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

Scientific Advisory Panel

2014 Annual Science Update

2014 was marked by a number of new studies and reports, which have improved our understanding of the very large impacts of SLCPs in air quality, human health, and climate, and strengthened the scientific basis for near-term action on SLCP. This Scientific Advisory Panel (SAP) Annual Science Update summarizes some of the influential and important new scientific findings of 2014 most relevant to the work and interest of the CCAC.

In 2014 the CCAC SAP also produced two formal scientific briefings:

1. The first briefing summarized the coverage of SLCPs in the IPCC Working Group I Fifth Assessment report (AR5), noting that "AR5 finds larger contributions to climate change from methane and carbonaceous aerosols than the previous IPCC assessment while noting that uncertainties in the influence of aerosols remain large."[i]
2. The second briefing summarized the current state of knowledge of the emissions and impacts of kerosene lamps and concluded that "no other major BC source has such a combination of readily available alternatives and definitive climate forcing effects."[ii]

Summary

Black Carbon & Co- Emissions

Work to characterize carbonaceous aerosol-related emissions continues, and suggests missions may be greater and/or more warming than previously believed, though uncertainties remain large. One study based on recent satellite observations suggests that historical and present-day emissions of BC may in fact be roughly twice the value used in nearly all current inventories. Another study estimates that African emissions of BC, organic carbon, carbon monoxide, and other pollutants that come from biomass burning may increase dramatically in the coming decades. Multiple papers reported new results concerning light absorption of co-emitted brown carbon indicating that in many cases, brown carbon may indeed be a fairly strong absorber, making the overall net forcing from sources such as biomass burning more positive than previously estimated.

HFCs

HFC emissions continue to increase sharply. According to the WMO/UNEP, HFCs grew at roughly 7% per year between 2010 and 2012 in terms of their 100-yr global warming potential. A new study by Montzka et al., based on atmospheric measurements shows that between 2008 and 2012 HFC emissions (excluding HFC-23) grew between 10 and 15% per year, confirming projections by Velders et al. (2009).

Methane

Substantial uncertainties remain in our understanding of the methane emissions from particular sources. A comprehensive review of estimates of global methane emissions between 1980 and 2009 found that bottom-up emission inventories tend to be lower than emissions from top-down inverse models using direct measurements of the methane concentration in the atmosphere. A number of studies of methane emissions from the natural gas sector in the U.S. found that existing inventories may underestimate actual emissions by as much as 150%. Current inventories may be missing large emissions sources from fugitive leaks from coal bed methane and shale gas production. Considerably more data and direct measurements are needed to improve existing emission inventories in order to explain the current divergence.

Health & SLCPs

Our knowledge of the very high toll of air pollution on human health continues to strengthen. In 2014, the WHO released new estimates of the global disease burden attributable to outdoor and household air pollution. These estimates indicate that household air pollution from the use of solid fuels for cooking and heating was responsible for 4.3 million deaths per year in 2012 (7.7 % of the global total) with a further 3.7 million deaths per year (6.7% of the global total) attributable to outdoor air pollution. The WHO also released indoor air quality guidelines which specified emission rate targets for household fuel combustion (for cooking and heating). These guidelines

For household fuel combustion also recommend that unprocessed coal should not be used as a household fuel, discouraged the use of kerosene fuel, and recommended "governments and other agencies developing and implementing policy on climate change mitigation consider action on household energy and carry out relevant assessments to maximize health and climate gains."

Climate Impact of SLCPs

Two new studies buttressed the scientific case for reducing SLCPs emissions in order to mitigate near-term climate change at global and regional scales. The studies showed the significant regional climate impact of aerosols and tropospheric ozone over the Northern Hemisphere extratropics, where climate sensitivity is especially large.

Agriculture and Ecosystem Impacts of SLCPs

Two new studies focused on the impact of SLCPs on crop yields in India. The first concluded that anthropogenic ozone-induced destruction of wheat and rice in the Indo-Gangetic plains affected an amount of food sufficient to feed 95 million people living below the poverty line in India. The second found that the combination of climate change and increase in SLCP emissions have reduced wheat yields in India (mostly the northern states) by as much 36%, and about 90% of this decrease is due to the direct effect of SLCPs.

