earth. Climatic Change, 134, 1-14

[29] Fan et al. 2015. Substantial contribution of anthropogenic air pollution to catastrophic floods in Southwest China. Geophysical Research Letters. DOI: 10.1002/2015GL064479

[30] Fan et al 2016. Mechanisms contributing to suppressed precipitation in Mt. Hua of Central China, Part I - Mountain Valley Circulation. J. Atmos. Sci., 73, 1351–1366. doi: http://dx.doi.org/10.1175/JAS-D-15-0233.1

[31] Wang et al 2015. The interactions between anthropogenic aerosols and the East Asian summer monsoon using RegCCMS. J Geophysical Research: Atmospheres. DOI: 10.1002/2014jd022877

[32] Stohl et al. 2015. Evaluating the climate and air quality impacts of short-lived pollutants. Atmos. Chem. Phys., 15, 10529-10566

The WHO/CCAC scoping report on reducing global health risks through SLCP mitigation[33] as well as a 2015 commentary[34] accentuate the impact and health benefits of reducing SLCPs. The report shows that reducing SLCP emissions could provide health benefits in three key ways including:

- Direct health benefits through substantial reduction in incidence of diseases such as stroke, ischaemic heart disease, acute lower respiratory disease, chronic obstructive pulmonary disease, and lung cancer which have been attributed to air pollution.
- Indirect health benefits through reduced impacts of SLCPs on weather patterns and melting of snow ice, which could harm human health through extreme weather, and through improved agricultural yield which could help improve food security and nutrition.
- Benefits associated with some SLCP mitigation actions such as (1) diet change to nutritious plant-based food which could reduce health risk whilst decreasing SLCP emissions from livestock through decreased demand and (2) prioritizing dedicated rapid transit, walking and cycling networks which promotes improved human health and reduces air pollution as well as related health risks.

The WHO/CCAC report also show that some health-enhancing strategies for SLCP emission reduction could also lead to considerable co-reduction in CO_2 emissions therefore contributing both near- and longer-term climate change benefits.

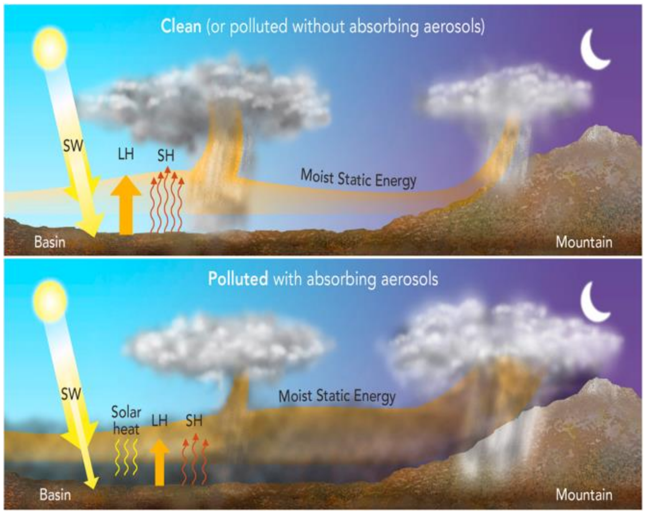

Figure 2.1. Mechanism of aerosol-enhanced conditional instability leading to extreme precipitation.
Source: Fan et al. 2015. See footnote 29

