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Wintertime Air Quality

Progress and Challenges

Contemporary Wintertime
Air Quality Challenges

by James Kelly and Golam Sarwar

Air pollution levels vary dramatically throughout the world and by season, and many areas of the world experience especially severe air pollution during winter. Severe wintertime air pollution is driven in part by meteorology, but also by pollutant emissions specific to the season. Cold temperatures lead to enhanced emissions associated with home heating, for example. The articles presented in this issue of *EM*, describe several different examples of wintertime air pollution from around the world.

The photo was taken from the NOAA Twin Otter research aircraft on January 17, 2017, over Salt Lake City and shows the haze layer over the urban area with the Wasatch Mountains in the background. Credit: Alessandro Franchin of NOAA and the University of Colorado.

Features

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Thank You!

by Michele E. Gehring, P.E. » president@awma.org

How is it already December? For the past 11 months, I've welcomed you to our monthly *EM* magazine, updated you on what the Association is doing, and introduced the topic of the month. This month, however, is different. I'm going to let the excellent writing introduce itself and just quickly mention that we have two great events coming up in December: 44th Annual Information Exchange (http://www.awma.org/infoexchange) in Raleigh, NC, and Bracing for Climate Change (http://www.awma.org/climatechange) in Santa Barbara, CA. What I really want to do with my space this month is say thank you!

Thank you to the amazing team of Directors and Association staff that I've had the pleasure of working with this year. Thank you to each of the conference planning committees that have worked so hard to bring together an amazing slate of specialty conferences. Thank you to our Annual Conference Local Host Committee in Québec that brought us an experience to remember north of the border. Thank you to each of the Sections and Chapters that welcomed me to their events. And last, but certainly not least, thank you to our Executive Director, Stephanie Glyptis, who works tirelessly for this Association, often spending late nights and early mornings at the office or by her laptop to make sure that this business runs smoothly and continues to bring value back to our members. As I get ready to hand things off to President-Elect Kim Marcus next month, I feel good about all that we have accomplished this year and look forward to watching those accomplishments feed plans and programs for 2020 and beyond.

It's been a busy 2019 as President. I have had the fortune of traveling all of over North America to greet members, provide Association updates, and tie together what you are doing on the local level with the priorities and agenda of the International Association. Sit back and take a little trip down memory lane with me to hear about the faces and voices I've had the honor of spending time with this past year.

My Year in Review

It all started at the Intercouncil meetings in Québec City in January. Our Board of Directors and Council members came together to outline objectives for the year, pull together the Annual Conference technical program, and align our priorities. It was cold. Really cold. And we took some time to play in the snow, throw snowballs at one another, enjoy the winter wonderland that Québec provided, and managed not to lose anyone on the ski slopes. Travel to and from Québec did provide a challenge and I want to thank each of you who made it for your persistence and patience in your journeys to and from the great White North. Fortunately, everyone did make it home safely, albeit it a few days later than planned, and the busy weekend in conference rooms allowed us to make a great start to the New Year.

Once February came around, it was time to journey to Santa Rosa, CA, for our inaugural Wildfires specialty conference. Past-President Scott Freeburn and his conference steering committee did an amazing job pulling together conversations on both environmental and health impacts from wildfires. We were lucky to be joined by local political representatives who relayed firsthand accounts of the trauma and devastation unloaded on the area by the Tubbs Fire in October 2017. As I told our attendees at the conference, so many times in the modern environmental dialogue, the impacts we talk about from air pollution are on the microscale. But with wildfires, the impacts are in your face—they are your colleague who lost their home, belongings, pets, or loved ones; they are people you know living in a community that is forever changed from an event that happened in a matter of hours. In 1907, when what is now the Air & Waste Management Association got its start as the International Association for the Prevention of Smoke, we faced another type of smoke problem in the United States. We were able to step in and help advance the conversation then and I'm honored that we are able to help advance the conversation on a very different smoke problem today. To me, the dialogue we had in Santa Rosa and the one we are planning for Sacramento in 2020 is one of the most important that we are helping to facilitate. Together, with our colleagues in the public health profession, I'm convinced we can truly make a difference in affected communities and in those communities that are holding their breath, knowing that eventually the wind will blow the fires their direction.

After taking some time to feed the day-job, I started out March at the Measurements specialty conference in Raleigh, NC. Ray Merrill and Ian MacGregor brought together a committee and program that fostered tremendous dialogue on the latest advances in ambient and stack measurement techniques. We once again had a sold-out exhibit hall with vendors displaying high-tech, lost-cost sensors, and highlighting their emissions measurement capabilities. We were also fortunate to have a tremendous U.S. Environmental Protection Agency (EPA) involvement in the event, from attendees to speakers and even session chairs. The program drove directly to achieving our key mission—providing a neutral forum for the exchange of information and an opportunity for collaboration between the regulated community, the regulators, and the technology and service providers that are working to help both of them.

After chasing down the Dark Side in the Disney Star Wars race weekend and putting another 22.4 miles on my running shoes, it was back on a plane and off to Pittsburgh for our annual Leadership Training Academy (LTA) in April. Tony van der Vooren and the Association staff put in a ton of work to provide this program to the Section and Chapter leadership each year and, as predicted, this year's program was another huge success. I really enjoy the time I spend at LTA each year and was surprised by the number of LTA graduates that I ran into as I traversed the country this year at Section and Chapter events. If you have never been to LTA (http://www.awma.org/LTA), be sure to put it on your calendar for next year and join us in Pittsburgh April 24–26. I promise that you won't be disappointed.

Come May, I was off to Louisiana to join our Louisiana Section for their annual golf outing. Each year, the Section hosts a golf outing to fund an outstanding Young Professional to attend our Annual Conference. We won't speak to the score that our foursome put forward, but, as always, it was a pleasure to meet up with members of one of our most successful sections, talk about the Association, share some laughs, and put that mulligan fund to a good cause. A special thank you to Jennifer Tullier, Jessica Miller, Paul Algu, Bill Palermo, and Greg Johnson for your hospitality, uber services, and event coordination.

After enjoying some much-needed time at home for a few weeks, it was full speed ahead to the 2020 Annual Conference in Québec City in June. Jean-Luc Allard, Nicholas Turgeon, and the members of the Québec Local Host Committee went all out to make sure this year's program was a glowing success, and I'm happy to report it was. We unveiled some new areas in the exhibit hall, introduced some new program elements, and are already making plans to carry many of them forward to the 2020 Annual Conference in San Francisco. I look forward to seeing each of you at the Hyatt on the waterfront June 29 through July 2.

Thankfully, I managed to fit a vacation with my family in and put down some miles for work travel in **July** and August before summer's end. Beginning with September, it was once again off to the races. During the fall is when most of our Section and Chapters host their annual conferences and, as President, it's an honor to attend these events, provide Association updates, and meet with the local member units to discuss challenges and successes. This year, I was fortunate to join members at the Southern Section meeting at Callaway Gardens in Georgia. The facilities at the Gardens are perfect for a 100- to 200-person conference and also include many other attractions, such as a watersport activities, a very impressive Butterfly exhibit, and two very challenging golf courses. While I didn't make it to the Butterfly exhibit, my boyfriend and I did find time to enjoy the sand traps, water hazards, and occasional fairway on the golf courses. A special thank you to Dallas Baker, Chris Hurst, and Stephen Ellingson for their invitation to the conference. I was impressed with the depth of the technical program and the representation provided by each of the Section's Chapters. It's often challenging with our larger sections to host a conference that draws across multiple states, and the Southern Section did a great job of incorporating regulatory participation and talks from every single one of the states within their region.

With October came a crazy barrage of events. I was able to open a conference that I've been attending for the entire course of my career—the International Conference on Thermal Treatment Technologies (IT3)—and meet back up with many of those within the industry and EPA who drove the development of regulations that have been the backbone of my business. With the sudden focus on thermal treatment of per- and poly-fluoroalkyl substances (PFAS) and the impacts from PFAS air emissions, the gang was once again back together to talk about another set of emerging contaminants and potential future regulation. Thank you to Bill Norris, the conference chair, for allowing me to share the stage for the opening and to the others on the conference planning committee for bringing together a great program with broad interest across the country. Look for more PFAS-focused programming in 2020.

Board of Directors Meeting, January 2019.

Fun in the Snow at Intercouncil in Québec, January 2019.

Wildfires Specialty Conference, Santa Rosa, CA, February 2019.

A&WMA Leadership Training in Pittsburgh, April 2019.

With Jessica Miller at the Louisiana Section Golf Outing, May 2019.

Some candid shots from ACE 2019 in Québec, June 2019.

My badge from Southern Section Meeting, September 2019.

Scenic views from Montana for the PNWIS Conference, October 2019.

Opening of IT3, October 2019.

Last but not least, thank you for allowing me serve as your president and guide the Association in 2019, and best of luck to Kim Marcus, A&WMA President for 2020.

After jumping off the stage at IT3, it was off to Montana for the Pacific Northwest International Section (PNWIS) Conference. Kumar Ganesan, the PNWIS conference chair, and Rachel Buckabee, the PNWIS president were wonderful hosts to me and my boyfriend and the rumors I've heard about the PNWIS gang all rang true. The PNWIS program provides an awesome balance between air, water, and waste issues, and works in some unique and fun networking opportunities as well. Unfortunately, I wasn't able to stick around to congratulate this year's Black Banana award winner, but I'm sure the story around the award was, once again, one for the record books. Oh, and kudos to Kumar for arranging the snow on Wednesday night. There's nothing quite like soaking in a hot spring outside while snow falls around you to put a smile on your face and melt the stress away.

After a weekend at home, I was off again, this time to a location with plenty of sun and no snow. The annual Florida Section meeting in Tallahassee afforded me the opportunity to pull back out my summer clothes and meet a whole other slate of members and Association customers. Each Section often has their own unique event woven into the technical program and the Florida Section's Joe Brown AnnualChick-fil-A breakfast is no exception. I thoroughly enjoyed meeting all of the students who attended the breakfast and wish them all success in their future endeavors. The carb-loaded breakfast also provided the perfect fuel for the 5K and half marathon that I closed out the week with in Orlando—only 16.2 miles for the Wine and Dine weekend—I was tired from all the Association travel. The technical program was also, as expected, top-notch. Once again, there were talks focused on PFAS. A special thanks to Liz Foeller for setting up everything for me in Tallahassee.

There is, alas, one more trip to make to finish out my year as President. I'll be heading to Madrid, Spain, to attend the 25th session of the Conference of the Parties (COP 25) to the UNFCCC, December 2–13. A&WMA has once again been granted Official Observer status, and I'll be joined on the journey by Jeff Muffat, a Past-President of A&WMA and current Treasurer, and Jack Broadbent, a long-time member and past Director of the Association and current director of the Bay Area Air Quality Management District. Be sure to check out our blog (https://www.awma.org/blog_home.asp) and video feed on the A&WMA website and stay tuned for further details on our journey in future Association publications.

I'm going to close out this final message just as I closed the first message I wrote to you back in January. ***Thank you for the opportunity to guide the sticks and serve as President of this wonderful Association.*** I feel confident that we have successfully built on the 112 years that this Association has served members throughout the world and have done a lot of positive work together to ensure the Association continues to grow in the years ahead. Please be sure to welcome Kim as next year's leader with the same smiling faces and supportive mindset that you welcomed me with this year. He has a lot of exciting things he wants to do for you and I'm confident he will. **em**

The photo was taken from the NOAA Twin Otter research aircraft on January 17, 2017, over Salt Lake City and shows the haze layer over the urban area with the Wasatch Mountains in the background. Credit: Alessandro Franchin of NOAA and the University of Colorado.

Contemporary Wintertime Air Quality Challenges

This month's issue highlights several examples of wintertime air pollution issues from around the world.

Air pollution is a major risk factor for premature mortality worldwide. In 2017, fine particulate pollution is estimated to have contributed to 2.9 million premature deaths globally and ozone pollution to nearly a half million deaths.[1] Air pollution levels vary dramatically throughout the world and by season, and many areas of the world experience especially severe air pollution during winter. For example, the highest concentrations of fine particulate matter ($PM_{2.5}$) occur in winter in Delhi, India;[2] Beijing, China;[3] Dhaka, Bangladesh;[4] and San Joaquin Valley, California, USA.[5] The timing of the peak in national average $PM_{2.5}$ concentrations in the United States recently switched from summertime to wintertime.[6,7]

Severe wintertime air pollution is driven in part by meteorology. Cold ground temperatures cause the layer of air close to the surface to be cooler than the air above. Layering of cool air under warm air promotes atmospheric stability, which suppresses vertical mixing and dilution of surface emissions. Stagnant air conditions can be intensified by high pressure systems that further suppress atmospheric mixing and trap air pollutants near the surface. Wintertime pollution can be especially bad in valleys where horizontal air transport and ventilation is blocked by terrain.