SLCP Policy

Three studies examined the effects of measures or policies designed to reduce SLCP emissions. One showed that, as expected, if there were to be a massive, worldwide shift to a very low carbon society combined with large increases in the wealth of the poorest parts of society, SLCP reductions would be very large and hence there would be little effect of additional SLCP measures. That study also found, however, that compared to a baseline case with relatively high SLCP emissions, the benefits of SLCP reductions would be quite large. Another study examined the effects of Russian policy on methane emissions in the oil and gas sector highlighting how the existence of financial incentives to reduce methane emissions alone is not enough to ensure their impact. Lastly, a reviewed Commentary in Nature argued for stronger coordinated action that jointly considers climate and air quality benefits of emissions reduction strategies. This highlights the value of an activity such as the CCAC.

BLACK CARBON & CO-EMISSIONS

New studies have continued to add to our knowledge of both historical and potential future emissions of BC and co-pollutants. One study based on recent satellite observations suggests that historical and present-day emissions of BC may in fact be roughly twice the value used in nearly all current inventories.[iii] Another estimates that African emissions of BC, organics, carbon monoxide, and other pollutants that come from biomass burning may increase dramatically in the coming decades.[iv] Without regulation, the study estimates that by 2030 African emissions could represent 54% of global emissions of organic carbon alone, up from 20% in 2005, and between 20-30% of global emissions of BC, CO NO_x, SO_2, and NMHC. These studies indicate the potential for the multiple benefits associated with BC-related emissions reductions may be even larger than previously supposed. Another study showed that BC emissions continued to increase at the global level through at least 2007. Globally, the BC emitted per unit of energy production decreased, but this 'BC intensity' increased in the agriculture and industrial sectors in some countries, mainly due to an expansion of low-efficiency industry (coke and brick production) in developing countries and to an increasing usage of diesel in agriculture in developed countries.[v]

Multiple paper reported new results concerning light absorption by co-emitted organic carbon, so-called 'brown carbon'.[vi] The degree to which organic carbon absorbs visible light is extremely important for accurate evaluation of the net impact of highly absorbing BC and the co-emitted reflective organics. Many models do not account for brown carbon at all, while others incorporate brown carbon but it has been suspected that these likely underestimate its absorption. The new results indicate that in many cases, brown carbon may indeed be a fairly strong absorber, making the overall net forcing from sources such as biomass burning more positive than previously estimated. The 2011 Integrated Assessment of Black Carbon and Tropospheric Ozone identified the original BC measures based upon the net-climate forcing from all BC co-pollutants, these results thus strengthen the arguments for reducing BC-rich emissions and may increase the climate benefit of targeting other sources with higher ratios of organic carbon.

Finally, several studies reported observational and modeling results related to black carbon (BC) and co-emitted pollutants. As discussed in the SAP comment on Hodnebrog et al., scientists have long known that there have been some outstanding discrepancies between composition computer models and observations regarding BC, primarily: (1) the models showing too little BC over much of Asia, and (2) too much BC out over remote Pacific and at high altitudes. The Hodnebrog study showed that the modeled emissions can be reconciled with observations by increasing emissions by varying factors and reducing the atmospheric lifetime.[vii] The main result of the study is that the direct radiative forcing from BC remains nearly unchanged with these two changes as their impacts largely offset one another.

HYDROFLUOROCARBONS (HFCS)

The 2014 WMO/UNEP scientific assessment of ozone depletion updated the findings on hydrofluorocarbons (HFCs) from the previous reports and the 2011 UNEP HFC report.[viii] Briefly, the assessment found the following regarding HFCs:

(1) HFCs emissions grew at roughly 7% per year between 2010 and 2012 in terms of their 100-yr global warming potential. This includes HFCs, which are currently used as replacements for ozone-depleting substances (representing the largest proportion of HFCs), and HFC-23, which is a byproduct of HCFC-22 production.

(2) A new study by Montzka et al., based on atmospheric measurements, of all HFCs except HFC-23, also shows that between 2010 and 2012 HFCs emissions (excluding HFC-23) grew at rates noted by the assessment and roughly in line with the projections by Velders et al. (2009).[ix] However, Montzka et al. notes that HFC growth in the future may not increase at the same rate.

(2) Use and emissions of these HFCs are projected to grow rapidly. Indeed, if the use of the current mix of HFCs remains unchanged, the report projects that the emissions would be roughly comparable to the peak emission of CFCs, in the late 1980s.

