Chapter IV. Way Forward

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4.1 Introduction

The previous chapters have emphasized that while we have made progress in understanding aerosol forcing of the climate system, there are still many uncertainties. To put the work in perspective, serious investigation of this issue has only been occurring for about the last 20 years. Given all the complexities, such as the varying aerosol types and emissions, uncertain refractive indices, great heterogeneity, and the added issue of interactions with clouds, it is not hard to believe that work of at least that many more years will be necessary before we can define aerosol forcing with a sufficient degree of confidence. And without improved understanding of how much aerosols have offset the better known greenhouse gas forcing for the last 150 years, we cannot use the past temperature record to determine the climate sensitivity over that time, or indeed the likely magnitude of climate response to future greenhouse gas (and aerosol) increases.

As discussed in Chapter 2, improved observations are already helping us to obtain an empirical estimate of the current direct effect of aerosols on climate, independent of models. Continued and even better observations are needed to refine this estimate. To be able to estimate climate forcing due to the indirect effect of aerosols, via their impact on cloud reflectivity and lifetime, will require much more extensive and coordinated campaigns. While choice of a target accuracy requirement for aerosol forcing is somewhat subjective (Schwartz, 2004), a possible target might be ± 0.3 W m^{-2}, comparable to the uncertainty associated with forcing by tropospheric ozone.

Predictions of the future effects of aerosols will have to rely on models, and as indicated in Chapter 3, the current state of observations is inadequate to allow us to assess model performance for anything other than total optical depth (and even that is somewhat uncertain, especially over land). Models produce much more in the way of specificity concerning aerosol distributions than the observations can verify. Improving observations for the purpose of validating models is another future goal.

Models also need to specify aerosol emissions and various aerosol properties. Modelers have also developed crude parameterizations for the interactions of aerosols with clouds. Better observations of all these particulars need to be obtained; many are in situ and in cloudy regimes, so we will need more than just surface or satellite platforms. This then is a third category of observational needs, to enable us to improve the various components of aerosol models.

On the modeling side, given the interactive nature of aerosols and climate, the most realistic results will ultimately be obtained when climate models incorporate aerosols "on-line" as part of their climate change simulations. This will require improved understanding, obtained both from observations of how aerosols are acting within the climate system, and laboratory assessments of aerosol physics/atmospheric chemistry. It will also require improved model meteorology, including better simulation of parameters directly affecting aerosols such as clouds and precipitation. These parameters are obviously important for their own purposes in modeling the climate system. Currently, climate models exhibit substantial error in shortwave cloud albedo in zonal monthly means, even when driven by observed sea surface temperature (Bender et al, 2006), the errors arising from errors in cloud amount and/or reflectivity. It is clear that models must accurately represent such cloud properties accurately if they are to be trusted for reliably calculating the future climate that would result from alternative scenarios of emissions of greenhouse gases, aerosols and aerosol precursors.

Coupling aerosol calculations into the standard climate models will require increased computational power, since many of the interactions are quite computer-intensive – and this will be competing with other computational demands, such as the desire for finer horizontal resolution.

In the rest of this chapter we discuss the primary observational and modeling needs, recognizing that the two are highly interactive, with observations helping to improve models, and models indicating what observations and what degree of accuracy are needed.

4.2 Requirements for Future Research – Observations

As noted above, observations are needed to observe aerosol radiative forcing directly and to improve models, in a variety of ways. We review the relevant types of needed research.

4.2.1. *In-situ measurements of aerosol properties and processes*

Recent work has shown the ubiquity of organic aerosols, especially secondary organic aerosols, and rapid rates of production of organic particulate matter, especially in photochemically active air influenced by recent urban emissions of hydrocarbons and nitrogen oxides. Recent measurements have also shown the widespread occurrence of new particle formation events; these are particularly important as they influence the dynamics of aerosol evolution affecting optical and cloud nucleating properties. Large scale field campaigns, e.g., ICARTT, MILAGRO, have been particularly valuable in studying aerosol evolution processes and in identification especially of the rapid formation of secondary organic aerosol. The advantage of such studies is that they bring to bear many measurement capabilities, multiple aircraft platforms. Clearly such campaigns are required in the future, with enhanced measurement capabilities, especially for the organic precursor gases. Such field campaigns also serve to provide highly detailed data sets for development and/or evaluation of models describing aerosol evolution.

