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Climate & Clean Air Coalition (CCAC) Annual Science Update 2016

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

ANNUAL SLCP SCIENCE UPDATE 2016

Every year, the Climate and Clean Air Coalition's (CCAC) Scientific Advisory Panel reviews the latest scientific and policy-relevant publications on the short-lived climate pollutants (SLCPs) of interest to the Coalition: methane, black carbon, tropospheric ozone and hydrofluorocarbons. This "Annual Science Update" is published as a background document for the first of two annual meetings of the Coalition's Working Group, which usually takes place during the first or second quarter of every year. This document is the science update for the 2017 annual meetings of Coalition and contains a summary of some of the important scientific findings relevant to the work and activities of the Coalition.

SUMMARY OF MAIN FINDINGS

Emissions and inventory of Short-Lived Climate Pollutants

- The emissions, and consequently the concentration of methane in the atmosphere, continue to increase. Findings from recent studies, as well as analysis by the World Meteorological Organization, indicate that methane concentrations in the atmosphere reached a new high of up to 1845±2 ppb in 2015 (Figure S1) – a 144% increase compared to pre-industrial era.
- One analysis suggested that the more than 30% increase in methane emissions between 2002 and 2014 in the United States, could be responsible for between 30-60% of the global growth of atmospheric methane in the past 10 years. Another study also show that the oil and gas industry in Russia as well as coal exploitation in China are significant contributors to the global methane emissions increase.
- A sustained increase in methane emissions could thwart efforts to limit global warming to well below 2 degrees as agreed under the Paris Agreement. While CO_2 mitigation efforts must continue, they need to be done simultaneously with methane mitigation actions in order to increase the chance of meeting climate targets.

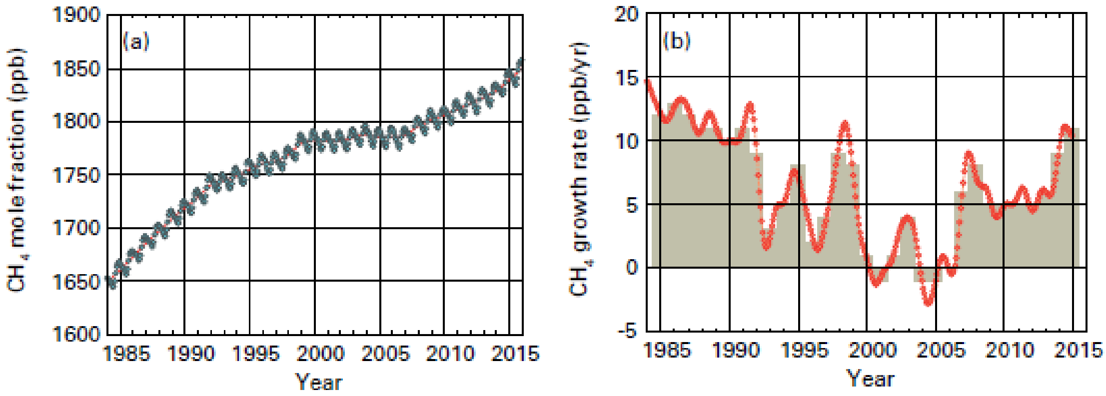

Figure S1: Globally averaged methane mole fraction (a) and its growth rate (b) from 1984 to 2015.
Source: WMO Greenhouse Gas Bulletin. 12, 24 October 2016

- Although there is consensus among various studies on the increase in emissions and concentration of methane in the atmosphere, a review of recent studies show a divergence on the sources of these methane emission increases. While some studies suggest these increases have come from biogenic sources, including agricultural sources such as enteric fermentation and rice paddies, others have indicated fossil fuel activities, including oil and gas production. These differing conclusions on emission sources highlight a need for a robust assessment of methodological differences in the estimation of anthropogenic methane emissions in order to better determine the causes of the current increase, which will be useful for identifying and prioritising relevant mitigation measures.

- In a new global estimate of anthropogenic particulate matter, total black carbon emissions in 2000 and 2010 were estimated to be 6.6 and 7.2Tg respectively. Black carbon emissions, under current policies, are projected to decline as have been noted in previous studies. The transportation and residential sectors are still expected to dominate black carbon emissions between now and 2100.
- An estimate of current and future global emissions of fluorinated greenhouse gases (or F-gases, which are comprised of hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6)) show that their total emissions) in 2005 and 2010 was 0.7 and 0.89 $PgCO_2eq$ respectively, with HFCs dominating the total emitted F-gases at about 75% of total (Figure S2). Emissions are projected to increase to 3.7 $PgCO_2eq$ by 2050 if control technologies are only deployed at current levels.

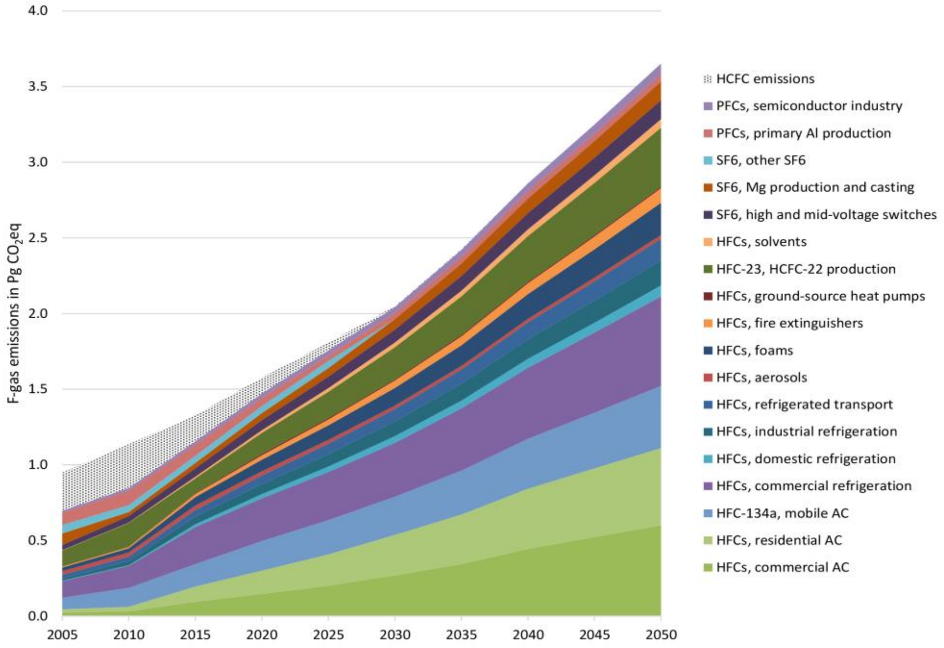

Figure S2: Baseline emissions of F-gases (HFCs, PFCs, and SF_6) 2005 to 2050 by source sector. Source: Purohit & Höglund-Isaksson

IMPACTS OF SHORT-LIVED CLIMATE POLLUTANTS

Climate Impacts

- Knowledge of methane's strong global warming impact continues to advance. One new study showed that methane's global warming potential (GWP) was previously underestimated because its shortwave adsorption behaviour was largely ignored. The study revised the GWP_{100} of methane to 32 from the 28 indicated in the 2013 IPCC assessment. Another study indicated that because of the ability of methane to boost positive carbon cycle feedbacks[1], the net global warming property of the gas is enhanced by up to 25%, indicating a stronger warming effect than current estimates suggest.

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[1] Carbon cycle feedbacks in this case are the interactions between temperature change, and the various parts of the carbon cycle including the atmosphere, ocean, and biosphere

- Recent studies suggest that the amount of non-black carbon particles emitted alongside black carbon could play significant role in climate warming by enhancing the light absorbing properties of black carbon, thereby increasing its warming impact. The studies indicate that warming from sources such as biomass burning and sources containing nitrates and sulphates could be higher than previously thought.

Impact on Sea-level Rise, Regional Climate and Weather patterns

- Methane and other SLCPs were shown to have a significant longer term effect on sea-level rise than previously thought because their effects persist long after they disappear from the atmosphere. The impact of methane and HFCs on sea-level rise was shown was shown to remain for centuries even if emissions cease completely", indicating that their continued emissions will lock-in levels of sea-level rise that will affect coastal and small island countries for multiple centuries.
- The impact of anthropogenic aerosols, including black carbon, on regional climates and the hydrological cycle is also becoming clearer with absorbing aerosols[2], mainly black carbon, shown to be responsible for approximately 40% reduction in summer precipitation over Mt. Hua in China, a 20-30% decrease in rainfall in southern Africa, around 25% reduction in regional rainfall over North Africa, and changes in the monsoon pattern and widespread solar dimming over both South and East Asia.

Crop Yield Impacts

- Because non-CO_2 emissions including methane, HFCs and black carbon do not fertilize crops as CO_2 does, the climate change they cause will result in significantly more crop yield losses than the equivalent emissions of CO_2. This has been demonstrated in a study which shows that 93% of the total percentage yield loss (9.5±3.0%) in worldwide agricultural yields to date was caused by non-CO_2 emissions. More than half of this yield loss was attributable to methane emissions. Methane, along with black carbon and HFCs were projected to cause the greatest agricultural damage per ton on crops in the first decades over the remainder of the 21st century if no action is taken to reduce their emissions.

Health Impacts

- An assessment of the direct link between black carbon and mortality in the United States show that approximately 14,000 deaths (Figure S3), as well as hundreds of thousands of illnesses including hospitalizations, emergency visits and minor respiratory symptoms can be attributed to black carbon, with sensitivity analysis suggesting that total black carbon-related deaths may be substantially more.
- Furthermore, a global estimate of preterm births linked to $PM_{2.5}$ concentrations indicated that about 2.7 million preterm births (18% of total preterm births) globally may be due to maternal exposure to ambient $PM_{2.5}$ concentrations. Also, an assessment of health impacts linked 24,000 (range 14,500–37,500) premature deaths annually in East Asia to $PM_{2.5}$ and ozone emissions from shipping, while another analysis linked 341,000 premature deaths in China to $PM_{2.5}$-related emissions from residential combustion, equivalent to a third of total deaths caused by all ambient $PM_{2.5}$ pollution in the country. Yet another study found that 366,000 premature deaths in China in 2013 is linked to coal combustion - the single largest source of air pollution-related health impacts.
- Ozone exposure has been linked with the incidence of diabetes and risk of respiratory and circulatory mortality. Projected ozone concentration and exposure, partly due to methane emissions, could lead to increased global mortality burden ranging from 121,000 to 728,000 deaths per annum in 2000 to between 1.09 and 2.36 million deaths per annum in 2100.

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[2] Absorbing aerosols are components of aerosol that have the ability to absorb light and heat for example black carbon and brown carbon.

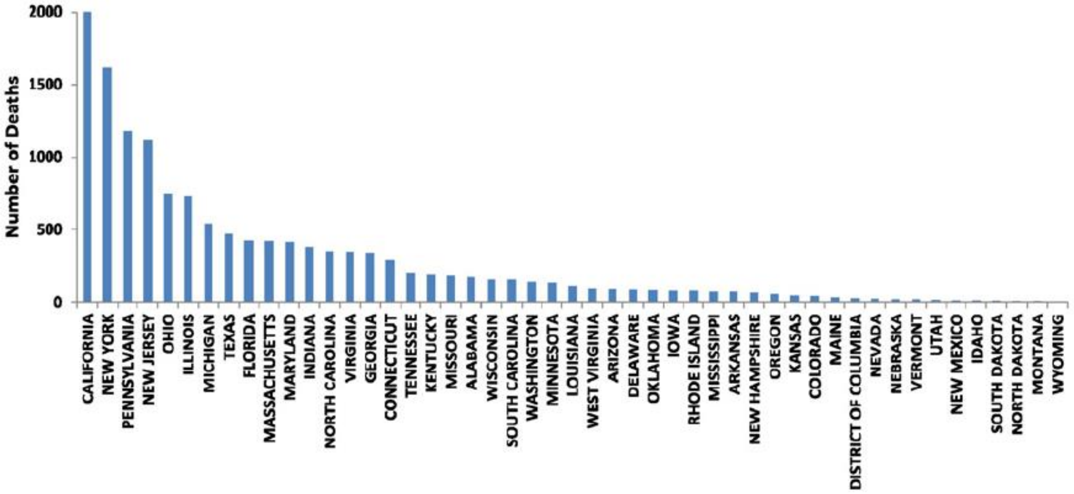

Figure S3: Annual BC-related mortality by State in the United States. Source: Li et al

- With regard to global air pollution impact, the WHO indicated that nine out of ten people breathe air polluted beyond acceptable WHO guidelines, while UNICEF found approximately 2 billion children live in areas where outdoor air pollution exceeds WHO guidelines. Furthermore, the Health Effect Institute reported that exposure to outdoor $PM_{2.5}$ is the leading environmental risk factor for death and the fifth overall risk factor worldwide for all ages and sexes. The report also identified exposure to household (indoor) $PM_{2.5}$ and ozone exposure as the tenth and thirty third leading risk factor for death.

Socio-economic impacts

- The social cost of methane based on its impact on climate, health and agriculture was estimated to be up to $2400 and $3600 per ton using a 5% and 3% discount rates respectively (2010 US$). These estimates are 100 and 50 times greater than the social cost of CO_2 using the same discounts rates. Furthermore, increased methane emissions in the future, if not controlled, could counter much of the societal benefits gained from reducing the rate of CO_2 emissions.
- The World Bank estimated the global cost associated with outdoor and indoor air pollution, including particulate matter and ozone pollution, in 2013 at USD 5.11 trillion with East and South Asia, and the Pacific suffering the highest costs. The OECD projected that outdoor air pollution could cause 6 to 9 million premature deaths a year by 2060 and scrape off 1% of global GDP, if not curbed. They estimated that by 2060 the cost of air pollution impacts could be as high as USD 3.4-3.5 trillion in OECD countries and USD 15-22 trillion in non-OECD countries.