(3) Not only the projected emissions but also the HFCs contained in existing refrigeration and air conditioning equipment, chemical stockpiles, foams, and other products, known collectively as 'HFC banks,' pose a problem in the future. If left unabated, these banks may need to be destroyed in the future to eliminate their influence on climate.

(4) If the currently used HFCs were to be replaced by low-GWP compounds and not-in-kind technologies, HFCs would not pose a significant threat to the climate system.

(5) There are pathways to avoid using the current mix of HFCs. This includes use of low-GWP candidates such as are hydrofluoro-olefins (HFOs) and not-in kind technologies. One such low-GWP compound is HFO-1234yf, which is becoming available already. This compound breaks down in the environment into trifluoroacetic acid (TFA), as do many other fluorocarbons currently in use, and increases the natural concentration of TFA in the hydrosphere.

TFA is a persistent toxic chemical, nonetheless, it was estimated that if this chemical was used in place of HFC-134a that is currently in use, TFA does not pose a problem. But the report noted that potential longer-term problems posed by TFA and similar compounds warrant evaluations.

(6) Emissions of HFC-23, a by-product of HCFC-22 production and a chemical that has been subject to CDM credits, have continued and increasing despite mitigation efforts.

Since the WMO/UNEP 2014 assessment, there have been a few further developments that have appeared in peer-reviewed publications. It should be noted that there will be more work appearing in the literature in the coming year quantifying emissions of various HFCs from different parts of the world- such papers are already in preprint forms; but they are not reviewed here.

First, updated emissions of various HFCs from different parts of the world have continued to appear. There have been no major changes to our understanding of the emissions from these studies. Another noteworthy conclusion of Montzka et al is that HFC emissions (not reported under UNFCCC) by non-Annex I parties are likely equal to that from Annex I parties' emissions reported to UNFCCC. This is not surprising since the HFC usage is expected to increase rapidly in the non-Annex I countries.

Kazil et al. published their results on the formation of TFA from HFO-1234yf.[x] They show that the amount of TFA deposited over continental U.S. is about the same as that estimated previously by Luecken et al. even though Kazil et al. used larger emissions.[xi] This study shows that a larger fraction of the emitted HFO-1234yf (and other similar shorter lived chemicals) escape the boundary layer and are distributed across the globe. This study further adds support to the conclusion that the emissions of HFO-1234yf at levels equivalent to those of HFC-134a would not pose a problem to the continental U.S. Similar results have been found for Europe by Henne et al.[xii] Both U.S. and European emissions are not slated to increase too much more than the current levels. However, these studies suggest further investigations in regions of rapid growth may be warranted, adding to the conclusion of the WMO/UNEP 2014 assessment.

Methane

In 2014 a number of studies identified large uncertainties between model estimates of global, and sectoral, methane emissions and bottom-up emission inventories.[xiii] Uncertainties are particularly high in the estimates of fugitive methane emissions from oil and gas extraction. A number of studies looking specifically at the U.S. have found that actual methane emissions, particularly from the oil and natural gas sector, may be significantly higher than published estimates and some emissions sources may be missing from inventories.

A comprehensive review of estimates of global methane emissions in the period 1980 to 2009 using results from both top-down inverse models and bottom-up emission inventories indicates that global estimates of bottom-up emission inventories tend to be lower than the estimates following from top-down inverse model results using direct measurements of the methane concentration in the atmosphere.[xiv] The agreement between top-down and bottom-up estimates improves for the years after 2000.[xv] Despite relatively good agreement on total global emissions from year 2000 onwards, there remain considerable differences in emission estimates at the sector level between inventories. There are relatively few bottom-up global inventories of anthropogenic methane and considerably more data and direct measurements are needed to improve existing emission inventories in order to explain the current divergence between top-down and bottom-up estimates of global methane emissions.[xvi] [xvii]