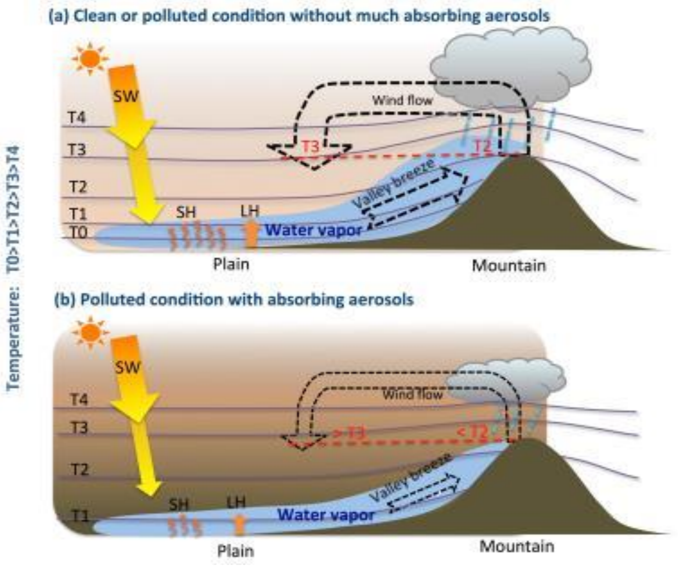

Figure 2.2. Mechanism for weakened valley breeze and reduced precipitation due to air pollution.
(Source: Fan et al 2016. See footnote 30)

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[33] WHO/CCAC 2015. *Reducing* he/publications/climate-reducing-health-risks/en/

[34] Scovronick et al. 2015. Reduc -6736(15)61043-1

Apart from the WHO report, other research also provided insight into the health benefits of SLCP mitigation. One study[35] which presented public health benefits in terms of reduction in life expectancy indicated that the implementation of SLCP abatement measures would improve life expectancy in the European Union, China and India by one, two and twelve months respectively by 2030 compared to a scenario where the measures are not implemented. In another study,[36] focused on replacement of coal with natural gas for residential and commercial space heating and cooking in Turkey, it was shown that this change has resulted in significant reduction in the rate of infant mortality estimated to be approximately 348 infant lives in 2011 alone.

Also, a recent analysis,[37] focused on the climate and health benefits of adhering to an emissions pathway consistent with 2°C warming in the US, show that reducing greenhouse gases and aerosols including CO_2, methane, ozone, SO_2, NO_x and black carbon, through clean energy policies could help avoid approximately 175,000 premature deaths by 2030 with approximately 22,000 fewer deaths annually in subsequent years, while clean transportation policies could help prevent 120,000 premature deaths by 2030 with 14,000 fewer deaths annually subsequently. The study values the near-term national benefits from implementing these policies at approximately US$250 billion and indicates that these benefits could increase almost fivefold when longer-term worldwide climate impacts are considered. This study further strengthens the need to vigorously focus on both SLCP and CO_2 mitigation in order to harness health benefits as well as increase the chance of staying well below 2°C temperature rise target as called for in the Paris Agreement.

2.3. Ecosystem and agriculture impacts/benefits

New research findings have shed more light on the ability of fish populations to adapt to rapid warming of oceans due to climate change. According to a new study[38], the rapid warming of sea surface temperatures in the Gulf of Maine which is estimated to be 99% faster than that of the global ocean, has led to the reduction in recruitment[39] and increased mortality, which coupled with overfishing, have resulted in fishery collapse in that part of the Atlantic Ocean. These findings emphasize the need to urgently reduce the rate of warming so as to increase the ease of adaptation by organism and the ecosystem. Mitigation of SLCP emissions provides the required opportunity for reducing the rate of near-term climate change.

Evidences continue to emerge on the impact of surface ozone on vegetation. A recent study looking at the combined impacts of ozone and drought on food security in China[40] estimated an annual mean crop yield reduction of 10.0% or 55 million tons between 1981 and 2010, with the largest crop yield losses occurring in northern China. Also, a review

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[35] Stohl et al. 2015. Evaluating the climate and air quality impacts of short-lived pollutants. Atmos. Chem. Phys., 15, 10529-10566.

[36] Cesur et al (2015). Air Pollution and Infant Mortality: Evidence from the Expansion of Natural Gas Infrastructure. The Economic Journal. DOI: 10.1111/ecoj.12285

[37] Shindell et al 2016. Climate and health impacts of US emissions reductions consistent with 2°C. Nature Climate Change, doi:10.1038/nclimate2935

[38] Pershing et al (2015). Slow adaptation in the face of rapid warming leads to collapse of the Gulf of Maine cod fishery. Science, 350, 809-812.

