A Summary of the 45th A&WMA Critical Review: Air Quality and Climate Connections

by Arlene M. Fiore, Vaishali Naik, and Eric M. Leibensperger

Multiple connections link air quality and climate change. Many sources of carbon dioxide (CO_2), the dominant anthropogenic greenhouse gas (GHG), also emit particles and gaseous precursors that adversely affect public health and the environment. The 45th Annual A&WMA Critical Review[1] examines the major components of particulate matter (PM), ozone (O_3) and their precursors.

Ambient levels of PM and O_3 exceed the U.S. National Ambient Air Quality Standards (NAAQS) over wide regions. Through their interactions with solar and terrestrial radiation, PM, O_3, and some of their precursors contribute to climate change by perturbing the planetary energy balance and the hydrological cycle. Climate change alters the frequency, severity, and duration of heat waves, precipitation, and other meteorological factors that influence air pollutant accumulation. These interactions occur on a range of space and time scales (see Figure 1). Incorporating high-quality emissions inventories and improved process-level understanding into models is crucial to assess reliably the climate and air quality implications of past and future air pollution control programs.

Effects of Air Pollution on Climate

Perturbations to tropospheric O_3 and its precursors, including methane (CH_4), volatile organic compounds (VOCs), carbon monoxide (CO), and nitrogen oxides (NO_x), and components of PM, most notably black carbon (BC), organic carbon (OC), and sulfate, all influence the climate system. Due to their much shorter lifetimes than CO_2, they are termed "near term climate forcers" (NTCFs) to emphasize that changes in their emissions alter their atmospheric abundances on time scales ranging from weeks (PM components, O_3) to a few decades (CH_4). The warming agents CH_4, O_3, and BC are sometimes referred to as short-lived climate pollutants (SLCPs). The short lifetimes of PM and O_3 concentrate their abundances downwind of source regions, predominantly in the northern hemisphere. By inducing regional temperature, precipitation, and circulation responses, PM and O_3 can trigger climate effects that differ from those resulting from the more uniformly distributed well-mixed GHGs. Another important distinction arises from the short PM and O_3 lifetimes

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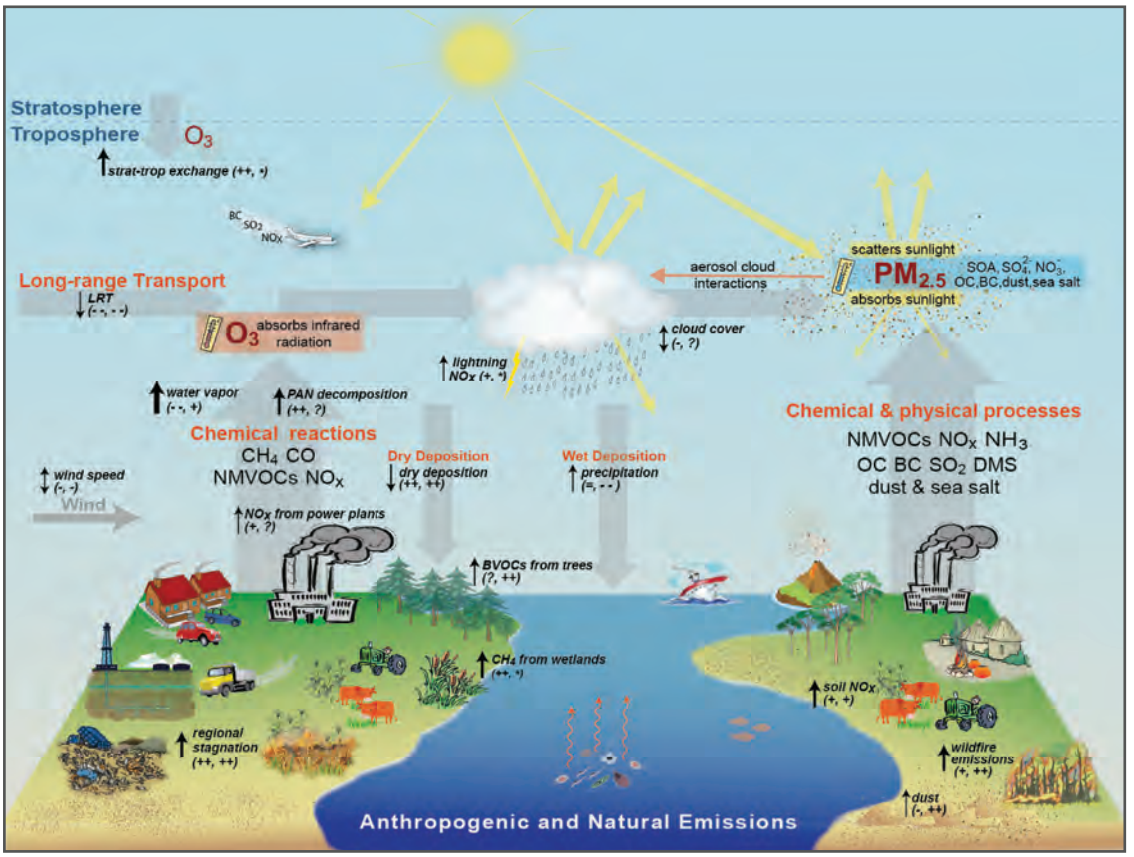

