

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, that concerted effort has been directed toward this issue only for 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 much 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 total anthropogenic greenhouse gas and aerosol impacts on climate must be much reduced from its current level to allow meaningful predictions of future climate.** Using statistical methods, IPCC AR4 concluded that the present-day global-average anthropogenic RF is $2.9 \pm 0.3 \text{ W m}^{-2}$ 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 $0.3 - 1.1^\circ\text{C}/(\text{W m}^{-2})$. This translates to a possible surface temperature increase from 1.2°C to 4.4°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

1 objective should be to reduce the uncertainty in global average RF by anthropogenic
2 aerosols over the industrial period to $\pm 0.3 \text{ W m}^{-2}$, equal to the current uncertainty in RF
3 by anthropogenic greenhouse gases over this period. Then, taking the total anthropogenic
4 forcing taken as the IPCC central value, 1.6 W m^{-2} , the range in transient climate
5 sensitivity would be reduced to $0.37 - 0.54^\circ\text{C}/(\text{W m}^{-2})$, and the corresponding increase in
6 global mean surface temperature change at the time of doubled CO_2 forcing would be
7 between 1.5°C and 2.2°C . This range is small enough to make more meaningful global
8 predictions pertinent to planning for mitigation and adaptation.

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

16 **3. Understanding of the aerosol effects on global water cycle should be much**
17 **advanced.** Besides the radiative forcing, aerosols have other important climate effects.
18 They heat the atmosphere and cool the surface, thus affecting atmospheric circulations
19 and water cycle. The level of scientific understanding of these effects is much lower than
20 that for aerosol direct RF; it requires concerted research effort to move forward.

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

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

40 Measurement accuracy for remotely sensed aerosol optical and physical properties (e.g., SSA, g,
41 size) is poorer than needed to significantly reduce uncertainty in aerosol direct radiative forcing
42 and to effect satisfactory translation between AOD retrieved from radiation-based remote-
43 sensing measurements and AOD calculated from CTMs based on aerosol mass concentrations

1 (the fundamental quantities tracked in the model) and optical properties. Combinations of
2 remote-sensing and targeted *in situ* measurement with modeling are required for near-term
3 progress in this area.

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

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

10 **4.2. Priorities**

11 **4.2.1. Measurements**

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

26 ***Maintain, enhance, and expand the surface observation networks.*** Long-term surface-based
27 networks such as the NASA AERONET network, the NOAA ESRL and the DOE ARM sites
28 have for several decades been providing essential information on aerosol properties that is vital
29 for satellite validation, model evaluation, and climate change assessment from trend analysis.
30 Observation should be enhanced with additional, routine measurements of size-resolved
31 composition, more lidar profiling of vertical features, and improved measurements of aerosol
32 absorption with state-of-art techniques. This, along with climate-quality data records constructed
33 from satellites, would help establish connections between aerosol trends and the observed trends
34 in radiation (e.g., dimming or brightening).

35 ***Execute a continuing series of coordinated field campaigns.*** These would aim to: (1) broaden
36 the database of detailed particle optical, physical, and chemical (including cloud-nucleating)
37 properties for major aerosol types, (2) refine and validate satellite and surface-based remote-
38 sensing retrieval algorithms, (3) make comprehensive, coordinated, multi-platform
39 measurements characterizing aerosols, radiation fields, cloud properties and related aerosol-
40 cloud interactions, to serve as testbeds for modeling experiments at several scales, and (4)
41 deepen the links between aerosol (and cloud) measuring and modeling communities. New and

1 improved instrument capabilities will be needed to provide more accurate measurements of
 2 aerosol absorption and scattering properties across the solar spectrum.

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.						

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 4 **Measure aerosol, clouds, and precipitation variables jointly.** Measurements of aerosol
 5 properties must go hand in hand with measurements of cloud properties, and also with
 6 measurements of precipitation and meteorological variables, whether this will be from aircraft,
 7 ground-based remote sensing or satellite. Assessing aerosol effects on climate has focused on the
 8 interactions of aerosol with Earth’s radiation balance (i.e., radiative forcing), but in the near
 9 future, focus will shift to include aerosol effects on precipitation patterns, atmospheric
 10 circulation, and weather.

11 **Fully exploit the existing information in satellite observations of AOD and particle type.** An
 12 immense amount of data has been collected. Table 4.1 lists the most widely used aerosol
 13 property data sets retrieved from satellite sensors. A synthesis of data from multiple sensors
 14 would in many cases be a more effective resource for aerosol characterizing than data from
 15 individual sensors alone. However, techniques for achieving such synthesis are still in their
 16 infancy, and multi-sensor products have only begun to be developed. The full information
 17 content of existing data, even with individual sensors, has not been realized. There is a need to:

1 (1) refine retrieval algorithms and extract greater information about aerosols from the joint data
2 sets, (2) quantify data quality, (3) generate uniform (and as appropriate, merged), climate-quality
3 data records, and to apply them to: (4) initialize, constrain, and validate models, (5) conduct
4 detailed process studies, and (6) perform statistical trend analysis.

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

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

23 **4.2.2. Modeling**

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

41 **Advance the capability for modeling aerosol-cloud interaction.** The interaction between
42 aerosols and clouds is probably the biggest uncertainty of all climate forcing/feedback processes.
43 The processes involved are complex, and accurate simulation will require sub-grid calculations

1 or improved aerosol and cloud parameterizations on global-model scales. Among the key
2 elements required are: (a) cloud nucleating properties for different aerosol types and size
3 distributions, (b) CCN concentrations as functions of supersaturation and any kinetic influences,
4 (c) algorithms to simulate aerosol influences on cloud brightness, that include cloud fraction,
5 cloud liquid water content, and precipitation efficiency, and (d) cloud drop concentration for
6 known (measured) updraft, humidity, and temperature conditions. Improved aerosol-cloud
7 interaction modeling must be built upon more realistic simulation of clouds and cloud process in
8 GCMs. Cloud-resolving models offer one approach to tackling these questions, aided by the
9 continual improvement in computing capability that makes possible simulations at the higher
10 resolutions appropriate to these processes. Realizing the latter approach, however, may be a
11 long-term goal.

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

30 **4.2.3. Emissions**

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

1 **4.3. Concluding Remarks**

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

13