MITIGATION MEASURES AND BENEFITS

Methane mitigation and benefits

- New measures for reducing methane emissions were highlighted in recent publications, including the possibility of converting gaseous methane into liquid methanol as an alternative to gas flaring in the oil and gas sector; the identification and targeting "super-emitters" in the same sector for leakage prevention; the use of 3-nitrooxypropanol to reduce emissions from ruminant animals; and decreasing the use of antibiotics - the use of which resulted in a 2-fold increase in methane emission from dung compared with untreated animals.
- Human dietary change was identified as a significant way to reduce methane and other greenhouse gases. One analysis showed that changing diets could reduce land use and greenhouse gas emissions, including methane, CO_2 and N_2O by as much as 70-80%; dietary change could also reduce water use by 50%, while also providing modest

health benefits. Another analysis found that, apart from potentially reducing food-related greenhouse gases by 29-70%, the economic benefits associated with dietary change could be between 1 and 31 trillion US dollars, equivalent to 0.4–13% of global GDP in 2050, with a significant portion of the benefits accruing to developing countries.

- A low emissions trajectory that reduces global warming agents could help increase crop yields by 25±11% by 2100 compared to a high emissions trajectory, with the largest benefits (15.6±5.1%) accruing from reduced methane emissions.
- An analysis of the benefits realized due to the US EPA programs and policies to reduce methane between 1993 and 2013 show that by 2013 they helped avoid a global temperature rise of 0.006 °C. The monetary value of these benefits was estimated at $255 billion US dollars - indicating a significant economic and societal benefits from methane emission reduction.

Black carbon mitigation and benefits

- New gasoline direct-injection engines are gaining popularity because of their fuel efficiency and consequent CO_2 emission reductions. However studies suggest these engines release high amounts of black carbon and toxic volatile organic compounds, including benzene and toluene, which could negate the expected climate and health benefits from CO_2 emissions reduction. It is therefore important to consider the unintended consequences of this new engine before their mass deployment.
- Phasing out aerosol emissions from traditional biomass- or coal-burning cookstoves over the next 20 years in countries where more than 5% of the population use solid fuels for cooking could help reduce warming by 0.08ºC by 2050. The earth-cooling benefits from reducing black carbon, CO_2, and methane would offset the warming effect of removing co-emitted substances like organic carbon and sulphates. Interventions in China, India, and Ethiopia are expected to provide the largest climate benefits. This phase-out would also yield health benefits by preventing approximately 22.5 million premature deaths between 2000 and 2100 with the largest benefits accruing to China, India, and Bangladesh.
- A life cycle inventory of an improved cookstove showed that the emissions avoided by replacing traditional stoves with a fuel-efficient biomass cookstove is significantly higher (roughly 440 times CO_2-equivalent) than emissions associated with the materials, manufacturing, transportation, and end-of-life of the stove. However, several recent studies indicate that some improved biomass-burning stoves do not deliver expected climate and health benefits. One evaluation of a Clean Development Mechanism-approved improved stove replacement program showed higher black carbon emissions compared to laboratory results. Another study showed no evidence that cleaner burning stoves reduce the risk of pneumonia in young children compared to traditional open fires.
- An analysis of European air pollution legislation and technology measures found emission control measures decreased annual mean concentrations of $PM_{2.5}$, sulphate, black carbon, particulate organic matter by 35%, 44%, 56% and 23% respectively in 2010. This prevented an average of 80,000 premature deaths annually across the European Union while yielding an economic benefit of about US$232 billion annually, equivalent to 1.4% of the EU's 2010 GDP. However, the analysis also showed that the measures resulted in an unintended global warming impact with European annual mean surface temperature rising by 0.45±0.11 °C due to reduction in emission of cooling substances like sulphates. This highlights the importance of developing holistic policies that effectively integrate climate and air quality objectives.

Policies and measures for clean air

- A special International Energy Agency (IEA) report on air pollution and energy, presented a Clean Air Scenario that outlined policies and measures for achieving cleaner air, through energy efficiency, higher fuel efficiency and vehicle emissions standards, better public transport and urban planning, improved fuel quality, a phase-out of fossil fuel subsidies and other interventions (see Table S1).

Table S1: Policy pillars to avoid or remove air pollutant emissions in the Clean Air Scenario. Source: IEA[102]

Avoid	Reduce
Strong push for industrial and power sector efficiency: For industry, the introduction or strengthening of existing minimum energy performance standards (MEPs) for electric motor-driven systems. In the power sector, reduced use of inefficient coal-fired power plants (typically subcritical) and a ban on new inefficient coal-fired power plants.	**Stringent emissions limits for new and existing combustion plants.** For plants above 50 MW_{th} using solid fuels, emissions limits are set at 30 mg/m^3 for PM and 200 mg/m^3 for NO_X and SO_2. Existing plants need to be retrofitted within 10 years. Emission limits for smaller plants (below 50MW_{th}) depending on size, fuel and combustion process.[11] Industrial processes required to be fitted with the best available techniques in order to obtain operating permits.[12]
Strong efficiency policies for appliances and buildings: Introduction or strengthening of existing MEPs for appliances, lighting, heating and cooling. Introduction of mandatory energy conservation building codes.	**Stringent controls for biomass boilers in residential buildings:** Emissions limits for biomass boilers set at 40-60 mg/m^3 for PM and 200 mg/m^3 for NO_X.[13]
Higher fuel-efficiency standards: Adoption or strengthening of fuel-economy standards for road vehicles, including for both light- and heavy-duty vehicles.	**Higher vehicle emissions standards:** For light-duty diesel vehicles: limits as low as 0.1 g/km for NO_X and 0.01 g/km for PM. For heavy-duty diesel vehicles and machinery: limits of 3.5 g/km for NO_X and 0.03 g/km for PM. For all vehicles, full on-road compliance by 2025. A ban on light-duty gasoline vehicles without three-way catalysts and tight evaporative controls, and a phase-out of two-stroke engines for two-and three-wheelers.
Increased support to non-thermal renewable power generation: Increased investment in renewable energy technologies in the power sector.	**Fuel switching to lower emissions fuels:** Increased coal-to-gas switching and use of low-sulfur fuels in maritime transport.
Better public transport, urban planning and support to alternative transport fuels: Promotion of public transport, a switch to electric two- and three-wheelers, electric commercial vehicles and natural gas buses.	**Improved fuel quality:** Maximum sulfur content of oil products capped at 1% for heavy fuel oil, 0.1% for gasoil and 10 ppm for gasoline and diesel.
Access to electricity / clean cooking facilities: Enhanced provision of electricity and clean cooking access based on renewable technologies.	**Access to electricity / clean cooking facilities:** Enhanced provision of improved cookstoves and modern fuels for cooking.
Support avoid and/or reduce via a change in economic incentives	
Phase-out fossil-fuel consumption subsidies Pricing reforms that remove the incentives for wasteful consumption of fossil fuels.	

Notes: MW_{th} =megawatts thermal; mg/m^3 = micrograms per cubic metre; g/km = grammes per kilometre; ppm = parts per million.

DETAILED SCIENCE UPDATE

1. METHANE EMISSIONS AND INVENTORIES

1.1. Emission Trends

Several studies in the past year have alluded to methane's increasing role in global warming, with many indicating increasing emissions and concentration of methane in the atmosphere. A World Meteorological Organization analysis of observations from the Global Atmosphere Watch, reported that methane concentrations (as well as that of carbon dioxide and nitrous oxide) reached new highs in 2015 at 1845±2 ppb. This is a 144% increase compared to the pre-industrial era. The 2014 and 2015 increase also exceeded observed growth between 2013 and 2014[3]. Furthermore, in an analysis of the global methane budget[4] and an editorial on the growing role of methane in anthropogenic climate change[5], Saunois and colleagues showed that methane concentration in the atmosphere started increasing in 2007 and surged in 2014 and 2015. They estimated global methane emissions of 558 (range 540–568) $TgCH_4yr^{-1}$ between 2003 and 2012, with 60% (range 50–65 %) coming from human activities (Figure 1). Other studies were consistent with the WMO and Saunois findings. For example, Nisbet and colleagues also showed that methane concentration in the atmosphere increased between 2007 and 2013, with significant growth in 2014[6]. Two other studies also reported an increased atmospheric concentration of methane post-2006[7,8]. Similarly, a long-term trend analysis, using a top-down estimate from ethane and methane column observations[9] showed consistent methane increases each year since 2007 and an overall methane emission increase of 24–45 $Tgyr^{-1}$.

At the national scale, satellite data and surface observations of atmospheric methane, suggested that United States emissions increased by more than 30% between 2002 and 2014 and could be responsible for 30–60% of the global growth of atmospheric methane in the past 10 years[10]. An analysis[11] of ethane and methane emissions from oil and natural gas extraction in North America from 2008-2014 showed methane emissions from oil and gas extraction grew from 20 to 35 $Tgyr^{-1}$. Another study[12] showed that a significant portion (more than 50%) of the methane emissions from natural gas systems in the United States is caused by just 5% of identified leakage sources. It must be noted however, that results from Saunois and colleagues indicates no significant trend in United States methane emissions despite the recent growth of the shale gas industry.

A global analysis[13] of methane emissions from oil and gas operations between 1980 and 2012 indicated that the Russian oil industry contributed significantly to global methane emissions. The analysis further suggests that the global decline in oil and gas methane emissions between 1990 and 2000 is linked to reduced Russian emissions as the industry stalled following the collapse of the Soviet Union, and increased flaring, as opposed to venting, of unrecovered gas.

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[3] WMO. The State of Greenhouse Gases in the Atmosphere Based on Global Observations through 2015. WMO Greenhouse Gas Bulletin. 12, 24 October 2016. http://library.wmo.int/opac/doc_num.php?explnum_id=3084

[4] Saunois et al. The global methane budget 2000–2012. Earth Syst. Sci. Data, 8, 697–751, 2016

[5] Saunois et al. The growing role of methane in anthropogenic climate change. Environ. Res. Lett. 11, 2016.

[6] Nisbet et al. Rising atmospheric methane: 2007–2014 growth and isotopic shift. Global Biogeochem. Cycles, 30, 1356–1370, 2016.

[7] Schaefer et al. A 21st century shift from fossil-fuel to biogenic methane emissions indicated by 13CH4. Science, 10.1126/science.aad2705 (2016).

[8] Rice et al. Atmospheric methane isotopic record favors fossil sources flat in 1980s and 1990s with recent increase. PNAS, 113 , 10791–10796, 2016.

[9] Hausmann et al. Contribution of oil and natural gas production to renewed increase in atmospheric methane (2007–2014): top-down estimate from ethane and methane column observations. Atmos. Chem. Phys. 16, 3227–44, 2016.

[10] Turner et al. A large increase in U.S. methane emissions over the past decade inferred from satellite data and surface observations. Geophys. Res. Lett., 43, 2218–2224, 2016

[11] Franco et al. Evaluating ethane and methane emissions associated with the development of oil and natural gas extraction in North America. Environ. Res. Lett. 11, 044010, 2016

[12] Brandt et al. Methane Leaks from Natural Gas Systems Follow Extreme Distributions. Environ. Sci. Technol., 50, 12512−12520, 2016.

[13] Höglund-Isaksson. Bottom-up simulations of methane and ethane emissions from global oil and gas systems 1980 to 2012. Environ. Res. Lett. 12, 024007, 2017.

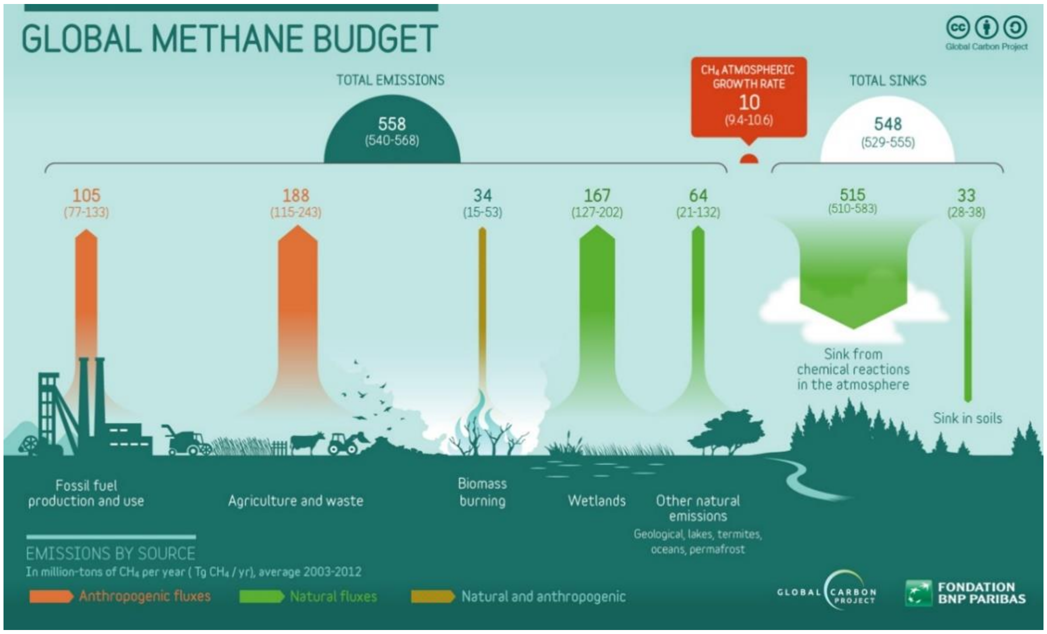

Figure 1: Global Methane Budget; source:

A study by Peng and colleagues[14] showed that China's methane emissions grew rapidly between 2000 and 2010 contributing more than 10% of global methane emissions. The study, which looked at the eight major emissions sectors in China, highlighted an emission surge to 44.9 (range 36.6-56.40) $TgCH_4yr^{-1}$ in 2010 from 24.4 (range 18.6–30.5) $TgCH_4yr^{-1}$ in 1980, with most of the increase occurring in the 2000s and driven by coal exploitation which overtook rice cultivation as a major source (Figure 2).