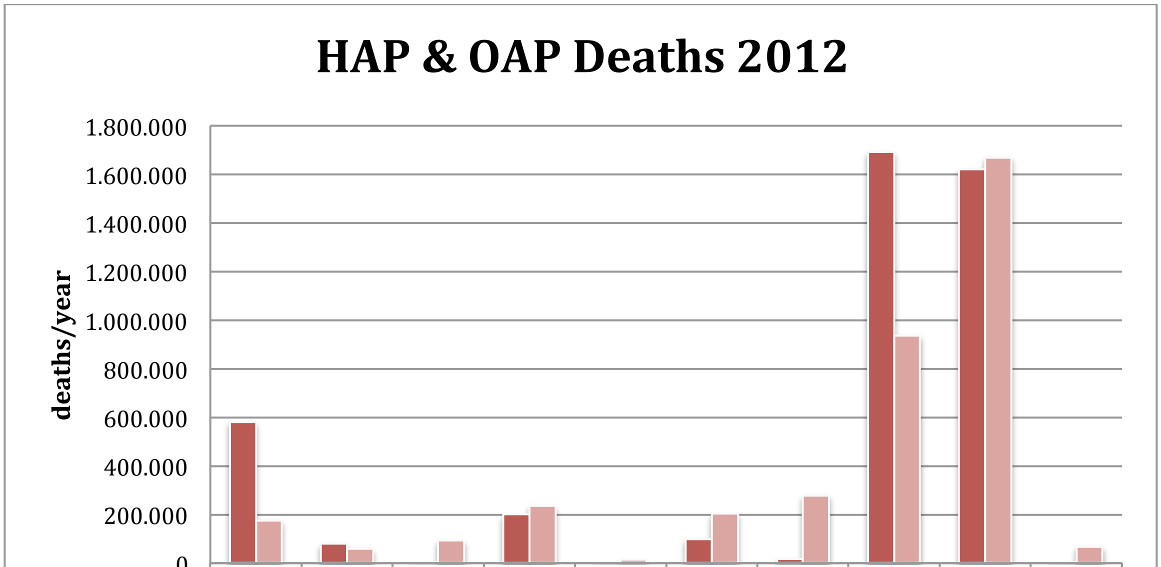
Brandt et al. (2014), in a survey of natural gas emission measurements published for the U.S. over the past 20 years, found that actual emissions may be 1.5 times higher than the national inventory compiled by the U.S. EPA.[xviii] They also found that when adding up site-specific measurements, total emissions are often dominated by a few "super-emitters." Schneising et al. showed that methane emissions from the oil and gas sector can be detected from space and that corresponding regional emissions can be constrained using satellite observations. On the basis of a mass-balance approach, they estimated that methane emissions for two of the fastest growing production regions in the U.S., the Bakken and Eagle Ford formations, increased by 990 ± 650 $ktCH_4\ yr^{-1}$ and 530 ± 330 $ktCH_4\ yr^{-1}$ between the periods 2006–2008 and 2009–2011. Relative to the respective increases in oil and gas production, these emission estimates correspond to leakages of 10.1% ± 7.3% and 9.1% ± 6.2% in terms of energy content, indicating that current inventories likely underestimate the fugitive emissions from these formations.[xix]

Another study using ground and satellite measurements over the Four Corners area in the South Western U.S. showed that large local regional emissions sources are missing in current EPA inventories, likely from fugitive leaks from coal bed methane production.[xx] A study of shale gas wells in southwestern Pennsylvania found a significant regional flux of methane over a large area of shale gas pads identified as in the drilling process, a preproduction stage not previously associated with high methane emissions, suggesting a possible missing contribution to current bottom-up methane emission inventories.[xxi]

Health & SLCPs

In 2014, the World Health Organization (WHO) released new estimates of the global disease burden attributable to outdoor (OAP) and household (HAP) air pollution. These estimates indicated that household air pollution from the use of solid fuels for cooking and heating was responsible for 4.3 million deaths per year in 2012 (7.7 % of the global total) with a further 3.7 million deaths per year (6.7% of the global total) attributable to outdoor air pollution.[xxii]

Almost all of the deaths attributable to household air pollution were in low and middle-income countries, especially in South East Asia (1.7 million) and the Western Pacific (1.6 million) (Figure 1). These estimates for household air pollution are substantially larger than those previously reported by WHO (2 million deaths per year from household air pollution reported in 2004) as they incorporated new methodology developed for the Global Burden of Disease 2010 and due to increases in baseline rates of several non-communicable diseases (ischemic heart disease, stroke, chronic obstructive pulmonary disease and lung cancer) that are impacted by air pollution.[xxiii] The new methodology for the first time also included additional health outcomes such as ischemic heart disease and stroke as being impacted by household air pollution exposure.