[39] number of new fish that are added either by birth or migration

[40] Tian et al. 2015. Climate extremes and ozone pollution: a growing threat to China's food security. Ecosystem Health and Sustainability, 2, 1-10. http://onlinelibrary.wiley.com/doi/10.1002/ehs2.1203/full

paper focused on China[41] estimates that elevated ozone concentrations experienced in 2000 could be responsible for a 6.4-14.9% reduction in wheat crop yield and projected that this could increase to 14.8-23% in 2020. Furthermore, a new study[42] aimed at estimating the impact of ozone on crop production and consequently land use between 2005 and 2050, show that ozone was responsible for about 10% relative yield loss (RYL) of rice and maize in 2005 especially in the Middle East, India and China where high ozone concentration occurs during growing seasons. According to the study, without a large reduction in air pollutants, high ozone concentrations could result in as much as 20% RYL by 2050 in most part of the Middle East, India and China with a consequent need to expand agricultural land by 1.3 million km^2, equivalent to a 2.5% average increase globally with highest increase in Asia (8.9%). The study further shows that with stringent climate policies which also target ozone precursor emissions, RYL could be reduced to about 10% in China and India by 2050.

The use of different quantification metrics are also helping to provide better insight into the impact of ozone on vegetation. Those metrics that estimate the flux of damaging ozone into the plant, rather than those based upon concentrations, are finding increased impacts in some parts of Europe where the peaks are lower, but have higher total flux as emphasised in one study[43] looking into the impacts of ozone on trees. It shows that the trees in the Mediterranean are potentially affected less than trees growing further North, even though the peaks are higher in the South, but ozone uptake is higher around North due to differences in meteorological and plant conditions which determine the ozone flux. There also seems to be an impact of the increasing background levels of ozone on plants from upland peat bogs, increasing senescence, and also increases in methane emissions as ozone concentrations increased[44], all indicating that peatlands are sensitive to ozone concentrations. This potentially has implications for ability to sequester greenhouse gas and consequently the greenhouse gas budgets.

Another study[45] showed that whilst the frequency of ozone peaks have decreased in Europe, using the measured ozone concentrations from the UK 'EMEP Supersites', the flux-based metrics which quantify damaging ozone uptaken by the plant, indicate that the overall impact of ozone on vegetation may not have decreased. This is because of meteorological and plant conditions during peak ozone which limit plant ozone uptake. The use of concentration-based metrics for vegetation (i.e. AOT40) as well as a health-relevant ozone metric (SOMO35), however, show a decrease in impacts. Hence the severity of ozone impacts was dependent on the metric used to quantify vegetation and health impacts, but clearly the increasing background level of ozone is a concern. The need for hemispheric cooperation to reduce background ozone was therefore a focus in a recent review article[46].

2.4. Energy efficiency benefits

Science continues to highlight and reinforce the multifaceted benefits associated with SLCP mitigation including energy efficiency benefits. A new study[47] on the benefit of leapfrogging to super-efficiency and low GWP refrigerants in room air conditioning, shows that implementing HFC refrigerant transition and energy efficiency improvement policies in parallel for room air conditioning, roughly doubles the benefit compared to when policies are implemented separately. It was estimated that shifting to higher efficiency technology and low-GWP refrigerants in parallel from

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[41] Feng et al. 2015. Ground-level O_3 pollution and its impacts on food crops in China: A review. Environmental Pollution, 199, 42-48.

[42] Chuwah et al (2015). Global impacts of surface ozone changes on crop yields and land use. Atmospheric Environment, 106, 11–23

[43] Anav et al. 2016. Comparing concentration-based (AOT40) and stomatal uptake (PODY) metrics for ozone risk assessment to European forests. Global Change Biology, 22, 1608-27. doi: 10.1111/gcb.13138

[44] Williamson et al 2016. How do increasing background concentrations of tropospheric ozone affect peatland plant growth and carbon gas exchange? Atmospheric Environment, 127, 133–138

[45] Malley et al 2015. Trends and drivers of ozone human health and vegetation impact metrics from UK EMEP supersite measurements (1990–2013). Atmos. Chem. Phys., 15, 4025–4042.

