Interactions between Climate Change and U.S. Air Quality

An overview of AQAST activities examining the interactions between climate change and U.S. air quality. These activities utilize Earth System data and models, in addition to satellite observations.

by L.J. Mickley, A.M. Fiore, and D.K. Henze

L.J. Mickley is a senior research fellow in the School of Engineering and Applied Sciences at Harvard University; **A.M. Fiore** is an associate professor in the Department of Earth and Environmental Sciences and in the Lamont-Doherty Earth Observatory at Columbia University; and **D.K. Henze** is an assistant professor and Charles C. Gates Faculty Fellow in the Department of Mechanical Engineering at the University of Colorado at Boulder. E-mail: L.J. Mickley mickley@fas.harvard.edu.

In response to health concerns and subsequent regulations, U.S. air quality has shown remarkable improvement in recent years. Eight-hour averages of surface ozone (O_3) have declined by nearly 20% since 1990, while 24-hr averages of fine particulate matter ($PM_{2.5}$) have dropped by 25%.[1] However, unusual weather can interrupt that trend, as was seen in the hot dry summer of 2012, when Chicago and St. Louis experienced double the average number of O_3 episodes from the previous four years. A key question is whether such summers will become more common under climate change. More generally, will the day-to-day weather that accompanies climate change work against decades of air quality regulation?

Since particles and tropospheric O_3 are themselves radiative forcing agents, trends in their concentrations can, in turn, influence regional and global climate. A new direction in air quality research takes into account both the health and climate impacts of pollutants, and attempts to identify those emission controls that maximize the benefits to society.[2,3] The NASA Air Quality Applied Sciences Team (AQAST), which bridges the gap between NASA science and the needs of air quality management, has contributed toward this research and provides new tools for air quality managers.

Background

In much of the United States, cold fronts associated with the low pressure systems known as cyclones provide the main mechanism for ventilating surface

air and ending pollution episodes.[4,5] Model studies point to more heat waves and fewer mid-latitude cyclones in a future, warmer atmosphere,[6,7] suggesting that the frequency of pollution episodes may increase in the absence of additional emissions controls. For $PM_{2.5}$, increasing temperatures in a future climate could increase the emissions of some precursors such as ammonia and biogenic compounds, but simultaneously shift gas-aerosol partitioning toward the gas phase.[8,9] An AQAST-funded effort reviews the impacts of climate change on air quality.[10]

Both O_3 and $PM_{2.5}$ affect regional or hemispheric climate. Tropospheric O_3 absorbs infrared radiation upwelling from the Earth and is a major greenhouse gas. Particles interact with incoming sunlight and can lead to both regional cooling and warming. Light-colored particles like sulfate reflect sunlight and result in cooling, while black carbon particles (BC) absorb sunlight, warming the atmosphere but cooling the Earth's surface directly below. By providing nuclei upon which water can condense to form clouds, particles can increase cloud cover. BC deposited on snow and ice surfaces changes the surface albedo, decreasing the fraction of sunlight reflected to space and allowing warming.

Policy-makers rely on a metric of climate influence called radiative forcing to compare the impacts of one chemical species against another. Radiative forcing is reported in units of Wm^{-2} and represents the imbalance in the Earth's radiative budget introduced by a given species. The Intergovernmental Panel on Climate Change (IPCC)[11] estimates a global mean radiative forcing of tropospheric O_3 at +0.40 Wm^{-2}, and -0.90 Wm^{-2} for particles. By comparison, the global mean radiative forcing for carbon dioxide (CO_2) is +1.82 Wm^{-2}. The relatively short lifetimes of O_3 and particles (days to weeks) result in steep horizontal gradients in their forcings, which has implications for regional climate.

Results From AQAST

Effects of Climate Change on Ozone Air Quality

For a recent AQAST project, present-day and future meteorological fields from the NASA GISS climate model were applied to GEOS-Chem, a global chemical transport model.[12] The study found that higher temperatures and increased stagnation enhanced monthly mean O_3 by 2–6 parts per billion (ppb) across the United States in summer, indicating a "climate penalty." There remains uncertainty, however, in the biogenic component in this response. While warmer temperatures increase biogenic emissions, elevated CO_2 levels may suppress these emissions through biochemical mechanisms within the leaf.[13]

Climate change may also increase the flux of stratospheric O_3 into the troposphere over mid-latitudes.[14] Results from another AQAST study which relied on satellite observations and the GFDL chemistry-climate model point to a large contribution from stratospheric intrusions in springtime high O_3 events at high altitudes in the West.[15] We infer that such events may increase in frequency or severity in the future.

