CHAPTER 4

The Way Forward

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4.1. Major Research Needs

This review has emphasized that despite the increase in understanding aerosol forcing of the climate system, many important uncertainties remain. By way of perspective, concerted effort has been directed toward this issue for only about the past 20 years. In view of the variety of aerosol types and emissions, uncertain microphysical properties, great temporal and spatial variability, and the added complexity of aerosol-cloud interactions, it is easy to understand why more work is required to define anthropogenic aerosol forcing with confidence comparable to that for other climate forcing agents.

When comparing surface temperature changes calculated by climate models with those observed, the IPCC AR4 noted "broad consistency" between the modeled and observed temperature record over the industrial period. However, understanding of the degree to which anthropogenic aerosols offset the better-established greenhouse gas forcing is still inadequate. This limits confidence in the predicted magnitude of climate response to future changes in greenhouse gases and aerosols.

This chapter briefly summarizes the major research needs that have been highlighted in previous chapters, recognizing that achieving them will not necessarily be easy or straightforward. Although some important accomplishments will likely be possible in the next decade, others may, realistically, take considerably longer. Several important points should be kept in mind:

1. The uncertainty in assessing anthropogenic and aerosol impacts on climate must be much reduced from its current level to allow meaningful projections of future climate. Using statistical methods, IPCC AR4 concluded that the present-day global-average anthropogenic RF is 2.9 ± 0.3 W m^{-2} for long-lived greenhouse gases plus ozone, -1.3 (-2.2 to -0.5) W m^{-2} for aerosol direct plus aerosol-cloud-albedo, and +1.6 (0.6 to 2.4) W m^{-2} for total anthropogenic forcing (Figure 1.3 in Chapter 1). As shown in Chapter 1, the current estimate of total anthropogenic RF yields the transient climate sensitivity range of 0.3 – 1.1°C/(W m^{-2}). This translates to a possible surface temperature increase from 1.2°C to 4.7°C at the time of (equivalent) doubled CO_2 forcing, which will likely occur toward the latter part of this century. Such a range is too wide to meaningfully predict the climate response to increased greenhouse gases.

   The large uncertainty in total anthropogenic forcing arises primarily from current uncertainty in the current understanding of aerosol RF, as illustrated in Figure 1.3. One objective should be to reduce the uncertainty in global average RF by anthropogenic aerosols over the industrial period to ±0.3 W m^{-2}, equal to the current uncertainty in

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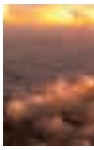
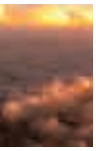


RF by anthropogenic greenhouse gases over this period. Then, taking the total anthropogenic forcing as the IPCC central value, 1.6 W m^{-2}, the range in transient climate sensitivity would be reduced to 0.37 – 0.54°C/(W m^{-2}), and the corresponding increase in global mean surface temperature change at the time of doubled CO_2 forcing would be between 1.5°C and 2.2°C. This range is small enough to make more meaningful global predictions pertinent to planning for mitigation and adaptation.

Evaluation of aerosol effects on climate must take into account high spatial and temporal variation of aerosol amounts and properties.

2. Evaluation of aerosol effects on climate must take into account high spatial and temporal variation of aerosol amounts and properties. Determining the global mean aerosol TOA RF is necessary but far from sufficient, because of the large spatial and temporal variation of aerosol distributions and composition that is in contrast to the much more uniformly distributed longer-lived greenhouse gases such as CO_2 and methane. Therefore, aerosol RF at local to regional scales can be much stronger than its global average.



Understanding of the aerosol effects on the global water cycle requires much improvement.

3. Understanding of the aerosol effects on global water cycle requires much improvement. Besides the radiative forcing, aerosols have other important climate effects. Their heating the atmosphere and cooling the surface affect atmospheric circulations and water cycle. The level of scientific understanding of these effects is much lower than that for aerosol direct RF; concerted research effort is required to move forward.

The approach taken for assessing aerosol forcing of the climate system includes both measurement and modeling components. As discussed in Chapters 2 and 3, improved observations, with some assistance from models, are already helping produce measurement-based estimates of the current aerosol direct effect on climate. Global models are now converging on key parameters such as AOD, and thanks to satellite and other atmospheric measurements, are moving toward better assessments of present-day aerosol RF. However, given the relatively short history of satellite observations and the nature of future climate prediction, the assessment of anthropogenic aerosol climate impact for past and future times will inevitably depend on models. Models are also required to apportion observed aerosols between natural and anthropogenic sources. Therefore, improving model predictions of aerosol climate forcing is the key to progress. To do so, it is essential to advance the current measurement capabilities that will allow much better validation of the models and fundamental improvement of model components.