[46] Monks et al 2015. Tropospheric ozone and its precursors from the urban to the global scale from air quality to short-lived climate forcer. Atmos. Chem. Phys., 15, 8889-8973. doi:10.5194/acp-15-8889-2015. http://www.atmos-chem-phys.net/15/8889/2015/

[47] Shah et al. 2015. Benefits of Leapfrogging to Superefficiency and Low Global Warming Potential Refrigerants in Room Air Conditioning. http://eetd.lbl.gov/publications/benefits-of-leapfrogging-to-superef-0

low efficiency technology using high-GWP refrigerants by 2030 would save between 340-790 gigawatts (GW) of peak power load globally. This is roughly equivalent to avoiding 680-1550 peak power plants of 500MW each. Apart from energy efficiency benefit, this transition is estimated to also lead to an avoided CO_2 emissions of up to approximately 25 billion tonnes in 2030, 33 billion in 2040, and 40 billion in 2050, equivalent to a cumulative savings of approximately 98 billion tonnes of CO_2 by 2050.

3. Policies for SLCP abatement

An opinion piece in Nature Climate Change[48] argues that tackling SLCP emissions provides a political opportunity to delivers tangible benefits and help governments to build confidence that collective action on climate change is feasible. It was suggested in the article that a new vision is emerging that recognizes that effective action must happen on many fronts and in many forums, not just the UNFCCC. It highlights the Climate and Clean Air Coalition (CCAC), the Montreal Protocol, bilateral programmes on climate change such as that between the US and China[49] as well as unilateral actions such as those of the EU and California where deep cuts in SLCPs are being implemented, as examples of these type of fronts and forums. Another recent example is the joint commitment between US and Canada on climate, energy, and arctic leadership[50].

The Rockefeller Foundation–Lancet Commission on planetary health, in its report[51], called for the mitigation of SLCP emissions in order to safeguard planetary health and achieve environment benefits. The report[52] of the 2015 Lancet Commission on Health and Climate Change formed to assess the health impacts of climate change, and identify necessary policy responses, also made a similar policy recommendation. It indicated that tackling climate change and its impacts could in fact be the greatest global health opportunity of the 21st century. The Commission recommends the mitigation of SLCPs, especially black carbon, in order reduce the associated health burden and harness the immediate gains from this action to society. The report further indicates that the health dimension of the climate change crisis has been neglected and therefore calls for increased health consideration in climate change-related discourse as well as more monitoring and holding of governments accountable for progress and action on emissions reduction and adaptation through an independent accountability and review process.

Also, a commentary on how to implement the outcome of the December 2015 Climate Agreement[53], suggested carbon pricing as one of the efficient ways to reduce carbon emissions as it will help take into account the health impact of emissions. The article suggest that greater understanding of the health and other benefits associated with emissions reduction, including for methane and black carbon, could help increase the political and economic acceptability of carbon taxation. It quoted another publication which estimated that carbon taxation could yield revenue worth about 2.6% of global gross domestic product, while also simultaneously reducing CO_2 emissions by 23% and pollution-related mortality by 63%. Similarly, another publication[54] on the policy implication of methane emissions and climatic warming risk from hydraulic fracturing and shale gas development, also argued in support of

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[48] Victor et al. 2015. Soot and short-lived pollutants provide political opportunity. Nature Climate Change 5, 796–798. doi:10.1038/nclimate2703

[49] See: https://www.whitehouse.gov/the-press-office/2015/09/25/us-china-joint-presidential-statement-climate-change

[50] https://www.whitehouse.gov/the-press-office/2016/03/10/us-canada-joint-statement-climate-energy-and-arctic-leadership