Wintertime air pollution is also driven by pollutant emissions specific to the season. Cold temperatures lead to enhanced emissions associated with home heating. Use of raw coal for home heating has been identified as a major pollution source in Ulaanbaatar, Mongolia,[8] and residential wood combustion is an important pollution source in mountain valleys in the United States.[9-11] In Northern India, residential biomass burning is the major contributor to $PM_{2.5}$ concentrations in December–February (see Venkataraman et al., in this issue) and burning of crop stubble from farms in Punjab and Haryana is a major pollution source in October–November.[12] Open burning of municipal solid waste has also been recognized as an important wintertime emission source in Indian cities.[13]

In this issue, several examples of wintertime air pollution are described. First, de la Paz et al. discuss the occurrence of high concentrations of nitrogen dioxide (NO_2) in Madrid, Spain under stagnant meteorological conditions in winter. Using high-resolution air quality modeling, de la Paz et al. find that mobile sources are the dominant contributors to elevated NO_2 concentrations, and the authors recommend sustained measures to reduce emissions throughout the Madrid metropolitan region.

Second, Venkataraman et al. discuss carbonaceous aerosol emissions in the context of India's air quality and near-term climate concerns. They identify mitigation strategies, including increased access to residential clean energy, expanded air quality monitoring and enforcement actions at the city level, programs to curb emissions from agricultural residue burning, and partnerships to advance measures related to short-lived climate pollutants.

Third, Moniruzzaman discusses severe wintertime concentrations of $PM_{2.5}$ (>200 µg m^{-3}) in Dhaka, Bangladesh. Brick-kilns and road and soil dust are identified as major contributors to Dhaka's wintertime pollution, and development of emission inventories and modeling capabilities are identified as research needs to address air pollution in Bangladesh.

Fourth, Avise et al. discuss the distinct characteristics of wintertime $PM_{2.5}$ pollution in four regions of California. They describe the successes of air quality management plans implemented since the early 2000s and a strategy for continued improvement involving advanced clean cars and trucks, cleanerheating devices, and increased partnerships at the local, national, and international levels.

Lastly, Brown discusses how intensive field studies involving highly instrumented aircraft have been used to investigate wintertime air quality in the United States. Although challenging to perform, the field intensives provide comprehensive scientific datasets critical for understanding and mitigating the most complex air quality problems. Two important new field campaigns are currently being planned to characterize wintertime air pollution processes in Alaska and the western United States.

We invite readers to enjoy the tour of wintertime air quality topics provided by these articles and consider the common factors that underlie air pollution in these diverse parts of the world. **em**

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What's on the Horizon for *EM* in 2020?

EM will explore environmental issues of supreme importance at the local, national, and international levels. Kicking off the year will be a focus on International Approaches to Waste Management (January), followed by Environmental Education (February), Waste Management in the United States (March), Light-Duty Motor Vehicle Emissions (April), Offshore Wind (May), and Wildfire (June).

In addition to the January and March issues, *EM* will expand its content coverage of waste management issues, with waste-themed articles appearing at regular intervals throughout the year as part of a "Waste Management Corner".

The complete 2020 EM Editorial Calendar is available online at **ttp://pubs.awma.org/em/EMEditorialCalendar2020.pdf.**

Have an idea for an article or issue theme that you would like to share with your peers? Contact Managing Editor Lisa Bucher **lbucher@awma.org** with questions and ideas.

High NO_2 Levels in Madrid, Spain

by David de la Paz, Rafael Borge, Javier Perez, and Juan Manuel de Andrés

Results from a modeling study to investigate nitrogen dioxide pollution in Madrid, Spain.

Air pollution is a major environmental concern with severe health effects. According to the World Health Organization (WHO), poor outdoor air quality is associated with 4.2 million premature deaths annually.[1] Exposure to air pollution is particularly important in urban areas,[2-4] where both emissions and population concentration hot-spots are common.[5] Even in regions where significant abatement efforts have been made in recent years, such as Europe, air pollution causes serious impacts (around 0.5 million attributable deaths).[3] Many urban areas, including the largest cities in Spain, are struggling to meet air quality standards, especially those related to nitrogen dioxide (NO_2). This pollutant is known to cause a series of health effects, including lung and cardiovascular diseases.[6] In addition to direct health effects, nitrogen oxides (NOx) are precursors of particulate matter (PM) and other photochemical pollutants such as tropospheric ozone (O_3),[7] a potent oxidant with significant environmental and health effects.

NOx emissions are related to combustion processes in a variety of anthropogenic activities. However, road traffic is a major source in urban areas.[8] According to the Madrid regional inventory,[9] road traffic (SNAP 07 group) accounted for 62–71% of NOx emissions in 2010–2017 (see Figure 1). The contribution of residential, commercial, and institutional (RCI) combustion (SNAP 02) is around 15–20%, while other mobile sources (SNAP 08) are responsible for 8–12% of total NOx emissions. The contribution from industry and power generation is rather small, around 5%. As shown in Figure 1, total NOx emissions were reduced by 11,700 t yr^{-1} (19%) in the 2010–2017 period. This downward trend is mainly related to abatements in the road transport sector (5,800 t yr^{-1}). Nonetheless, traffic remains the main contributor to NOx emissions and the primary target of air quality plans in the region.[10,11]

Despite such reductions, NO_2 air quality standards (Directive 2008/50/EC) are often exceeded in the region, especially in Madrid City. In 2017, 15 (8 traffic and 7 background) out of the 24 air quality monitoring stations in the city exceeded the annual limit value (40 µg m^{-3} as an annual mean). As for the hourly limit value (200 µg m^{-3}), it was exceeded more than 18 times in 7 monitoring stations (5 traffic and 2 background). Most of these exceedances were recorded in downtown Madrid (see Figure 2a). The analysis of hourly NO_2 records shows that both traffic and urban background monitoring stations record higher concentrations in fall and winter, especially in December (Figure 2b). High NO_2 episodes in Madrid are typically related to high pressure synoptic conditions, characterized by low wind and thermal inversion that favor air stagnation[12] and, consequently, the build up of pollutant concentrations at surface level.

In this study, we apply a mesoscale Eulerian air quality model to provide a comprehensive picture of the NO_2 concentration dynamics in Madrid during the most unfavorable

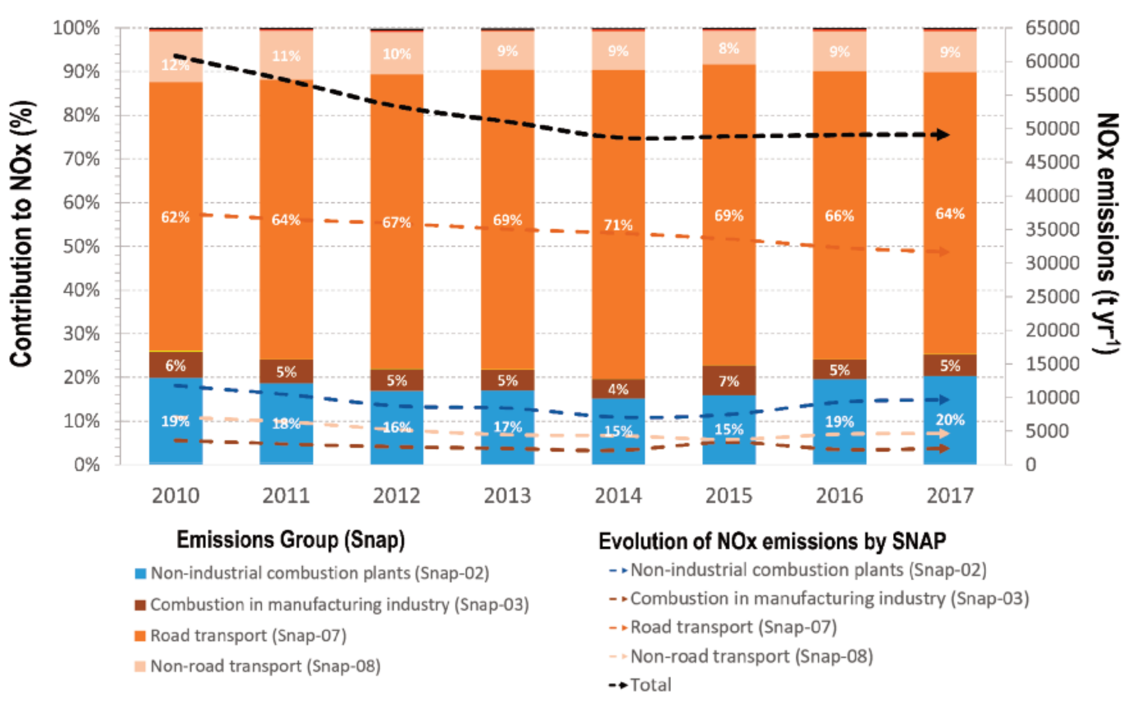

Figure 1. Evolution of NOx emissions, represented by dashed lines (right axis) and sectoral contribution (left axis), in the 2010–2017 period in the Greater Madrid Region.[9]

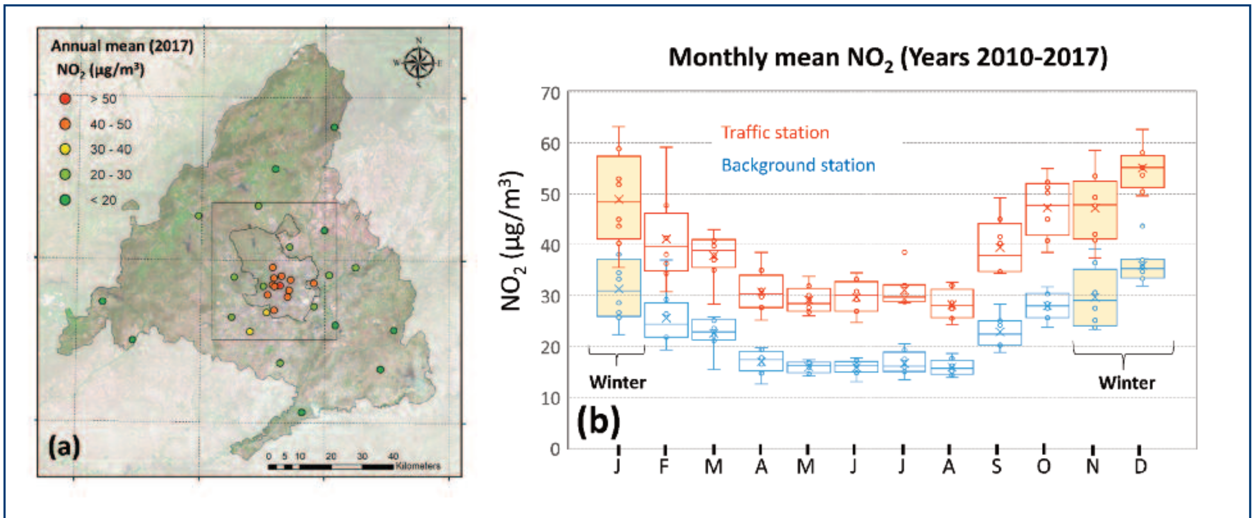

Figure 2. (a) Observed NO_2 annual mean (2017) in the air quality monitoring stations across the Madrid Greater Region; and (b) Box and whisker plot of monthly means (2010–2017) by monitoring station type.

conditions (December) for a better understanding of (a) regional concentration gradients; (b) source apportionment; and (c) outcome of potential abatement measures, both permanent and short action plans.

Study Methodology

The state-of-the-science modeling system used in this study consists of three main components, applied in four nested domains with a maximum resolution of 1 km^2:

- Weather Research and Forecasting, v 3.8 meteorological model (WRF)[13,14]
- Sparse Matrix Operator Kernel Emissions, v 3.6.5 emission processing system (SMOKE)[15,16]
- Community Multiscale Air Quality Modeling, v 5.0.2 chemical-transport model (CMAQ)[17,18]

This modeling system is able to simulate air pollution levels as the combination of emission, dispersion, deposition, and chemical reactions in the urban atmosphere. The source apportionment analysis carried out is based on a zero-out methodology.[19,20] First, a baseline scenario (2015 is used as a representative year), considering all emission sources, is modeled to depict current air quality conditions. Then, emissions from the main sectors are removed in SMOKE and the CMAQ model is re-run using exactly the same meteorological conditions. The contribution of each sector is computed as the difference between each perturbed simulation (where emissions from that particular sector have been zeroed-out) and the baseline scenario. Similarly, the effect of potential abatement measures are derived from the comparison of the CMAQ simulations of the emission scenario and the baseline (without measures). The results are shown as control minus baseline, e.g. negative values imply air quality improvements.

Table 1. Ambient NO_2 concentration source apportionment for Madrid City.