The accuracy of regional to global-scale AOD measured by satellites is currently poorer than needed to substantially reduce uncertainty in direct radiative forcing by aerosols, but the required capability is within reach, based on the accuracy of current local surface-based measurement techniques. Problems remain in converting total aerosol forcing to forcing by anthropogenic aerosols. The accuracy of aerosol vertical distributions as measured by Lidar from space is approaching that required to be useful for evaluating chemical transport models, and is within reach of that required to reduce uncertainties in aerosol direct radiative forcing.

Measurement accuracy for remotely sensed aerosol optical and physical properties (e.g., SSA, *g*, size) is poorer than needed to significantly reduce uncertainty in aerosol direct radiative forcing and to effect satisfactory translation between AOD retrieved from radiation-based remote-sensing measurements and AOD calculated from CTMs based on aerosol mass concentrations (the fundamental quantities tracked in the model) and optical properties. Combinations of remote-sensing and targeted *in situ* measurement with modeling are required for near-term progress in this area.

Measurements for aerosol indirect effect remain a major challenge. Sensitivity of remote-sensing measurement to particle size, composition, concentration, vertical distribution, and horizontal distribution in the vicinity of clouds is poor. Combinations of detailed *in situ* and laboratory measurements and cloud-resolved modeling, along with spatial extrapolation using remote-sensing measurements and larger-scale modeling, are required for near-term progress in this area.

The next sections address the priorities and recommend approach to moving forward.

4.2. Priorities

4.2.1. Measurements

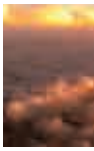
Maintain current and enhance the future satellite aerosol monitoring capabilities. Satellites have been providing global aerosol observations since the late 1970s, with much improved accuracy measurements since late 1990s, but some of them, such as the NASA EOS satellites (Terra, Aqua, Aura), are reaching or exceeding their design lives. Timely follow-on missions to at least maintain these capabilities are important. Assessment of aerosol climate impacts requires a long-term data record having consistent accuracy and high quality, suitable for detecting changes in aerosol amount and type over decadal time scales. Future satellite sensors should have the capability of acquiring information on aerosol size distribution, absorption, vertical distribution, and type with sufficiently high accuracy and adequate spatial coverage and resolution to permit quantification of forcing to required accuracy. The separation of anthropogenic from natural aerosols, perhaps based on size and shape, is essential for assessing human impacts. A brief summary of current capabilities and future needs of major aerosol measurement requirements from space is provided in Table 4.1. (More detailed discussion is in Chapter 2.)

Maintain, enhance, and expand the surface observation networks. Long-term surface-based networks such as the NASA AERONET network, the NOAA ESRL and the DOE ARM sites have for more than a decade been providing essential information on aerosol properties

Table 4.1. Summary of current status and future needs of major aerosol measurements from space for characterization of tropospheric aerosol and determination of aerosol climate forcing.

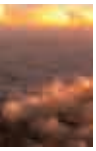
Satellite instrument	Time Period	AOD	Size or Shape[1]	Absorption[2]	Vertical Profile	Global Coverage
Historic / Current						
AVHRR	Since 1981	√	√			Ocean only
TOMS	1979-2001	√		√		√
POLDER	Since 1997	√	√			√
MODIS	Since 2000	√	√			√
MISR	Since 2000	√	√	√		√
OMI	Since 2004	√		√		√
GLAS	Since 2003[3]		√		√	
CALIOP	Since 2006		√		√	
Scheduled to Launch						
VIIRS (on NPP/NPOESS)	2009-	√				√
OMPS (on NPP)	2009-	√		√		√
APS (on Glory)	2009-	√	√	√		
HSRL (on EarthCARE)	2013-				√	
Future Needs						
Next generation instruments (polarimeter, lidar, etc.) with much improved detection accuracy and coverage for AOD and absorption, enhanced capability for measuring vertical profiles, aerosol types and properties, augmented capacity with measurements of aerosol, clouds, and precipitation.						

[1] Size is inferred from the spectral variation of AOD, expressed as the Ångström exponent.
[2] Determination of absorption from MISR is conditional and not always available.
[3] Aerosol detection by GLAS is limited to only a few months each year because of laser power problems.



that is vital for satellite validation, model evaluation, and climate change assessment from trend analysis. Observation should be enhanced with additional, routine measurements of size-resolved composition, more lidar profiling of vertical features, and improved measurements of aerosol absorption with state-of-art techniques. This, along with climate-quality data records constructed from satellites, would help establish connections between aerosol trends and the observed trends in radiation (e.g., dimming or brightening).