Figure 1. Air quality and climate connections.

Notes: Anthropogenic and natural emitted species include methane (CH_4) carbon monoxide (CO), non-methane volatile organic chemicals (NMVOC), nitrogen and sulfur oxides (NO_x, SO_2), ammonia (NH_3), black and organic carbon particles (BC,OC), dimethyl sulfide (DMS), mineral dust, and sea salt. Orange text describes atmospheric processing (formation, removal, and transport) of air pollutants. Black text with black arrows indicates the sensitivity of individual processes to climate warming; thinner arrows denote lower confidence or regional variability in the sign of the change (increase is up; decrease is down; double-headed arrow implies no clarity on the sign of change) in response to a warming climate. Dual black symbols in the parentheses indicate how O_3 and PM respond to the change indicated for each process (for double-headed arrows, the (O_3, PM) response denoted is for an increase in the process): ++ consistently positive, + generally positive, = weak or variable; - generally negative, -- consistently negative, ? uncertainty in the sign of the response, * the response depends on changing oxidant levels.

in contrast to CO_2: the climate impacts from CO_2 (or other long-lived GHGs) depend on cumulative emissions whereas those from NTCFs depend on emission rates.

After CO_2, increases in CH_4 and tropospheric O_3 since the pre-industrial era have exerted the most warming influence of any anthropogenic GHG, with CH_4 the best documented of any NTCF. PM components exert opposing influences on the climate system. While BC alone is a strong warming agent, by some estimates even surpassing CH_4, its capacity to alter climate is subject to much larger uncertainties surrounding its interactions with clouds and the relative amount of cooling OC particles co-emitted with BC, which may produce a slight net cooling from some BC-emitting sources. Brown organic carbon (BrC), a portion of OC that is both directly emitted and produced from gaseous organic precursors, absorbs light and thus warms, but is not well quantified at present. Cooling sulfates have dominated the increase in anthropogenic PM during the industrial era, partially masking the warming from rising CO_2 and other GHGs and confounding detection of climate sensitivity (e.g., global mean surface temperature increase from a doubling of CO_2) from observed climate changes. Both BC and sulfates alter precipitation patterns through interactions with clouds, in addition to circulation and other changes in response to altered local-to-global radiation budgets.

Many source categories emit multiple GHGs and NTCFs. Accurate estimates of the near- and long-term effects of reducing some or all of the emissions from these sources require consideration of the combined effects of the entire mix of emitted pollutants. Over the past 40 years, air pollution control programs implemented to protect public health and welfare have decreased PM and O_3 precursors from stationary and mobile sources, particularly in developed nations. These emission controls had little impact on CO_2 and CH_4 emissions, which continued to rise. For many air pollutants, the regional emission reductions have been offset at the global scale by increases in developing countries with rapidly expanding economies. An exception is sulfur dioxide (SO_2) emissions, which

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Arlene M. Fiore

Presented by Arlene M. Fiore
Associate Professor, Dept. of Earth & Environmental Sciences
Lamont-Doherty Earth Observatory
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Tuesday, June 23, 9:00–11:45 a.m.
Ballroom BC (4th Floor) | Raleigh Convention Center

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Following the review presentation, a panel of invited experts will critique the presentation and the authors' conclusions, and will offer their views on the topic.

This year's invited discussants are:

John D. Bachmann, Vision Air Consulting, LLC, and 2015 Local Host Committee Liaison to the Critical Review Committee;
J. Jason West, Department of Environmental Sciences and Engineering, University of North Carolina;
Howard J. Feldman, American Petroleum Institute; and
David McCabe, Clean Air Task Force.

Join the Discussion

Comments will be solicited from the floor and from written submissions to the Critical Review Committee Chair. The Chair will then synthesize these points into a Discussion Paper that will be published in the November 2015 issue of *Journal of the Air & Waste Management Association (JA&WMA)*. Comments should be submitted in writing to Michael T. Kleinman, Critical Review Committee Chair, at mtkleinm@uci.edu by no later than **July 30, 2015**.