Sector	Contribution NO_2 (%)			
	Annual mean		December	
	Total	Local sources	Total	Local sources
RCI (SNAP 02)	5.9	8.2	6.6	10.2
Industry (SNAP 03-04)	0.3	0.4	0.3	0.5
Road traffic (SNAP 07)	**53.3**	**74.4**	**46.4**	**71.9**
Other mobile sources (SNAP 08)	2.7	3.7	2.8	4.3
Other sectors	9.5	13.3	8.3	12.9
Local	**71.7**	**100**	**64.4**	**100**
External	**28.3**	-	**35.6**	-

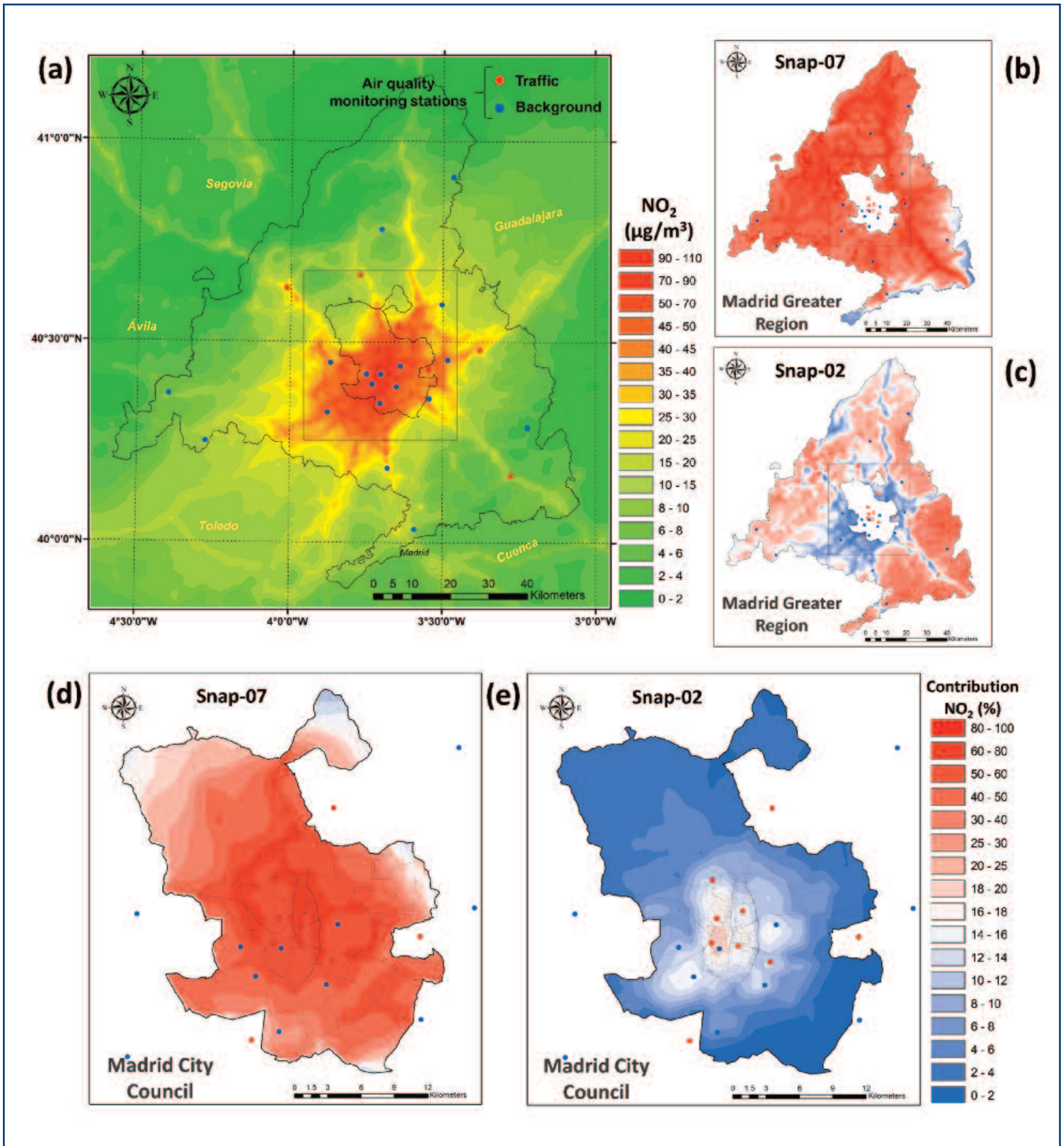

Figure 3. (a) December NO_2 mean for the baseline scenario; (b) Contribution of road traffic (SNAP 07) and (c) RCI (SNAP 02) to NO_2 December average concentration in the Greater Madrid Region; and (d, e respectively) Same for Madrid City.

Study Results

The simulation of the baseline scenario (see Figure 3a) suggests that the highest NO_2 concentration values are related to the main roads, especially within the city. The model yielded a citywide average December mean concentration of 53 µg m^{-3}, approximately double the corresponding annual mean (26 µg m^{-3}). The monthly mean reaches values above 100 µg m^{-3} in the city center. The source apportionment analysis confirms that road traffic is the main contributor to NO_2 levels in the whole region, both outside (Figure 3b) and inside (Figure 3d) the city. Table 1 shows a summary of the contributions of the main sectors as an average for the grid cells within Madrid City.

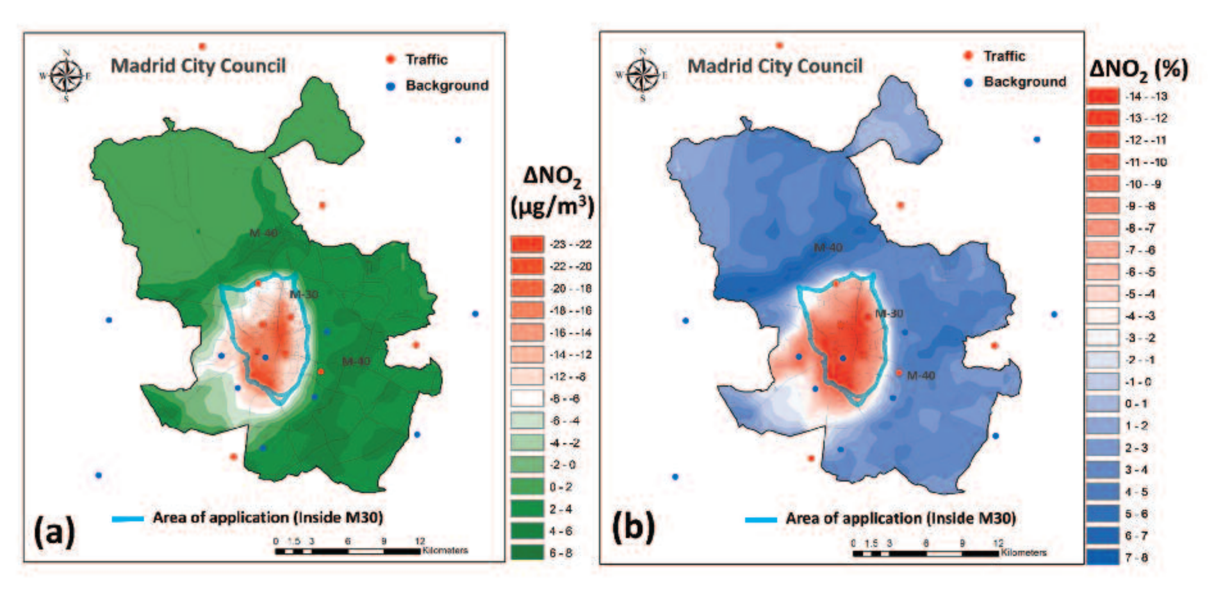

Figure 4. (a) Variation on 1-hr maximum NO_2 ambient concentration (stage 3): absolute and (b) relative to the baseline scenario. Traffic restrictions associated to the NO_2 protocol are applied inside the M-30 ring road, highlighted in blue.

Road traffic is responsible for 53.3% of NO_2 annual mean levels. This contribution represents 74.4% of local sources (those inside the Madrid City). The relative relevance of traffic is slightly smaller in winter (46.4%), when the contribution from heating systems is maximum. The contribution of power generation and industry is negligible throughout the year. Although the external contribution is significant (up to 35.6% in December), it should be noted that it is also originated from road traffic emissions in contiguous municipalities (Figure 3b). This clearly indicates that air quality plans intended to meet NO_2 standard should be primary targeted at reducing traffic emissions in the entire metropolitan area. Of note, the contribution of this sector to ambient NO_2 concentration is higher than that for NOx emissions. This points to the fact that abating traffic emissions is particularly effective to reduce NO_2 levels.

In addition to necessary permanent measures aimed at meeting the annual limit value, the Madrid City Council has enforced a short-term action plan for high NO_2 episodes. The so-called NO_2 protocol considers several stages depending on observed concentration levels that involve speed limit reductions, parking restrictions, and access restriction to the city center[21] (inside the innermost ring road, M-30; see Figure 4). A detailed simulation of the most restrictive scenario (stage 3) suggests that NOx emissions may be reduced by 23.6% within M-30 by preventing 50% of non-resident passenger cars from circulating in that area.[21]

The effect of such drastic measures has been evaluated for a strong NO_2 episode that took place in December 2016[13] (Figure 4). Under typical unfavorable conditions in winter, NO_2 peak values can be reduced by 23 μg m^{-3} (around 14%) in Madrid City. However, the effect of the abatement measures outside the intervention area was practically negligible, or may even produce slight concentration increase due to traffic diversion.

Conclusion

This modeling study investigated NO_2 pollution features in Madrid by means of the WRF–SMOKE–CMAQ modeling system (using 2015 as baseline). We found that the average concentration in Greater Madrid in December reached 53 μg m^{-3}, with values over 100 μg m^{-3} in Madrid. City

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This concentration broadly doubles that of the annual mean value. Very high NO_2 episodes are associated with strong high pressure conditions with weak pressure gradients at surface that favor the formation of thermal inversions that bring about shallow mixing heights and reduced ventilation. Road traffic (SNAP 07) was found to be the main contributor to ambient NO_2 concentrations, with a contribution of 74.4% to the annual mean value. Consequently, the options to meet European standards have to address this sector. We found that permanent measures that can reduce traffic emissions in the entire Madrid metropolitan area are the most effective strategy. However, the simulations demonstrate that the application of short-term measures under very unfavorable conditions have a very limited potential. This highlights the need to implement bold permanent traffic-related measures to meet NO_2 air quality standards. **em**

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Carbonaceous Aerosol Emissions Sources

Dominate India's Wintertime Air Quality

by Chandra Venkataraman, Arushi Sharma, Kushal Tibrewal, Suman Maity, and Kaushik Muduchuru

An analysis of regional-scale wintertime concentrations of fine particles in India.

Exposure to fine particles (particle mass with aerodynamic diameter <2.5 µm, or $PM_{2.5}$), constitutes a grave public health problem in India. Several cities, including Delhi, Raipur, Gwalior, and Lucknow, rank among the world's top 10 polluted cities.[1] A comprehensive analysis of disease and death in India from 1990 to the present, made under The India Health of the Nation's States Initiative, has identified air pollution as a leading risk factor for disease, premature death and reduced life expectancy in India.[2] Wintertime air quality, especially in northern India, is degraded to much greater levels than the annual average, from an interplay between meteorological conditions of lower surface winds and shallower mixed layer depths[3] and seasonal influences of biomass burning and secondary processes.[4–7] Wintertime daily average concentrations of $PM_{2.5}$ in locations like New Delhi range as high as 200–400 µg m^{-3}.[8] The meteorological definition of seasons in India identifies October to December as post-monsoon and January to February as winter.[9] However, much of northern India experiences low temperatures throughout this period, considered for analysis in this article.

Air pollution prevention is directly linked to the sustainable development goals (SDGs) of improving health, enhancing the livability of India's cities, and mitigating climate change. Concurrently, the Paris Agreement of the United Nations Framework Convention on Climate Change (UNFCCC) clearly links global long-term climate to near-term SDGs.[10] While major greenhouse gases (GHGs) like carbon dioxide (CO_2) and nitrous oxide (N_2O) are not implicated in air quality degradation, short-lived climate pollutants (SLCPs) can offer co-benefits to climate change and air quality management. SLCPs include particulate black carbon (BC) and organic carbon (OC), which interact directly with radiation; and ozone (O_3) precursors like methane (CH_4), carbon monoxide (CO), nitrogen oxides (NOx), non-methane volatile organic compounds (NMVOCs), and sulfur dioxide (SO_2), which forms particulate sulfate. While BC and O_3 precursors exert a net warming influence, OC and SO_2 exert a cooling. Specific to India, GHG and SLCP emissions arise from *unrelated* sectors and economic activities,[11] making additional climate action on SLCPs imperative.