Execute a continuing series of coordinated field campaigns. These would aim to: (1) broaden the database of detailed particle optical, physical, and chemical (including cloud-nucleating) properties for major aerosol types, (2) refine and validate satellite and surface-based remote-sensing retrieval algorithms, (3) make comprehensive, coordinated, multi-platform measurements characterizing aerosols, radiation fields, cloud properties and related aerosol-cloud interactions, to serve as testbeds for modeling experiments at several scales, and (4) deepen the links between the aerosol (and cloud) measuring and modeling communities. New and improved instrument capabilities will be needed to provide more accurate measurements of aerosol absorption and scattering properties across the solar spectrum.



Initiate and carry out a systematic program of simultaneous measurement of aerosol, clouds, and precipitation variables. Measurements of aerosol properties must go hand in hand with measurements of cloud properties, and also with measurements of precipitation and meteorological variables, whether this will be from aircraft, ground-based remote sensing or satellite. Assessing aerosol effects on climate has focused on the interactions of aerosol with Earth's radiation balance (i.e., radiative forcing), but in the near future, focus will shift to include aerosol effects on precipitation patterns, atmospheric circulation, and weather.

Fully exploit the existing information in satellite observations of AOD and particle type. An immense amount of data has been collected. Table 4.1 lists the most widely used aerosol property data sets retrieved from satellite sensors. A synthesis of data from multiple sensors would in many cases be a more effective resource for aerosol characterizing than data from individual sensors alone. However, techniques for achieving such synthesis are still in their infancy, and multi-sensor products have only begun to be developed. The full information content of existing data, even with individual sensors, has not been realized. There is a need to: (1) refine retrieval algorithms and extract greater information about aerosols from the joint data sets, (2) quantify data quality, (3) generate uniform (and as appropriate, merged), climate-quality data records. These must be applied to: (4) initialize, constrain, and validate models, (5) conduct detailed process studies, and (6) perform statistical trend analysis.

Measure the formation, evolution, and properties of aerosols under controlled laboratory conditions. Laboratory studies are essential to determine chemical transformation rates for aerosol particle formation. They can also provide information, in a controlled environment, for particle hygroscopic growth, light scattering and absorption properties, and particle activation for aerosols of specific, known composition. Such measurements will allow development of suitable mixing rules and evaluation of the parameterizations that rely on such mixing rules.

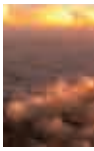
Improve measurement-based techniques for distinguishing anthropogenic from natural aerosols. Current satellite-based estimates of anthropogenic aerosol fraction rely on retrievals of aerosol type. These estimates suffer from limited information content of the data under many circumstances. More needs to be done to combine satellite aerosol type and vertical distribution retrievals with supporting information from: (1) back-trajectory and inverse modeling, (2) at least qualitative time-series of plume evolution from geosynchronous satellite imaging, and (3) surface monitoring and particularly targeted aircraft *in situ* measurements. Different definitions of "anthropogenic" aerosols will require reconciliation. The anthropogenic fraction of today's aerosol, estimated from current measurements, will not produce the same aerosol radiative forcing defined as the perturbation of the total aerosol from pre-industrial times. Consistently defined perturbation states are required before measurement-based and model-based aerosol radiative forcing estimates can be meaningfully compared.

4.2.2. Modeling

Improve the accuracy and capability of model simulation of aerosols (including components and atmospheric processes) and aerosol direct radiative forcing. Spatial and temporal distributions of aerosol mass concentrations are affected primarily by sources, removal mechanisms, atmospheric transport, and chemical transformations; calculations of aerosol direct RF require additional information about aerosol optical properties. Coordinated studies are needed to understand the importance of individual processes, especially vertical mixing and removal by convection/precipitation. Observational strategies must be developed to constrain and validate the key parameters describing: (a) aerosol composition, (b) mass concentration, (c) vertical distribution, (d) size distribution, (e) hygroscopic growth, (f) aerosol absorption, (g) asymmetry parameter and (h) aerosol optical depth. As many models now include major aerosol types such as sulfate, BC, primary POM, dust, and sea salt, progress is needed on simulating nitrate and secondary organic aerosols. In addition, aerosol microphysical processes should be much better represented in the models. In practice, improving the capability of aerosol composition modeling will require improved remote sensing and in situ observations to discriminate among aerosol components. Improvement in modeling radiative forcing could be aided by data assimilation methods, in which the observed aerosol distributions that are input to the model, and the modeled short-term response, could be compared directly with RF observations.