Effects of Climate Change on $PM_{2.5}$ Air Quality

The sensitivity of the Earth's climate to changing greenhouse gases varies from model to model. To gain confidence in predictions of the impact of future climate change on $PM_{2.5}$ air quality, two AQAST projects have employed results from an ensemble of climate models archived for the fourth IPCC. The first analyzed 1999–2010 surface observations to identify the dominant meteorological modes driving $PM_{2.5}$ variability across the United States.[16,17] Using the IPCC ensemble, Tai et al.[17] found that the projected trends in these modes would likely have minimal impacts on $PM_{2.5}$ in the 2000–2050 timeframe.

The second study examined the impact of changing wildfire on U.S. air quality. Yue et al.[18] diagnosed observed relationships between area burned and meteorology, and then applied these relationships to 2050s meteorology from the IPCC ensemble. A robust result is that the warmer, drier atmosphere of the 2050s will likely lead to increased fire activity. In contrast to the first study, $PM_{2.5}$ air quality in this study significantly worsened due to enhanced

Both O_3 and $PM_{2.5}$ affect regional or hemispheric climate.

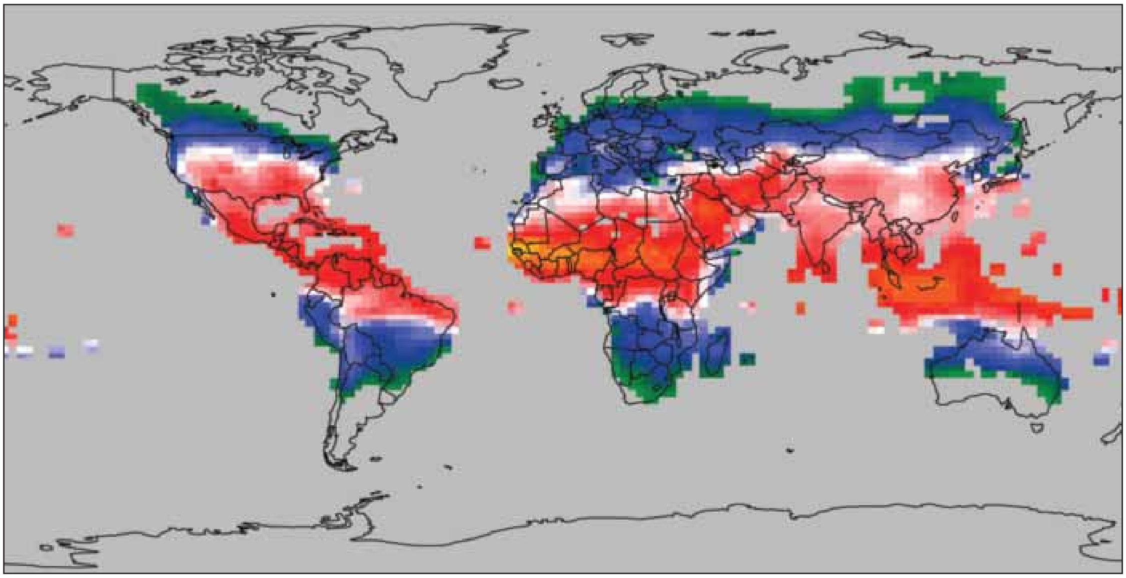

Figure 1. The impact of NO_X emission locations on O_3 radiative forcing, shown here relative to the impact of these emissions on O_3 concentrations for August 2006. In regions where this ratio is greater than one, changes to NO_X emissions are especially efficient in driving O_3 radiative forcing. From Bowman and Henze.[19]

wildfire activity by 2050. Summertime surface organic carbon particles over the West increased by 50–70%, while black carbon increased by approximately 25%, relative to 2000. This work emphasizes the need for careful forest management as climate changes.

Linking Emissions to Ozone and Aerosol Radiative Forcing

In considering the climate impacts of pollutant, policy-makers are often faced with complex choices that simultaneously affect the abundance of many co-emitted species. There is thus a push to consider the radiative forcing of emissions rather than concentrations of the resulting species. Recent AQAST work has developed a new approach to quantifying the radiative forcing of air pollution emissions at much higher spatial scales than previously explored, 250 km rather than continental.