What portfolio of mitigation solutions might best address India's immediate air quality concerns, while stimulating progress toward temperature targets of climate action? An understanding of sources influencing atmospheric abundance of air pollutants, several of which also have near-term influences on climate variables like temperature and rainfall, relies crucially on accurate, quantitative, source apportionment.

Sources Influencing Air Pollution in India

There are two major approaches to source apportionment. The first relies on "top-down" receptor modeling methods using in-situ measurements of particle composition, sometimes enhanced by specific markers, satellite data, and trajectory ensembles, to identify detailed source types on monitoring station to city scales. The second uses "bottom-up" methods, or emissions inventory-driven atmospheric chemical transport modelling, to provide a broad understanding of source influence on city to regional scales, even addressing pollutant transport on transboundary and inter-hemispheric scales.

While India has implemented urban networks for air pollution measurements since the 1980s, speciated particle composition data are highly incomplete. Thus "top-down" or receptor modeling methods, have largely been limited to research studies using short-term campaign measurements, from varying seasons and sampling locations, leading to diverging conclusions.[12] Most studies on urban scales have moderate to poor source resolution citing contributions from vehicular emissions to fine particulate matter and undifferentiated natural and road dust to coarse particulate matter on urban scales. Recent studies resolve broad source categories like biomass burning, secondary inorganics, industrial and dust factors. However, robust source apportionment is inhibited by measurement drawbacks, including inadequate numbers of samples and chemical species and a lack of key information (particle size-fractionation, regional source profiles, and measured components like thermal-optical carbon fractions, organic molecular markers, isotope markers of carbon and other inorganic species), needed to resolve similar sources (diesel and gasoline vehicles or different sources of dust).

There is an emerging convergence in "bottom-up" approaches to source apportionment of air pollution and related mortality and morbidity in India, combining data from chemical transport models and observational platforms, on regional scales.[13-17] Elevated annual mean $PM_{2.5}$ concentrations are a pan-India problem, with a regional character, not limited to urban areas or megacities. Simulated $PM_{2.5}$ concentrations in most states are above the national annual $PM_{2.5}$ standard of 40 µg m^{-3}. While the studies differ among themselves in emission datasets and model physics and chemistry, they identify residential biomass combustion (for cooking and heating) as the major source of ambient $PM_{2.5}$, and related mortality, throughout India.[13-17]

A high regional $PM_{2.5}$ background level, is further increased by emissions from local sources in peri-urban areas and megacities.[18] In northern India, primary particulate mass is dominated by residential and industry activities, while secondary inorganic particle mass is attributed to energy and industry sectors.[6] Source shares reported using city level analyses,[19] reveal additional contributions from municipal waste burning, informal and semiformal industrial activity and construction-related emissions, on city scales.

Carbonaceous Aerosol Emission Sources

Traditional stationary (including industry, electricity generation) and transportation sources, have been typical targets of air pollution control in other world regions (like North America and Europe), and such emissions regulations are being considered in India as well. In India, the emerging understanding of the importance of activities such as residential-biomass cooking/heating and kerosene lighting, agricultural residue burning, brick kilns, and other activities (including trash burning), needs further evaluation. These sources contain significant carbonaceous aerosols in their emissions.

We evaluated the influence of these major carbonaceous aerosol emission sources on annual and wintertime air quality in India. $PM_{2.5}$ concentration fields were generated from simulations with the European Centre for Medium-Range Weather Forecasts-Hamburg (ECHAM6)[20] general circulation model, extended by the Hamburg Aerosol Module (HAM2),[21] input with present-day 2015 emissions from the SMoG-India-V1a emissions inventory,[22] nested in the IPCC global emission inventory.[23] Concentrations of $PM_{2.5}$ from baseline simulation, including all sources, were compared to those from a sensitivity simulation excluding the sources identified above.

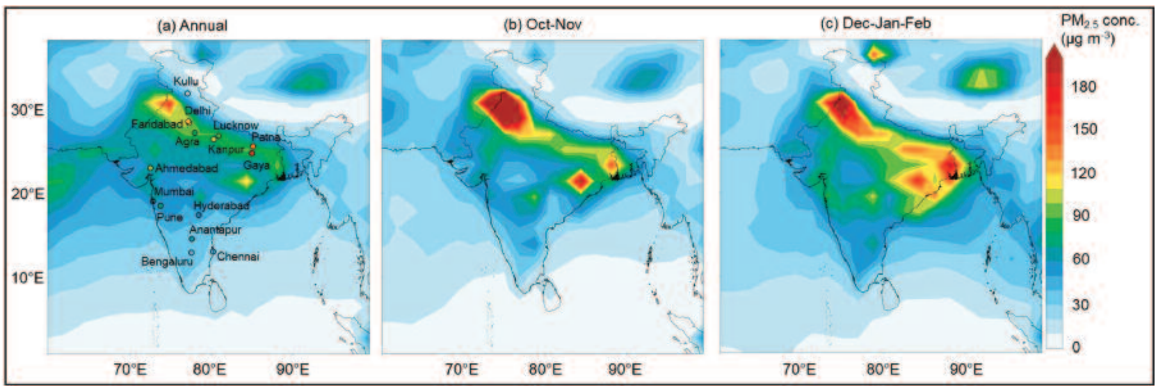

Figure 1. Simulated mean $PM_{2.5}$ concentrations for (a) Annual, (b) Oct--Nov, and (c) Dec--Feb periods.

Simulated $PM_{2.5}$ concentrations capture a typical north-south gradient, with annual mean values (see Figure 1a) ranging from 70 to 150 µg m^{-3} in northern India, predominantly from emissions from widespread use of residential biomass fuels and seasonal agricultural residue burning, 60–120 µg m^{-3} in central–east India, largely from coal-fired electricity generation and 20–70 µg m^{-3} in peninsular India. Available station measurements, averaged during 2011–2014 (Figure 1a) appear as colored circles, superimposed on simulated values for comparison. Simulated wintertime air quality in Oct–Nov (Figure 1b) and Dec–Jan-Feb (Figure 1c) is significantly degraded compared to annual mean levels, increasing to 100–200 µg m^{-3} in northern India.

Differences in the spatial distribution of $PM_{2.5}$ concentrations arise both from differences in synoptic meteorology and spatial location of carbonaceous aerosol emission sources. Agricultural residue burning emissions, in north–west India, dominate in Oct–Nov, but residential biomass emissions, over the entirety of north India, dominate in Dec–Feb. The $PM_{2.5}$ concentrations simulated here far exceed the annual air quality standards of India of 40 µg m^{-3}, the U.S. standard of 12 µg m^{-3} and the annual WHO guideline of 10 µg m^{-3}.

The average mean $PM_{2.5}$ concentrations and source contributions during the winter season of Oct–Feb, over major states of India (see Figure 2). There is a large contribution from carbonaceous aerosol emission sources to wintertime $PM_{2.5}$ levels, ranging from 60–80% in northern India (Figure 2a) to 40–70% in peninsular India and the rest of India (Figure 2b and 2c). The dominance of carbonaceous aerosol source emissions in northern India arises from residential-biomass cooking/heating and agricultural residue burning. Thus, carbonaceous aerosol emission sources have a dominant influence on wintertime $PM_{2.5}$ levels, across most states of India.

Strategies for Future Mitigation

Ongoing air pollution mitigation programs in India include enhanced emission standards for coal-fired power generation,[24] including flue gas desulfurization and leapfrogging to low emission vehicles under the auto-fuel policy.[25] Further, India has made significant commitments to social welfare programs to provide increased access to residential clean energy for cooking/heating,[26] enabling substitutions from biomass stoves to liquefied petroleum gas to 80 million rural households by 2020 and from polluting kerosene wick lamps to clean solar lighting.[27]

Second, India is moving toward implementation of the National Clean Air Program (NCAP),[28] a comprehensive nationwide initiative, include expansion of air quality monitoring and implementing enforcement actions of city-level sources, including waste disposal and road or construction dust, specifically in identified non-attainment cities. Third,

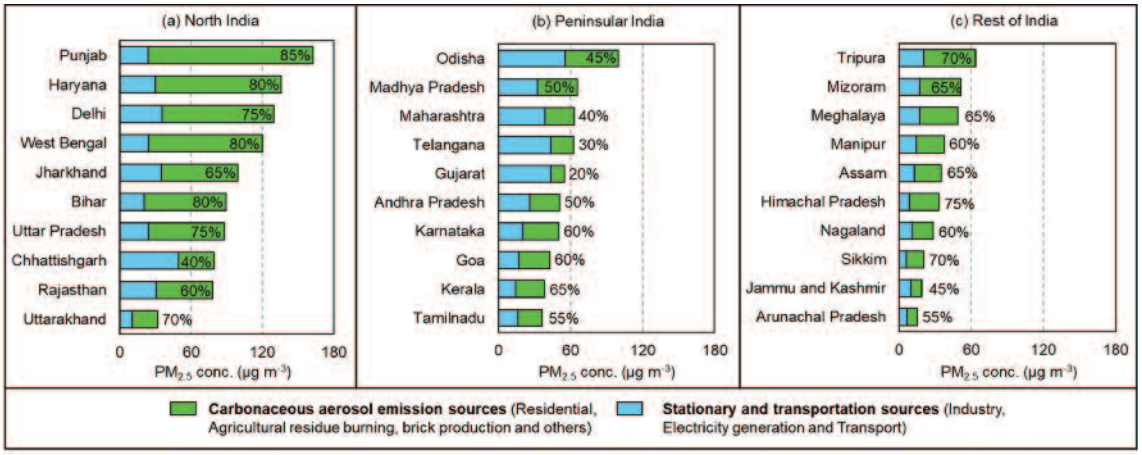

Figure 2. Winter-time $PM_{2.5}$ concentrations and percent contribution of carbonaceous aerosol emission sources for major states of India.

additional air-quality programs aim to curb emissions from agricultural residue burning,[29] through deep-sowing and mulching technologies and from brick production, through technology upgradation and emission standards for brick kilns.[30] Lastly, as a recent signatory of the Climate and Clean Air Coalition,[31] India would move toward an accounting of mitigation measures related to SLCPs.[32]

It is important to seek synergy in programs of concern to both air quality and near-term climate, to reap the largest co-benefits. India emissions of both primary $PM_{2.5}$ and SLCPs are evaluated (see Figure 3), using the SMoG-India-V1a[22] emission inventory, disaggregated by technologies and activities in all major sectors. The significance of emitting sectors of SLCPs, is evaluated in terms of net CO_2-eq emissions, of CH_4, CO, NOx, NMVOC, SO_2, BC, and OC from combustion sources, using their global warming potential (GWP-20) values,[33] which represent the ratio of the radiative impact of unit mass of a pollutant emitted to that of unit mass of CO_2 over a 20-year time horizon. Once again, carbonaceous aerosol emission sources, including residential, agricultural residue burning, and brick production (first three bars in Figure 3), dominate emissions of both primary $PM_{2.5}$ and SLCPs. Thus, emissions mitigation in these source-sectors is a crucial element in a portfolio of solutions to India's air quality and near-term climate concerns.

Summary

In addition to existing measures addressing industrial and transportation sources, mitigating carbonaceous aerosol emission sources is important to both India's air quality and near-term climate concerns. This has the additional potential to yield social welfare and sustainable development benefits. Achieving this requires explicit mechanisms for synergy among ongoing initiatives, coordinated by different ministries and tasked to different implementing agencies to reduce emissions. Importantly, national and state level climate change action plans must be coordinated with city level plans of the national

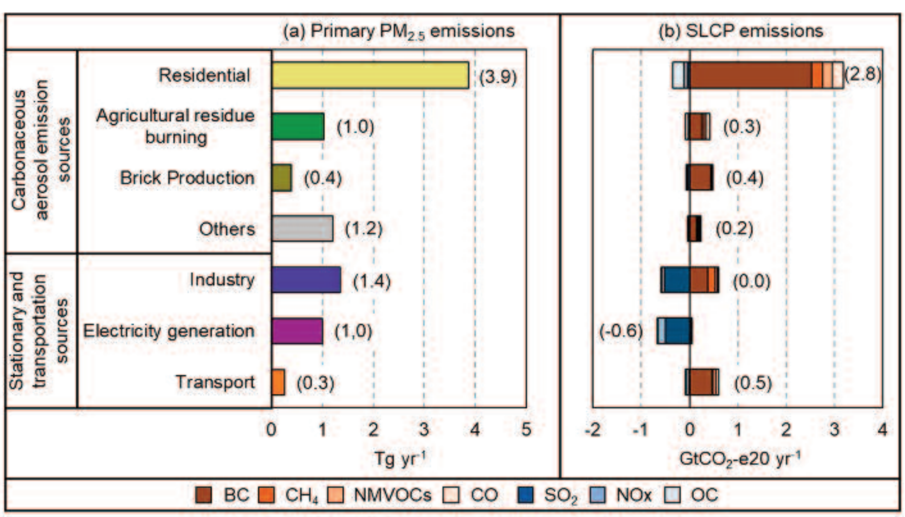

Figure 3. Estimated (2015) Indian sectoral emissions of (a) primary $PM_{2.5}$ and (b) short-lived climate pollutants (SLCPs).

clean air program. The implementation success of social welfare schemes delivering clean energy and the mitigation of agricultural residue burning, should be linked to an SLCP accounting and reporting framework, under climate action plans of the country. Bringing non-formal sectors like residential, agriculture and brick production under the joint purview of clean air and climate action is crucial to achieving air quality and near-term climate change amelioration in the Indian region. **em**

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Wintertime Air Quality in Dhaka, Bangladesh

A brief look at factors affecting Dhaka's air quality during winter.