	Africa	Amr LMI	Amr HI	Emr LMI	Emr HI	Eur LMI	Eur HI	Sear	Wpr LMI	Wpr HI
Household	581.300	80.000	1.300	200.800	100	99.500	17.700	1.691.600	1.620.100	100
Outdoor	176.000	58.000	94.000	236.000	14.000	203.000	279.000	936.000	1.669.000	68.000

Figure 1. Premature deaths per year attributable to air pollution by type and region. Amr: America, Emr: Eastern Mediterranean, Sear: South-East Asia, Wpr: Western Pacific, LMI: Low- and Middle-income; HI: High-income.[xxiv]

Nearly 90% of the deaths attributable to outdoor air pollution occur in low- and middle-income (LMI) countries, with the Western Pacific and South East Asian regions accounting for 1.7 and 0.9 million deaths, respectively. These estimates for outdoor air pollution are substantially larger than those previously reported by WHO (1.3 million deaths per year from outdoor air pollution reported in 2008) as they incorporated new methodology developed for the Global Burden of Disease 2010[xxv] and due to increases in baseline rates of the non-communicable diseases (ischemic heart disease, stroke, chronic obstructive pulmonary disease and lung cancer) that are specifically impacted by air pollution. The new methodology for the first time included the entire global population (previously only urban populations had been included), incorporated substantial additional evidence on the magnitude and shape of the relationship between exposure to air pollution and health outcomes and the application of a lower baseline exposure against which the impact of air pollution is compared.

In addition to the currently available estimates of attributable mortality and disease burden for air pollution and numerous other modifiable risk factors at the country-level for 2010, updates for the year 2013 and, beginning in 2015, annually will soon be published as part of the Global Burden of Disease.

WHO Indoor Air Quality Guideline for Household Fuel Combustion

In 2014 the WHO also released indoor air quality guidelines for household fuel combustion.[xxvi] In addition to providing detailed evidence reviews on household air pollution emissions, the scope of exposures and disease burden due to household fuel use, the guidelines include 5 detailed recommendations:

1) Emission rate targets: Specifically, in order to meet existing WHO air quality guidelines for fine particle air pollution (PM2.5) and carbon monoxide, maximum emission rates for household fuel combustion (with separate values for vented and unvented appliance) were specified, based on the specified values for kitchen volume, air exchange and duration of device use per day which are representative of conditions in low- and middle-income countries.

2) Policy during transition to technologies and fuels that meet WHO air quality guidelines: Specifically the guidelines recommend that governments and their implementing partners develop strategies to accelerate efforts to meet the emission rate targets and that transition fuels and technologies that offer substantial health benefits should be prioritized in cases where intermediate steps are necessary.

3) Household use of coal: Unprocessed coal should not be used as a household fuel. This recommendation is supported by an evidence review describing intrinsic hazardous substances released during coal combustion and their health impacts.

4) The household use of kerosene is discouraged while further research into its health impacts is conducted. Note that the CCAC SAP produced a briefing report on kerosene in 2014 describing in detail the evidence related to health and climate impacts as well as mitigation strategies.[xxvii] The WHO guidelines also include a detailed evidence review describing risks of burns and poisoning related to kerosene use.

5) Good practice: securing health and climate co-benefits: This recommendation is of direct relevance to the CCAC as it highlights the opportunities for synergy between climate and health actions and specifies that "governments and other agencies developing and implementing policy on climate change mitigation consider action on household energy and carry out relevant assessments to maximize health and climate gains."

The accompanying evidence reviews also include specific chapters describing the modeling used to support the emission rate targets, the impacts of intervention strategies on air pollution concentrations and personal exposures, factors influencing the adoption and sustained use of lower emission cookstoves and discussion of the financing options for adoption of lower emissions technologies at large scale.

CLIMATE IMPACT OF SLCPs

Our basic understanding of the climate impact of SLCPs was not fundamentally changed in 2014. Additional evidence reinforced our understanding of the strong global and regional climate impacts of SLCPs. In particular, one analysis showed that historical aerosol and tropospheric ozone changes have had an outsized impact on global climate change relative to their global mean radiative forcing.[xxviii] This is due to their having taken place largely over the Northern Hemisphere extratropics where climate sensitivity is especially large, and they have thus contributed greatly to regional climate changes in that region. Complementary analyses showed that projected changes in aerosols over the coming decades, which again are likely to be greatest over the Northern Hemisphere mid-latitudes, will have large impacts on regional climate in that area.[xxix] Specifically, by altering the Northern Hemisphere westerly jet stream, they may have substantial effects on regional temperatures, precipitation, and extreme weather events. Both studies buttress the scientific case for reducing SLCP emissions in order to mitigate near-term climate change at global and regional scales.

