EXECUTIVE SUMMARY

Particulate Matter Science for Policy Makers: A NARSTO Assessment was commissioned by NARSTO, a cooperative public-private sector organization of Canada, Mexico and the United States. It is a concise and comprehensive discussion of the current understanding of airborne particulate matter (PM) among atmospheric scientists.[1] Its goal is to provide policy makers who implement air-quality standards with this relevant and needed scientific information. Policy development and revision is an ongoing process, and scientific understanding is continually improving. This assessment describes current science in a manner that reflects the needs of policy makers in addressing current and anticipated standards.

This assessment is organized using the following considerations for dealing with air-quality issues:

- Perspective for Managing PM
- Health Effects Context
- Atmospheric Aerosol Processes
- Emission Characterization
- Particle and Gas Measurements
- Spatial and Temporal Characterization of PM
- Receptor Methods
- Chemical Transport Models
- Visibility and Radiative Balance Effects.

Conceptual models of PM for nine geographic regions in North America illustrate the application of these considerations for developing management strategies.

This **Executive Summary** condenses the current understanding of the PM problem, focusing on the following key topics:

- $PM_{2.5}$ responses to changes in emissions
- Local, regional, and continental management
- Predictive capabilities
- Copollutant interactions
- Improved measurement tools
- Links with health-effect and climate-change studies
- Tracking success of air-quality management.

The **Synthesis** following this Executive Summary answers specific policy questions, developed through interviews with policy makers, with summary information from this assessment.

$PM_{2.5}$ MASS AND COMPOSITION RESPONSES TO CHANGING EMISSIONS

Ambient $PM_{2.5}$ results from direct particle emissions (carbon and soil dust, for example) and secondary particles (generated by atmospheric reactions of precursor gas emissions). Ambient PM is also influenced by meteorology. The major precursor gases are sulfur dioxide (SO_2), nitrogen oxides (NO_x), ammonia (NH_3), and volatile organic compounds (VOCs). Ambient PM mass is thus a mixture composed mostly of sulfate ($SO_4^=$), nitrate (NO_3^-), ammonium (NH_4^+), organic carbon (OC), black carbon (BC), and soil dust.

The relative mass fractions of secondary PM can change in a nonlinear manner with changing precursors owing to the complex chemistry of secondary PM formation. As SO_2 emissions decline, so will particulate $SO_4^=$ concentrations. The presence of NH_3 allows the formation of ammonium nitrate (NH_4NO_3) and ammonium sulfate [$(NH_4)_2SO_4$]. As $SO_4^=$ is removed, more NH_4NO_3 can be formed, provided sufficient NH_3 and nitric acid (HNO_3) are present. Consequently, the response of particulate NO_3^- to changing NO_x or VOCs is less clear, as it depends upon the amount of NH_4^+ and $SO_4^=$ present in particles in addition to VOC- or NO_x-limiting processes. In most locations, insufficient information exists on both emissions and ambient levels of NH_3 to predict how particle mass and composition would change in response to changing NH_3 emissions.

[1] The major emphasis of this assessment is on fine particles ($PM_{2.5}$), although larger particle sizes (PM_{10} and $PM_{10-2.5}$) are discussed.

The BC fraction will decrease in direct response to reductions in source emissions from, for example, diesel combustion. The OC fraction stems from both direct emissions of organic PM and the oxidation and polymerization of VOC emissions. Consequently, the extent to which the organic fraction may be managed depends upon both direct OC emissions and the attendant occurrence of oxidants and acids. As the particle-forming VOCs, acids, and oxidants decrease, so would the secondary OC fraction. Considerable uncertainty exists about the chemical composition of organic carbon particles, both at the source and in the atmosphere. Individual organic-carbon species are not measured routinely. Thus, explaining the response of the OC fraction of PM to changing precursor emissions is in its very early stages.

What we know and expect…

Based upon current understanding of secondary particle formation, it is anticipated that the existing management strategies in North America focused on the reduction of SO_2 will reduce $PM_{2.5}$ mass concentration, as will reductions in direct particle emissions, notably of BC and OC. The benefits of reducing nitrogen oxides or VOCs are uncertain.

LOCAL, REGIONAL, AND CONTINENTAL MANAGEMENT OF $PM_{2.5}$

Particles typically remain in the atmosphere for days to a few weeks, depending on their size and the rates at which they are removed from the atmosphere, for example, by precipitation. Particles in any given area may originate locally or from sources hundreds to thousands of kilometers away, or be formed during atmospheric transport from precursor gases originating from sources locally or far away.

