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Connecting air quality and climate change

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Introduction

The 45th Annual A&WMA Critical Review "Connecting Air Quality and Climate Change" (Fiore et al., 2015) is a comprehensive examination of interconnections between emissions, concentrations, and alterations of environmental contaminants and climatic effects as elucidated by current scientific research. The review extends findings from the recent IPCC Fifth Assessment Report (Intergovernmental Panel on Climate Change [IPCC], 2013). The review presents some limitations of our current understanding and offers a comprehensive list of recommendations for future research to address these limitations. This critical review discussion presents written submissions from four invited discussants, followed by a response from the original authors. A number of recent studies were referenced in these comments, and it is hoped that the readers will find these to be a useful addition to the already comprehensive Fiore et al. review. Each discussion is self-contained, and joint authorship of this article does not imply that a discussant subscribes to the opinions expressed by others. A discussant's commentary does not necessarily reflect the position of his or her respective organization. Invited discussants are as follows:

(1) Michael T. Kleinman is an adjunct professor in the Department of Medicine, University of California, Irvine. He is the co-director of the Air Pollution Health Effects Laboratory and is the Chair of the A&WMA Critical Review Committee.
(2) John D. Bachmann is principal for Vision Air Consulting, where he advises on environmental science/policy issues. He was formerly Associate Director for Science/Policy and New Program Initiatives at the U.S. Environmental Protection Agency (EPA).
(3) Howard J. Feldman is Director of Regulatory and Scientific Affairs for the American Petroleum Institute (API). He is charged with developing and promoting credible, cost-effective policies, strategies, positions, standards, and practices; supporting federal and state regulatory and legislative initiatives; and developing and managing relevant, scientifically sound research. He has served as the co-chairman of the NARSTO Executive Steering Committee, which addresses the management of regional and urban air quality in North America.
(4) David McCabe is an atmospheric scientist with the Clean Air Task Force since 2010, working primarily on short-lived climate pollutants, and was an AAAS Science and Technology Policy Fellow serving at the U.S. EPA in Washington, DC.
(5) J. Jason West is an associate professor in the Department of Environmental Sciences and Engineering at the University of North Carolina at Chapel Hill, where he performs interdisciplinary research addressing air pollution and climate change, by using models of atmospheric chemistry and transport, and tools for quantitative policy analysis.
(6) Arlene Fiore is an associate professor in the Department of Earth and Environmental Sciences and Lamont-Doherty Earth Observatory of Columbia University and is the senior author of the 2015 A&WMA Critical Review.

Invited Comments from John D. Bachmann

Fiore et al. (2015) is an excellent examination of the rapidly growing body of scientific information underlying our understanding of the many linkages connecting air quality and climate change. The introduction section is worth reading for all levels of environmental managers, as it outlines essential concepts and provides an overview of these important linkages. The remainder of the paper goes into some depth on key pollutants, emissions, interactions between air pollution and climate in both directions, and a discussion of what we know

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—and don't know—about policy-relevant science that would facilitate more holistic, multipollutant strategies for air quality and climate programs. Because not all of the authors' efforts could be fitted into the confines of the journal, interested readers will find expanded discussions on emissions, climate change, evaluation of climate and air quality models, climate variability and more in the supplemental material available online at http://dx.doi.org/10.1080/10962247.2015.1040526. This year's critical review, references, and supplemental materials will be a valuable resource for air quality and climate experts, researchers, students and others interested in the important science and policy issues addressed.

From a science/policy perspective, the authors' examination and recommendations regarding a holistic approach are of particular interest. Some past critical reviews and related discussions, notably Hidy et al. (2010), Chow et al. (2010), and to a lesser extent Bachmann (2007), have stressed the importance of considering multipollutant strategies for air pollution, but far less attention was given to integrating air pollution programs with climate programs (Chow et al., 2010). In recent years, the rapid expansion of both modeling and field work on air quality and climate interactions in the United States, by the Environmental Protection Agency (EPA), National Oceanic and Atmospheric Administration (NOAA), National Aeronautics and Space Administration (NASA), National Science Foundation (NSF), and others, led to many of the scientific advances and analyses discussed in the critical review (Bachmann, 2015). It also formed the basis for a number of policy recommendations, as well as significant international, governmental, and private efforts that called for developing programs to address these near-term climate forcers (NTCF), or more recently the subset of NTCF that contribute to warming—short-lived climate pollutants (SLCP) (Ramanathan and Xu, 2010; United Nations Environemental Programme [UNEP], 2011; Climate and Clean Air Coalition [CCAC], 2012; Pearson et al., 2013; Arctic Monitoring and Assessment Programme [AMAP], 2013; World Bank, 2013; International Geosphere-Biosphere Programme and International Global Atmospheric Chemistry [IGBP/IGAC], 2013; Bachmann and Seidel, 2013; Institute for Governance and Sustainable Development [IGSD], 2013).

One class of SLCP not considered in the critical review deserves some mention here. These are the hydrofluorocarbons (HFC), developed as replacements for ozone-depleting refrigerants. They were excluded because they are not part of traditional air pollution programs. While their contribution to warming is small today, some growth projections suggest they could be very significant in the future, given fairly high potency as greenhouse gases (GHG) (Xu et al., 2013). In this case, the approach would be to prevent acceleration of near-term warming caused by unconstrained growth.