Agriculture and Ecosystem Impacts of SLCPs

Scientists have known for a long time that ozone exposure reduces crop yields significantly in all parts of the globe and can also decrease terrestrial ecosystem carbon sequestration. The UNEP/WMO report made the first assessment of impact of SLCP mitigation on global crop yields and concluded that reducing SLCPs, through correlative reductions in ozone, would avoid crop yield losses of about 51 million metric tons per year. Two new studies were published recently focusing on the impact of SLCPs on crop yields in India. The first one, led by the Indian Institute of Tropical Meteorology, is a bottom-up regional high-resolution modeling study.[xxx] Gudhe et al. concluded that anthropogenic ozone induced destruction of wheat and rice in the Indo-Gangetic plains reduced yields by an amount that would be sufficient to feed 95 million people living below the poverty line in India. The other study is a statistical-dynamical study that considered emissions of NO_X, VOCs and other SLCPs and arrived at the finding that the combination of climate change and increase in SLCPs emissions has reduced wheat yields in India (mostly the northern states) by as much 36%, and about 90% of that reduction is due to the direct effect of SLCPs.[xxxi] The implication is that mitigation of SLCPs could boost India's crop yields by up to a bit more than 30%. Both these independent studies, confirm the UNEP/WMO findings reported in Shindell et al. (2012).[xxxii]

SLCP Policy

Only a few studies in the peer-reviewed literature explicitly examined the effects of measures or policies designed to reduce SLCP emissions. One showed that, as expected, if there were to be a massive, worldwide shift to a very low carbon society combined with large increases in the wealth of the poorest parts of society, SLCP reductions would be very large (e.g. there would be no more petrol-powered vehicles or use of solid biomass fuels) and hence there would be little effect of additional SLCP measures.[xxxiii] The study explored other scenarios as well, and in particular, found that compared to a baseline case with relatively high SLCP emission (following current legislation as in the UNEP/WMO Integrated Assessment of Black Carbon and Tropospheric Ozone), the benefits of SLCP reductions would be quite large. This result is consistent with the UNEP/WMO Integrated Assessment of Black Carbon and Tropospheric Ozone and contradicts a 2013 study suggesting that the Assessment had overestimated the benefits of SLCP reductions.[xxxiv]

Another study examined the effects of Russian policy on methane emissions in the oil and gas sector.[xxxv] Russia is one of the few countries in the world with policy specifically aimed at reducing methane emissions economy-wide. They highlight how the existence of financial incentives to reduce methane emissions alone is not enough to ensure their impact, which also depends on their transparency and accessibility, as well as issues such as inaccurate perceptions of costs and fear that finding previously undetected emissions will increase regulation. They also conclude that based on Russian experience, measurement of emissions and common reporting rules should be integral parts of a comprehensive policy strategy. Finally, they point out that Russia has conducted significant scientific research on methane emissions in the oil and gas sector in preparing its emission methodologies. Other countries would likely benefit from this research and more serious review of the Russian methodologies as they assess their own emissions.

Lastly, a reviewed Commentary in Nature argued for stronger coordinated action that jointly considers climate and air quality benefits of emissions reduction strategies.[xxxvi] This highlights the value of an activity such as the CCAC.

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[i] CCAC (2014) SCIENTIFIC ADVISORY PANEL: SHORT-LIVED CLIMATE POLLUTANTS IN THE FIFTH IPCC ASSESSMENT REPORT WORKING GROUP I THE PHYSICAL SCIENCE BASIS.

[ii] CCAC (2014) SCIENTIFIC ADVISORY PANEL BRIEFING: KEROSENE LAMPS & SLCPS.

[iii] Cohen, J. B., & C. Wang (2014) *Estimating global black carbon emissions using a top-down Kalman Filter approach*, JOURNAL OF GEOPHYSICAL RESEARCH 119(1):307-323.

[iv] Liousse, C. *et al.* (2014) *Explosive growth in African combustion emissions from 2005 to 2030*, ENVIRONMENTAL RESEARCH LETTERS 9:1-10.

[v] Wang, R. *et al.* (2014) *Trend in Global Black Carbon Emissions from 1960 to 2007*, ENV. SCI. TECHNOL. 48(12):6780-6787.