The concentration of particulate matter (PM) in Bangladesh's capital Dhaka is significantly higher in winter than in summer showing a characteristic seasonality. Dhaka, the ninth largest megacity in the world,[1] faces severe winter air quality. The daily average concentration of fine PM ($PM_{2.5}$) reaches as high as 280 µg/m³ in January and February, exceeding the World Health Organization (WHO), the U.S. Environmental Protection Agency (EPA), and Bangladesh standards, as shown in Figure 1. This wintertime high PM concentration becomes a significant environmental and public health concern in Dhaka. The high PM concentration in winter also contributes to the formation of the regional haze (see Figure 2).

Megacity Dhaka

Dhaka currently has a population of 19 million and is on its way to being the fourth largest megacity (of 28 million people) by 2030.[1] Despite its unique environment-friendly emission characteristics, such as low stubble burning (see Figure 3), few coal-fired power plants (see Figure 4), and natural gas use in motor vehicles,[2] Dhaka's winter air quality is found to be "unhealthy" and ranked second worst among the measured $PM_{2.5}$ data at U.S. diplomatic posts in 29 cities around the world.[3] Dhaka's economy is growing fast with the turbo-charged Bangladesh economy with an 8% annual growth rate.[4] Dhaka's continuous urban growth[5] and ongoing mega construction projects[6] are directly and indirectly contributing to PM emissions from construction and brick kilns.

Dhaka's Winter Air Quality

PM concentrations are measured to be higher in winter than in summer.[2,7-9] Winter (Dec-Feb) in Dhaka is relatively dry and calm having low wind speed and lower planetary boundary layer height.[2,10] The wind directions in winter are typically from the North and Northwest.[8,10,11] The PM in winter in Dhaka comes from mainly three sources: brick kilns, motor vehicles, and road and soil dust.[8,12] The brick-kilns' contribution to $PM_{2.5}$ comes from three brick-kiln areas: Savar in the West, Gazipur in the North, and Narayanganj in the South.[13] The primary reasons for the increase of PM concentrations in winter are seasonal winter

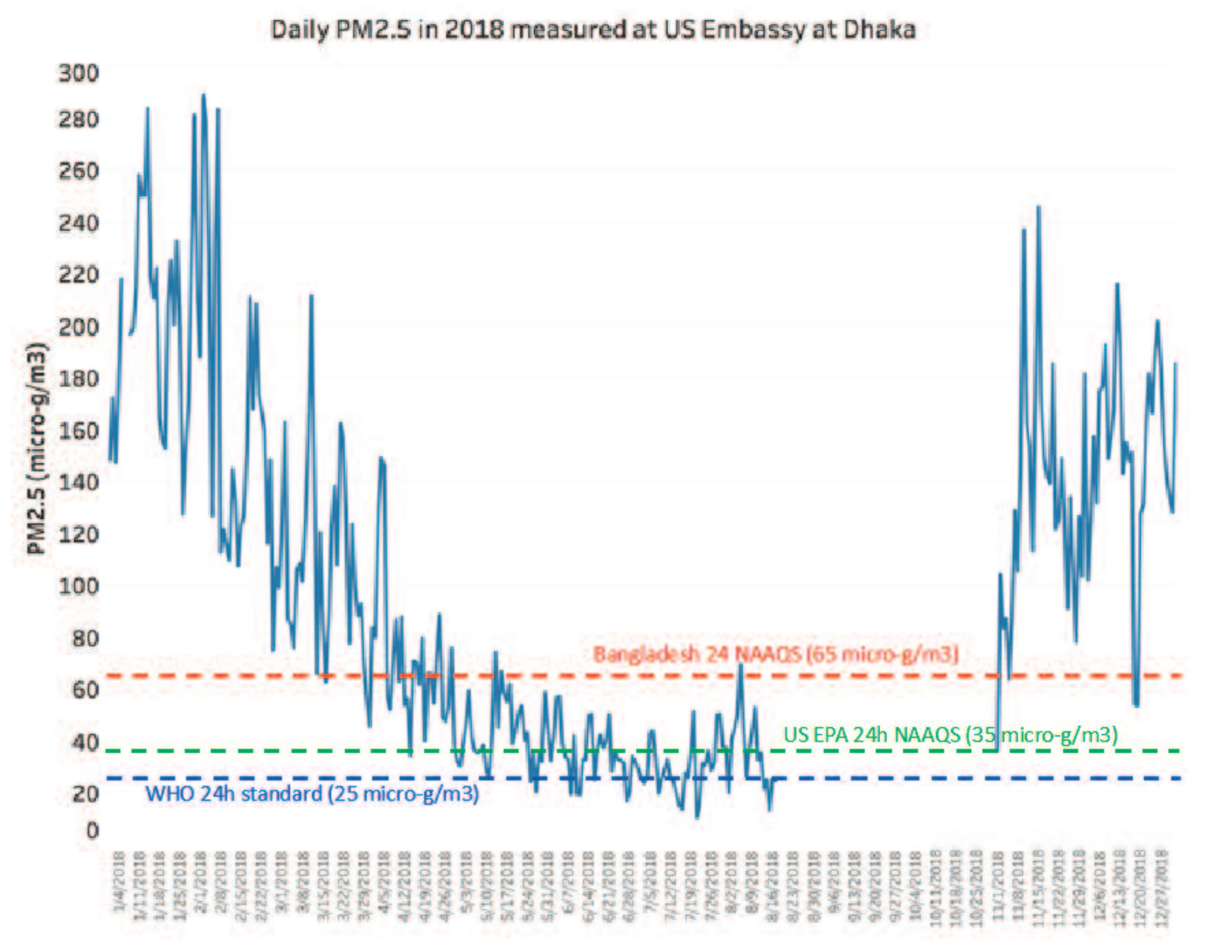

Figure 1. 2018 Daily $PM_{2.5}$ concentrations measured at the U.S. Embassy in Dhaka.
Source: www.airnow.gov/index.cfm?action=airnow.global_summary#Bangladesh$Dhaka

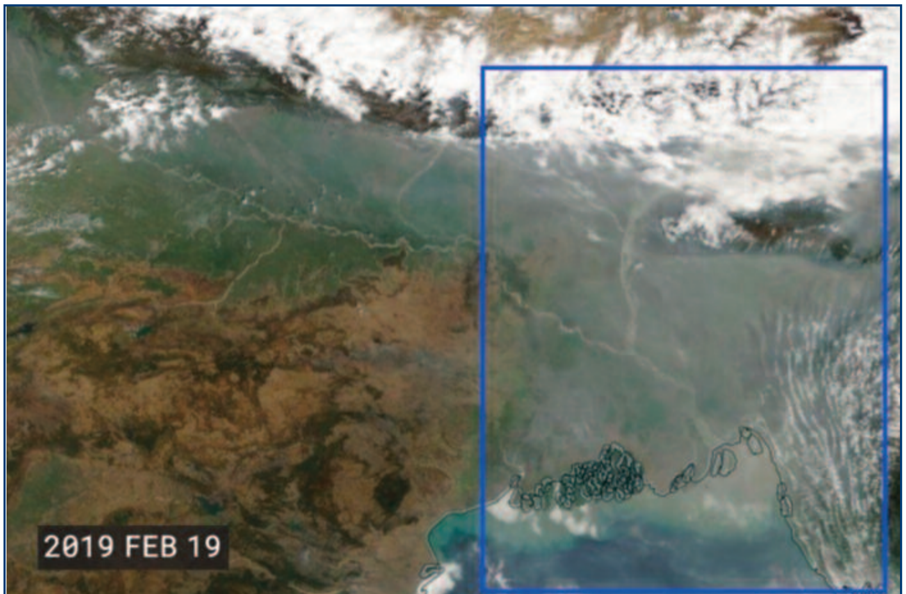

Figure 2. Winter haze over Bangladesh, February 19, 2019, visible via NASA's MODIS reflectance imagery from the Terra satellite (Bangladesh is highlighted in the blue rectangle).
Source: https://worldview.earthdata.nasa.gov/

operation of a 1,000 brick-kiln[14] surrounding Dhaka; increase in road and soil dust emissions caused by the higher construction activity and increased soil erosion in dry season, and reduced wet deposition in dry season; lower planetary boundary layer height during winter, which traps air pollutants leading to higher concentrations; low wind speed, which traps the pollutants at Dhaka; and trans-boundary transport through the Indo-Gangetic Plain (IGP) corridor from neighboring countries.[9,15] NASA's Aqua satellite's Moderate Resolution Imaging Spectroradiometer (MODIS) data reporting aerosol optical depth shows that aerosol is spread through the IGP corridor and some high aerosol concentration plume is entering Bangladesh from Northwest border in January (see Figure 5).

Bangladesh has had some recent successes in reducing emissions from brick kilns primarily through conversion of traditional high-emitting fixed chimney kilns into less-emitting zigzag kilns at some brick factories, where emissions have been reduced more than 50%.[2] Conversion to zigzag kilns needs careful consideration, as it increases carbon dioxide emissions,[16] which contribute to global warming through positive radiative forcing.

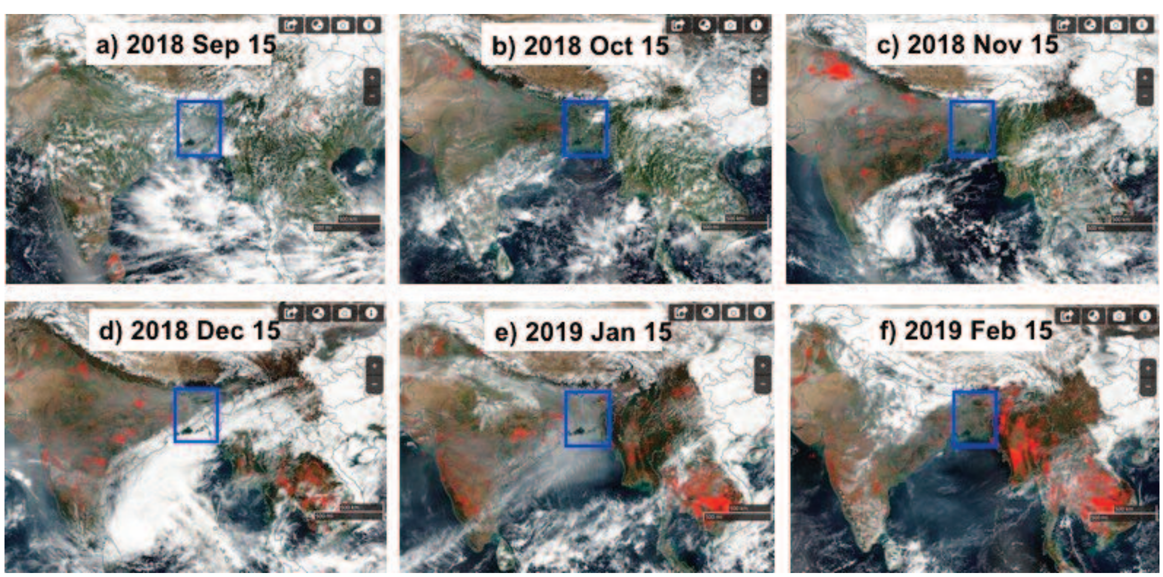

Figure 3. Bangladesh's stubble burnings (fewer red dots representing fewer fire counts in the blue rectangle) compared with other Asian countries recorded at 15th of each month, September 2018 to February 2019, via NASA's Aqua and Suomi-NPP satellites' active fire count data.
Source: https://worldview.earthdata.nasa.gov/