In Bowman and Henze,[19] satellite observations of O_3 radiative forcing from the Tropospheric Emission Spectrometer were combined with GEOS-Chem. Significant regional variability was found—in some places by more than a factor of 10—in how efficiently O_3 trapped heat in Earth's atmosphere, depending upon the locations of precursor emissions (see Figure 1). In regions such as the Southeast United States where strong convection carries O_3 aloft, the O_3 forcing showed large sensitivity to nitrogen oxides (NO_X) emissions.

In another AQAST effort, Henze et al.[20] used GEOS-Chem to consider the emissions of primary particles and particle precursors, and found that the emissions controls required to attain a specific radiative forcing target varied spatially by up to a factor of 4. These AQAST efforts demonstrate both the need and a means for incorporating spatially refined radiative forcing into the design of air quality and climate change mitigation policies.

Climate and Air Quality Co-Benefits

Policy-makers seek emissions strategies that have co-benefits for both health and climate. To address this issue, AQAST has incorporated the emissions-specific forcings from Henze et al.[19] into a new decision support tool, GLIMPSE.[21] The GLIMPSE model provides insights into the consequences of technology and policy decisions on human health, ecosystems, and global climate. The utility of GLIMPSE was demonstrated by analyzing several future energy scenarios under existing air quality regulations and potential CO_2 emission reduction policies. Opportunities were found for substantial co-benefits in setting air quality targets for both climate change mitigation and health benefits. Though current policies which prioritize public health protection increase near-term warming, establishing new policies that also reduce greenhouse gas emissions could offset warming in the near-term and lead to significant reductions in long-term warming.

AQAST also explored another approach for accounting for the co-benefits of emissions controls on climate and health. For this study, the EPA-MARKAL model of the U.S. electricity sector was used to examine how imposing emissions fees based on estimated health and environmental damages might change electricity generation.[22] Fees were imposed on the life-cycle emissions of the criteria pollutants (sulfur dioxide, nitrogen oxides, and particulate matter) and greenhouse gases from 2015 through 2055. One key finding was that fees imposed solely on pollutants did not significantly affect greenhouse gas emissions. Conversely, charging fees only on greenhouse gas fees reduced NO_x emissions up to ~10%, with only a slight increase in sulfur dioxide emissions. Therefore, carefully formulated fees may be needed to achieve significant reductions in both greenhouse gases and the criteria pollutants.

Summary

Average surface temperatures over the continental United States are projected to increase by 1–3 °C by the mid-21st century.[11] By providing information and tools based on Earth System science, AQAST can aid policy-makers in designing air quality strategies that maximize the benefits to human health and global climate. **em**