The continued increase in methane emissions could thwart efforts to limit global warming to well below 2 degrees as agreed under the Paris Agreement. While CO_2 mitigation efforts must continue, they should be done simultaneously with methane mitigation actions, in order to increase the chance of meeting climate targets.

1.2. Emission Sources

While there is overall agreement in recent publications that the atmospheric concentration of methane is growing, there are some divergent results on the emission sources. Some studies such as those by Saunois et al [2]; Nisbet et al.[4]; Schaefer et al.[5]; point to biogenic sources, including agriculture emissions from enteric fermentation and rice paddies, as the main culprit, while other studies have suggested otherwise. For example, Haussmann and colleagues reported a strong connection between the increase in atmospheric methane and fossil fuel production and use[15]. Similarly, Rice et al[16] suggested that fossil fuel-related methane emissions increased substantially between 2000 and 2009, although they also highlighted increased emissions from other anthropogenic sources including agriculture - due to an increase in livestock populations and waste. Furthermore, Helmig and colleagues[17] as well as Kort and colleagues[18] reported a linkage between increased oil and natural gas activities in

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[14] Peng et al. Inventory of anthropogenic methane emissions in mainland China from 1980 to 2010. Atmos. Chem. Phys., 16, 14545–14562, 2016

[15] Hausmann et al. Contribution of oil and natural gas production to renewed increase in atmospheric methane (2007–2014): top-down estimate from ethane and methane column observations Atmos. Chem. Phys. 16, 3227–44, 2016

[16] Rice et al. Atmospheric methane isotopic record favors fossil sources flat in 1980s and 1990s with recent increase. PNAS, 113, 10791–10796, 2016.

[17] Helmig et al. Reversal of global atmospheric ethane and propane trends largely due to US oil and natural gas production. Nature Geoscience 9, 490–495, 2016.

[18] Kort et al. Fugitive emissions from the Bakken shale illustrate role of shale production in global ethane shift. Geophys. Res. Lett., 43, 4617–4623, 2016

the United States and an increase in global atmospheric ethane emissions, which could suggest a significant increase in associated methane emissions.

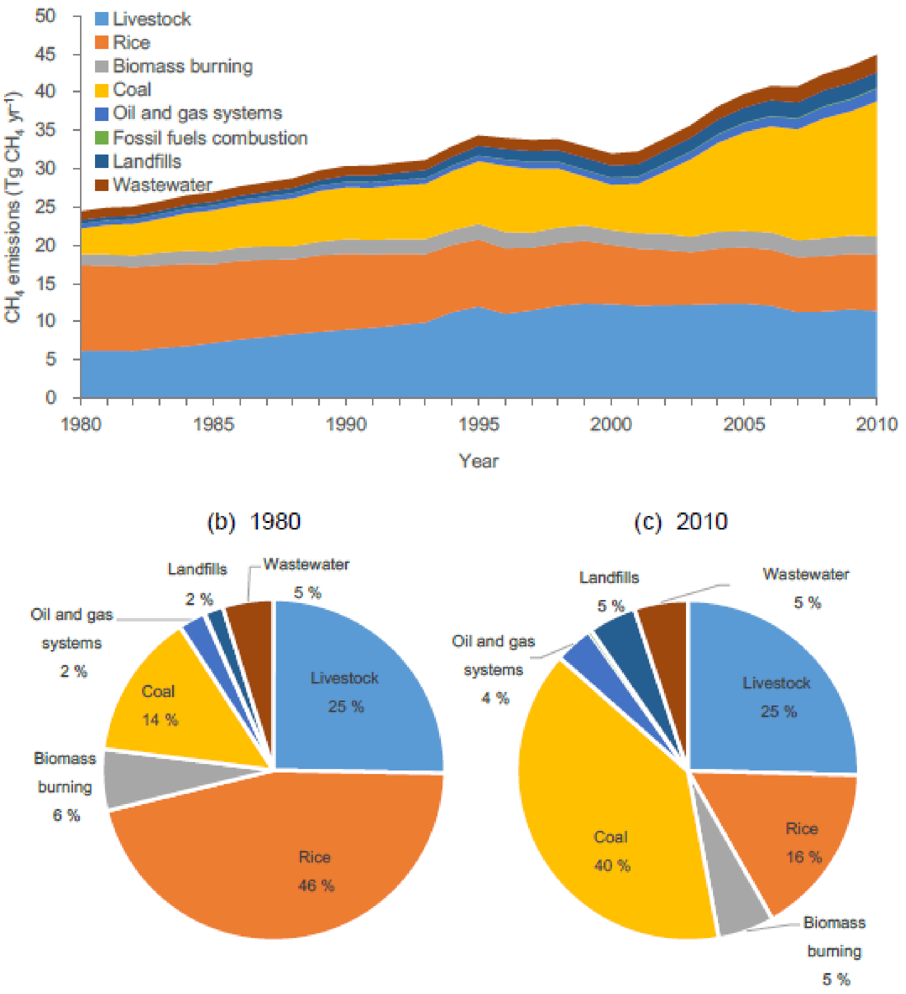

Figure 2: Methane Emissions in China between 1980 and 2010; source: Peng et al.[14]

However, a study by Schwietzke and colleagues[19], found that while total methane emissions from natural gas production has declined over the last 30 years -- from 8% to around 2% -- there is a need for an upward revision of current methane inventories from the fossil fuel industry due to an underestimation of between 20 and 60%. This is further supported by another study[20] which simulated methane emissions in over 100 countries. It showed that methane emissions from oil and gas were at times double, especially in the 1980s, global inventory estimates (Figure 3). The study also reported that overall oil and gas emissions have been fairly constant since 2005 due to increased emissions from shale gas production which countered emission reductions achieved through the increased adoption of methane recovery systems. Another study by Lavoie and colleagues[21] also indicate that emissions from power plants fuelled by natural gas in the United States could be 21 to 120 times higher than

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[19] Schwietzke et al. Upward revision of global fossil fuel methane emissions based on isotope database. Nature, 538, 88-91, 2016

[20] Höglund-Isaksson. Bottom-up simulations of methane and ethane emissions from global oil and gas systems 1980 to 2012. Environ. Res. Lett. 12, 024007, 2017.

[21] Lavoie et al. Assessing the methane emissions from natural gas-fired power plants and oil refineries. Environ. Sci. Technol., DOI: 10.1021/acs.est.6b05531, 2017

inventory figures while that from oil refineries could be between 11 to 90 times higher than US EPA inventory estimates.

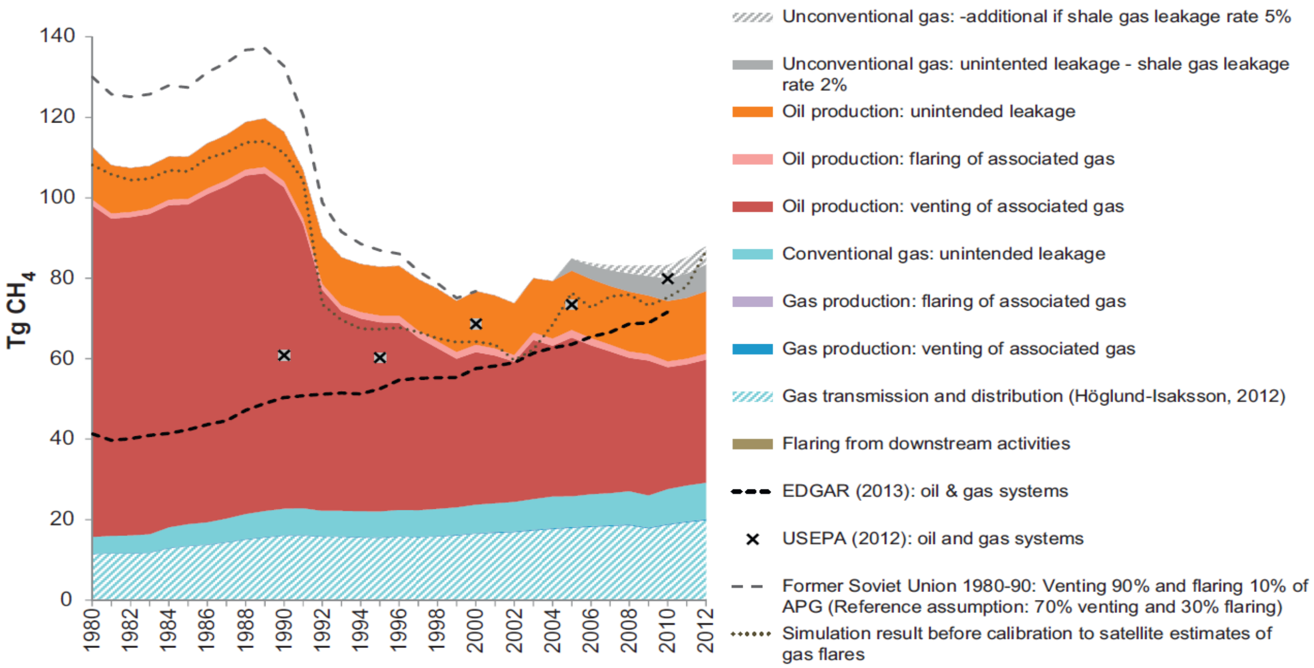

Figure 3: Global Methane Emissions from the fossil fuel industry; that is from the production and usage of natural gas, oil and coal. Source: Höglund-Isaksson, L.[20]

These findings highlight the need for a reassessment of current climate prediction emissions scenarios to account for revised values for anthropogenic methane emissions. The findings also suggest that there is a need for a robust assessment of methodological differences in estimating anthropogenic methane emissions in order to determine the source of the current spike in atmospheric concentrations. Furthermore, the findings also indicate that there is greater potential to mitigate methane driven climate change from fossil fuel and agriculture industries than earlier thought.

2. IMPACTS OF METHANE

2.1. Climate Impacts

Recent publications have improved our knowledge of methane's climate impacts. For example, a study conducted by Etminan and colleagues[22] revealed that methane's impact on the climate has been largely undervalued because previous calculations excluded its shortwave absorption characteristics. The study reported that the direct climate effect of increased methane concentration in the atmosphere is 25% higher than the values used in the Intergovernmental Panel on Climate Change (IPCC) 2013 assessment, and estimated the 100 year global warming potential (GWP) of methane as 32 instead of 28 as indicated in the IPCC assessment. This new estimate means that the present day radiative forcing of methane is about one third that of carbon dioxide, relative to preindustrial values, instead of just above a quarter as reported in previous studies. Another publication[23] showed that the

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[22] Etminan et al. Radiative forcing of carbon dioxide, methane, and nitrous oxide: A significant revision of the methane radiative forcing. Geophys. Res. Lett., 43, doi:10.1002/2016GL071930, 2016.

[23] MacDougall and Knutti. Enhancement of non-CO2 radiative forcing via intensified carbon cycle feedbacks. Geophys. Res. Lett., 43, 5833–5840, doi:10.1002/2016GL068964, 2016

climate forcing from non-CO_2 greenhouse gases including methane is able to boost positive carbon cycle feedbacks[24] by a factor of more than 1.15 depending on how long the gas is present in the atmosphere. According to the paper, this enhances the effective strength of methane-like gases and increases their net warming of global climate by up to 25% after 150 years. They attributed this effect to the fact that non-CO_2 greenhouse gases warm the Earth but are not able to induce CO_2 fertilization effect in plants or enhance the ability of oceans to take up CO_2. The study therefore concluded that the interaction of climate forcing from non-CO_2 gases with carbon cycle feedbacks will increase their warming impacts, indicating a stronger warming effect than current GWP numbers suggest.

2.2. Impact on Sea-level Rise

Zickfeld and colleagues[25] showed that the impacts of methane and other short-lived greenhouse gases on sea-level rise have a longer term effect than previously thought. The paper, which analysed the impact of methane, chlorofluorocarbons, hydrochlorofluorocarbons, hydrofluorocarbons, and perfluorinated gases on sea-level rise, found that their effects persist long after they are present in the atmosphere. According to the study, despite the short lifetime of methane in the atmosphere, at least half of the methane-induced thermal expansion of the ocean - which is one of the factors responsible for sea-level rise - persist for more than 200 years even after emissions have completely ceased. This means that continued emissions of methane and other short-lived gases continues, will lock-in levels of sea-level rise, affecting many coastal and small island countries in the future, even if emissions stop immediately.

2.3. Impact on Crop Yield

With respect to crop yield impacts, one analysis showed that while carbon dioxide is the largest driver of climate change, the reduction in crop yield due to climate change will be primarily driven by non-CO_2 climate pollutants including methane, black carbon and halocarbons[26]. This is because CO_2 fertilizes crops thereby counteracting some of the damages caused by its warming ability, while methane do not fertilize crops, but increases surface ozone – which is toxic to plants. The combination of ozone toxicity and warming ability of methane result in significant crop losses (Figure 4).The study showed that human induced emissions to date have led to a 9.5±3.0% decrease in agricultural yields worldwide with about 93% of these losses caused by non-CO_2 emissions, in particular methane (-5.2±1.7%) (Figure 5).