Important developments in air pollution science understandably not explored in the critical review include findings that the multiple air pollutants that contribute to fine particles and ozone (O_3) result in serious health effects and death at levels low enough to make transoceanic transport an important consideration in air pollution policy (United Nations Economic Commission for Europe [UNECE], 2010; Anenberg et al., 2010; Fann et al., 2015). Based on recent global assessments of air quality and public health, there is amble reason to support expansion of aggressive programs to improve air quality, with or without climate programs. Based on estimates by the World Health Organization (WHO), the combination of ambient and household (e.g., cooking and heating) air pollution is responsible for up to 7 million premature deaths in 2012 (WHO, 2015). But the lack of progress in reducing ambient and household exposure to air pollutants in Asia, Africa, and some other less developed regions raises questions about whether the substantial air quality improvements forecast in widely used climate scenarios (Fiore et al., 2015, supplemental material, Figure S2d) over the next 50 to 100 years may be overly optimistic. WHO estimates of residual mortality from air pollution are much lower in developed countries but still significant; ambient air results in an estimated 290,000 premature deaths in high-income European countries and 94,000 in high-income nations in the Americas. We are far from finished with air pollution.

The critical review pays particular attention to evaluating the varying effects of different air pollutants on climate. Reducing sulfates and some other light-scattering particles that serve to cool the earth surface actually "unmasks" warming caused by carbon dioxide (CO_2) and other GHGs. This means that continued reductions in sulfur oxide (SOx) emissions to meet air quality goals will increase near-term warming caused by existing levels of GHG. Some have raised questions about the extent to which sulfates contribute to the significant health effects of particulate matter (PM) (Grahame et al., 2014), but recent multipollutant epidemiology and some toxicology studies continue to show sulfates are associated with mortality and other important health outcomes (Lippmann et al., 2013; Vedal et al., 2013; Dominici et al. 2015; Adams et al., 2015). Recent reviews of the body of relevant literature still conclude that it is not possible to exclude any source or component as a contributor to adverse PM health effects (EPA, 2009; Health Effects Institute [HEI], 2013; Wyzga et al., 2015). SO_x emissions are also major contributors to regional haze (Watson 2002), acid rain (National Acid Precipitation Assessment Program [NAPAP], 1990; Zhao et al., 2013), atmospheric "dimming" (Ramanathan et al., 2009) and changes in precipitation patterns (Levy et al., 2013). In summary, even considering the "beneficent" (cooling) effects of sulfates, these multiple adverse health and environmental effects will drive air programs to continue to reduce SO_x emissions.

Other fine particle types include both cooling (most organics, nitrates) and warming (black carbon, some organics) components, making the relative composition of these particles from different source categories decisive in whether controls would result in a net cooling. The critical review points out that PM reductions from sources with high contribution of black carbon (BC) relative to cooling organic carbon (OC) (e.g., diesels, kerosene lamps) are most likely to produce climate benefits; but all BC sources are of concern to health. Because O_3 is a GHG, all O_3 precursors contribute to warming, although the combined effect of nitrogen oxide (NO_x) emissions appears to be a net cooling (Fiore et al., 2015, Figure 1). In terms of climate effects, the most important O_3 precursor is methane (CH_4), which is itself a major GHG. While, due to its low reactivity, CH_4 has generally been excluded from regulation in local and regional O_3 programs, it is a major contributor to international transport of O_3 on a global scale (UNECE, 2010).

A multipollutant look at anthropogenic sources of PM, O_3, and GHGs shows some overarching patterns (Fiore et al., 2015, Table 2 and Figure 12 text box). All major combustion sources emit multiple pollutants, including CO_2 and varying combinations of particles and O_3. Some examples are that power plants and some industrial sources emit CO_2, SO_x, and NO_x; reducing CO_2 would slow long-term temperature increase, but would be accompanied by near-term warming from reduced cooling related to the other air pollutant reductions. Cars and light trucks emit CO_2 and O_3 precursors. Switching vehicles to electric power would more likely to produce near-term as well as long-term benefits, depending on the source of electric power. Diesels have a high BC to OC ratio, so particle controls would reduce near-term warming but not reduce CO_2. The strongest anthropogenic sources of CH_4 do not overlap greatly with CO_2 and combustion sources. Globally, agriculture is the largest anthropogenic source of CH_4 and the long-lived GHG nitrous oxide. In the United States, leaks from the oil and gas industry are among the largest sources of CH_4, as well as a significant source of volatile organic chemicals (VOC). Coal mining and waste management are globally significant source of CH_4. Most CH_4 reductions for these source categories are unlikely to affect other near-term climate forcers. The lack of overlap among sources of CH_4 and combustion sources of CO_2 and SO_x, NO_x, and in some cases BC or VOC has important implications for holistic climate and air pollution programs.

Over the last decade, a number of scientific studies, assessments, and media reports have considered or advocated policies regarding the appropriate role for SLCPs in climate programs. Most of these, including those highlighting the relative importance of SLCPs, have made it clear that SLCPs—while helping in the near term—cannot address the long-term consequences of continuing current CO_2 and other GHG emissions, for example, Jacobson (2002), Hansen et al. (2007), and Ramanathan and Xu (2012). A few have argued that adopting programs for one or all SLCPs would provide a "window of opportunity" to delay CO_2 programs and develop more cost-effective technologies for GHG (e.g., Baron et al., 2010). Others have more modestly suggested that adopting SCLP controls in the near future can "buy time" to overcome the obstacles to more serious efforts to reduce CO_2 (Victor et al., 2012; Biello, 2012). As indicated in the critical review discussion, the concept of using SLCP controls as a basis for intentionally delaying CO_2 reductions has no scientific credibility (e.g., Kandlikar et al., 2010; Shindell et al., 2012; Roglej et al., 2014).