[vi] Saleh R. *et al.* (2014) *Brownness of organics in aerosols from biomass burning linked to their black carbon content*, NATURE GEOSCIENCE 7:647-650; Feng, Y. *et al.* (2013) *Brown carbon: a significant atmospheric absorber of solar radiation?* ATMOSPHERIC CHEMISTRY AND PHYSICS 13(17):8607–8621; Jacobson, M. J. (2014) *Effects of biomass burning on climate, accounting for heat and moisture fluxes, black and brown carbon, and cloud absorption effects*, JOURNAL OF GEOPHYSICAL RESEARCH: ATMOSPHERES 119(14):8980-9002; Liu, J. *et al.* (2014) *Brown carbon in the continental troposphere*, GEOPHYSICAL RESEARCH LETTERS (Early View).

[vii] Hodnebrog, O. *et al.* (2014) *How shorter black carbon lifetime alters its climate effect*, NATURE COMMUNICATIONS 5:5065.

[viii] WMO/UNEP (2014) SCIENTIFIC ASSESSMENT OF OZONE DEPLETION: 2014; UNEP (2011) HFCS: A CRITICAL LINK IN PROTECTING CLIMATE AND THE OZONE LAYER, A UNEP Synthesis Report.

[ix] Montzka, S. A. *et al.* (2014) *Recent Trends in Global Emissions of Hydrochlorofluorocarbons and Hydrofluorocarbons: Reflecting on the 2007 Adjustments to the Montreal Protocol*, J. PHYS. CHEM. A.; Velders G. J. M., *et al.* (2009) *The large contribution of projected HFC emissions to future climate forcing*, PROC. NAT'L. ACAD. SCI. U.S.A. 106:10949-10954.

[x] Kazil J. *et al.* (2014) *Deposition and rainwater concentrations of trifluoroacetic acid in the United States from the use of HFO-1234yf*, JOURNAL OF GEOPHYSICAL RESEARCH: ATMOSPHERES 119(24):14,059-14,079.

[xi] Luecken, D. J. *et al.* (2014) *Ozone and TFA impacts in North America from deregulation of 2,3,3,3-Tetrafluoropropene (HFO-1234yf), a potential greenhouse gas replacement*, ENVIRON. SCI. TECHNOL. 44(1)343-348.

[xii] Henne, S. *et al.* (2012) *Future emissions and atmospheric fate of HFC-1234yf from mobile air conditioners in Europe*, ENVIRON. SCI. TECHNOL. 46(3):1650-1658.

[xiii] Allen, D. T. *et al.* (2013) *Measurements of methane emissions at natural gas production sites in the United States*, PROCEEDING OF THE NATIONAL ACADEMY OF SCIENCES OF THE UNITED STATES OF AMERICA, 110 (44):17768–17773; Harrison, M. R. *et al.* (2011) NATURAL GAS INDUSTRY METHANE EMISSION FACTOR IMPROVEMENT STUDY. FINAL REPORT PREPARED UNDER COOPERATIVE AGREEMENT NO. XA-83376101, United States Environmental

Protection Agency; Höglund-Isaksson, L. (2012) *Global anthropogenic methane emissions 2005-2030: technical mitigation potentials and costs*, Atmospheric Chemistry and Physics 12:9079-9096; Johnson, M. R. & A. R. Coderre (2011) *An analysis of flaring and venting activity in the Alberta upstream oil and gas industry*, Journal of Air and Waste Management 61:190-200; Karion, A., *et al.* (2013) *Methane emissions estimate from airborne measurements over a western United States natural gas field*, Geophysical Research Letters 40:4393-4397; Pétron, G. *et al.* (2012) *Hydrocarbon emissions characterization in the Colorado Front Range: A pilot study*, Journal of Geophysical Research 111:1-19; USEPA (2012) Global anthropogenic non-CO2 greenhouse gas emissions: 1990-2030, EPA 430-R-12-006, US Environmental Protection Agency, Washington D.C.

[xiv] Nisbeth, E. G. *et al.* (2014) *Methane on the Rise – Again*, Science 343(6170):493-495.

[xv] Kirschke, S. P. *et al.* (2013) *Three decades of global methane sources and sinks*, Nature Geoscience 6:813-823.