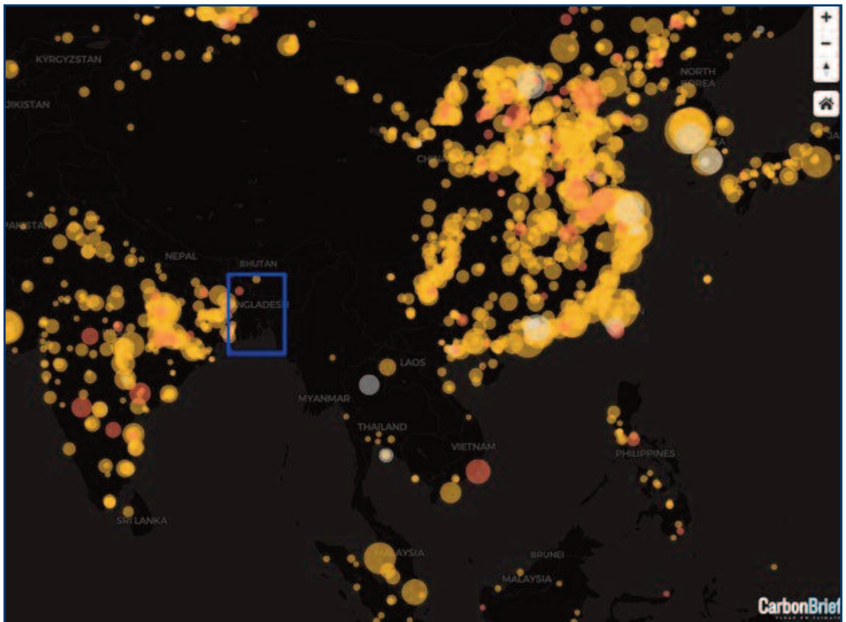

Figure 4. Coal-fired power plants in South and Southeast Asia, where Bangladesh is shown in blue rectangle.
Source: www.carbonbrief.org/mappedworlds-coal-power-plants

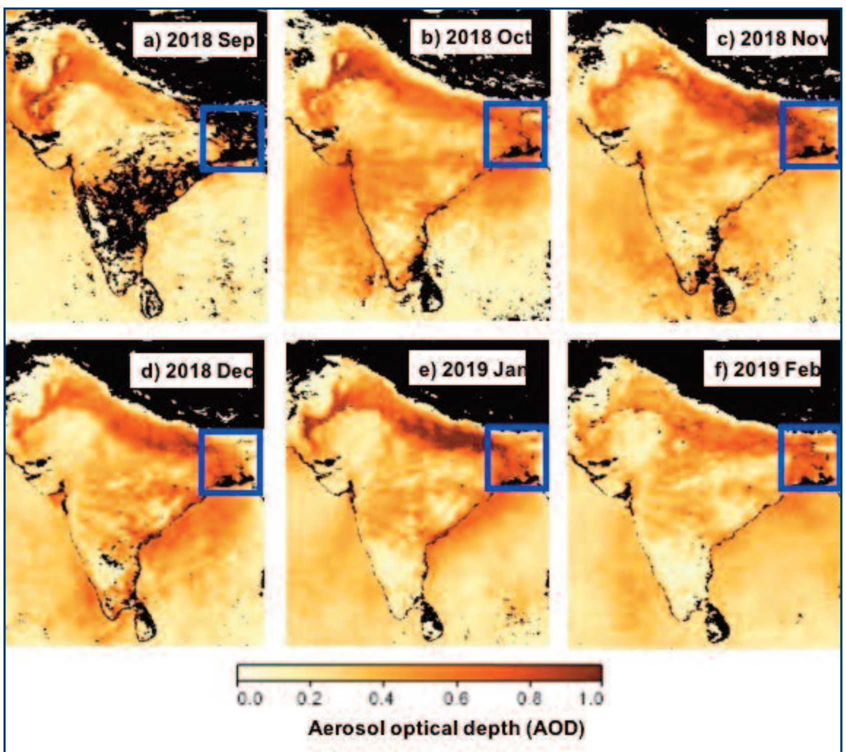

Figure 5. Aerosol optical depth over South Asia, 2018--2019, via NASA's Terra satellite's MODIS data.
Source: https://neo.sci.gsfc.nasa.gov/view.php?datasetId=MODAL2_M_AER_OD

Research Needs and Mitigation

Bangladesh needs both field campaign and modeling studies to better characterize the air pollution problem in Dhaka. Bangladesh does not have a detailed high spatial-and-time resolution emission inventory for air pollutants for all of the emission sectors. Currently, a 3x3-km emission inventory exists for Dhaka for traffic, road dust, and brick kiln emissions.[17] Because Bangladesh is a densely populated country, any high-resolution emission inventory would be beneficial to air quality modeling and health effect study capturing better spatial variability.

To improve the air quality modeling capability, Bangladesh needs to develop a state-of-the-art high-resolution emissions inventory for air quality modeling. One idea for developing a finer-resolution, more comprehensive inventory is to explore whether Bangladesh government's "Access to information (a2i)" web portal[18] can be used to make a nationwide emission inventory for all sectors. The air quality modeling capability in Bangladesh can also be improved through use of some open-source models, including a meteorology model (e.g., Weather Research and Forecasting Model [WRF]);[19] an emissions processing model (e.g., Sparse Matrix Operator Kernel Emissions [SMOKE]);[20] a chemical transport model (e.g., Community Multiscale Air Quality Model [CMAQ]);[21] and a dispersion model (e.g., AMS/EPA Regulatory Model [AERMOD]).[22]

As PM composition and secondary PM formation data are scarce for Dhaka, a full measurement campaign and additional modeling of PM composition are recommended. The government should intervene to reduce emissions from brick kilns and soil and road dust to reduce PM concentrations in winter in Dhaka, while preserving existing beneficial environmental practices. **em**

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Wintertime $PM_{2.5}$ Pollution in California

by Jeremy Avise, Jianjun Chen, Kasia Turkiewicz, John DaMassa, and Sylvia Vanderspek

A brief discussion on the nature of wintertime elevated fine particulate matter concentrations in four regions of California.

Since the early 2000s, significant progress has been achieved in reducing ambient fine particulate matter ($PM_{2.5}$) concentrations throughout California (see Figure 1). However, despite the reductions in emissions of direct $PM_{2.5}$ and precursors (i.e., pollutants that can react in the atmosphere to form $PM_{2.5}$) that were responsible for this progress (see Figure 2), wintertime $PM_{2.5}$ continues to be an issue in several areas within the state.

Specifically, the San Joaquin Valley (SJV), Plumas County (Portola), Imperial County (Calexico), and the South Coast (SC) all experience elevated $PM_{2.5}$ levels during winter months, and are designated as non-attainment areas for the 2006 24-hr and/or 2012 annual U.S. National Ambient Air Quality Standard (NAAQS) for $PM_{2.5}$ of 35 µg/m³ and 12 µg/m³, respectively (see Figure 3).

It is these elevated wintertime $PM_{2.5}$ concentrations that drive exceedance of both the 24-hr and annual standards in California. Reducing wintertime $PM_{2.5}$ in each of these regions is critical to protecting human health, and presents unique challenges due to differing topographical features and meteorological influences, as well as emission sources and activity patterns that contribute to elevated $PM_{2.5}$ during winter months. A brief discussion on the nature of the wintertime $PM_{2.5}$ in each of these regions follows.

Wintertime $PM_{2.5}$ in California

San Joaquin Valley

The SJV region covers the southern half of California's Central Valley, and is home to approximately 4 million residents, with the majority of the population residing in the larger urban areas within the cities of Bakersfield, Fresno, Modesto, and Stockton. The valley is surrounded by mountain ranges to the south (Tehachapi Mountains), east (Sierra Nevada range), and west (Coastal range), which serve to trap pollution within the valley, allowing for significant buildup of pollution over multi-day episodes. The worst $PM_{2.5}$ air quality within the SJV region occurs in the central and southern portions of the valley near the Fresno and Bakersfield urban centers, respectively, where geography, meteorology, and the interaction between urban (e.g., on-road mobile, cooking, residential wood burning) and rural (e.g., off-road mobile, dairies, animal feedlots, fertilizer) emission sources results in wintertime $PM_{2.5}$ that is primarily comprised of ammonium nitrate (~40%), formed through complex chemical reactions involving ammonia (NH_3) and nitrogen oxides (NOx), and directly emitted organic matter (~45%; see Figure 4a), and which represents some of the highest ambient $PM_{2.5}$ levels in the United States. The abundance of NH_3 emissions from agricultural activities in the SJV region, means that reducing ammonium nitrate levels is most efficiently done through controls on NOx emissions as opposed to NH_3 emissions.[1]

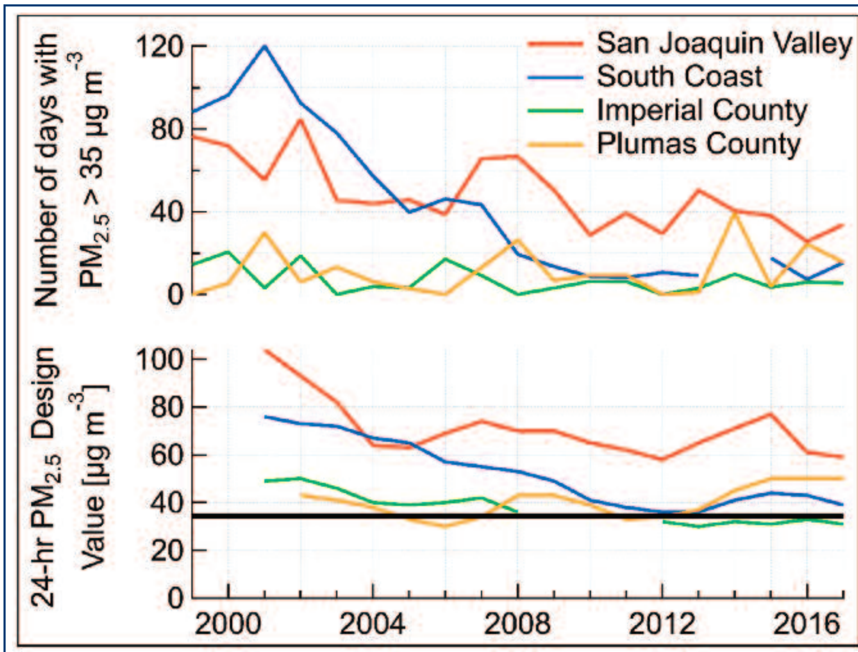

Figure 1. Trends in ambient $PM_{2.5}$ for the four $PM_{2.5}$ nonattainment regions in California. Number of days with $PM_{2.5}$ exceeding 35 µg m^{-3} represents the total number of days across all monitors within the nonattainment region. Design value represents the three-year average of the 98th percentile 24-hr $PM_{2.5}$ concentration.

Plumas County (Portola)

The city of Portola and its surrounding region are located in an intermountain basin on the leeward side of the Sierra Nevada mountain range in northern California. Although the population of Portola is small (~2,100 residents), the local topography and strong wintertime temperature inversions create a shallow surface layer, which traps pollution within the basin. Residents in the Portola region typically burn wood for heat, which results in $PM_{2.5}$ that is predominantly composed of organic matter (~85%; see Figure 4b). Overnight and during the early morning hours, as the surface temperature inversion settles over the basin, the local emissions from wood stoves and fireplaces are trapped within the shallow surface layer leading to a buildup of $PM_{2.5}$ to levels that consistently exceed the 24-hr $PM_{2.5}$ standard.[2]

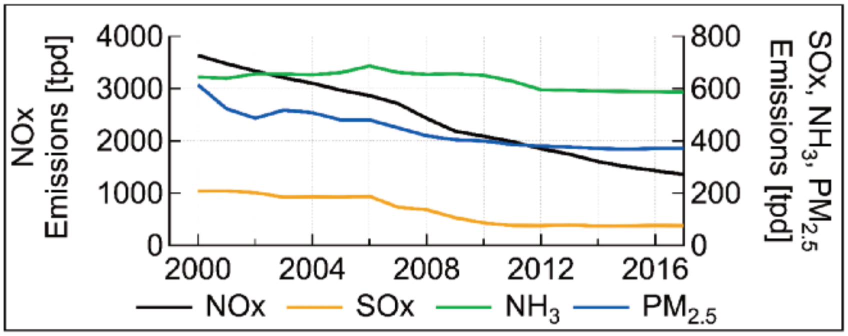

Figure 2. California statewide wintertime (January–March; October–December) emissions trends.

Imperial County (Calexico)

The city of Calexico is located along the border between the United States and Mexico, and shares the border with the densely populated city of Mexicali, Mexico. The region includes a major port of entry into the United States, as well as robust farming operations. Analysis of the $PM_{2.5}$ composition and air mass trajectories along the border, coupled with photochemical modeling, suggest that a large fraction of the $PM_{2.5}$ in Calexico is transported from upwind sources in Mexicali.[3,4] Directly emitted $PM_{2.5}$ organic matter from sources such as off-road vehicles, farming operations, managed burning, and residential wood burning contribute the most to wintertime $PM_{2.5}$ (~45%), followed by inorganic aerosols (ammonium–nitrate and ammonium–sulfate), which make up an additional ~25% (see Figure 4c). Unique to Calexico is a significant presence of elemental species, which contribute about 8% to the wintertime $PM_{2.5}$, and originate from poorly controlled industrial sources and burning of refuse in Mexicali.