Nevertheless, some studies and strategy assessments cited in the critical review may have gone too far in dismissing the importance of near term reductions in SLCP because of concerns they would delay needed GHG reductions. Pierhumbert (2014), for example, argues that while SLCP can be helpful for climate programs, "there is little to be gained by implementing SLCP mitigation before stringent carbon dioxide controls are in place and have caused annual emissions to approach zero." This position ignores other analyses supporting the critical review conclusion that SCLP mitigation can be an important supplement to GHG programs by offsetting the "unmasking" of GHG from sulfate reductions that will occur both as the result of air pollution and GHG programs. Others, including some emissions scenarios used in climate modeling, assume that air pollution programs and climate programs will be so effective on the major sources of CH_4, O_3, and BC that additional efforts to promote them will not be needed, or at best provide smaller near-term benefits than earlier studies have suggested (Rogelij et al., 2014). As noted earlier, most programs aimed at CO_2 would not lead to CH_4 reductions, and it is questionable whether air pollution concerns alone would lead to international efforts needed to reduce hemispheric transport of O_3. See the recent commentary by Victor et al. (2015) for further discussion, including why policies that promote both SCLP mitigation and GHG can be developed and promoted a variety of fronts and forums, for example, the bilateral agreement between the United States and China.

The suggestion that air pollution and climate programs become more holistic is a laudable goal, but can be difficult to implement in practice. In this regard, in the United States, the recent Clean Power Plan (CPP) presents an opportunity as well as a difficult challenge. The CO_2 reductions alternatives adopted in responding to these requirements would result in significant SO_x, NO_x, and mercury reductions (EPA, 2015). To the extent possible, these multipollutant air–climate links should be considered in developing the state plans responding to the CPP under Section 111(d) of the Clean Act and review and revisions to applicable state implementation plans for $PM_{2.5}$, O_3, toxics, regional haze, and related programs that affect the power sector.

Approaches to addressing climate and air pollution continue to evolve with emerging science and continued negotiations over global, multilateral, and some unilateral approaches (Revkin, 2015). Reductions in CO_2 and other long-lived GHG clearly must be the primary focus to limit peak temperatures forecast for the 21st century. As these climate and some air pollution strategies are implemented, they will accelerate near-term warming from current GHG levels. As the critical review shows, reducing or preventing increases in SLCPs are an effective way to counter these effects. Moreover, given the programs that address already address air pollution, it makes little sense to suggest that delaying programs for SLCPs will somehow slow new CO_2 programs. It is, however, worth considering separate climate policies to reduce CH_4 that discourage trading with CO_2, recognizing that in some cases that flexibility may be politically necessary (Victor et al., 2015). As noted earlier, the case for addressing all BC emissions sources to protect health is particularly strong in developing countries. Due to strong regional differences in the nature of BC health and climate effects, it may be appropriate to consider supplemental programs for BC that address regional effects not well addressed by air pollution programs, for example, deposition of BC in the snow and ice covered Arctic (AMAP, 2013). Consideration of the variety of effects, properties, and sources among air pollutants and long-lived GHG discussed in the critical review will be important in formulating the multifaceted approaches that will be needed to meet the challenges of climate change and air pollution.

Invited Comments from Howard J. Feldman

Fiore et al. (2015) provides a comprehensive summary of current research and findings related to the potential interaction of climate change and air pollution. Much of the basis regarding the findings in this review is based on meteorological and regional or global air quality modeling.

Models provide useful tools regarding the investigation of changes in the climate and related air quality, but models are simplified descriptions of actual complex interactions in the environment. They require extensive evaluations against measurements, as well as sensitivity analyses regarding the predicted consequences compared to input assumptions. The critical review could have provided more information regarding the verification of the models being used. Such information would have enhanced the review.

Organizationally, better top-down organization would help the reader follow the review, such as sections focusing on "Air Quality Impacts on Climate" including historic and projected changes, and "Climate Impacts on Air Quality" including historic and projected changes. Each of those sections would include perspectives reflecting monitoring, measurements and modeling.

Modeling and meteorology

Moving on to the substance of the modeling and meteorology discussion in the critical review, the following points are noteworthy but are often unrecognized, and should be further emphasized:

- "Climate change can alter regional meteorology conducive to pollutant buildup, imposing a 'climate penalty' or, for example, enhance ventilation of the polluted boundary layer, yielding a 'climate benefit.'"
- "An improved understanding of air pollutant impacts on climate is necessary to assess the unintended climate impacts of recent and future air quality regulations."
- "A quantitative understanding of how air pollution meteorology responds to climate change and natural variability is needed to inform air quality planning and regulation accountability for the coming decades."
- "Models simulate different atmospheric distributions even when driven by the same emission inventories, leading to different RF (and ERFs) for the same emission perturbation in different models."
- "Observations, both in the source regions and in remote regions, are needed to differentiate among the wide range or geographical and altitudinal distributions of NTCFs in current models."

These statements emphasize the need for additional measurements, model data comparisons to evaluate model accuracy over wide ranges on input, and sensitivity evaluations to aid in focusing model evaluation. Specifically, the review would have been enhanced by providing more information on the accuracy of models. The correlation coefficient is only one metric for determining model accuracy. Model performance could also be evaluated using modeling statistics developed for regional air quality modeling.