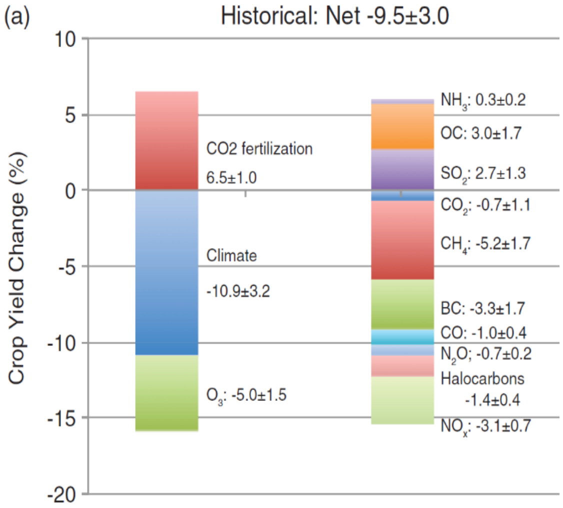

Figure 5: Historical impacts of climate forcing agents on crop yield. Source: Shindell D.T.[26]

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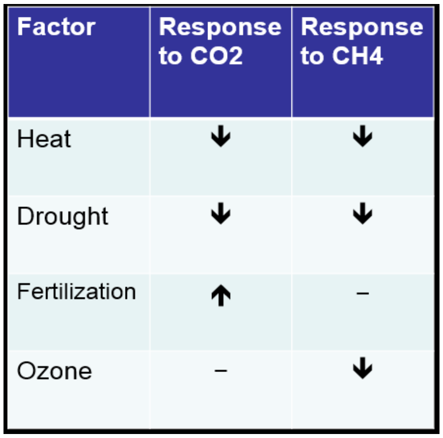
[24] Carbon cycle feedbacks in this case are the interactions between temperature change, and the various parts of the carbon cycle including the atmosphere, ocean, and biosphere.

[25] Zickfeld et al. Centuries of thermal sea-level rise due to anthropogenic emissions of short-lived greenhouse gases. www.pnas.org/cgi/doi/10.1073/pnas.1612066114, 2016.

[26] Shindell, D. T. Crop yield changes induced by emissions of individual climate-altering pollutants, Earth's Future, 4, doi:10.1002/2016EF000377. 2016.

2.4. Ozone-related Impacts – Crop Yield and Health



Factor	Response to CO2	Response to CH4
Heat	↓	↓
Drought	↓	↓
Fertilization	↑	–
Ozone	–	↓

Figure 4: Comparing methane and CO2 crop damage impacts; credit: Drew Shindell

Methane is one of the atmospheric substances responsible for forming tropospheric ozone – a major cause of crop yield losses globally. More and more publications[27] highlight not only ozone's damaging impact on crops but also its impacts on biodiversity[28]. This emphasizes the need to reduce emissions of all ozone precursors, including methane, NO_X, carbon monoxide, and non-methane volatile organic compounds. The recent Convention on Long-Range Transboundary Air Pollution Scientific Assessment Report[29] suggested that increased methane emissions, including from outside of Europe, is an important contributing factor to ozone concentration in Europe. It postulated that the effectiveness of methane emission controls within and outside of Europe will determine how much ozone concentration can be reduced in the region. Karlsson and colleagues also highlighted the need to include methane in ozone abatement actions in order to reduce concentrations in northern Europe[30].

Several studies have linked exposure to ozone with incidence of diseases and mortality. Jerrett and colleagues highlighted a positive relationship between ozone exposure and incidence of diabetes in African American women[31]. Turner and colleagues indicated that long-term exposure to ozone can contribute to risk of respiratory and circulatory mortality[32]. Bero and colleagues showed that short-term exposure to ozone is linked to a 1.72% increase in mortality in people with a previous history of cardiovascular diseases[33]. Silva and colleagues[34] found that various models show that future change in ozone concentration relative to year 2000 levels could lead to increased global mortality burden from a range 121 000 to 728 000 deaths per annum in 2000 to between 1.09 and 2.36 million deaths per annum in 2100, with increase in methane emissions, climate change impacts, and population growth playing important roles in this increase.

2.5. Societal/Economic Impacts

In an attempt to assess the societal and economic cost of the climate and environmental damage caused by methane, Shindell and colleagues[35] used a framework that takes into consideration methane's atmospheric lifetime as well as properties that differentiate it from CO_2 -- such as its inability to induce ecosystem fertilization and it ozone-forming properties. They found that the social cost of methane could be up to $2400 and $3600 per ton using a 5% and 3% discount rates respectively (2010 US$) or 100 and 50 times greater than that of CO_2 using

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[27] For example, Lobell & Asseng. Comparing estimates of climate change impacts from process-based and statistical crop models. Environ. Res. Lett. 12, 015001, 2017. Karlsso et al. Past, present and future concentrations of ground-level ozone and potential impacts on ecosystems and human health in northern Europe. Science of the Total Environment, 576, 22–35, 2017. Hewitt et al. N-fixation in legumes – an assessment of the potential threat posed by ozone pollution. Environmental Pollution, 208, Part B, 909–918, 2016. Yi et al. The impacts of surface ozone pollution on winter wheat productivity in China – An econometric approach. Environmental Pollution, 208, Part B, 326–335, 2016.

[28] For example, Fuhrer et al. Current and future ozone risks to global terrestrial biodiversity and ecosystem processes. Ecology and Evolution 6: 8785–8799, 2016; Calvete-Sogo et al. Heterogeneous responses to ozone and nitrogen alter the species composition of Mediterranean annual pastures, Oecologia, 181: 1055. doi:10.1007/s00442-016-3628-z, 2016. Bergmann et al. Impact of tropospheric ozone on terrestrial biodiversity: A literature analysis to identify ozone sensitive taxa. Journal of Applied Botany and Food Quality. 90, 83 – 105, DOI: http://dx.doi.org/10.5073/JABFQ.2017.090.012, 2017.

[29] Maas et al. Towards Cleaner Air. Scientific Assessment Report 2016. EMEP Steering Body and Working Group on Effects of the Convention on Long-Range Transboundary Air Pollution, Oslo. http://www.unece.org/fileadmin/DAM/env/lrtap/ExecutiveBody/35th_session/CLRTAP_Scientific_Assessment_Report_-_Final_20-5-2016.pdf

[30] Karlsso et al. Past, present and future concentrations of ground-level ozone and potential impacts on ecosystems and human health in northern Europe. Science of the Total Environment, 576, 22–35, 2017.

[31] Jerrett et al. Ambient ozone and incident diabetes: A prospective analysis in a large cohort of African American women. Environment International, http://dx.doi.org/10.1016/j.envint.2016.12.011

[32] Turner et al. Long-Term Ozone Exposure and Mortality in a Large Prospective Study. American Journal of Respiratory and Critical Care Medicine. **DOI:** http://dx.doi.org/10.1164/rccm.201508-1633OC

[33] Bero et al. Short-term exposure to ozone & mortality in subjects with and without previous cardiovascular disease. Epidemiology, 27, 663-9. 2016

[34] Silva et al. The effect of future ambient air pollution on human premature mortality to 2100 using output from the ACCMIP model ensemble. Atmos. Chem. Phys., 16, 9847–9862, 2016

[35] Shindell et al. The Social Cost of Methane: Theory and Applications. Faraday Discuss. DOI: 10.1039/C7FD00009J, 2017.

the same discounts rates. They also noted that increased methane emissions in the future could counter much of the societal benefits gained from reducing the rate of CO_2 emissions. Sarofim and colleagues[36] showed that the global mitigation of methane, and the consequent reduction in ozone pollution, could provide global premature mortality benefits estimated at USD 790 and USD 1775 per ton of methane based on changes in short- and long-term exposure, respectively (2011 US$).

3. BLACK CARBON EMISSIONS AND INVENTORIES

3.1. Emission Trends

A recent assessment[37] of global anthropogenic particulate matter (PM) put the emissions of black carbon in 2000 and 2010 at 6.6 and 7.2Tg respectively (Figure 6a & b). The study, which used GAINS integrated assessment model, shows that about 15% of global $PM_{2.5}$ emissions is black carbon with some $PM_{2.5}$ sources, like traffic emissions, containing up to 50% black carbon. The study included sources that previous assessments have not accounted for or often misallocated, -- such as kerosene lamps, gas flaring, diesel generators and trash burning --leading to higher emissions estimations than previous studies. Another study[38], which looked at the future trend of black carbon emissions, projected a decline in emissions between now and 2100. The study, using different assessment models, indicated that under business as usual conditions, black carbon emissions will be dominated by the transportation and residential sectors between now and 2100. It further projected that implementing climate policies to reduce CO_2 emissions will affect black carbon emissions differently depending on the level of ambition. Moderate climate policies that aim to reduce CO_2 by 50% would lead to only a 10-20% reduction in black carbon emissions. However, ambitious climate policies aimed at negative CO_2 emissions by the end of the century, reduced black carbon emissions from 20 to 80% depending on the model assumptions. This analysis suggests that actions to reduce black carbon will still be required even with ambitious implementation of CO_2 mitigation actions.

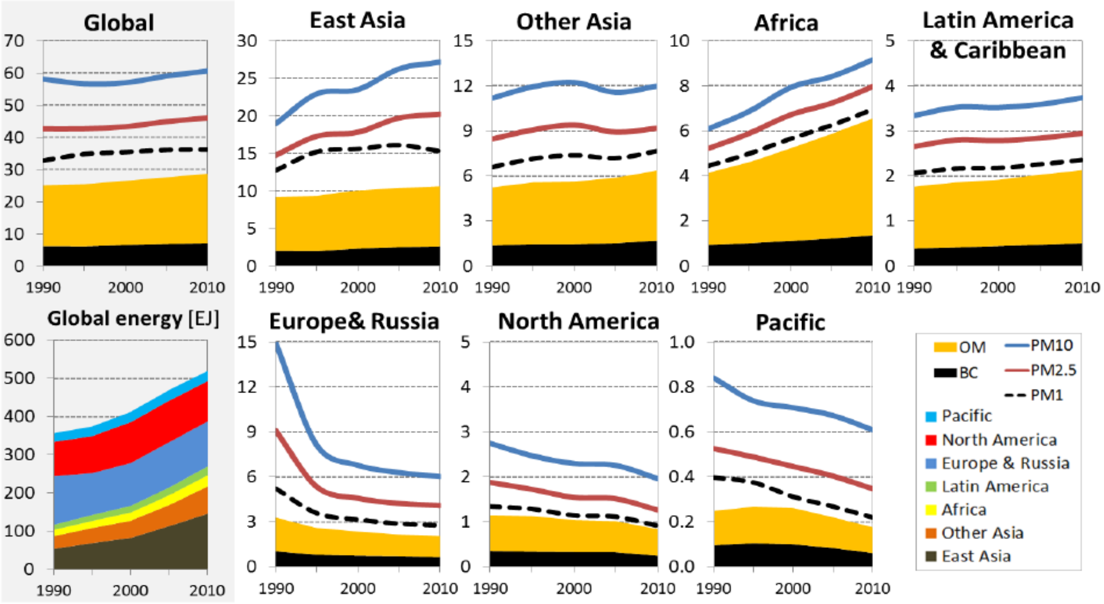

Figure 6a: Global and regional emissions of PM species including black carbon. Source: Klimont et al.[37]

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[36] Sarofim et al. Valuing the Ozone-Related Health Benefits of Methane Emission Controls. Environ Resource Econ, 66:45–63, DOI 10.1007/s10640-015-9937-6, 2017

[37] Klimont et al. Global anthropogenic emissions of particulate matter including black carbon. Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2016-880, 2016.

[38] Smith et al. Future aerosol emissions: a multi-model comparison. Climatic Change, 138:13–24, DOI 10.1007/s10584-016-1733-y, 2016

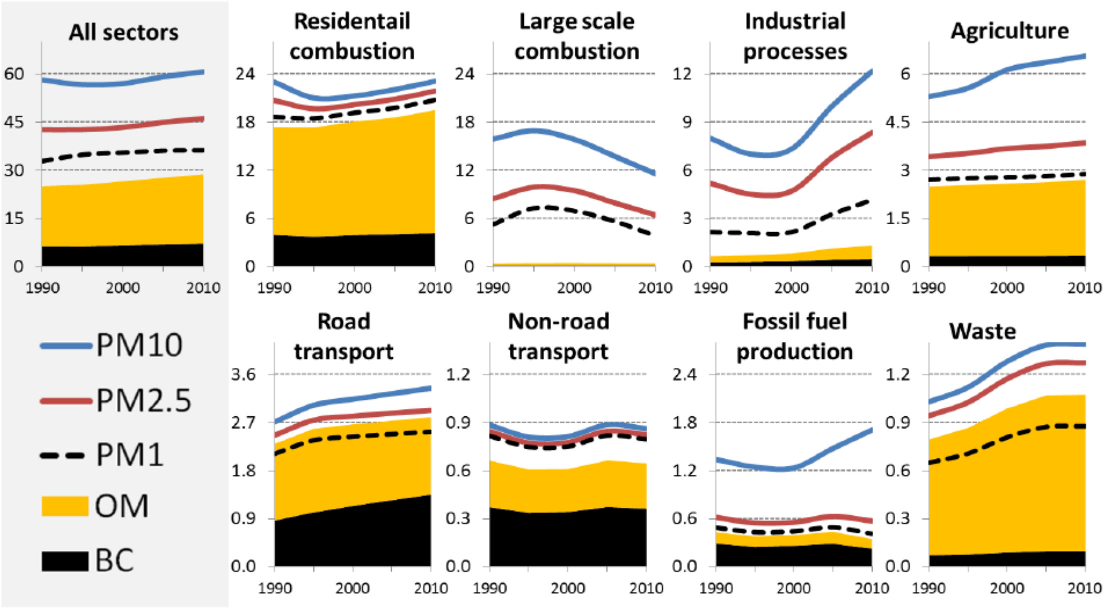

Figure 6b: Global and sectoral emissions of PM species including black carbon. Source: Klimont et al.[37]

3.2. Emission Sources

One study[39] seeking to fill in the dearth of data on black carbon concentrations in the Siberian Arctic found the area to have higher black carbon concentrations compared to Arctic sites closer to Europe, even though it is far less populated. The study used both observations and models to ascertain the sources of black carbon and found that transportation (38%) and residential heating (35%) are the main sources of black carbon in the region. This is contrary to previous research which had suggested gas flaring as a possible major source. It found that gas flaring only contributes 6% while open fires and power plants contribute 12 and 9% respectively. They further show that traffic emissions mostly from Europe, China and densely populated areas of Russia are responsible for the observed high transportation emissions. A 2015 observation study using samples from the Arctic region close to Norway also found that residential biomass burning and fossil fuels contributed substantially to black carbon concentrations, with 13 of the 16 samples analyzed indicating no significant contributions from gas flaring[40].