References

1. *Our Nation's Air: Status and Trends through 2010;* U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards: Research Triangle Park, North Carolina, 2012.
2. West, J.J.; Fiore, A.M.; Horowitz, L.W. Scenarios of methane emission reductions to 2030: Abatement costs and co-benefits to ozone air quality and human mortality; *Climatic Change* **2012**, *114*, 441-461.
3. Shindell, D.; Kuylenstierna, J.C I.; Vignati, E.; Van Dingenen, R.; Amann, M.; Klimont, Z.; Anenberg, S.C.; Muller, N.; Janssens-Maenhout, G.; Raes, F.; Schwartz, J.; Faluvegi, G.; Pozzoli, L.; Kupiainen, K.; Hoglund-Isaksson, L.; Emberson, L.; Streets, D.; Ramanathan, V.; Hicks, K.; Oanh, N.T.K.; Milly, G.; Williams, M.; Demkine, V.; Fowler, D. Simultaneously mitigating near-term climate change and improving human health and food security; *Science* **2012**, *335*, 183-189.
4. Vukovich, F.M. Regional-scale boundary layer ozone variations in the eastern United States and their association with meteorological variations; *Atmos. Environ.* **1995**, *29*, 2259-2273.
5. Leibensperger, E.M.; Mickley, L.J.; Jacob, D.J. Sensitivity of U.S. air quality to mid-latitude cyclone frequency and implications of 1980–2006 climate change; *Atmos. Chem. Phys.* **2008**, *8*, 7075-7086.
6. Schär, C.; Vidale, P.L.; Lüthi, D.; Frei, C.; Häberli, C.; Liniger, M.A.; Appenzeller, C. The role of increasing temperature variability in European summer heatwaves; *Nature* **2004**, *427*, 332-336.
7. Turner, A.J.; Fiore, A.M.; Horowitz, L.W.; Bauer, M. Summertime cyclones over the Great Lakes Storm Track from 1860–2100: Variability, trends, and association with ozone pollution; *Atmos. Chem. Phys.* **2013**, *13*, 565-578.
8. Jacob, D.J.; Winner, D.A. Effect of climate change on air quality; *Atmos. Environ.* **2009**, *43*, 51-63.
9. Tai, A.P.K.; Mickley, L.J.; Jacob, D.J. Correlations between fine particulate matter ($PM_{2.5}$) and meteorological variables in the United States: Implications for the sensitivity of $PM_{2.5}$ to climate change; *Atmos. Environ.* **2010**, *44*, 3976-3984.
10. Fiore, A.M.; Naik, V.; Spracklen, D.V.; Steiner, A.; Unger, N.; Prather, M.; Bergmann, D.; Cameron-Smith, P.J.; Cionni, I.; Collins, W.J.; Dalsøren, S.; Eyring, V.; Folberth, G.A.; Ginoux, P.; Horowitz, L.W.; Josse, B.; Lamarque, J.-F.; MacKenzie, I.A.; Nagashima, T.; O'Connor, F.M.; Righi, M.; Rumbold, S.T.; Shindell, D.T.; Skeie, R.B.; Sudo, K.; Szopa, S.; Takemura, T.; Zeng, G. Global air quality and climate; *Chem. Soc. Rev.* **2012**, *41*, 6663.
11. *Climate Change 2014: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate;* IPCC; Cambridge University Press, Cambridge, 2014.
12. Tai, A.P.K.; Mickley, L.J.; Heald, C.L.; Wu, S. Effect of CO_2 inhibition on biogenic isoprene emission: Implications for air quality under 2000 to 2050 changes in climate, vegetation, and land use; *Geophys. Res. Lett.* **2013**, *40*, 3479-3483.
13. Rosenstiel, T.N.; Potosnak, M.J.; Griffin, K.L.; Fall, R.; Monson, R.K. Increased CO_2 uncouples growth from isoprene emission in an agriforest ecosystem; *Nature* **2003**, *421*, 256-259.
14. Hegglin, M.I.; Shepherd, T.G. Large climate-induced changes in ultraviolet index and stratosphere-to-troposphere ozone flux; *Nature Geoscience* **2009**, *2*, 1-5.
15. Lin, M.; Fiore, A.M.; Cooper, O.R.; Horowitz, L.W.; Langford, A.O.; Levy, H.; Johnson, B.J.; Naik, V.; Oltmans, S.J.; Senff, C.J. Springtime high surface ozone events over the western United States: Quantifying the role of stratospheric intrusions; *J. Geophys. Res.* **2012**, *117*.
16. Tai, A.P.K.; Mickley, L.J.; Jacob, D.J.; Leibensperger, E.M.; Zhang, L.; Fisher, J.A.; Pye, H.O.T. Meteorological modes of variability for fine particulate matter ($PM_{2.5}$) air quality in the United States: implications for $PM_{2.5}$ sensitivity to climate change; *Atmos. Chem. Phys.* **2012**, *12*, 3131-3145.
17. Tai, A.P.K.; Mickley, L.J.; Jacob, D.J. Impact of 2000–2050 climate change on fine particulate matter ($PM_{2.5}$) air quality inferred from a multi-model analysis of meteorological modes; *Atmos. Chem. Phys.* **2012**, *12*, 11329-11337.
18. Yue, X.; Mickley, L.J.; Logan, J.A.; Kaplan, J.O. Ensemble projections of wildfire activity and carbonaceous aerosol concentrations over the western United States in the mid-21st century; *Atmos. Environ.***2013**, *77*, 767-780.
19. Bowman, K.; Henze, D.K. Attribution of direct ozone radiative forcing to spatially resolved emissions; *Geophys. Res. Lett.* **2012**, *39*.
20. Henze, D.K.; Shindell, D.T.; Akhtar, F.; Spurr, R.J.D.; Pinder, R.W.; Loughlin, D.; Kopacz, M.; Singh, K.; Shim, C. Spatially refined aerosol direct radiative forcing efficiencies; *Environ. Sci. Technol.* **2012**, *46*, 9511-9518.
21. Akhtar, F.H.; Pinder, R.W.; Loughlin, D.H.; Henze, D.K. GLIMPSE: A rapid decision framework for energy and environmental policy; *Environ. Sci. Technol.* **2013**, 131022075515008.
22. Brown, K.E.; Henze, D.K.; Milford, J.B. Accounting for climate and air quality damages in future U.S. electricity generation scenarios; *Environ. Sci. Technol.* **2013**, 130319124055007.