[xvi] Nisbeth, E. G. *et al.* (2014) *Methane on the Rise – Again*, Science 343(6170):493-495; *and* Bergamaschi, P. *et al.* (2014) *Top-down estimates of European CH4 and N2O emissions based on four different inverse models*, Atmos. Chem. Phys. Discuss. 14:15683-15734.

[xvii]

[xviii] Brandt, A. R. *et al.* (2014) *Methane Leaks from North American Natural Gas Systems*, Science 343 (733-735).

[xix] Schneising, O. *et al.* (2014) *Remote sensing of fugitive methane emissions from oil and gas production in North American tight geologic formations*, Earth's Future 2(10):548-558.

[xx] Kort, E. A. *et al*. (2014) *Four corners: the largest US methane anomaly viewed from space*, Geophysical Research Letters 41(19):6898-6903.

[xxi] Caulton, D. R. *et al.* (2014) *Toward a better understanding and quantification of methane emissions from shale gas development*, Proceedings of the National Academy of Sciences of the United States of America 111(7).

[xxii] World Health Organization (2014) Burden of disease from Ambient Air Pollution for 2012; *and* World Health Organization (2014) Burden of disease from Household Air Pollution for 2012.

[xxiii] Smith, K. R. *et al.* (2014) *Millions dead: how do we know and what does it mean? Methods used in the Comparative risk assessment of houshold air pollution*, Annu. Rev. Public Health. 35:185-206; Lim, S. S. *et al.* (2012) *A comparative risk assessment of burden of disease and injury attributable to 67 risk factors and risk factor clusters in 21 regions, 1990–2010: a systematic analysis for the Global Burden of Disease Study 2010*, The Lancet 380(9859):2224-60.

[xxiv] A list of specific countries in each WHO grouping can be found at: World Health Organization, Annex I – Regional Classifications, http://www.who.int/nutgrowthdb/annex_regional_classifications.pdf.

[xxv] Brauer, M *et al.* (2012*) Exposure assessment for estimation of the global burden of disease attributable to outdoor air pollution*, Environ Sci Technol. 46(2):652-60; Lim, S. S. *et al.* (2012) *A comparative risk assessment of burden of disease and injury attributable to 67 risk factors and risk factor clusters in 21 regions, 1990–2010: a systematic analysis for the Global Burden of Disease Study 2010*, The Lancet 380(9859):2224-60.

[xxvi] World Health Organization (2014) Indoor Air Quality Guidelines: Household Fuel Combustion.

[xxvii] CCAC (2014) Scientific Advisory Panel Briefing: Kerosene Lamps & SLCPs.

[xxviii] Shindell, D. (2014) *Inhomogeneous forcing and transient climate sensitivity*, Nature Climate Change 4:274-277.

[xxix] Rotstayn, L. D. *et al.* (2014) *Declining Aerosols in CMIP5 Projections: Effects on Atmospheric Temperature Structure and Midlatitude Jets*, J. Climate 27:6960-6977.

[xxx] Ghude, S. D. *et al.* (2014) *Reductions in India's crop yield due to ozone*, Geophys. Res. Lett. 41(15):5685–5691.

[xxxi] Burney, J., & V. Ramanathan (2014) *Recent climate and air pollution impacts on Indian agriculture*, Proc. Natl. Acad. Sci. 111(46):16319–16324.

[xxxii] UNEP/WMO (2011) Integrated Assessment of Black Carbon and Tropospheric Ozone; Shindell D., *et al.* (2012) *Simultaneously mitigating near-term climate change and improving human health and food security*, Sci. 335(6065):183-189

[xxxiii] Rogelj, J. *et al.* (2014) *Disentangling the effects of CO_2 and short-lived climate forcer mitigation*, Proc. Natl. Acad. Sci. 111(46):16325-16330.

[xxxiv] Smith, S. J. *et al.* (2013) *Near-term climate mitigation by short-lived forcers*, Proc. Natl. Acad. Sci. 110(35):14202-14206.

[xxxv] Evans, M., & V Roshchanka (2014) *Russian policy on methane emissions in the oil and gas sector: A case study in opportunities and challenges in reducing short-lived forcers*, Atmospheric Environment 92:199-206.

[xxxvi] Schmale, J. *et al.* (2014) *Air pollution: Clean up our skies*, Nature 515:335-337; *see also* Victor, D. G. *et al.* (2014) *Air pollution: Harmful soot spurs climate-policy action*, Nature 517:21.