It should be noted however that an in-the-field measurement of black carbon emissions rates from oil and gas flaring by Conrad and Johnson[41] suggested that the overall black carbon-related impacts of gas flaring on global warming including in the Arctic may be underestimated. The study, which used measurement and imaging techniques to compute the instantaneous black carbon emission rate, suggested that the GAINS model emission factor used to estimate black carbon emissions from flaring could be low by almost a factor of two. They also found significant variability in the emission rates between flares with differences that span an order of magnitude of more than four, indicating the existence of individual super-emitter flares of importance for global emission

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[39] Winiger et al. Siberian Arctic black carbon sources constrained by model and observation. www.pnas.org/cgi/doi/10.1073/pnas.1613401114. 2016

[40] Winiger at al. Isotope-Based Source Apportionment of EC Aerosol Particles during Winter High-Pollution Events at the Zeppelin Observatory, Svalbard. Environ. Sci. Technol., 49, DOI: 10.1021/acs.est.5b02644, 1959−11966, 2015.

[41] Conrad and Johnson. Field Measurements of Black Carbon Yields from Gas Flaring. Environ. Sci. Technol. DOI: 10.1021/acs.est.6b03690, 2016

inventories. The existence of super-emitters is supported by another recent study[42] that found that less than 100 out of 20,000 flares in the United States are responsible for over half of total emissions in current emission inventories of black carbon, methane and CO_2.

A global black carbon emissions inventory from gas flaring was recently developed by Huang and Fu[43]. Their results show that Russia and Nigeria remain the top two highest gas flaring countries by volume globally. They found that black carbon emissions from flaring have generally declined since 2005 with emissions of about 180 Gg/yr in 2005 and about 150 Gg/yr in 2012. Russia significantly dominates total global emissions (57%), with the Middle East and Mid and West Africa contributing about 12 and 14%, respectively. The rest of the world contributes about 17% (Figure 7).

4. BLACK CARBON IMPACTS

4.1. Climate Impacts

Black carbon possesses warming characteristics because of its ability to absorb visible light, which disturbs the planetary radiation balance and eventually leads to warming. Additionally, when black carbon is deposited on ice or snow, it reduces their ability to reflect light and increases heat absorption thereby increasing both atmospheric warming and ice/snow melting rates. Black carbon is almost always emitted with other co-pollutants at varying proportions, depending on the combustion source. These co-pollutants include sulphates, nitrogen oxides (NOx), carbon monoxide, methane, non-methane volatile organic compounds, and organic carbon (OC, which includes brown carbon)[44]. Brown carbon, like black carbon, also absorbs sunlight and causes warming and is therefore categorized as a light-absorbing-organic carbon. Sulphates and other forms of organic carbon are cooling agents. Hence, the overall warming effect of black carbon from any particular source depends on the ratio of black carbon to these cooling co-pollutants.

Laboratory- and field-based results indicate that aging affects the radiative forcing of black carbon. Results have shown that as soot ages, its ability to absorb light is altered depending on where in the atmosphere the soot particles are located and the prevailing chemical composition of the environment[45]. Peng and colleagues show that this aging process could amplify black carbon's light-absorbing properties by a factor of up to 2.4 within 2 to 18hrs in polluted and non-polluted urban environments respectively[46], which is higher than what is commonly used in global climate models. Recent results[47] also show that climate models need to consider the important role of brown carbon plays on the impact aerosols have on overall warming. This is because the light absorbing properties of organic carbon at short wavelengths – due to their brown carbon content – could contribute significantly to the total warming impacts of aerosols, yet this has been sometimes ignored in some climate models.

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[42] Allen et al. Carbon dioxide, methane and black carbon emissions from upstream oil and gas flaring in the United States. Current Opinion in Chemical Engineering, 13:119–123, 2016

[43] Huang and Fu. Data Descriptor: A global gas flaring black carbon emission rate dataset from 1994 to 2012. Sci Data. 3: 160104, 2016.

[44] Brown carbon is an atmospheric aerosol mainly emitted during biomass and coal combustion. It plays a key role in the warming of the atmosphere through its light absorbing characteristics, with strong absorbing characteristic of short wavelength solar radiation. It is termed the light absorbing-organic carbon

[45] For example, China et al. Morphology of diesel soot residuals from supercooled water droplets and ice crystals: implications for optical properties. Environ. Res. Lett. 10, 114010, 2015. Ueda et al. Light absorption and morphological properties of soot-containing aerosols observed at an East Asian outflow site, Noto Peninsula, Japan. Atmos. Chem. Phys., 16, 2525–2541, 2016; Fierce et al. Black carbon absorption at the global scale is affected by particle-scale diversity in composition. Nature Communications, 7:12361, DOI: 10.1038/ncomms12361, 2016; Wu et al. Black carbon radiative forcing at TOA decreased during aging, Scientific Reports, 6:38592, DOI: 10.1038/srep38592; Chen et al. Light absorption enhancement of black carbon from urban haze in Northern China winter, Environmental Pollution, 221, 418–426, 2017; Doner and Liu. Impact of morphology on the radiative properties of fractal soot aggregates. Journal of Quantitative Spectroscopy & Radiative Transfer 187, 10-19, 2017.

[46] Peng et al. Markedly enhanced absorption and direct radiative forcing of black carbon under polluted urban environments. PNAS, 113, 4266–4271, 2016.

[47] For example, Gustafsson & Ramanathan 2016, Convergence on climate warming by black carbon aerosols, Guang-Ming et al. 2016. Brown carbon in the cryosphere: Current knowledge and perspective, Advances in Climate Change Research 7 (2016) 82e89; Yuan et al. Light absorption of brown carbon aerosol in the PRD region of China. Atmos. Chem. Phys., 16, 1433–1443, 2016; Shamjad et al. Refractive Index and Absorption Attribution of Highly Absorbing Brown Carbon Aerosols from an Urban Indian City-Kanpur. Scientific Reports, 6:37735 | DOI: 10.1038/srep37735, 2016; Cui et al. Radiative absorption enhancement from coatings on black carbon aerosols. Sci Total Environ 551-552:51–56, 2016

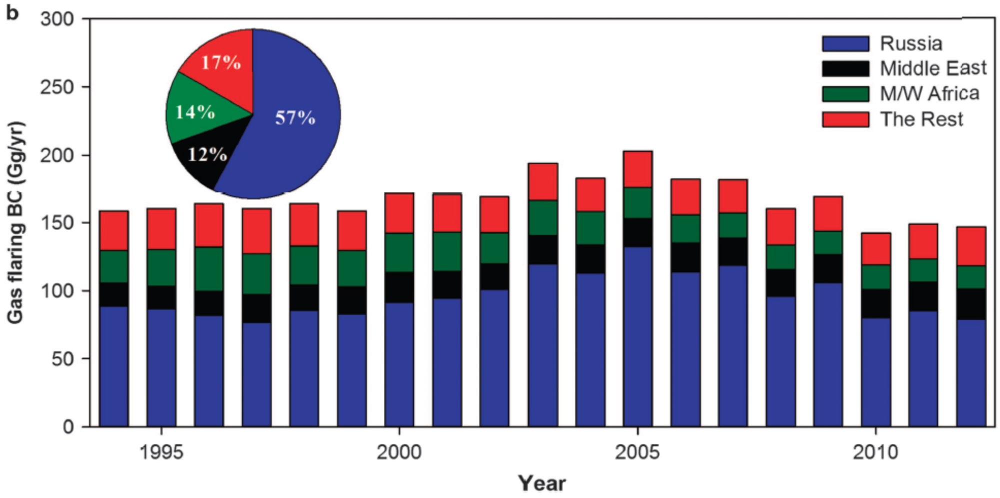

Figure 7: Global black carbon emissions from gas flaring. Source: Huang and Fu[43]

It is also important to consider the role aerosol's non-black carbon content plays in the ability of black carbon to absorb light and induce warming. A new study shows that enhanced light absorption depends on the mass ratio of non-black carbon to black carbon in aerosols. According to Liu and colleagues[48], enhanced light absorptionwas not observed in aerosols with a non-black carbon to black carbon mass ratio of below 1.5, which is typical of emissions from fresh traffic sources. However, with a non-black carbon to black carbon mass ratio above 3–which is commonly found in soot from biomass burning – light absorption enhancement was detected. This was attributed to non-black carbon particles coating black carbon particles, and causing black carbon's stronger interaction with light. Another study[49] found that an increased absorption of ranging from 1.3 to 2.2, depending on the time of the day, was associated with nitrate and sulphate content of aerosols. Cui and colleagues[50] also reported an enhancement ranging between 1.4 and 3 for fresh and aged Chinese aerosols, with sulphate content primarily responsible for the enhancement.

4.2. Impacts on Regional Climate and Weather Pattern

Some studies have further linked anthropogenic aerosols, including black carbon, with changes in regional climates and the hydrological cycle. Fan and colleagues show that aerosols contributed to approximately 40% reduction in summer precipitation over Mt. Hua in China. They attributed this to induced warming by heat absorbing aerosols, mainly black carbon, at the top of the mountain and cooling near the surface causing achange in moisture movement (Figure 8)[51]. Similarly, Hodnebrog and colleagues, using global and regional models, showed a 20-30% decrease in rainfall in southern Africa was caused by the warming and drying the atmosphere by aerosol emissions, in particular black carbon from local biomass burning[52]. Another study by Yoon and colleagues showed that carbonaceous aerosols, including black and organic carbon, may have led to a 25% reduction in rainfall over North Africa[53].

A review of existing literature and models also suggests that black carbon and other aerosols, influenced the monsoon and resulted in widespread solar dimming over both South and East Asia, leading to an increase in

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[48] Liu et al. Black carbon absorption enhancement in the atmosphere determined by particle mixing state. Nature Geoscience. http://dx.doi.org/10.1038/ngeo2901, 2017

[49] Chen et al. Light absorption enhancement of black carbon from urban haze in Northern China winter. Environmental Pollution, 221, 418–426, 2017

[50] Cui et al. Radiative absorption enhancement from coatings on black carbon aerosols. Science of The Total Environment, 551–552, 51–56, 2016.

[51] 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.

[52] Hodnebrog et al. Local biomass burning is a dominant cause of the observed precipitation reduction in southern Africa. Nature Communications, 7:11236, 2016

[53] Yoon et al. The role of carbonaceous aerosols on short-term variations of precipitation over North Africa. Atmos. Sci. Let. 17: 407–414, 2016.

atmospheric solar heating[54]. The study indicates that aerosols are responsible for a significant change to Asia's hydrologic cycle in the 21st century, including a weakening of the Asian monsoon. This is further supported by another study by Lau and colleagues[55].

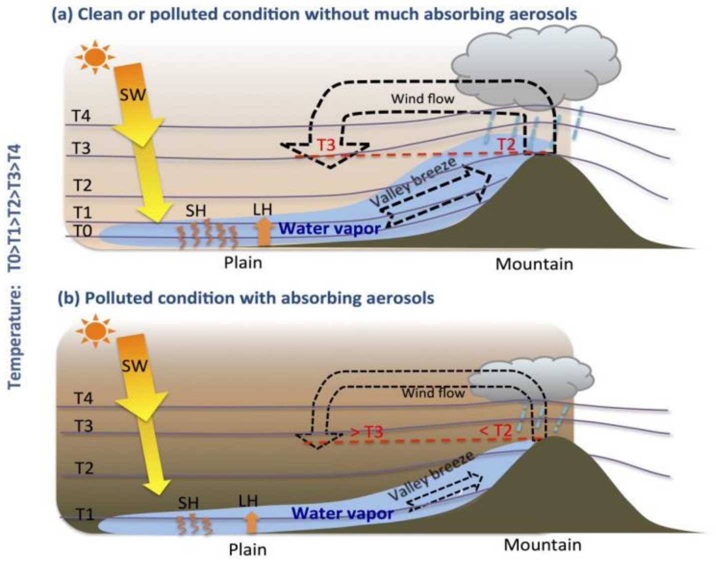

Figure 8: Mechanism leading to precipitation reduction due to increased black carbon pollution. Source: Fan

4.3. Impacts on Crops

Black carbon affects ecosystem and agriculture productivity through its ability to alter weather and precipitation patterns. It can lead to increased frequency of drought and flood (see section 5.2), negatively effecting crop yield. Furthermore, its increased Earth warming effect also impacts agricultural productivity. An analysis of the impact of emissions of individual climate-altering pollutants including black carbon, HFC, N_2O, organic carbon, SO_2, and NH_3 on crop yield, shows that black carbon will have the greatest agricultural damages per ton on crops in the first decades over the remainder of the 21st century, although this overall loss is reduced when the effect of co-emitted substances are taken into consideration[56].

4.4. Health Impacts

Black carbon, organic carbon and other co-pollutants are significant components of fine particulate matter (PM_{25}). $PM_{2.5}$ is a major cause of ill health and premature deaths globally. Most studies usually assess the impacts of PM_{25} on health rather than direct impacts of black carbon. However, a recent assessment[57] analysed the public health impact of black carbon concentrations in the United States in 2010. According to the assessment, approximately 14,000 deaths (Figure 9), as well as hundreds of thousands of illnesses including hospitalizations, emergency visits and minor respiratory symptoms can be attributed to black carbon. The study's sensitivity analysis further suggested that total black carbon-related deaths may be substantially more.

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[54] Li et al. Aerosol and monsoon climate interactions over Asia, Rev. Geophys., 54, 866–929, doi:10.1002/2015RG000500, 2016

[55] Lau et al. Impacts of aerosol–monsoon interaction on rainfall and circulation over Northern India and the Himalaya Foothills. Climate Dynamics. DOI 10.1007/s00382-016-3430-y

[56] Shindell, D. T. Crop yield changes induced by emissions of individual climate-altering pollutants, Earth's Future, 4, doi:10.1002/2016EF000377. 2016.