Air quality impacts

Dr. Fiore indicates that "In the absence of changes in other factors, warmer temperatures during stagnation episodes are expected to exacerbate peak pollution levels." This observation is not necessarily true. In many cases PM episodes are a result of emissions with little plume rise under cold temperatures, with very stable conditions and with very low mixing heights.

Another point raised with respect to the impact of climate change on U.S. air quality is "There is little agreement across models, with regional changes often conflicting in sign." Figure 8 shows that models indicate a climate penalty on surface O_3 over the northeastern United States but disagree over other regions.

Other noteworthy points raised by Dr. Fiore are often unrecognized, and should be further emphasized:

- "Stringent precursor emission reductions projected in the RCP scenarios … more than offset any climate penalty incurred from rising GHGs."
- "Observed ambient U.S. $PM_{2.5}$ decreased by more than 25% between 1990 and 2004 with even larger relative decreases before 1990."
- "The net RF of U.S.-sourced PM is a negative, so that a reduction of the PM leads to warming."
- "Lower NAAQS levels raise the relative importance of background levels, which do not respond directly to regulated U.S. emission sources, but include components such as global CH_4 or transported foreign pollution that *might* be addressed through international negotiations" [emphasis mine].

In public policy discussions, many of these points are overlooked and the impacts of climate change and precursor reductions may be portrayed incorrectly. the critical review could have explored some of these policy relevant points further.

Emissions

The review could have been modified to indicate that fugitive releases of CH_4 from natural gas production are not necessarily a result of hydraulic fracturing, but result from other processes as well.

Dr. Fiore indicates that "Observational analyses find that emission inventories underestimate U.S. CH_4 emissions, particularly those from fossil fuel extraction and refining." This is primarily based on satellite-based measurements. Satellite measurements do not measure emissions but rather ambient concentrations over a region, and concentrations must be converted to emissions through some form of inverse modeling. This type of modeling introduces additional uncertainties in estimating emissions. Care must be exercised in terms of the conclusions reached in the referenced studies regarding fugitive CH_4 emissions from oil and gas operations. These studies were based on top-down inventories based on ambient measurements and inverse modeling. These estimates were then compared to bottom-up inventories based on engineering calculations. It is important that the time scale of emission inventories be identified, and emissions need to be based on long-term average emissions (annual average). Some recent emission estimates using inverse modeling for oil and gas emissions develop instantaneous emission inventories, and these are compared to annual inventories. If emissions are constant over a year, then emissions from the instantaneous and long-term inventories will be equal, but temporal emissions from very few source types have this level of consistency.

Wecht et al. (2014) find that satellite-inferred CH_4 emissions suggest little need to revise the overall U.S. oil and gas emission budget, but that the livestock source requires upward revision, also noted by Miller et al. (2013). Measurements are crucial to validate the emission inventories used in life-cycle assessments of changes in GHG emissions resulting from fuel switching within the energy sector (e.g., Burnham et al., 2012).

It was also surprising that the critical review omitted two key CH_4 emissions measurement studies led by Dr. David Allen, with funding from the Environmental Defense Fund and several oil and gas companies, one on CH_4 emissions from natural gas sites (Allen et al., 2013) and a follow-up study focused on emissions from production site pneumatic controllers (Allen et al., 2015).

The first of these papers found that a relatively small subset of devices dominates total emissions. It went on to find that average emission rates per controller were comparable to the most recent EPA inventory estimates, though the controller count may be underestimated in the EPA inventory.

It should have been noted that natural gas and petroleum systems are 28.7% of EPA's total CH_4 emissions inventory. The critical review should have also described the trend in CH_4 emissions. From 2005 through 2013 U.S. EPA data indicate that CH_4 emissions from production have declined significantly at the same time that U.S. shale production has increased more than fivefold (U.S. EPA, 2015; U.S. Energy Information Agency [EIA], 2014). It is noteworthy that most of the decline in emissions occurred before EPA promulgated emissions regulations on oil and gas operations in April 2012. Furthermore, the use of more natural gas in U. S. electricity production has contributed to CO_2 emissions from that sector reaching a 27-year low earlier this year, according to the U.S. Energy Information Agency (U.S. EIA, 2015).

Dr. Fiore has provided a comprehensive summary of current research and findings related to the potential interaction of climate change and air pollution. As indicated, there are areas where additional clarity and information would have benefitted the reader and policy-makers.

Invited Comments from David McCabe

Fiore et al. (2015) have produced a helpful and remarkably clear summary of the many complex relationships between air quality and Earth's climate. "Traditional" air pollution such as particulate matter (PM) and O_3 remains detrimental to public health and welfare. Globally, the WHO estimates that ambient air pollution caused 3.7 million deaths in 2012 (WHO 2015). In the United States, 44% of the population lives in areas where at least one criteria air pollutant exceeds health-based standards (American Lung Association, 2015), and while emissions from power plants and the resulting mortality have dropped dramatically in recent years, PM from this sector still led to 7,500 premature deaths in 2012 (Banks and Marshall, 2015). Meanwhile, climate change poses a serious threat to public health and welfare in the United States and globally.