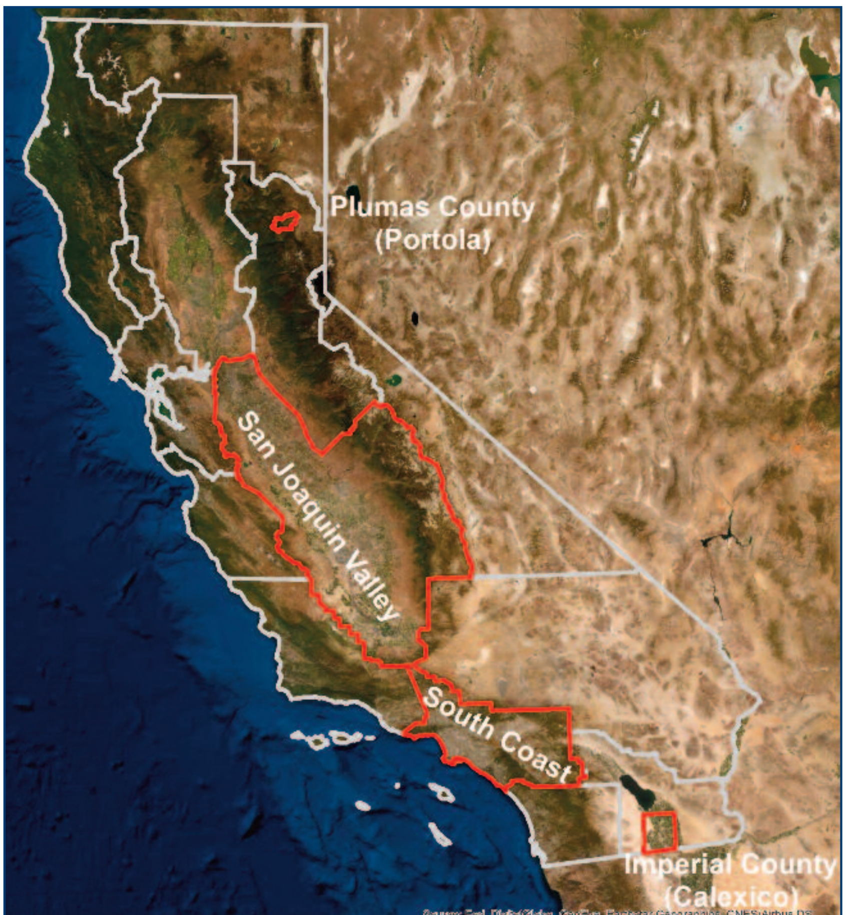

Figure 3. Non-attainment regions in California (outlined in red) for the 2006 and/or 2012 $PM_{2.5}$ standards. California air basins are outlined in gray.

South Coast

The South Coast (SC) air basin is home to over 16 million people and includes the two largest shipping ports in the United States, the Ports of Los Angeles and Long Beach. The basin is surrounded by mountain ranges on three sides, with the Transverse Ranges to the north and east, and the Peninsular Ranges to the southeast, with the Pacific Ocean to the west. The SC topography, when combined with the warm air masses that frequently descend over the cool, moist marine layer, serves to trap emissions near the surface, and the abundant sunlight then kick starts the photochemical reactions that produce much of the $PM_{2.5}$ pollution. This results in wintertime $PM_{2.5}$ that is comprised primarily of ammonium nitrate (~35%) formed in the atmosphere from the chemical interaction between motor vehicle NOx emissions and NH_3 from sources such as landfills, industrial processes, farming operations, motor vehicles, and household activities. The remaining $PM_{2.5}$ is comprised primarily of organic matter (~35%), which is directly emitted from sources such as residential fuel combustion, cooking, motor vehicles, and

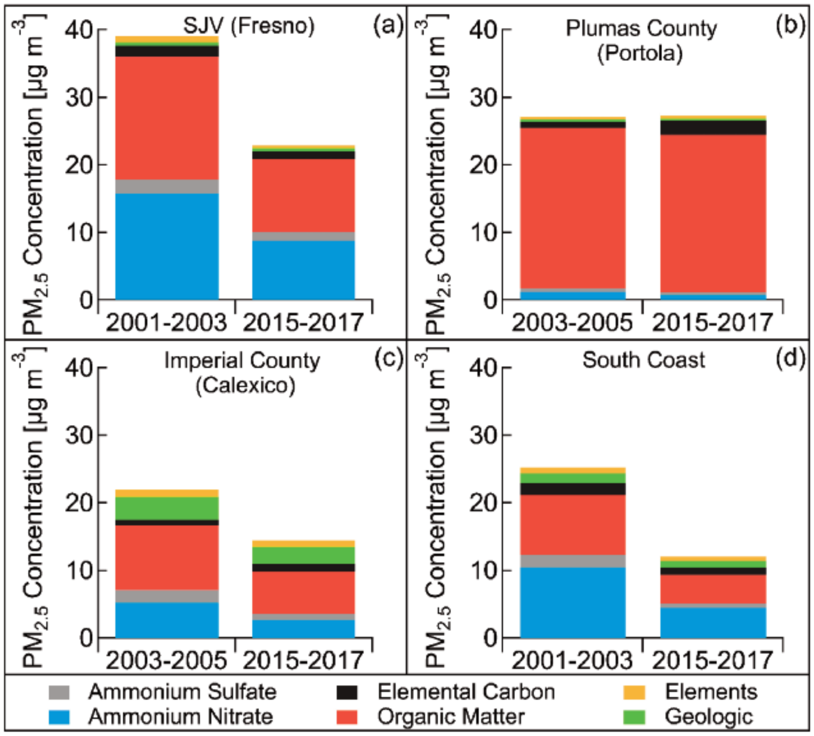

Figure 4. Change in average wintertime (January–February; November–December) $PM_{2.5}$ composition. SJV (Fresno) and South Coast represent changes from 2001–2003 to 2015–2017, while Plumas County (Portola) and Imperial County (Calexico) represent changes from 2003–2005 to 2015–2017. South Coast composition represents an average of the Los Angeles Main Street and Riverside monitors.

various stationary sources (see Figure 4d). In contrast to the SJV region, NH_3 emissions in the SC region are sufficiently low such that NH_3 controls will reduce ammonium nitrate levels; however, the level of NOx reductions needed to attain the ozone standards are, by themselves, sufficient to reduce ammonium nitrate to levels needed to attain the $PM_{2.5}$ standards.[5]

Reducing Wintertime $PM_{2.5}$

The unique nature of wintertime $PM_{2.5}$ within these four regions requires a multifaceted approach to developing policies across differing time scales that will lead to improved wintertime air quality in each region, and ultimately to attainment of the National Ambient Air Quality Standards (NAAQS) for $PM_{2.5}$. Specifically, the California Air Resources Board's (CARB) approach focuses on three key policy areas:

1. Transformation of the vehicle and truck fleets to low- or zero-emission vehicles;
2. Moving away from wood burning to cleaner heating sources; and
3. Fostering partnerships both internationally and with local air districts.

Although improving wintertime $PM_{2.5}$ will require emission reductions across other sectors, and particularly those with direct $PM_{2.5}$ emissions, these three policy areas are likely the most critical to attaining the $PM_{2.5}$ NAAQS in California.

Advanced Clean Cars and Trucks

The level of NOx emission reductions needed to attain the NAAQS for $PM_{2.5}$ and ozone (O_3) in California[1,5] requires a transformation of the vehicle fleet to Low-Emission Vehicles (LEVs) and Zero-Emission Vehicles (ZEVs). The LEV program began in 1990, requiring automobile manufacturers to introduce progressively cleaner vehicles with more robust emission controls. The LEV program was expanded in 1998 (LEV II) and again in 2012 (LEV III) as part of the Advanced Clean Cars rulemaking package, which also included regulations requiring manufacturers to produce a specified number of ZEVs and plug-in hybrids each year. From 1993 (the last year prior to the implementation of the LEV regulations) to 2019, NOx emissions from light- and medium-duty (i.e., passenger vehicles) declined by over 90%, due in large part to the LEV regulations, and despite a 25% increase in population. In future years, the LEV and ZEV programs will continue to provide emission reductions through vehicle fleet turnover, but a greater emphasis will need to be placed on the Advanced Clean Trucks program, with an initial focus on introducing zero-emission technology to truck fleets operating in urban centers.

Cleaner Heating Sources

In 2017, California Senate Bill 563 (SB-563) established the Woodsmoke Reduction Program (https://www.arb.ca.gov/planning/sip/woodsmoke/reduction_program.htm), which was designed to promote the voluntary replacement of old wood burning stoves with cleaner, more efficient alternatives. Under the Program, CARB coordinates with air districts to provide financial incentives for replacing older, less efficient, uncertified wood-burning devices, such as woodstoves and wood inserts, with cleaner burning, more efficient home heating alternatives, such as heat pumps and solar, electric, and natural gas heaters, as well as certified woodstoves when the non-wood burning alternatives are not feasible or are cost prohibitive. This statewide program builds off of previously established local air district programs, such as the

Burn Cleaner fireplace and woodstove change-out program established by the San Joaquin Valley Air Pollution Control District (SJVAPCD). Since 2009, SJVAPCD's Burn Cleaner program has issued over 16,600 vouchers to install cleaner heating devices in residential homes, with roughly 80% of those vouchers for gas replacement devices, and a total of over US$24 million in allocated funding to date (see list of funded projects; http://valleyair.org/grants/documents/List-of-Projects-Funded-10-years.pdf).[6]

In addition to the state and local incentive programs, local rules, such as those implemented by SJVAPCD (e.g., District Rule 4901 (http://www.valleyair.org/Rule4901/), limiting wood burning activities on days when $PM_{2.5}$ levels are forecasted to reach unhealthy levels are also a critical component of the comprehensive regulatory control program needed to reduce woodsmoke impacts on air quality. However, the efficacy of these programs is largely contingent on both community outreach and enforcement, which can be more difficult to implement given the nature of the source and activity.

Partnerships

Strengthening existing partnerships with local air districts, as well as federal and international partners, is critical to further reducing wintertime $PM_{2.5}$ in California. Within the state, CARB has a long history of partnering with local air districts to reduce emissions through such programs as the Goods Movement Emission Reduction Program, which began in 2006 with the passage of Proposition 1B and continues to this day. More recently, in response to Assembly Bill 617 (C. Garcia, Chapter 136, Statutes of 2017), CARB established the Community Air Protection Program (CAPP; https://ww2.arb.ca.gov/our-work/programs/community-air-protection-program), which is focused on reducing pollution exposure in communities most impacted by air pollution, and includes local community air monitoring and emission reduction programs, as well as targeted incentive funding to deploy cleaner technologies in these communities. In 2018, the CAPP selected 10 communities for initial participation in the program, including communities in the South Coast, San Joaquin Valley, and Imperial County, and will expand the list of communities in future years.

Internationally, CARB is engaged in various memorandums of understanding with other air quality agencies, cities, and federal governments to collaborate and learn from CARB's experience in implementing and enforcing emission controls across a variety of emission sources. More direct collaboration is occurring between CARB and the Mexico government as part of a joint, two-year study of particulate matter in Mexicali, Mexico to better understand the nature and sources of $PM_{2.5}$, which contribute to the poor air quality locally in Mexicali, as well as downwind across the border into Calexico.

Summary

Although California has made tremendous gains in reducing $PM_{2.5}$ over the past decades, there is still much work to be done, with multiple regions in nonattainment of the $PM_{2.5}$ NAAQS. Despite a substantial reduction in wintertime $PM_{2.5}$ in most regions, the main emissions sources contributing to wintertime $PM_{2.5}$ and the composition of $PM_{2.5}$ remain much the same from the early 2000s (Figure 4). Further reducing wintertime $PM_{2.5}$ will require a continued focus on California's mobile source strategy through a committed shift toward low- and zero-emission vehicle technologies, taking actions to strengthen direct $PM_{2.5}$ emissions controls, and focused local and international partnerships, which will place the state in a strong position to achieve its long-term air quality goals and ensure that all communities within California breathe cleaner air. **em**

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Recent Research Directions in U.S. Winter Air Quality:

Progress and Challenges

An overview of research efforts that focus on winter air quality, an important issue in the United States and elsewhere.