Prevailing meteorology, topography and seasonal influences also alter the bulk $PM_{2.5}$ mass concentration and composition of particles. Intercontinental transport of dust from both Asia and Africa occurs. It does not contribute significantly to annual-average concentrations in North America, but may occasionally contribute significantly to 24-hr concentrations. Forest fires and biomass burning both contribute locally and regionally during certain seasons. Satellite imagery and PM-composition measurements are used to identify the influence of these large-scale events.

Both local and regional emissions contribute to local concentrations in many urban areas. Regional contributions from sources distant to eastern North American urban areas can account for 50% to 75% of the total observed $PM_{2.5}$ mass concentration within a specific urban area.

What we know and expect …

$PM_{2.5}$ management strategies need to include the impact of both local and distant sources, within the context of prevailing meteorology and seasonal variability. Consequently, a management approach for one region or airshed may not be applicable in another. Each needs to be assessed individually to develop the most effective management approach.

PREDICTIVE CAPABILITIES

Several strategy-development tools are available utilizing analysis (e.g., receptor modeling) and simulation (e.g., chemical-transport modeling). Receptor models and chemical-transport models can be used in a complementary fashion to develop advice for policy makers, as part of a corroborative approach to providing guidance based on the best scientific understanding available. Receptor models are useful in selecting scenarios and identifying contributing sources and/or source types.

Current chemical-transport models are one useful tool for guiding policy as part of the collective scientific analysis, being most informative regarding the inorganic fraction ($SO_4^{=}$, NO_3^{-}, and NH_4^{+}) on regional and episodic (days to weeks) scales.

What we know and expect…

Source-specific options to reduce PM concentrations are best approached through corroborative analyses using emission inventories, ambient concentration measurements, and air-quality modeling. Capabilities of chemical-transport models, as well as being bound by current understanding of atmospheric processes, are limited by the type and quality of the ambient, meteorological, and emission information used to evaluate and run them. Evaluated, policy-ready models that can be applied routinely will become available gradually as these data needs are met; such models can be applied with growing confidence over the next five to ten years.

COPOLLUTANT INTERACTIONS

$PM_{2.5}$ and ground-level ozone, with other air contaminants, are closely related through common precursors, sources, physicochemical pathways, and meteorological processes. Thus, changes in the emissions of one pollutant can lead to changes in the concentrations of other pollutants. All fine particles, including those composed of carbonaceous materials, $SO_4^{=}$, and NO_3^{-}, scatter incoming and, lesser so, outgoing radiation. Black carbon and other dark particles absorb radiative energy. Coarse particles and cloud droplets formed by the condensation of water vapor on particles also have radiative effects. These radiative effects of PM can have local and global impacts on photochemistry and climate change. The scattering and absorption of visible radiation (light) can also obscure visibility and result in regional haze.

What we know and expect…

The current understanding of atmospheric processes shows that $PM_{2.5}$ problems are related to ground-level ozone, acid rain, and climate issues and share many of the same sources. This recognition provides the impetus for integrated and optimized management strategies that accommodate different atmospheric responses for each pollutant.

NEW INSIGHTS FROM IMPROVED MEASUREMENTS AND MONITORING

Considerable advances have been achieved in the real-time measurement of particle size and composition. Many of the new measurements are still research activities, but they demonstrate how more detailed measurements can provide insights to the fundamental atmospheric chemical processes and source contributions, and be used in chemical-transport model development and evaluation. For example, size-resolved composition measurements can help differentiate between local and regional source contributions, primary vs. secondary particle components, and natural vs. anthropogenic contributions.

Insufficient ambient data are available to examine fully all of the hypothesized causal elements for health effects, either due to lack of data or lack of suitable measurement technology. As the measurement techniques evolve toward more robust methods, suitable for mid- to long-term monitoring, it will become possible to include many more aspects of PM composition and characteristics in studies of population exposure and health outcomes.

What we know and expect…

Health-impact indicators based on epidemiology can be derived only for PM characteristics for which ambient measurements are available, and effects can be assigned only to those specific source types represented in the ambient concentration measurements. Linking of health effects to sources is being explored by way of source apportionment and toxicological studies. The rapid evolution in ambient and source monitoring methods will improve the capability to assign exposure and health links to sources.