Given the harm caused by poor air quality and climate change and the linkages between the two, a synthetic, integrated approach to the two problems is called for. As described by the critical review, joint mitigation of both problems may increase benefits and reduce costs. The critical review also makes clear that if, as predicted, emissions of cooling PM precursors such as sulfur dioxide from the developing world are reduced, this may lead to an acceleration of warming in future decades (Raes and Seinfeld, 2009; Wigley et al., 2009). Reductions of PM certainly make compliance with climate goals such as limiting temperature rise to 2 degrees Celsius more challenging. For this linkage between air quality and climate, the pressing need to reduce PM for health reasons will drive reductions forward, essentially independent of concerns about warming due to PM reductions. Nevertheless, quantification of the climate effects of PM reductions will be critical; this is a key motivation for the development of the Representative Concentration Pathways.

Pollutants that degrade air quality and increase radiative forcing, such as CH_4 and BC, are critical mitigation priorities. In order to reduce warming over the next few decades, it is important to abate pollution of these SCLPs, which are a subset of the NTCFs. Substantially reducing CO_2 emissions must remain the highest priority for climate mitigation: CO_2 is the most important warmer now, it is likely to become more predominant over the coming decades, and, unlike CH_4, CO_2 emissions will increase radiative forcing for centuries (Pierrehumbert, 2014; Shoemaker and Shrag, 2013; National Research Council [NRC], 2010). Nevertheless, reducing the rate of warming in the coming decades must also be a climate policy priority (Raes and Seinfeld, 2009). As a practical, empirical matter, reducing CH_4 emissions is also critical to meeting U.S. climate commitments (U.S. Department of State, 2014; Larsen et al., 2014). Mitigation of both CO_2 and NTCFs is essential (Shoemaker et al., 2013). If a broad-based, multi-GHG policy is enacted to mitigate climate change, the metric used for trading or offsets between CO_2 and CH_4 must be appropriate for the goals of the policy (long-term climate stabilization, near-term deceleration of temperature increase, both, etc.). In the absence of such a broad, multi-GHG policy, I am aware of no evidence that efforts to mitigate short-term climate forcers have detracted in any way from efforts to mitigate CO_2 emissions.

The air quality benefits of reducing these pollutants should also be considered when evaluating policy options. As documented by the substantial health literature linking particulate matter to premature death (U.S. EPA, 2009), for BC, immediate health benefits are likely to dominate the benefits (relative to climate benefits) of any mitigation efforts. For CH_4, the EPA has moved toward accounting for both climate and health benefits of emissions abatement in two very recent analyses supporting proposed standards (U.S. EPA, 2015a, 2015b). In these analyses, recent estimates of the social cost of CH_4 (Martin et al., 2015) were used to quantify the economic benefits of the standards. The analyses also discuss an economic quantification of the global mortality benefits of CH_4 mitigation due to surface O_3 abatement (independent of climate change) (Sarofim et al., 2015). While the O_3–health benefit is not included in the calculation of the monetized total benefits of the proposed standards, it is a positive indication that this type of analysis is moving into regulatory assessments.

While climate policy assessments, by their nature, require the use of global, multisector emissions inventories, projections, and models, caution must be used when communicating evaluation of specific policy choices based on these broad, integrated data sets and tools. For example, as noted by Fiore et al. (2015), a significant driver of uncertainty or disagreement over the potential avoided warming from NTCF abatement can be uncertainty/disagreement in the magnitude of potential future emissions abatement (Shindell et al., 2012; Smith and Mizrahi, 2013). This situation should be carefully differentiated from uncertainty/disagreement in the climate response per unit emission of NTCF. When the overall uncertainty is discussed without clear differentiation of these effects, this can cause confusion over the utility of abating present-day known emissions of NTCFs.

As a second example, while uncontrolled coal combustion emits substantial amounts of climate-cooling sulfate, emissions controls for sulfate have decoupled the emissions of CO_2 and sulfate from coal combustion in the developed world, and more recently in China (Kurokawa et al., 2013). While it is important to account for the climate effects of sulfate reductions, the reductions are largely occurring because of health concerns via emissions control, rather than reductions in coal consumption. This pattern seems likely to continue: It is difficult to imagine a society not taking steps to reduce sulfate emissions from coal combustion for health reasons before reducing coal consumption out of concern for climate. Treating future sulfate reductions as a consequence of climate-motivated reductions in coal consumption (Wigley, 2011), rather than a response to health concerns, arguably leads to an inaccurate estimate of the climate benefits of reducing coal consumption.

These examples illustrate the importance of applying specific sectoral knowledge to provide the proper context for understanding the results from integrated multisectoral models. In a similar vein, it is important to consider that while economy-wide approaches to reducing GHG emissions that allow emissions trading or offsets will generally reduce emissions very efficiently, noncost barriers to mitigation will exist for many emissions sources, including NTCF sources. There will remain an important role for actions and regulatory initiatives to reduce emissions directly from these sources.

As discussed by Fiore et al. in their recommendations, improvements in emissions inventories will be very important as efforts to abate air pollutants such as NTCFs continue. A large number of recent studies have examined emissions from the oil and natural gas sector; many of these have concluded that emissions in the study area (ranging from a single oil and gas producing basin to, roughly, the continental United States) are significantly higher than would be predicted by U.S. EPA CH_4 emissions inventories (Brandt et al., 2014). While measurements at large geographic scale are particularly important as an independent check of the accuracy of inventories, it is challenging to attribute any observed discrepancies to specific sources in the inventories based on these large-scale studies. More granular measurements at the process and/or facility level are also essential. More accurate activity data for sources emitting these pollutants, and work to provide accurate activity data in appropriate formats for atmospheric modeling, would also be particularly helpful in improving understanding of these emissions sources. Finally, proper policy evaluation requires emissions projections grounded in realistic sector-specific projections of activity (Matthews and Baum, 2011).