Fine particulate matter (particulate matter with dimeter less than 2.5 microns; $PM_{2.5}$) is an important worldwide health and air quality issue.[1] Recent dramatic decreases in emissions of major air pollutants have resulted in significant reductions in $PM_{2.5}$ mass across the United States. Annual emissions of sulfur dioxide (SO_2) have decreased by over 90% since 1990, while nitrogen oxides ($NOx = NO + NO_2$) and volatile organic compounds (VOCs) have fallen by 60% and over 30%, respectively.[2] At the same time, however, the seasonality of U.S. $PM_{2.5}$ has shifted. Urban areas exhibit both a summer and a winter maximum in $PM_{2.5}$, but since the year 2000 the summer maximum has declined while the winter maximum has remained relatively constant, leading to higher average levels of $PM_{2.5}$ in winter than summer.[3] Chemical speciation of $PM_{2.5}$ shows nationwide declines in sulfate during the summer, but lesser or negligible declines in nitrate and organic carbon that are more prevalent during winter, particularly in the western United States. Similar trends are apparent in other regions with recently declining emissions (e.g., Eastern China).[4]

This summer to winter shift in U.S. $PM_{2.5}$ with declining emissions suggests complex changes in atmospheric chemical mechanisms that convert precursor gases into secondary PM. For example, while SO_2 reductions lead to overall reductions in sulfate, they may also lead to unintended increases in nitrate due to the replacement of sulfate by nitrate at relatively constant ammonia levels, an effect that is pronounced in winter. Emissions changes also lead to responses in the availability of oxidants that may actually increase oxidation rates even as levels of precursor gases decline. For example, recent models suggest that heterogeneous (i.e., gas to particle or droplet reactions) sulfur oxidation has increased during winter. Oxidation of NOx occurs through both gas phase and heterogeneous mechanisms that are known to be strong, non-linear functions of the NOx emissions themselves. Winter oxidation rates of VOCs leading to particulate organic carbon remain poorly defined but may be regionally significant.

Although the national trend in $PM_{2.5}$ emissions and response is clear, winter air quality issues also remain region-specific and responsive to local emission sources. For example, Fairbanks, Alaska is well known for high winter $PM_{2.5}$ likely resulting from a combination of residential wood combustion and heating oil use. Contrasting to Fairbanks is Salt Lake City, Utah, which has high winter ammonium nitrate resulting from a combination of urban and agricultural emissions in confined valleys. Denver, Colorado suffers from winter haze that is similar in composition and origin to that of Salt Lake City, but that does not currently exceed regulatory standards. California's San Joaquin Valley (SJV) has severe winter $PM_{2.5}$ resulting from widespread agricultural emissions and a collection of smaller urban areas. Emissions of VOCs from the oil and gas industries have led to recent, unusual events of high wintertime ozone in sparsely populated mountain basins of Utah and Wyoming. The northeastern United States has winter $PM_{2.5}$ that is generally below regulatory standards but due to a mix of mobile source, home heating, electric power generation and agricultural emissions across a wide region. The midwestern United States suffers from periodic episodes of ammonium nitrate during cold periods.

Common to all of these regional $PM_{2.5}$ issues is winter meteorology, characterized by generally shallow boundary layers that confine surface level emissions in a more concentrated layer near the surface than is typical in summer. This effect is particularly pronounced in the western United States, where meteorological inversions below the confining terrain of mountain basins lead to multi-day stagnation events known as persistent cold air pools (PCAPs). The interaction between boundary layer meteorology, emission sources and atmospheric chemical cycles is extremely complex. Mixing of surface level emissions throughout the boundary layer during daytime is weaker and shorter in duration, and vertical stratification from early evening through mid-morning leads to differences in conversion rates of precursor gases to secondary pollutants as a function of height. These effects are particularly important for ammonium nitrate, a common component of winter $PM_{2.5}$.

Measurement of chemical composition as a function of height above ground are important to understanding these interactions between atmospheric chemistry and meteorology. Field intensives with highly instrumented aircraft provide the most detailed characterization of these processes but are expensive and difficult to carry out. A particular challenge is the requirement for sustained low altitude flights in the range characteristic of winter boundary layers from 150–800 m (~500–2,500 feet) above ground level.

Several recent aircraft-based field intensives have investigated

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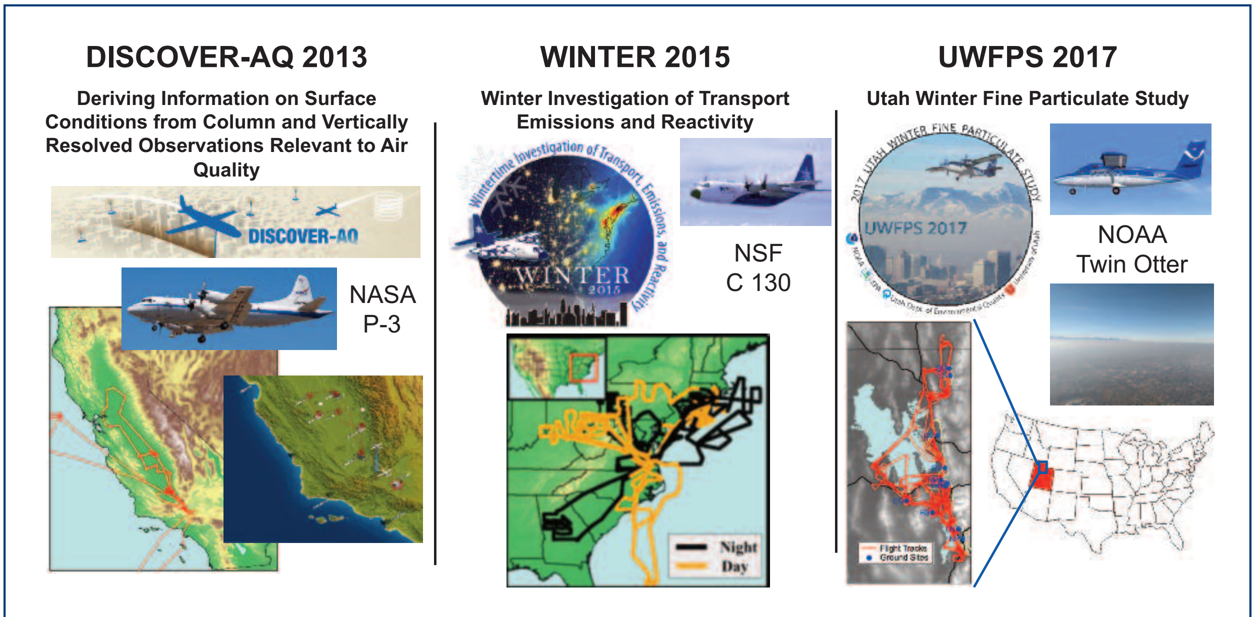

Figure 1. Overview of recent aircraft-based winter field intensives in the United States.

winter atmospheric chemistry and air quality in the United States, as Figure 1 illustrates. The DISCOVER-AQ campaign (Deriving Information on Surface Conditions from Column and Vertically Resolved Observations Relevant to Air Quality) used the National Aeronautics and Space Administration (NASA) P-3 aircraft to investigate air quality in the SJV region of California during January–February 2013. The sampling strategy included daytime flights with a repeated flight pattern that incorporated vertical profiles from 3,000 m to the surface using low approaches at airfields. Major findings demonstrated the response of $PM_{2.5}$ to decreasing NOx emissions and suggested that declining NOx will shift the mechanism for ammonium nitrate production from nighttime to daytime dominated.[5,6]

The WINTER campaign (Wintertime Investigation of Emissions, Transport and Reactivity) surveyed the eastern United States with the heavily instrumented NCAR/NSF C-130 aircraft during February–March 2015. Flights sampled a wide region, from the Ohio River Valley to the waters off the coast of New England, and as far south as Atlanta, Georgia and coastal Florida. Flights were evenly distributed between nighttime and daytime, with 70% of the ~100 research flight hours in the boundary layer below 1-km altitude. Major findings showed that wintertime emissions inventories, particularly for NOx, appear to be accurate,[7] that chemical mechanisms for nighttime NOx oxidation and halogen activation are not well represented in models[8] and that winter organic aerosol is widespread.[9]

The UWFPS campaign (Utah Winter Fine Particulate Study) investigated the factors governing high levels of $PM_{2.5}$ in the mountain basins of northern Utah during January–February 2015. The study utilized the much smaller National Oceanic and Atmospheric Administration (NOAA) Twin Otter, which executed 23 separate short (~3 hour) research flights during both daytime and nighttime, sampling an altitude range from the surface (~1,300 m at Salt Lake City) through approximately 4,000 m with a limited chemical payload. Major findings showed that the region as a whole is primarily nitrate limited but that ammonia limitation may be important in the urban area of Salt Lake City.[10] A NOx–VOC analysis that is more typically used in the analysis of summertime ozone showed that initial VOC control may be a more effective s trategy for reducing $PM_{2.5}$ than NOx control.[11]

Despite these recent field intensives, multiple scientific questions remain. These include the emission sources most relevant to winter $PM_{2.5}$ as overall precursor emissions continue to decline, the resulting response of chemical mechanisms for production of secondary sulfate, nitrate and organic carbon and improved measurement and modeling of wintertime boundary layer meteorology. Future field intensives are currently in the planning stages to address these issues. The forthcoming ALPACA study (Alaskan Pollution and Chemical Analysis; https://alpaca.community.uaf.edu), currently planned for the winter of 2020–2021, will provide the first chemically detailed investigation of pollution events in that area. The AQUARIUS study (Air Quality Research in the western United States; https://www.atmos.utah.edu/aquarius/index.php) is in early stages of planning to provide both aircraft and ground based measurements of mountain basins subject to cold pool meteorology and air quality issues across the western United States, with a focus on the exceedance areas in the San Joaquin Valley and Salt Lake City regions. The tentative time frame for this study is the winter of 2022–2023.

Winter air quality continues to be an important issue in the

United States and other nations. Domestic and international research efforts focused on this problem are intended to provide improved scientific understanding of the relevant emissions, chemical transformations and boundary layer meteorology that are specific to winter. These efforts are taking place against a backdrop of rapidly changing emissions in the United States, Europe, and Asia, illustrating the global context of these regionally focused field studies. **em**

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'Those who ignore history are bound to repeat it.'

A look back at this month 15 years ago in *EM* Magazine: December 2004.


IN THIS ISSUE

Features

COLUMNS

DEPARTMENTS

The December 2004 issue of *EM* discussed the use of coal gasification coupled with integrated gasification combined cycle (IGCC) technology as an alternative method to generate electricity. In an IGCC system, a gasifier converts coal into synthetic gas, which is used as fuel for a gas turbine equipped with a heat recovery steam generator. Because air pollutants can be removed before the synthetic gas is fed into the turbine, emissions from IGCC plants are typically much lower than those of traditional pulverized coal plants. Furthermore, IGCC enables carbon capture and sequestration at lower costs than traditional power plants. The integration of coal gasification and IGCC technologies was the subject of three articles in the December issue.

In the article, **The Case for Gasification**, by Gary J. Stiegel and Massood Ramezan, the authors took an in-depth look at the U.S. Department of Energy's gasification program and built a case for the technology's role in meeting the demands of growing energy markets.

Quoting from the article: "In today's business environment, markets and market drivers are changing at a rapid pace. Environmental performance is a much greater factor for U.S. industry now than in previous years as emission standards tighten and market growth occurs in areas where total allowable emissions are capped. In addition, the reduction of carbon emissions is one of the major challenges facing industry in response to global climate change. To help meet these challenges, there is a need for more environmentally sound, flexible, efficient, and reliable systems, while still meeting the ever-present demand for increased profitability. Gasification is one technology that is poised to meet these requirements."

Elsewhere in this issue, Clifford M. Olson considered the business opportunities in selling industrial wastes in **Waste Not: A Business Strategy for Selling Manufacturing Wastes**. Manufacturing facilities generally regard "waste" as a cost of doing business. DuPont Surfaces was no exception until the company developed a nine-step program to market and sell its waste as byproducts and realized that an annual return of more than US$1 million was possible from the sale of routinely generated wastes.

Quoting from the article: "For other businesses to duplicate DuPont's success, it is recommended that they adapt the lessons that DuPont Surfaces has learned. Most important, businesses should realize that there is great potential in re-directing waste materials from landfill disposal to sale. But it takes a commitment from management and a dedicated person (familiar with operations and sales) to oversee the process using a systematic approach to blend an entirely new business into an existing manufacturing operation."

Maintaining a waste theme, in **Waste 101—"Let's Talk About RCRA"** Terry Polen presented what was the first in a series of columns published over the course of year looking at the issues surrounding hazardous waste management, with emphasis on the Resource Conservation and Recovery Act (RCRA).

Quoting from the article: "These columns are not intended as a comprehensive review of RCRA, but more of a primer. Future topics will include more detail on hazardous waste, solid waste, underground storage tanks, special waste, universal waste, and medical waste, among other topics. These are issues and topics that many of you have to deal with daily, and I hope these columns will be of some help in your efforts. As we move through RCRA topics, we will continue to include related issues such as waste minimization, pollution prevention, federal and state waste regulations and requirements, and individual source types and categories (e.g., auto body shops, print shops). In this initial installment, however, we are just trying to get our arms around RCRA (how long are your arms?)." **em**

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