Get involved with the Critical Review Committee and help further our scientific understand by attending the Annual Meeting of the Critical Review Committee on Tuesday, June 23, 2015, Room: University Ballroom A, 1st Floor, Marriott Raleigh, at 3:00–4:00 p.m.

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have declined globally since the 1980s. Lowering the cooling sulfate burden "unmasks" near-term warming from GHGs (and warming particles).

Climate Influence on Ground-Level O_3 and PM

Climate change is expected to degrade air quality in many polluted regions by changing air pollution meteorology (ventilation and dilution), precipitation, and other removal processes, as well as the atmospheric chemistry, anthropogenic, and natural sources that respond to changing meteorology. Model projections under alternative climate and air quality scenarios indicate a wide range in projected U.S. surface O_3 and $PM_{2.5}$. Each individual model projection reflects the combined influences

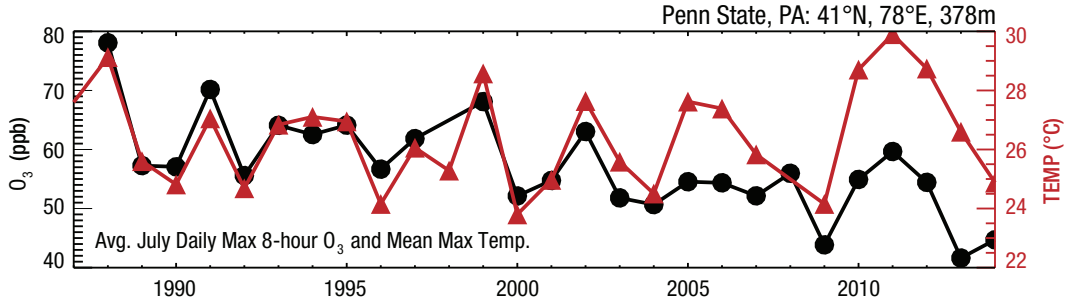


Figure 2 (right). Co-variance between O_3 and temperature as measured at the Pennsylvania State Clean Air Status and Trends Network site in Pennsylvania (41N, 78E, 378m).

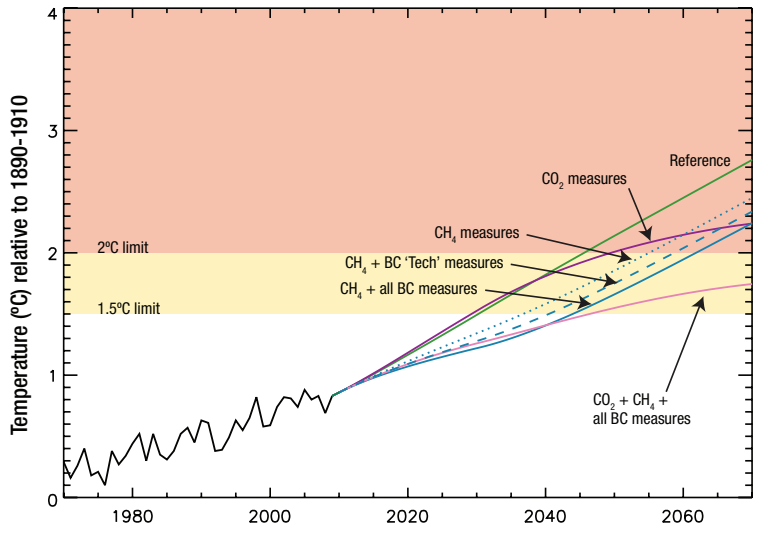
Notes: July mean maximum daily 8-hr average of O_3 (black line and circles; left axis) and July mean daily maximum temperature (red line and triangles; right axis) from 1988 to 2014. Before regional NO_x reductions in the eastern United States circa 2002 the mean July O_3 tracks temperature closely. This is consistent with the expectation that warmer summer temperatures associated with climate warming would increase O_3. Post-NO_x controls, the O_3–temperature relationship still exists, but the highest July mean O_3 levels are clearly attenuated (compare the O_3 levels during the warmest years, 2012 and 1988).

Figure 3 (below). Comparison of global mean surface temperature responses to possible CO_2 and short-lived climate pollution (SLCP) control strategies.