Our understanding of the impacts of SLCPs is less precise than our understanding of the impacts of CO_2. However, the sign of their effects is unambiguous—these pollutants harm the climate and human health. It is critical that policy move forward to mitigate the harm caused by these pollutants. At the same time, the uncertainty in emissions of NTCFs is greater than for most sources of CO_2—but for some priority sources, such as CH_4 from oil and gas, there is clear evidence that the uncertainly is asymmetric. While emissions may be substantially higher than inventories estimate, there is little chance that emissions are actually lower than the inventories (Brandt et al., 2014).

Moreover, abatement of air pollutants over the past few decades has moved forward despite significant uncertainty in the emissions and effects of those pollutants, to the enormous benefit of society. For example, even after many years of study, “reasonable agreement” between fleet-averaged measurements and mobile source emissions models for key air pollutants such as NO_x and nonmethane hydrocarbons (NMHC) is ±25% (Fujita et al., 2012). Given the dispersed and diverse nature of their sources, it is not reasonable to expect better precision for emissions of NTCFs from most sources in the coming years. However, as has happened with mobile source emissions of NO_x and NMHC, emissions of these NTCFs can certainly be reduced, with great benefit to society.

Invited Comments from J. Jason West

The problems of air pollution and climate change are interconnected in several important ways, and several of these interconnections lie at critical areas of scientific uncertainty.

Fiore et al. have done an outstanding job of clarifying these different interconnections and of comprehensively exploring what current scientific research reveals about these interconnections. The review is current as it extends findings from the recent IPCC Fifth Assessment Report (Intergovernmental Panel on Climate Change [IPCC], 2013). Also, the review discusses the limitations of current understanding and offers a comprehensive list of recommendations for future research to address these limitations. The review goes further to suggest, on the basis of these interconnections, how environmental policy in the United States and internationally might plan more effectively to address the problems of air quality and global climate change in a more coordinated way. I expect that this review will be widely used and referenced.

Similar to this review, I organize the interconnections between air pollution and climate change as:

(1) The effects of air pollutants on the climate system, including the radiative forcing of O_3 and of aerosols.
(2) The effects of climate change on air quality through changes in meteorology and related effects (e.g., changes in biogenic emissions and fires).
(3) The fact that air pollutants typically share common sources with GHGs in fossil fuel combustion, suggesting that there are opportunities to address both simultaneously.
(4) Climate change will affect the demands for energy (generally decreasing demands for heating and increasing those for cooling), with consequences for emissions of both air pollutants and GHGs.

The review addresses the first two of these extremely comprehensively, while the fourth is largely beyond its scope. Here I discuss some aspects of interconnections 1 and 2 related to the review, and highlight interconnection 3 in a way that goes beyond the review, but also do not discuss interconnection 4 here.

Regarding interconnection 1, the review rightly highlights opportunities for reducing CH_4 and sources rich in BC for the resulting benefits of improving air quality and slowing climate change. It is noteworthy that while SLCPs have important influences on present-day anthropogenic radiative forcing (RF), many SLCPs are not included in the basket of gases defined by the United Nations Framework Convention on Climate Change that is used in markets for GHG emission trading worldwide. Nonetheless, the SLCPs are getting attention through the international Climate & Clean Air Coalition (CCAC). Of the SLCPs, only CH_4 and HFCs are included in emissions trading, leaving out BC and O_3 precursors other than CH_4 (NO_x, nonmethane volatile organic compounds [NMVOCs], and CO). Of these, NO_x is thought to have a cooling influence on climate because it shortens the lifetime of CH_4 (Fry et al., 2012). Little policy attention has been given to CO and NMVOCs, as their RFs are smaller than those of BC or CH_4, but they are not negligible—the anthropogenic RF of CO is about 14% that of CO_2 itself and NMVOCs is about 6% (Myhre et al., 2013). One reason that BC and O_3 precursors are not included in GHG emissions trading is the complexity that results from different RFs depending upon the location of emissions. Research in my lab has shown that while the RF of NO_x and NMVOCs vary strongly for emissions from different continents (Fry et al., 2012; Fry et al., 2014), the RF of CO shows very little variation with emission location (Fry et al., 2013), as the lifetime of CO is significantly longer. Reducing CO also benefits air quality through reductions in both CO and O_3. Highlighting CO as an important SLCP, and to a lesser extent NMVOCs, and including it in emissions trading will increase incentives to reduce emissions, with important benefits for both air quality and climate change.