[57] Li et al. Assessing public health burden associated with exposure to ambient black carbon in the United States. Sci. of the Total Environment, 539. 515-525 2016.

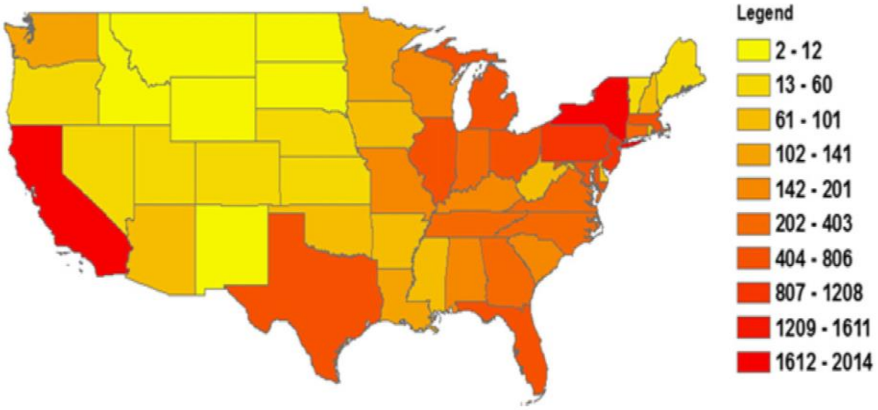

Figure 9: Annual premature mortality by State attributed to exposure to black carbon in the US. Source: Li et al[57]

A first of its kind study[58] looking at the role of air pollution, in particular black carbon, on the onset of respiratory disease shows that black carbon directly affects the main bacteria responsible for respiratory infections - *Streptococcus pneumoniae* and *Staphylococcus aureus*. The study found that exposure of these bacteria to black carbon leads to structural, compositional and functional changes that could cause the bacteria to spread from the nose to the lower respiratory tract - an essential process before subsequent infection. They also found that black carbon alters the bacteria's antibiotic tolerance increasing their resistance to multiple antibiotics, including penicillin – the leading treatment for pneumonia. Another study looking at the exposure of children to black carbon emissions from road traffic found that children living close to major roads had significantly poorer lung function than those living in less polluted areas. Kids living 100 meters away from traffic showed an average of 6 percent lower lung function than those living 400 meters or more away at the age of eight[59]. Another study further showed that black carbon exposure of children living in urban areas diminishes the health benefits that would normally accrue from daily physical activities[60]. Another study on traffic-related $PM_{2.5}$ including black carbon, also showed that a higher incidence of dementia is associated with living in close proximity to major roads with heavy traffic[61].

A global estimate of the number of preterm births associated with $PM_{2.5}$ concentrations, found that about 2.7 million preterm births (18% of the total number of preterm births) globally may be caused by maternal exposure to ambient $PM_{2.5}$ concentrations. This is important as preterm birth is associated with a number of post-natal health outcomes, including infant mortality and in some cases life-long morbidity impacts in survivors[62]. A recent analysis by Liu and colleagues[63] that focused on specific sectors found that increased emissions of $PM_{2.5}$ from ocean-going vessels in East Asia led to large adverse health impacts, especially near shore. They estimated a total of 24,000 (range 14,500–37,500) premature deaths annually in East Asia are associated with $PM_{2.5}$ and ozone emissions from shipping.

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[58] Hussey et al. rs Staphylococcus aureus and Streptococcus pneumoniae biofilms, antibiotic tolerance and colonisation.", Environ Microbiol. doi:10.1111/1462-2920.13686, 2017

[59] Rice et al. Lifetime Exposure to Ambient Pollution and Lung Function in Children. American Journal of Respiratory and Critical Care Medicine, 193, 881 DOI: 10.1164/rccm.2015061058OC, 2016

[60] Lovinsky-Desir et al. Physical activity, black carbon exposure and airway inflammation in an urban adolescent cohort. Environmental Research, 151, 756–762, 2016.

[61] Chen et al. Living near major roads and the incidence of dementia, Parkinson's disease, and multiple sclerosis: a population-based cohort study. The Lancet, 389, 718–726, DOI: http://dx.doi.org/10.1016/S0140-6736(16)32399-6, 2017

[62] Malley, C.S. et al. Preterm birth associated with maternal fine particulate matter exposure: A global, regional and national assessment, Environment International, http://dx.doi.org/10.1016/j.envint.2017.01.023. 2017.

[63] Liu et al. Health and climate impacts of ocean-going vessels in East Asia. Nature Climate Change, DOI: 10.1038/NCLIMATE3083, 6, 2016

A study of residential cooking and heating in China showed that an estimated 159,000 (range 142,000–172,000) and 182,000 (range 163,000–197,000) premature deaths can be attributed to the effects of heating and cooking emissions on outdoor (ambient) air quality, respectively; that is a total of 341,000 (range 306,000–370,000) premature deaths from $PM_{2.5}$-related emissions from residential combustion, equivalent to a third of total deaths caused by all ambient $PM_{2.5}$ pollution in China[64].

5. HYDROFLUOROCARBONS EMISSIONS AND INVENTORIES

5.1. Emissions Sources and Trends

A recent publication by Purohit and Hoglung-Isaksson[65] used the GAINS model framework to estimate current and future global emissions of fluorinated greenhouse gases (F-gases). They estimated the total emissions of F-gases (hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6)) in 2005 and 2010 to be 0.7 and 0.89 $PgCO_2eq$ respectively with HFCs dominating the total emitted F-gases at about 75% of total (Figure 10). The study also projected an increase to 3.7 $PgCO_2eq$ by 2050 if control technologies are only deployed at current levels, with a rapid growth expected in Article 5 (developing) countries. This future growth is expected to be dominated by China (39% of total global F-gas emissions due to a projected seven-fold increase between 2010 and 2050); followed by India (13%). Under business as usual conditions emissions are expected to double by 2050 in the United States and Canada but will fall to less than 2005 levels in Europe due to stringent controls.

5.2. Impacts of HFCs

The analysis by Zickfield et al[66] reported in section 2.2 also included the impact of HFCs on sea-level rise. They show that HFCs, like methane, have a disproportional impact on sea-level rise. Although they have a short lifetime in the atmosphere compared to CO_2, once emitted their effect on the thermal expansion of the ocean, and consequent sea level rise, will persist for several centuries. With respect to impact on agriculture, the analysis of crop yield damages caused by individual climate forcing agents reported in section 2.3 also shows that HFCs will have the second greatest negative impact on crop yield per ton in the first decades of the remainder of the 21st century.

6. MITIGATION MEASURES, POTENTIALS AND BENEFITS

6.1. Methane Mitigation Measures, Emission Reduction Potential and Benefits

New publications in the past year highlighted measures for reducing methane emissions from various sectors. In the oil and gas sector, Tomkins et al[67] show, for the first time, the possibility of converting gaseous methane into liquid methanol under conditions that could be industrially implemented. This was not possible previously due to a need to alternate the reaction environment's temperature between 200 and 450 degrees Celsius. Their novel work was able to produce methanol from gaseous methane in a constant temperature environment of 200 degrees Celsius, thereby opening up a range of possibilities, including as an alternative to gas flaring in the oil and gas sector. Furthermore, in the same sector, recent studies highlight the existence of so called "super-emitters" known to typically leak more methane than average, and therefore responsible for a significant percentage of methane emissions. For example, an analysis of the natural gas leakage dataset by Brandt et al[68] show that over half of all leaks were caused by 5% of the sources. An aerial survey of various emission sources including gas

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[64] Archer-Nicholls et al. The regional impacts of cooking and heating emissions on ambient air quality and disease burden in China. Environ Sci Technol., 6, 9416-23, doi: 10.1021/acs.est.6b02533. 2016.

[65] Purohit &Höglund-Isaksson. Global emissions of fluorinated greenhouse gases 2005–2050 with abatement potentials and costs. Atmos. Chem. Phys., 17, 2795-2816, 2017

[66] Zickfeld et al. Centuries of thermal sea-level rise due to anthropogenic emissions of short-lived greenhouse gases. www.pnas.org/cgi/doi/10.1073/pnas.1612066114, 2016.

[67] Tomkins et al. Isothermal Cyclic Conversion of Methane into Methanol over Copper-Exchanged Zeolite at Low Temperature. Angewandte Chemie International Edition, 2016; DOI: 10.1002/anie.201511065

[68] Brandt et al. Methane Leaks from Natural Gas Systems Follow Extreme Distributions. Environ. Sci. Technol. 50, 12512–12520, DOI: 10.1021/acs.est.6b04303, 2016

processing facilities, storage tanks, pipeline leaks, well pads, and a coal mine venting shaft by Frankenbergetal[69] found similar results, with the top 10% methane emitters responsible for 49 - 66% of emissions. Kemp et al[70] also show that 80% of leaks can be eliminated by selectively targeting these super-emitters. These findings suggest that super-emitters are low hanging fruit in methane mitigation and selectively targeting them to fix leaks will effectively reduce methane emissions and provide significant climate and economic benefits.

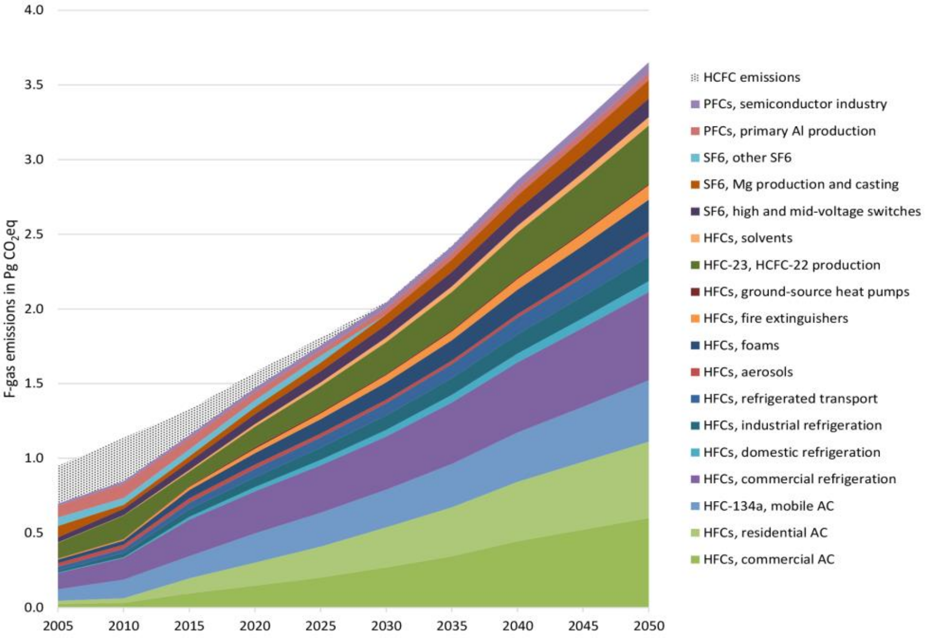

Figure 10: Baseline emissions of F-gases (HFCs, PFCs, and SF$_6$) 2005 to 2050 by source sector. Source: Purohit &Höglund-

In the agriculture sector, recent research shows how the compound, 3-nitrooxypropanol, can reduce methane emissions in ruminant animals without having negative impacts on animal's health and productivity. In a 2015 publication,[71] researchers showed that the compound was able to persistently decrease enteric methane emissions by 30%, without negatively affecting animal productivity. They discovered that unreleased methane was partially used as energy by the animal, resulting in increased body weight. Their more recent publication[72] highlighted the mechanisms that allow this to happen. They showed that the compound inactivates methane-forming bacteria in the animal's stomach but not the bacteria needed for effective growth and productivity; hence, reduced methane emissions and increase body weight.

Another recent publication[73] found that eliminating livestock antibiotics intake can reduce methane emissions. The study showed that the dung from cattle treated with antibiotics (tetracycline) had double the methane emissions of dung from untreated cattle. They suggested that the probable cause of these effects is the reduction of bacteria in the animal's guts leading to the growth of methanogenic archaea in their intestine. Apart from

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[69] Frankenberg et al. Airborne methane remote measurements reveal heavytail flux distribution in Four Corners region. PNAS, 113, 9734–9739, doi/10.1073/pnas.1605617113, 2016

[70] Kemp et al. Comparing Natural Gas Leakage Detection Technologies Using an Open-Source "Virtual Gas Field" Simulator. Environ. Sci. Technol. 50, 4546–4553, DOI: 10.1021/acs.est.5b06068, 2016

[71] Histrov et al. An inhibitor persistently decreased enteric methane emission from dairy cows with no negative effect on milk production. PNAS, 112, 10663–10668, doi: 10.1073/pnas.1504124112, 2015

[72] Duin et al. Mode of action uncovered for the specific reduction of methane emissions from ruminants by the small molecule 3nitrooxypropanol. PNAS, DOI: 10.1073/pnas.1600298113, 2016

[73] Hammer et al. Treating cattle with antibiotics affects greenhouse gas emissions, and microbiota in dung and dung beetles. Proc. R. Soc. B 283: 20160150. http://dx.doi.org/10.1098/rspb.2016.0150, 2016

increased methane emissions, antibiotic laced dung was also found to change the make-up of microbes in the guts of dung eating beetles, thereby negating the ecosystem services the beetles provide.

Furthermore, Herrero and colleagues[74] show that implementing management options that combine actions targeted toward sustainable livestock intensification, reduced emissions from manure, carbon sequestration in rangelands, and moderating the demand for livestock products could mitigate 50% of the total greenhouse gas emissions (mostly methane), from the agriculture, forestry, and land-use sectors combined. They however highlight the need for more research and investment in order to increase the affordability and adoption of mitigation practices, as well as to avoid negative impacts that the proposed changes could have on livelihoods and economic activities. Another study focused on the social cost of methane emissions found that reducing food waste and adopting the management practices proposed, could yield large societal benefits in the range of 50-150 billion US dollars per year[75].