LINKAGES BETWEEN THE HEALTH AND ATMOSPHERIC SCIENCE COMMUNITIES

A considerable and growing body of evidence shows an association between adverse health outcomes, especially of the cardio-respiratory system, and short- and long-term exposures to ambient PM, especially $PM_{2.5}$. Evidence, from both opportunistic studies of significant reductions in ambient PM over short time periods as well as long-term studies, also suggests that health improves when the ambient concentration of PM is reduced.

Hypotheses that explain how the various chemical and physical characteristics of PM cause specific adverse health impacts have been proposed and partially tested. Continuing to test these hypotheses will require ongoing close collaboration between the atmospheric and health-science communities.

> *What we know and expect…*
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> *Stronger linkages between the health, exposure, and atmospheric-science communities will strengthen our understanding. Examples include joint planning of field studies and projects, development of coordinated long-term research strategies that take into account the major areas of focus in each community, presentations/lectures at one another's conferences, and inclusion of contextual information on human health, exposure and atmospheric science within all major assessments/reports.*

TRACKING PROGRESS AND SUCCESS OF AIR-QUALITY MANAGEMENT

Long-term data sets of a basic suite of measurements (PM mass concentration and composition) are needed to track the impact of changing emissions and management actions. The information from such long-term monitoring, combined with model predictions, will provide the iterative guidance needed to revise and focus management strategies.

At present, considerable PM data for North America exist in many different data sets (both short term and long term), obtained from different networks or studies, using several measurement techniques. Investigations of regional and continental PM transport and formation have been limited, however, by discontinuities in these data sets as well as by inconsistent methodologies in their preparation.

> *What we know and expect…*
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> *Sulfate particle loadings have responded to SO_2 emission reductions in both eastern North America and California. It is anticipated that more responses to currently planned changes in emission rates will appear in the next five to ten years. This information will be needed to revise and optimize PM management approaches.*

SCIENTIFIC UNCERTAINTIES AND LOOKING FORWARD

The physics and chemistry of aerosols have been studied since before the 20th century. The in-depth study of aerosols in the context of air pollution is much more recent. The science community has a fundamental understanding of PM formation and transport, yet there remain several significant areas of uncertainty.

Qualitative uncertainties have been identified in emission-inventory information, monitoring, and chemical-transport models. Pollutant emissions from point sources which have been of management interest the longest are best characterized, while those from dispersed area sources for chemically complex pollutants or pollutants of recent interest, such as VOCs and NH_3, are much more uncertain. Confidence in the measurements of bulk PM mass concentration varies between measurement methods. Confidence in characterizing the carbon fraction is currently low because of unresolved sampling artifacts as well as ambiguities in determining the BC and OC fractions.

The current chemical-transport models for PM provide conceptually acceptable, though unevaluated, simulations for inorganic particulate species over episodic periods and regional scales.

> *What we know and expect…*
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> *Policy makers are currently benefiting from research initiated five to ten years ago, or longer. This research provides a basic understanding of PM formation, transport, and its major contributing sources. It characterizes the areas of North America where PM concentrations, visibility reduction, and potential population*

exposure are the greatest. Despite considerable scientific uncertainties, sufficient scientific confidence exists to devise management actions likely to improve air quality.

Policy makers are faced with the need to make decisions based on imperfect understanding of the atmosphere and human-health impacts. Therefore, this Assessment concludes with research recommendations that will substantially improve the ability of the atmospheric-science community to provide guidance for improving plans to implement air-quality standards and goals. Furthermore, continuing research will reduce the risk of erroneous decisions. Each recommendation addresses a consideration that is critical for improved understanding of the atmospheric environment. Because the individual recommendations cover areas that are respectively supportive, they should progress simultaneously. The result will be better science tools and stronger atmospheric-science analysis. The recommendations focus on:

- Improving the understanding of the carbonaceous fraction
- Performing long-term monitoring of PM, gaseous precursors, and copollutants
- Performing further evaluation and development of chemical-transport models
- Developing improved emission estimates (including chemical speciation)
- Making a commitment to the analysis of ambient data and fostering interactions between atmospheric, climate, and health-science communities
- Developing more systematic approaches for integrating diverse types of knowledge to guide development of PM management practices and tracking progress toward protecting health.

The atmospheric-science community has a sufficient understanding of particle formation and transport to support current directions for achieving air-quality standards and goals. The new science that is on the horizon will help refine the management actions for more effective approaches to address PM air-quality problems.