Ambient levels of PM and O₃ exceed the U.S. National Ambient Air Quality Standards (NAAQS) over wide regions. Through their interactions with solar and terrestrial radiation, PM, O₃, 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 O₃ and its precursors, including methane (CH₄), volatile organic compounds (VOCs), carbon monoxide (CO), and nitrogen oxides (NOₓ), 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 CO₂, 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, O₃) to a few decades (CH₄). The warming agents CH₄, O₃, and BC are sometimes referred to as short-lived climate pollutants (SLCPs). The short lifetimes of PM and O₃ concentrate their abundances downwind of source regions, predominantly in the northern hemisphere. By inducing regional temperature, precipitation, and circulation responses, PM and O₃ 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 O₃ lifetimes.

Incorporating high-quality emissions inventories and improved process-level understanding into models is crucial.

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in contrast to CO₂: the climate impacts from CO₂ (or other long-lived GHGs) depend on cumulative emissions whereas those from NTCFs depend on emission rates.

After CO₂, increases in CH₄ and tropospheric O₃ since the pre-industrial era have exerted the most warming influence of any anthropogenic GHG, with CH₄ 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 CH₄, 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 CO₂ and other GHGs and confounding detection of climate sensitivity (e.g., global mean surface temperature increase from a doubling of CO₂) 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 O₃ precursors from stationary and mobile sources, particularly in developed nations. These emission controls had little impact on CO₂ and CH₄ 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 (SO₂) emissions, which...

Figure 1. Air quality and climate connections.

Notes: Anthropogenic and natural emitted species include methane (CH₄), carbon monoxide (CO), non-methane volatile organic chemicals (NMVOC), nitrogen and sulfur oxides (NOₓ, SO₂), ammonia (NH₃), 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 O₃ and PM respond to the change indicated for each process (for double-headed arrows, the (O₃, 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.
Climate Influence on Ground-Level O₃ 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 O₃ and PM₂.₅. Each individual model projection reflects the combined influences
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 NOx 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 O3 seasonal cycle in some polluted regions. If global CH4 increases, as occurs under some future scenarios, it can raise U.S. background levels of O3, confounding efforts to reduce U.S. O3 via regional precursor emission controls.

**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 CO2. CO2 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 SO2 to meet health and other air quality goals, near-term warming accelerates due to “unmasking” of warming induced by rising CO2 and other warming agents. Near-term warming induced by decreasing SO2 emissions could be offset by air pollutant controls on sources of CH4, a potent GHG and precursor to global O3 levels, and on sources with high BC to OC ratios (see Figure 3). Reducing emissions of CH4 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.

References

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