A recent systematic review and analysis[76] of literature on the benefits of shifting from current dietary intakes to environmentally sustainable patterns (involving an analysis of 14 common sustainable dietary patterns) suggest that dietary change is an effective measure for emissions reduction. The analysis shows that dietary change could result in a 70-80% reduction in land use and greenhouse gas emissions, including methane, CO_2 and N_2O, and a 50% reduction in water use, while providing modest benefits for human health. Another analysis by Springmann et al[77] show that a shift toward standard dietary guidelines that call for more vegetables and less meat, have the potential to reduce food related greenhouse gases by 29-70%, while also reducing premature deaths globally by 6–10%, compared to a business as usual scenario, by 2050. They also reported that the economic benefits associated with improved diets to be between 1 and 31 trillion US dollars, equivalent to 0.4–13% of global gross domestic product (GDP) by 2050, with a significant portion of the benefits accruing to developing countries. Another study on the health benefits associated with diets high in fruits and vegetables estimated that 5.6 and 7.8 million premature deaths was attributed to a diet with less than 500 and 800g of fruits and vegetables respectively in 2013[78] indicating the health benefits from reduced meat consumption and increased plant based diet.

With respect to crop yield benefits associated with methane emissions mitigation, analysis by Shindell[79] show that following a low emissions trajectory that reduce emissions of global warming agents would increase crop yields

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[74] Herrero et al. Greenhouse gas mitigation potentials in the livestock sector. Nature Climate Change, DOI: 10.1038/NCLIMATE2925

[75] Shindell et al. The Social Cost of Methane: Theory and Applications. Faraday Discuss. DOI: 10.1039/C7FD00009J, 2017.

[76] Aleksandrowicz et al. The Impacts of Dietary Change on Greenhouse Gas Emissions, Land Use, Water Use, and Health: A Systematic Review. PLoS ONE 11, e0165797. doi:10.1371/journal.pone.0165797, 2016

[77] Springmann et al. Analysis and valuation of the health and climate change cobenefits of dietary change. PNAS, 113, 4146–4151, 2016.

[78] Aune et al. Fruit and vegetable intake and the risk of cardiovascular disease, total cancer and all-cause mortality–a systematic review and dose response meta-analysis of prospective studies. International Journal of Epidemiology, 1–28, doi: 10.1093/ije/dyw319, 2017

[79] Shindell, D. T. Crop yield changes induced by emissions of individual climate-altering pollutants, Earth's Future, 4, doi:10.1002/2016EF000377. 2016.

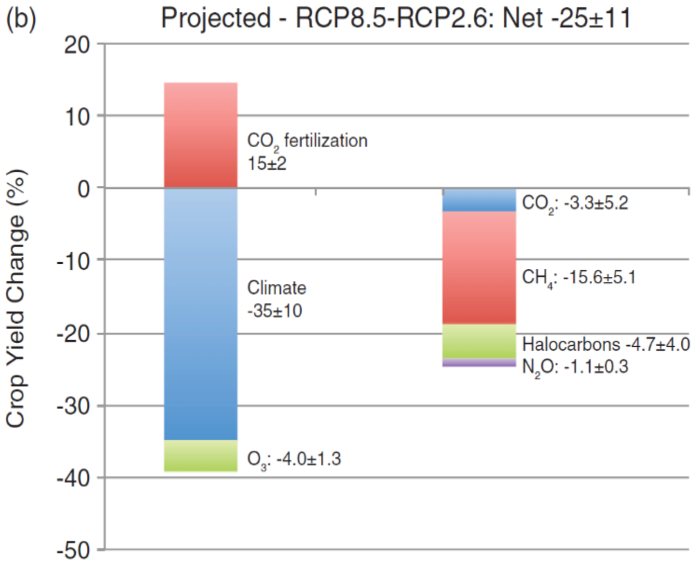

Figure 11: Projected impacts of climate forcing agents on crop yield. Source: Shindell D.T.[79]

by 25±11% by year 2100 compared to a high emissions trajectory, with the largest benefits (15.6±5.1%) coming from reduced emissions of methane (Figure 11).

Finally, an analysis[80] of the benefits realized due to the United States Environmental Protection Agency's programs and policies to reduce methane emissions from waste landfill, oil and natural gas, coal mining and agricultural manure management between 1993 and 2013, resulted in an avoided global temperature rise of 0.006 °C by 2013. The monetary value of the climate and ozone-health benefits of these methane reductions was estimated to be worth $255 billion US dollars indicating a significant economic and societal benefits from these methane emission reduction programs.

6.2. Black Carbon Mitigation Measures, Emission Reduction Potential and Benefits

A study by Lacey and colleagues[81] found that a phase-out of aerosol emissions from traditional biomass- or coal-burning cookstoves over the next 20 years in countries where more than 5% of the population use solid fuels for cooking, would yield significant climate and health benefits. The study found that about 0.08 ºC temperature cooling can be achieved by 2050 by reducing black carbon emissions from cookstoves. This increases to 0.12 ºC by 2100 when the cooling due to CO_2 mitigation kicks in. The earth-cooling benefits of reducing black carbon, CO_2, and methane offsets the warming effect from removing of co-emitting atmospheric coolants like organic carbon and sulphates. The study also found that emissions reductions in China, India, and Ethiopia would yield the largest climate benefit in 2050 while interventions in countries less commonly targeted for cookstove mitigation including Azerbaijan, Ukraine, and Kazakhstan would provide the largest per-cookstove climate benefits because black carbon from these countries is transported to the Arctic where they have disproportionate impacts. the study also found that approximately 22.5 million premature deaths could be prevented between 2000 and 2100 by implementing the phase-out of cookstove emissions (and consequently $PM_{2.5}$), with China, India, and Bangladesh benefitting the largest (preventing an average of 198,000 of the 260,000 global annual avoided deaths in 2050 in these countries). The largest per-cookstove health benefit was shown to accrue to Ukraine, Azerbaijan and Romania. The findings suggest that while a 100% elimination of cookstoves might not be feasible, a targeted approach to phasing out traditional cookstoves, based on identified countries, would yield significant climate and health benefits.

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[80] Melvin et al. Climate benefits of U.S. EPA programs and policies that reduced methane emissions 1993–2013. Environ. Sci. Technol. 50, 6873−6881, DOI: 10.1021/acs.est.6b00367, 2016

[81] Lacey et al. Transient climate and ambient health impacts due to national solid fuel cookstove emissions. www.pnas.org/cgi/doi/10.1073/pnas.1612430114, 2016

A study by Alexander et al[82] suggest that the incidence of hypertension and cardiovascular risk in pregnant women can be reduced by substituting biomass and kerosene cookstoves with clean-burning ethanol stoves. This finding is further supported by another study by Olopade et al[83].

A study[84] focused on the complete life cycle inventory of an improved cookstove[85] replacing traditional three-stone fires with the improved biomass-burning stove, avoided roughly 440 times more CO_2-equivalent emissions compared to emissions associated with the creation and distribution of the stove. However, several recent studies found that some improved biomass-burning stoves do not deliver the expected climate and health benefits. For example, an evaluation[86] of a Clean Development Mechanism (CDM)-approved stove replacements program in India found that the proportion of black carbon in the emitted $PM_{2.5}$ from intervention stoves were higher than emissions from the traditional stoves being replaced. This finding shows that the expected climate and health benefits based on the laboratory performance of efficient stoves do not fully materialize in the field. Another study[87] compared three different improved biomass stoves -- a low-cost ceramic model, two forced-draft cookstoves (FDCS; Philips HD4012LS and ACE-1) -- and three other stoves showed that only the Philips stove provided noteworthy reductions in elemental carbon emissions. As in the previous case, the study found that estimated health and climate co-benefits of all stoves were lower than their laboratory tests due to differences in real-world conditions such as fuel variability and non-ideal operation. A separate community-level study[88] comparing cleaner burning biomass stoves with traditional open fire cooking suggested no evidence that cleaner burning stoves reduce the risk of pneumonia in young children compared to open fires. A similar study[89] also indicated weak evidence of a decline in the incidence of acute lower respiratory infections in young children when improved stoves were introduced, with post-installation $PM_{2.5}$ concentrations remaining well above indoor air standards.

In order to understand the benefits of implementing mitigation measures, European legislative and technology measures to reduce air pollutants were analysed[90] for their impact on air quality, human health and climate. The study found that sulphur dioxide, black carbon and organic carbon emissions were reduced by 53%, 59% and 32% respectively compared to expected 2010 emissions had no action been taken. These emission reduction consequently resulted in reductions in annual mean concentrations of $PM_{2.5}$, sulphate, black carbon, particulate organic matter by 35%, 44%, 56% and 23%. The reduction $PM_{2.5}$ concentrations were estimated to have prevented an average of 80,000 premature deaths annually across the European Union and yielded a perceived economic benefit of about US$232 billion each year, equivalent to 1.4% of the EU's GDP in 2010. Their results however indicated that the regulations and technical measures may have caused an increase in precipitation of 13 ± 0.8 $mm yr^{-1}$ and an unintended global warming impact equivalent to an increased European annual mean surface temperature of 0.45 ± 0.11 °C. This highlights the importance of developing holistic policies that effectively integrate climate and air quality objectives.

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[82] Alexander et al. Replacing biomass and kerosene cookstoves used throughout the developing world with clean-burning ethanol stoves may reduce hypertension and cardiovascular risk in pregnant women. Am J Respir Crit Care Med. 2017 Jan 12. doi: 10.1164/rccm.201606-1177OC, 2016

[83] Olopade et al. Effect of a clean stove intervention on inflammatory biomarkers in pregnant women in Ibadan, Nigeria: A randomized controlled study. Environment International, 98, 181–190, 2017

[84] Wlison et al. Avoided emissions of a fuel-efficient biomass cookstove dwarf embodied emissions. Development Engineering, 1, 45–52, 2016

[85] The study focused on the "Berkeley–Darfur Stove" which was distributed in Sudan by the non-profit Potential Energy.

[86] Aung et al Health and climate-relevant pollutant concentrations from a carbon finance approved cookstove intervention in rural India. Environ Sci. & Tech., DOI: 10.1021/acs.est.5b06028, 2016

[87] Wathore et al. In-use emissions and estimated impacts of traditional, natural and forced draft cookstoves in rural Malawi, Environ. Sci. & Tech., DOI: 10.1021/acs.est.6b05557, 2017

[88] Mortimer et al. A cleaner burning biomass-fuelled cookstove intervention to prevent pneumonia in children under 5 years old in rural Malawi (the Cooking and Pneumonia Study): a cluster randomised controlled trial. The Lancet. http://dx.doi.org/10.1016/S0140-6736(16)32507-7, 2016

[89] Tielsch et al. Effect of an improved biomass stove on acute lower respiratory infections in young children in rural Nepal: a cluster-randomised, step-wedge trial. The Lancet. DOI: http://dx.doi.org/10.1016/S2214-109X(16)30024-9, 2016

[90] Turnock et al. The impact of European legislative and technology measures to reduce air pollutants on air quality, human health and climate. Environ. Res. Lett. 11, 2016.

Looking into the immediate future in the transportation sector, two recent studies[91,92] highlighted the need to consider the unintended consequences of the new gasoline-direct injection (GDI) engine which is gaining popularity because of its fuel efficiency and reduced CO_2 emissions. The study found that vehicles with GDI engines released high amounts of black carbon and toxic volatile organic compounds, including benzene and toluene, negating expected climate and health benefits from the engines' reduced CO_2 emissions. The studies also show that black carbon emissions and the climate and environmental benefits of GDI engines are dependent on factors such as fuel composition, ambient temperature and the lifetime of the vehicle.

6.3. HFCs Mitigation Measures, Emission Reduction Potential and Benefits

Purohit and Höglund-Isaksson[93] estimated the mitigation potential of F-gases: HFCs, PFCs, and SF_6. They show that it is possible to reduce the cumulative emissions of F-gases from 81 to 11 $PgCO_2$ eq between 2018 and 2050 through wide-ranging commercially available and already tested technologies and by switching to alternative low global warming potential-substances. Their results indicate that, at a marginal abatement cost below 10 Eur t^{-1} CO_2 eq, it is possible to reduce cumulative emissions to 23 $PgCO_2$ eq. in the same time period. This is equivalent to a 71% reduction in global cumulative emissions. Another publication emphasized the importance of taking early action to reduce HFC emissions, finding that more than 90% of climate change impacts and stratospheric ozone from HFCs can be avoided if emissions are stopped by 2030[94].

7. AIR POLLUTION TRENDS, IMPACTS, AND COSTS

7.1. Air Pollution Trends and Impacts

The World Health Organization published updated findings on mortality and morbidity linked to outdoor air pollution compiled from $PM_{2.5}$ and PM_{10} measurements from approximately 3,000 cities and towns worldwide.[95] The report shows that nine out of ten people breathe outdoor air polluted beyond acceptable WHO guidelines. A report by UNICEF, combining satellite imagery and ground-level $PM_{2.5}$ data, found that approximately 2 billion children live in areas where outdoor air pollution exceeds WHO guidelines, and 300 million children live in areas where outdoor air pollution is at least six times higher than recommended levels.[96]

Furthermore, a European Environment Agency report showed that in 2014, 8% of urban populations in 28 EU member states were exposed to $PM_{2.5}$ levels above EU target values, and 85% of urban populations were exposed to $PM_{2.5}$ concentrations above the WHO's stricter Air Quality Guideline (AQG) values. Despite the fact that $PM_{2.5}$ concentrations steadily decreased among 42 European countries between 2006 and 2014, air pollution levels will still exceed EU limit values in 2020 in some areas if further mitigation actions are not taken.[97]

According to the WHO report, globally, 3 million deaths are attributed to ambient air pollution, with nearly 90% of these deaths occurring in low- and middle-income countries, which represent 82% of the world population. The new State of Global Air Report by the Health Effect Institute indicated that exposure to outdoor $PM_{2.5}$ air pollution is the leading environmental risk factor for death and the fifth overall risk factor worldwide for all ages and sexes.[98]

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[91] Zimmerman et al. Assessing the climate trade-offs of gasoline direct injection engines. Environ. Sci. & Tech. DOI: 10.1021/acs.est.6b01800, 2016

[92] Zimmerman et al. Field Measurements of Gasoline Direct Injection Emission Factors: Spatial and Seasonal Variability. Environ. Sci. & Tech. DOI: 10.1021/acs.est.5b04444, 2016

[93] Purohit &Höglund-Isaksson. Global emissions of fluorinated greenhouse gases 2005–2050 with abatement potentials and costs. Atmos. Chem. Phys., 17, 2795-2816, 2017

[94] Hurwitz et al. Early action on HFCs mitigates future atmospheric change. Environ. Res. Lett. 11, doi:10.1088/1748-9326/11/11/114019, 2016

[95] World Health Organization (2016) Ambient air pollution: A global assessment of exposure and burden of disease.