Advance the ability to model aerosol-cloud-precipitation interaction in climate models, particularly the simulation of clouds. The interaction between aerosols and clouds is probably the biggest uncertainty of all climate forcing/feedback processes. The processes involved are complex, and accurate simulation will require sub-grid calculations or improved aerosol and cloud parameterizations on global-model scales. Among the key elements required are: (a) cloud nucleating properties for different aerosol types and size distributions, (b) CCN concentrations as functions of supersaturation and any kinetic influences, (c) algorithms to simulate aerosol influences on cloud brightness, that include cloud fraction, cloud liquid water content, and precipitation efficiency, and (d) cloud drop concentration for known (measured) updraft, humidity, and temperature conditions. Improved aerosol-cloud interaction modeling must be built upon more realistic simulation of clouds and cloud process in GCMs. Cloud-resolving models offer one approach to tackling these questions, aided by the continual improvement in computing capability that makes possible simulations at the higher resolutions appropriate to these processes. Realizing the latter approach, however, may be a long-term goal.

Incorporate improved representation of aerosol processes in coupled aerosol-climate system models to assess the climate change. Coupling aerosol processes in the GCMs would represent a major step in climate simulation beyond the IPCC AR4. This would enable aerosols to interact with the meteorological variables such as clouds and precipitation. Climate change simulations need to be run for hundreds of years with coupled atmosphere-ocean models. Inclusion of aerosol physics and chemistry, and increasing the model resolution, will put large demands on computing power and resources. Some simplification may be necessary, especially considering that other required model improvements, such as finer resolution and carbon cycle models, also increase computing time. The near-term step is to include simple representations of aerosols directly in climate models, incorporating the major aerosol types, basic chemistry, and parameterized cloud droplet activation schemes. Such models exist today, and are ready to be applied to long-term simulations, making it possible to calculate first-order aerosol climate feedbacks. The next generation of models will include aerosol processes that allow for more realistic interactions, such as aerosol and cloud microphysical processes; however, the complexity included should be commensurate with that for other relevant components of the simulation, such as clouds and convection. Fully coupled aerosol-chemistry-physics-climate models will likely be a model-development focus for at least the next decade. This should eventually lead to increasingly sophisticated model simulations of aerosol effects on climate, and better assessments of climate sensitivity.

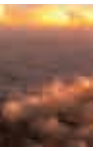


4.2.3. Emissions

Develop and evaluate emissions inventories of aerosol particles and precursor gases. A systematic determination of emissions of primary particles and of aerosol precursor gases is needed as input to modeling the geographical and temporal distribution of the amount and radiative forcing of aerosols. The required description of emissions includes the location, timing, activity, and amount. For particles, the emissions should be characterized by size distributed composition, not simply by mass emissions, because of the effects these properties have on direct and indirect forcings. Natural emissions from biogenic and volcanic sources should be systematically assessed. Satellite fire data are now being used to help constrain biomass-burning emissions, which include new information on aerosol injection height. Dust emission from human activities, such as from farming practices and land-use changes, likewise needs to be quantified. Characterization of aerosol trends and radiative forcing also requires historical emission data. For assessing anthropogenic impacts on future climate, projections of future anthropogenic fuel use and changes in wildfire, desert dust, biogenic, and other sources are needed, and methods used to obtain them carefully evaluated and possibly refined. Some such efforts are being pursued in conjunction with the IPCC.

Narrowing the gap between the current understanding of the contribution of anthropogenic aerosols to radiative forcing and that of the long lived greenhouse gases will require progress in all aspects of aerosol-climate science.

Greater synergy among different types of measurements, different types of models, and especially between measurements and models, is critical.



4.3. Concluding Remarks

Narrowing the gap between the current understanding of the contribution of anthropogenic aerosols to radiative forcing and that of the long lived greenhouse gases will require progress in all aspects of aerosol-climate science. Development of new space-based, field, and laboratory instruments will be needed, and in parallel, more realistic simulations of aerosol, cloud, and atmospheric processes must be incorporated into models. Most importantly, greater synergy among different types of measurements, different types of models, and especially between measurements and models, is critical. Aerosol-climate science must expand to encompass not only radiative effects on climate, but also aerosol effects on cloud processes, precipitation, and weather. New initiatives will strive to more effectively include experimentalists, remote sensing scientists and modelers as equal partners, and the traditionally defined communities of aerosol scientists, cloud scientists, radiation scientists increasingly will find common ground in addressing the challenges ahead.

Intense heat generated by the wildfires below causes smoke to rise in violent updrafts; updrafts and water vapor emanating from the fires also combine to produce towering pyrocumulus clouds. Photo taken from the NASA P-3B aircraft during the ARCTAS field experiment in July 2008 over Canada. Credit: Cameron McNaughton, University of Hawaii.