Recently, SLCP reductions have received much attention for their benefits of slowing near-term climate change while improving air quality (Shindell et al., 2012), as reflected in this review and in the development of the CCAC, although the extent of plausible SLCP reductions has been questioned (Smith and Mizrahi, 2013). Interaction 3 in the preceding list highlights another way that addressing climate change can benefit air quality, as actions to reduce GHG emissions are also generally expected to reduce emissions of air pollutants co-emitted from the same sources. The literature on the air quality and health co-benefits of GHG reductions was not a focus of this review, but has included contributions over roughly two decades (Working Group on Public Health and Fossil Fuel Combustion, 1997; Cifuentes et al., 2001; Bell et al., 2008; Nemet et al., 2010). Many co-benefits studies have estimated the monetized health benefits of GHG reductions, finding that these co-benefits are comparable to the costs of GHG reductions, but cover a wide range reflecting differences in methods and the different regions where these studies were performed. Recently, I led a study that brings improved methods to estimates of the co-benefits of GHG reductions (West et al., 2013). We used a global atmospheric model for the first time to study air quality and health co-benefits from reductions in both O_3 and fine particulate matter ($PM_{2.5}$), and based our estimates of co-benefits on realistic scenarios to 2100. We found that an aggressive global strategy to limit climate change would avoid millions of premature deaths each year by 2100. Monetized co-benefits are estimated to be US$50–380 per ton CO_2, which exceeds the costs of GHG controls beyond 2050. Our estimated co-benefits are also higher than the previous literature (Nemet et al., 2010) as we consider global impacts accounting for international air pollution transport (e.g., Anenberg et al., 2009), scenarios in which population and susceptibility to air pollution grow in the future, and economic growth that increases valuation of premature mortality. In addition, this study quantified co-benefits for the first time via two mechanisms: reductions in co-emitted air pollutants (interaction 3), and slowing climate change and the effects that it has on air pollution (interaction 2). We are now working to downscale this global study to the United States at fine resolution, and we hope that our improved methods will be adopted more widely in future studies of co-benefits.

The review presents an excellent set of recommendations. Regarding the effect of climate change on air pollution, the recommendation concerning ensembles of simulations to better separate climate variability and climate change is particularly important—the review is correct that modeling studies often simulate a few years from which they make conclusions about climate change, without evaluating the importance of climate variability. There are also important uncertainties in the effects of climate change on PM air quality, as models may be missing important processes or may have significant uncertainties in modeling the effects of climate change on biogenic, fire, dust, and sea salt emissions. Finally, while I have discussed studies on SLCPs and co-benefits, these analyses are not sufficient to fully inform decisions that allow air quality and climate change to be addressed in a coordinated manner. More research is needed to fully understand the effects of multiple control actions on emissions of multiple pollutants and their effects of air pollution and climate change. While some work in this area is promising (e.g., McCollum et al., 2013), no analysis has yet succeeded in including all four of the interactions mentioned earlier in a decision-support model.

In closing, there are good reasons to reduce emissions of SLCPs to both improve air quality and limit near-term climate change, and SLCPs are receiving attention internationally. The thinking that motivates a focus on SLCPs, however, comes in part from focusing on interaction 1 through the lens of the IPCC's RF bar chart, and searching for pollutants for which reductions will benefit both air quality and climate change. That is made difficult by the fact that reducing $PM_{2.5}$ for air quality would generally be expected to warm climate, and the action most frequently taken to reduce O_3—decreasing NO_x—may also warm climate. This thinking has led to a fixation on BC, even though BC is co-emitted with cooling OC, which may limit the climate benefits of many actions. However, research on co-benefits has shown that interaction 3 is also particularly strong, showing that most actions to reduce CO_2 emissions have substantial benefits for air quality—particularly actions that improve end-use efficiency and move away from use of coal. I anticipate that by demonstrating the air quality benefits of CO_2 reductions, co-benefits research will shift the discussion away from a focus on SLCPs, and back to CO_2. But in order to plan for emission reductions that meet air quality and climate goals simultaneously and at low cost, we need to visualize these interactions in a new way apart from the RF bar chart. Such visualization needs to account for the costs and reductions of multiple pollutants, and effects on air quality and climate change, of a large set of possible actions.

Author's Response to Comments

The critical review authors are grateful to the discussants for their thoughtful comments and perspectives, which serve to expand the context for the review, particularly with respect to policy considerations. While the review referred to some policies to provide context for the relevance of the science discussed, the focus was on the scientific knowledge of air quality–climate connections, and it was never intended to be a policy analysis. The discussion here thus provides a useful supplement to the review.

Mr. Bachmann, Dr. McCabe, and Dr. West call attention to the toll that air pollution takes on national and global public health, which received only cursory attention in the review. Public health concerns remain the primary motivation for controls on air pollutants that are also near-term climate forcers (NTCFs). Mr. Bachmann further emphasizes the continuing research and literature reviews regarding the potential impacts of particle composition on public health. We reiterate here the benefits to both O_3 air pollution and climate associated with lowering global CH_4 abundances. Dr. West further expands upon the co-benefits to air quality and health resulting from GHG mitigation, noted briefly in the review.

Mr. Feldman voiced some suggestions for restructuring the review, which might have helped its readability. We found sequential presentation to be challenging for this topic, which contains so many linkages among the various sections, and we considered various organizational strategies in the writing process. It is surprising to see Mr. Feldman's remark that discussion of model verification is completely lacking, as we indeed reviewed some of the large body of publications that evaluate models, though much of this discussion was relegated to the Supplemental Material to meet page limits. We call attention here to Supplemental Text S2 ("Climate Change," which includes a section on model evaluation); Supplemental Text S3 ("Evaluation of ACCMIP and AeroCom Models Used to Estimate RF"); and Supplemental Text S5 ("Evaluating Models Used To Study U.S. Air Quality Responses To Emissions"), all referenced from the main text when we briefly discuss previous efforts to evaluate models used to study air quality–climate connections. Many of the example references cited in Table S1 ("Summary of Methods Used to Study Air Quality–Climate Connections") also include evaluation of models with observations. We emphasize that modeling statistics developed for regional air quality modeling are not necessarily appropriate for evaluating the chemistry–climate models used to study air pollutant–climate interactions. While regional air quality models are usually driven by observed meteorology, with the goal of resolving plume transport in specific places and times, chemistry–climate models generate their own weather, and thus cannot be evaluated by exact space-time matching with observations as is typically done for regional air quality modeling (see also Schnell et al. [2014] cited in the critical review).