[96] UNICEF (2016) Clean the Air for Children. New York, USA. ISBN: 978-92-806-4854-6 "Using satellite imagery of outdoor air pollution, this study found that around 300 million children currently live in areas where outdoor air pollution exceeds international guidelines by at least six times. In total, around 2 billion children live in areas that exceed the World Health Organization annual limit of 10 μg/m3 (the amount of micrograms of ultra-fine particulate matter per cubic metre of air that constitutes a long term hazard)"

[97] European Environment Agency (2016) Air Quality in Europe – 2016 Report ("Significant decreasing trends in the PM10 annual mean were found in 2000–2014 for 75 % of a consistent set of stations. Similarly, PM2.5 concentrations, on average, tended to decrease between 2006 and 2014 for all station types. In fact, on 2014, the number of EU Member States with concentrations above the air-quality standards was lower than in 2013, as was the case for the urban population exposed to levels above those standards. However, current trends indicate that there will still be exceedances in 2020, so more has to be done to reach concentrations below the EU limit values by that year.")

[98] HEI & IHME (2017) State of Global Air 2017: A special report on global exposure to air pollution and its disease burden.

The report also identified exposure to household $PM_{2.5}$ as the tenth leading risk factor for death, while exposure to ozone air pollution is ranked 33.

The State of Global Air report also found that the absolute numbers of deaths attributable to outdoor $PM_{2.5}$ increased by 20% between 1990 and 2015 globally with India and Bangladesh experiencing some of the largest increases (50-60%). The report also found that while deaths attributable to ozone are smaller than $PM_{2.5}$, ozone-attributed deaths have increased faster than $PM_{2.5}$ over the 1990 to 2015 period by nearly 60%. In 1990, ozone was responsible for 5% of global deaths from chronic obstructive pulmonary disease (COPD) this increased to 8% by 2015. As with $PM_{2.5}$, the highest proportion of ozone-related COPD deaths were in India and Bangladesh (~10%).

Since 1990 the total number of deaths attributed to household $PM_{2.5}$ air pollution decreased by 15.5% globally. However, exposure to household $PM_{2.5}$ air pollution is the seventh leading risk factor for death among children under 5 years old, due to its impact on acute respiratory infections such as pneumonia. In South Asia, household air pollution is the fourth leading mortality risk factor and is the second leading risk factor among all low-income countries.

A joint study by Tsinghua University and the Health Effects Institute[99] found coal combustion-related air pollution is the single largest source of air pollution-related health impact in China, contributing to 366,000 premature deaths in 2013. The report further indicated that while ongoing pollution control programs in China will help avoid 275,000 premature deaths by 2030, the health effects from air pollution will continue to increase as the population continues to grow and age, unless further actions are taken.

7.2. Cost of Air Pollution and Benefits of Mitigation Action

A 2016 study by the OECD using the health impacts of air pollution from the Global Burden of Disease (GBD) projected that outdoor air pollution could cause 6 to 9 million premature deaths a year by 2060, and that the total annual market costs of reduced labour productivity, increased health expenditures, and crop yield losses from these will rise from 0.3% in 2015 to 1.0% of global GDP by 2060. The costs from premature deaths in OECD countries are projected to rise from USD $1.4 trillion in 2015 to $3.4-3.5 trillion in 2060, while the costs for non-OECD countries are expected to be higher and grow faster than in OECD countries, increasing roughly ten-fold from $1.7 trillion in 2015 to $15-22 trillion in 2060. The total global costs from the non-market impacts of morbidity are also expected to increase from $280 billion in 2015 to $2.2 trillion in 2060.[100]

A similar study by the World Bank looking at past impacts found that outdoor and household $PM_{2.5}$ and ozone air pollution in 2013 cost the world's economy $5.11 trillion.[101] Economic losses in terms of lost GDP were highest in east and south Asia and the Pacific (Figure 12).

A study by the Convention on Long-Range Transboundary Air Pollution (CLRTAP) found that the total economic costs of premature death attributed to air pollution in the European region[102] is about EUR 1 trillion, with an additional 10% added due to the cost of non-fatal illnesses.[103] Total costs in the US and Canada, according to the assessment, were estimated at USD $1 trillion and CAD 8 billion respectively. The study also found that air pollution related illnesses account for 5-10% of work absences. According to the study, meeting WHO air quality guidelines for $PM_{2.5}$ could extend the average life expectancy in Europe by almost six months and by about 20 months in the most polluted cities in Europe.

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[99] HEI & Tsinghua University. 2016. Burden of Disease Attributable to Coal Burning and Other Major Sources of Air Pollution in China. https://www.healtheffects.org/publication/burden-disease-attributable-coal-burning-and-other-air-pollution-sources-china

[100] OECD (2016) The Economic Consequences of Air Pollution. http://www.oecd.org/env/the-economic-consequences-of-outdoor-air-pollution-9789264257474-en.htm

[101] World Bank (2016) The Cost of Air Pollution: Strengthening the Economic Case for Action.

[102] The study focused on the European UNECE region, that is the United Nations Economic Commission for Europe member states

[103] Maas, R., P. Grennfelt (eds), 2016. Towards Cleaner Air. Scientific Assessment Report 2016. EMEP Steering Body and Working Group on Effects of the Convention on Long-Range Transboundary Air Pollution, Oslo. xx+50pp.

Finally, in 2016 the International Energy Agency (IEA) published a special report analysing the link between air pollution and energy production, transformation, and use.[104] The report includes a new Clean Air scenario which recommends a suite of measures (Table 1), and calls for an extra $2.3 trillion in global spending by 2040 on advanced pollution control technologies and $2.5 trillion for the rapid transformation of the energy sector. They found that implementing the proposed measures in the Clean Air scenario could reduce total premature deaths from outdoor air pollution by 1.7 million and from household air pollution by 1.6 million by 2040.

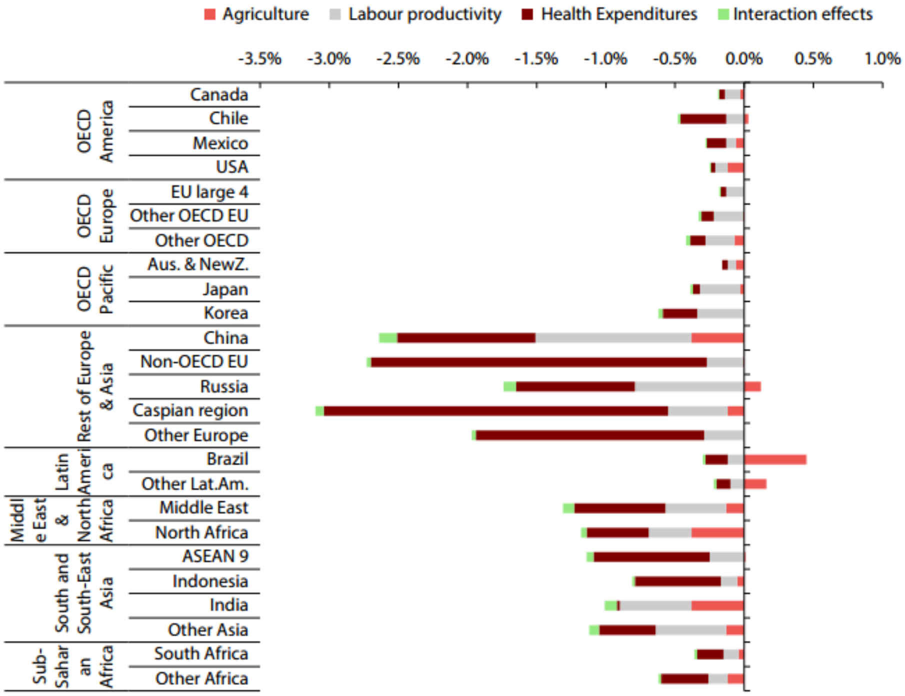
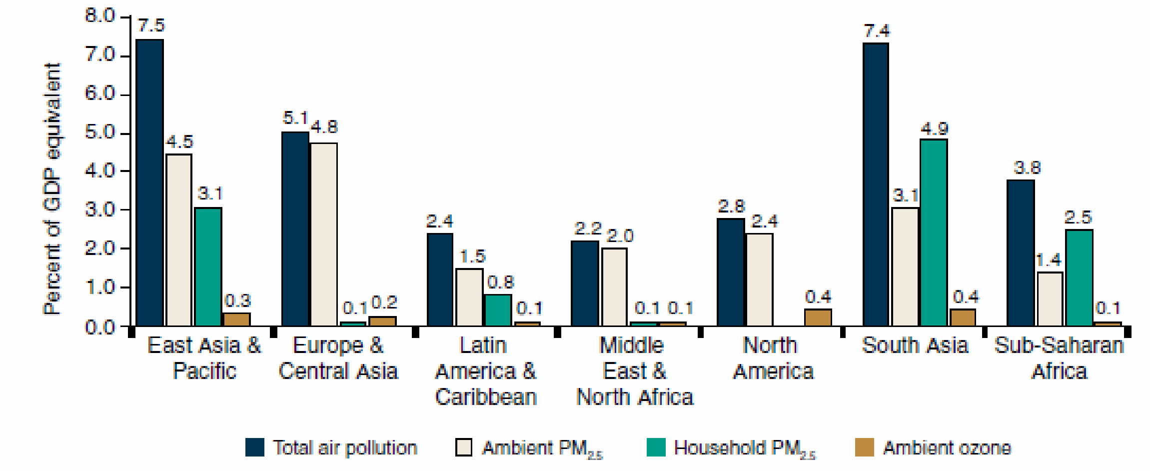


Figure 12: Change in regional GDP by 2060 from market and non-market economic impacts due to air pollution. Source: OECD[100]



Sources: World Bank and IHME.

Note: Total air pollution damages include ambient $PM_{2.5}$, household $PM_{2.5}$, and ozone. GDP = gross domestic product.

Figure 13: Welfare losses due to air pollution by region, 2013. Source: World Bank[101]

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[104] IEA (2016) Energy and Air Pollution: World Energy Outlook Special Report

Table 1: Policy pillars to avoid or remove air pollutant emissions in the Clean Air Scenario. Source: IEA[102]

Avoid	Reduce
Strong push for industrial and power sector efficiency: For industry, the introduction or strengthening of existing minimum energy performance standards (MEPs) for electric motor-driven systems. In the power sector, reduced use of inefficient coal-fired power plants (typically subcritical) and a ban on new inefficient coal-fired power plants.	**Stringent emissions limits for new and existing combustion plants.** For plants above 50 MW_{th} using solid fuels, emissions limits are set at 30 mg/m^3 for PM and 200 mg/m^3 for NO_X and SO_2. Existing plants need to be retrofitted within 10 years. Emission limits for smaller plants (below 50MW_{th}) depending on size, fuel and combustion process.[11] Industrial processes required to be fitted with the best available techniques in order to obtain operating permits.[12]
Strong efficiency policies for appliances and buildings: Introduction or strengthening of existing MEPs for appliances, lighting, heating and cooling. Introduction of mandatory energy conservation building codes.	**Stringent controls for biomass boilers in residential buildings:** Emissions limits for biomass boilers set at 40-60 mg/m^3 for PM and 200 mg/m^3 for NO_X.[13]
Higher fuel-efficiency standards: Adoption or strengthening of fuel-economy standards for road vehicles, including for both light- and heavy-duty vehicles.	**Higher vehicle emissions standards:** For light-duty diesel vehicles: limits as low as 0.1 g/km for NO_X and 0.01 g/km for PM. For heavy-duty diesel vehicles and machinery: limits of 3.5 g/km for NO_X and 0.03 g/km for PM. For all vehicles, full on-road compliance by 2025. A ban on light-duty gasoline vehicles without three-way catalysts and tight evaporative controls, and a phase-out of two-stroke engines for two-and three-wheelers.
Increased support to non-thermal renewable power generation: Increased investment in renewable energy technologies in the power sector.	**Fuel switching to lower emissions fuels:** Increased coal-to-gas switching and use of low-sulfur fuels in maritime transport.
Better public transport, urban planning and support to alternative transport fuels: Promotion of public transport, a switch to electric two- and three-wheelers, electric commercial vehicles and natural gas buses.	**Improved fuel quality:** Maximum sulfur content of oil products capped at 1% for heavy fuel oil, 0.1% for gasoil and 10 ppm for gasoline and diesel.
Access to electricity / clean cooking facilities: Enhanced provision of electricity and clean cooking access based on renewable technologies.	**Access to electricity / clean cooking facilities:** Enhanced provision of improved cookstoves and modern fuels for cooking.
Support avoid and/or reduce via a change in economic incentives	
Phase-out fossil-fuel consumption subsidies Pricing reforms that remove the incentives for wasteful consumption of fossil fuels.	

Notes: MW_{th} =megawatts thermal; mg/m^3 = micrograms per cubic metre; g/km = grammes per kilometre; ppm = parts per million.