Notes: Observed temperature trends for 1970–2010, expressed as increases relative to 1890–1910 (black line) and model projections under alternative future scenarios (2010–2070): reference reflecting no new strategies (green line), a climate strategy imposing CO_2 emission reductions to stabilize at CO_2 levels of 450 ppm (purple line), and alternative SCLP control measures phased in between 2010 and 2030 for CH_4 (blue dotted line), CH_4 plus BC (with technological measures only; blue dashed line), CH_4 plus all BC (both technological and regulatory measures; solid blue line). Also indicated are 1 and 2°C temperature thresholds relative to 1890–1910.

of a regional climate change (e.g., in response to rising GHGs), superimposed on naturally arising year-to-year and decade-to-decade climate variability. Isolating the effects of climate change on air quality thus requires substantial computational resources to discern climate change (signal) from climate variability (noise). Nevertheless, the range of projections offers a useful sampling of possible futures and reinforces the need to continue preparing for high air pollution years associated with weather fluctuations.

Multiple studies find that regional climate change and the processes it triggers can offset some of the benefits from anthropogenic emission controls. This "climate penalty" includes, but is not limited to, emissions increases from natural and manmade sources, with some regions more sensitive than others (e.g., increasing wildfires in the western U.S.A. from hotter, drier conditions). Continued regional NO_x emission reductions, such as across the eastern United States, may guard against this climate penalty (see Figure 2), and could lead to a full reversal of the O_3 seasonal cycle in some polluted regions. If global CH_4 increases, as occurs under some future scenarios, it can raise U.S. background levels of O_3, confounding efforts to reduce U.S. O_3 via regional precursor emission controls.



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Toward a Holistic Approach for Climate and Air Quality

The linkages between air pollution and climate outlined above suggest that joint mitigation might increase benefits and reduce costs, but challenges can arise as the priorities for each program may diverge. Lowering peak warming requires decreasing atmospheric CO_2. CO_2 emission controls, however, have little impact on near-term climate change. For some source categories, GHG reductions would also reduce co-emitted air pollutants or their precursors. Models indicate that as air pollution programs reduce SO_2 to meet health and other air quality goals, near-term warming accelerates due to "unmasking" of warming induced by rising CO_2 and other warming agents. Near-term warming induced by decreasing SO_2 emissions could be offset by air pollutant controls on sources of CH_4, a potent GHG and precursor to global O_3 levels, and on sources with high BC to OC ratios (see Figure 3). Reducing emissions of CH_4 and BC

would also lower both global background O_3 and regionally high PM levels, thereby diminishing the global health burden and other environmental costs incurred by exposure to O_3 and PM.

As health- and environmental-based standards become more stringent, the relative contribution of background levels to ambient pollutant concentrations increases. Multiple studies indicate that continued implementation of U.S. NO_x emission controls guards against rising O_3 pollution levels triggered either by climate change or by rising global emissions. Assessing the past and future climate and air quality impacts from changing emissions requires reliable models that are evaluated and interpreted with high-quality measurements. Satellite instruments measuring tropospheric composition offer much promise for improving global emission inventories and their changes over time, though these space-based estimates require ground-truthing with in-situ measurements. Continued efforts to synthesize findings from field, laboratory, theory, and modeling approaches that elucidate the fundamental processes connecting climate and air quality can help to ensure that a broad range of air quality and climate impacts are considered during the planning and implementation of air management programs. **em**

References

1. Fiore, A.M.; Naik, V.; Leibensperger, E.M. Air Quality and Climate Connections; *J. Air & Waste Manage. Assoc.* **2015**, 65 (6), 645-685.

About the Authors

▶ **Arlene M. Fiore** is an associate professor in the Department of Earth and Environmental Sciences at Columbia University and Lamont-Doherty Earth Observatory. Her research areas include understanding local-to-global sources of regional air pollution, both anthropogenic and natural, as well as connections between climate, global atmospheric chemistry, and air pollution. In addition to scientific publications in these areas, she contributed to the 2006 U.S. Environmental Protection Agency (EPA) Criteria Document and the 2012 Integrated Science Assessment for the Ozone National Ambient Air Quality Standards (NAAQS), led a multi-model study on intercontinental transport of ozone under the UNECE Task Force on Hemispheric Transport of Air Pollution, and contributed to the associated reports in 2007 and 2010. Dr. Fiore was a lead author of Chapter 11 and WG1 Annex II of the Intergovernmental Panel on Climate Change Assessment Report 5 (IPCC AR5). She currently serves on the IGAC/SPARC Chemistry-Climate Modeling Initiative steering committee, is a principal investigator on the NASA Air Quality Applied Sciences Team, and a new member of the National Academy of Science's Board on Atmospheric Sciences and Climate.

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