[51] Whitmee et al. 2015. Safeguarding human health in the Anthropocene epoch: Report of The Rockefeller Foundation–Lancet Commission on planetary health. http://www.thelancet.com/commissions/planetary-health

[52] Watts et al. 2015. Health and climate change: policy responses to protect public health. The Lancet. http://www.thelancet.com/commissions/climate-change-2015

[53] Cuevas and Haines 2015. Health benefits of a carbon tax. The Lancet. http://thelancet.com/journals/lancet/article/PIIS0140-6736(15)00994-0/fulltext

[54] Howarth 2015. Methane emissions and climatic warming risk from hydraulic fracturing and shale gas development: implications for policy. Energy and Emission Control Technologies, 2015:3, 45—54, DOI http://dx.doi.org/10.2147/EECT.S61539

carbon taxation that recognize not just CO_2 but also methane, emphasizing that taxation on methane emissions should reflect its 20-year GWP and therefore should be 86 times that of CO_2.

One commentary in the Lancet[55] emphasized the need to promote more inclusive accounting of the benefits of SLCP mitigation against associated costs in order to encourage action. The commentary highlighted the need to consider various impacts and benefits and use broader metrics beyond existing climate change metrics such as the 100-year time horizon (GWP) currently used by the UN Framework Convention on Climate Change. It also emphasized the need to take into consideration the fact that many governments are currently organized into separate departments and therefore may not be able to create policies that are targeted at achieving multiple beneficial outcomes for different departments as is the case with SLCP mitigation policies. Hence, systems that encourage cross-sectoral collaboration need to be encouraged.

Also on metrics and accounting for SLCPs, a recent study[56] has highlighted how the exclusion of short-lived emissions (including carbon monoxide, methane – as precursors to tropospheric ozone and black carbon), and near-term projections in GHG accounting is resulting in under-reporting of emissions and obscuring associated impacts. The study, focused on Australia, re-calculated emissions to include these short-lived gases and used a 20 year GWP. It was shown that annual emissions more than double when compared to the national inventory using these parameters, with agriculture producing 54% of the national total. The study calls for a reform of mitigations efforts to amplify and accelerate action on short-lived global warming species, knowing that this will have a quick payoff. It also emphasize the need for further research to tackle complexities and join the dots between dissimilar climate change fields.

A broad economic valuation methodology encompassing the SLCPs was also published in 2015[57]. The Social Cost of Atmospheric Release) that incorporates not only the climate-related damages attributable to emissions, as is done with carbon dioxide pricing or equivalent GWP-based methane pricing, but also the impacts on human health and agriculture. The study indicated that this broad metric differed substantially from valuation including only climate or only air-quality and suggested that incorporation of the full range of impacts could help identify policies with the greatest overall benefits to society.

Finally, a commentary reflecting on the findings of the AMAP assessment[58] which identifies Asia as the largest source of the emissions affecting the Arctic[59], argues for the importance of international co-operation and involvement of emitting nations outside of the Arctic region in policy discussions in order to effectively tackle the climate and air pollution-related challenges facing the Arctic. The article suggested that platforms such as the International Maritime Organization, the Convention on Long-Range Transboundary Air Pollution, the United Nations Environment Programme or the UN Framework Convention on Climate Change could help facilitate this needed international cooperation.

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[55] Scovronick et al. 2015. Reduce short-lived climate pollutants for multiple benefits. The Lancet. 386, e28–e31

[56] Wedderburn-Bisshop et al. 2015. Neglected Transformational Responses: Implications of Excluding Short Lived Emissions and Near Term Projections in Greenhouse Gas Accounting. International Journal of Climate Change: Impacts & Responses, 7, 11-27

[57] Shindel. 2015. The social cost of atmospheric release. Climate Change, 130, 313-326

[58] Schmale 2015. Arctic warming, short-term solutions. Nature Climate Change, 6, 234–235.

[59] This assertion is further supported by Liu et al. 2015. The importance of Asia as a source of black carbon to the European Arctic during springtime 2013. Atmos. Chem. Phys., 15, 11537–11555