We thank Mr. Feldman for noting the sentence that should have been specific to warm-season stagnation episodes (O_3 and secondary PM) as opposed to the cold-season PM episodes. We are not sure where the review implies hydraulic fracturing is the sole source of fugitive CH_4 release, and note on p. 659 that the opening sentence for the discussion of CH_4 emissions mentions "determining whether U.S. oil and gas operations, including expanded hydraulic fracturing, are in fact releasing much larger amounts of CH_4 to the atmosphere," indicating the broader emphasis in the critical review on these other processes in addition to hydraulic fracturing. Several observational studies cited in the critical review relied on in situ measurements (from aircraft, tower, and ground platforms; e.g., Caulton et al., 2014; Karion et al., 2013; Peischl et al., 2013; Pétron et al., 2012; Pétron et al., 2014; and synthesized in Miller et al., 2013, and Brandt et al., 2014; full citations provided in critical review), and thus the critical review does not rely primarily on satellite-based estimates as stated by Mr. Feldman. Nevertheless, Mr. Feldman's point regarding the temporally variable nature of the CH_4 source from oil and gas operations indeed complicates extracting robust conclusions from studies conducted over different time periods, which may appear to conflict. In the same section, we also made the points Mr. Feldman notes based upon the Wecht et al. (2014) and Miller et al. (2013) studies regarding the upward revision they find necessary for the livestock section and the need for measurements to support the inventories used in life-cycle assessments (Burnham et al., 2011; see p. 659). We thank Mr. Feldman for pointing out the studies by Dr. Allen, as well as for providing the current share of natural gas and petroleum systems in the EPA CH_4 emission inventory and recent trends therein. We are certain there other important references we have omitted; our citation list is by no means exhaustive, given the relatively broad scope of the review.

As we emphasize in the review, it is important to recognize the different time scales over which SLCPs (CH_4, BC, some HFCs, and O_3) versus CO_2 influence the climate system. Reducing climate change on both time scales is a reasonable policy goal, as noted by both Mr. Bachmann and Dr. McCabe. As Mr. Bachmann notes, the different time scales suggest that reduction approaches involving emissions trading markets should be conducted for SLCPs independently from CO_2 (e.g., see also Shoemaker and Schrag [2013], discussed in the critical review). He further notes that the role of some HFCs as SLCPs is crucial to complete any discussion of emissions trading among SLCPs, a topic not covered in the critical review. Among the SLCPs, differences in spatial and temporal time scales merit consideration for developing trading schemes. Any trading should be underlain by a clear scientific understanding of the climate impacts of the species included, which is not yet realized for many SLCPs, most notably light-absorbing ("brown") ones. Another complicating factor is that currently, as Dr. West notes, CH_4 and HFCs are included in emissions trading alongside CO_2, which implicitly involves trading near-term against long-term climate benefits. Ideally, both could proceed in parallel, with separate management of near-term and long-term climate goals, though some "cross-talk" is unavoidable, as Dr. West emphasizes that efforts to abate CO_2 often bring co-benefits to air quality through their impacts on NTCF (warming SLCPs plus cooling agents like sulfate) emissions. As Mr. Bachmann and Dr. McCabe both note, many NTCFs are already being reduced, and are anticipated to continue declining, in order to improve global health. This led the critical review to conclude that CO_2 controls, to address long-term climate, should proceed in parallel to reductions on SLCPs, whether they are imposed for air quality or climate purposes, and that SLCPs could be targeted to offset warming associated with reductions of cooling NTCFs like sulfate that are implemented to improve air quality.

Dr. McCabe differentiates between emission uncertainties and response uncertainty; careful communication of these distinctions is needed to allow users to parse sources of uncertainty and their relevance to policy decisions. In the critical review Supplemental Text S2, we have attempted to summarize the different types of uncertainty that are commonly used to frame discussions of uncertainty in climate change projections. Ideally, the expected contribution from each source of uncertainty would be communicated along with the projections, whether for air quality or for climate change.

On the topic of communication, Dr. West encourages deeper thinking in how best to visualize and convey clearly the multidimensional environmental costs and benefits associated with mitigating climate change and air pollution. The IPCC bar chart that we adapted for Figure 1 in the review is deceptively simple; interpreting it correctly requires knowledge of both the sign of the change in the atmospheric burden from preindustrial to present, and the sign of the radiative forcing response to that change in burden. Adding new metrics to illustrate the interactions between climate and other environmental outcomes is a challenge, but will ensure a broader discussion. Any new visualization should strive to distinguish between time scales to avoid misunderstandings in the trade-offs between short-term and long-term climate goals. The review outlines some recommendations to build the pieces needed for a decision-support tool for some of the interactions described by Dr. West. Adding anticipated changes in energy demand (Dr. West's interaction 4), as well as full-life-cycle assessments (noted by Mr. Bachmann and Mr. Feldman), should step us toward a more holistic approach to air quality management.

Supplemental Material

The list of citations mentioned in this discussion paper are included as supplemental material, which can be accessed on the publisher's website: http://dx.doi.org/10.1080/10962247.2015.1095599.