In addition to such large scale campaigns there is a requirement for a dispersed network of aerosol research observatories examining aerosol size-distributed composition and the relation between size-distributed composition, hygroscopic growth, optical properties, and CCN properties. Such systematic measurements are necessary do develop understanding of these relation and to test representation of this understanding in models. A set of such measurements, analogous to dispersed networks of measurements of aerosol optical depth, are necessary to evaluate the performance of hemispheric or global scale models that would calculate these properties. Such a dispersed network, in conjunction with surface based measurements of aerosol optical depth and column light scattering (e.g., AERONET) would provide many measurement constraints on remote-sensing determination of aerosol properties. Finally such a network would provide important ground truth for satellite determinations of aerosol properties.

4.2.2. *Laboratory studies of aerosol evolution and properties*

While field measurements can identify processes that are occurring in the ambient atmosphere, it is difficult to determine the rates of these processes and the dependence of these rates on controlling variables. Such information is necessary as input to models representing these processes. For such determinations laboratory studies are essential, for example to determine the dependence of the rate of new particle formation on the concentrations of precursor gases (sulfuric acid, ammonia, water vapor, specific organic compounds) and on other controlling variables such as temperature.

Analogously, laboratory studies can provide information in a controlled environment of hygroscopic growth, light scattering and absorption, and particle activation for aerosols of specific known composition, allowing development of suitable mixing rules and evaluation of parameterizations of such mixing rules.

4.2.3. *Surface- and satellite-based remote sensing*

Current remote sensing capabilities need to be maintained for constructing a long-term data record with consistent accuracy and high quality suitable for detecting changes of aerosols over decadal time scale. In future missions, satellite capabilities should be enhanced to acquire high quality measurements of aerosol size distribution, particle shape, absorption, and vertical profile with adequate spatial and temporal coverage. Multi-sensor studies are required to achieve maximized capability for characterizing multitudes of the global aerosol system. Observations should be explored to constrain model simulations via inversion and assimilation methods.

Continuation and enhancement of current observational capabilities. The global aerosol system is a moving target, changing over a wide range of time and spatial scales. To assess its climate impacts, it is necessary to construct a long-term data record with consistent accuracy and high quality suitable for detecting changes of aerosols over decadal time scale. Thus there is a need to maintain and increase ground-based and satellite observational networks with an eye to maintaining a consistent measurement strategy that spans decades. Long term surface-based networks such as the NOAA GMD sites, and NASA AERONET network have been for more than a decade providing essential information on aerosol properties that are vital for satellite validation, model evaluation, and climate change assessment. Current satellite capabilities with the designed lifetime of a few years must be continued for detecting the long-term trend and properties of aerosols on a global scale. Strategic plans need to be developed in a timely and systems manner to minimize the discontinuity of observational capability as the current sensors age. Observational capabilities also need to be augmented to improve the characterization of vertical distribution, absorption, size distribution, and type of aerosols. Surface remote sensing should be enhanced with more routine measurements of size-distributed composition, more lidar profiling of vertical features, and improved measurements of aerosol absorption with the state-of-art techniques such as photoacoustic methods and cavity rind down extinction cells. For satellite remote sensing, a multi-angle, multi-spectral polarimeter with sufficiently high accuracy and adequate spatial coverage is needed to acquire information on aerosol size distribution, absorption, and type. The Glory mission scheduled to launch late this year will provide high quality measurements, but Glory is severely limited in its global coverage, and partially limited in its spatial resolution. An alternative would be to develop remote sensing techniques that derive aerosol absorption properties in context with the properties of the underlying surface. Active lidar sensor in space, particularly the High Spectral Resolution Lidar (HSRL) should provide the additional capabilities for determining aerosol extinction above clouds. Aerosols, clouds, precipitation, weather and climate are inherently intertwined as one holistic global system. As observation systems and models are improved for better estimates of aerosol characteristics and forcing, similar improvements are needed for measurements of cloud properties, precipitation, water vapor and temperature profiles, and underlying surface properties. A summary of current, follow-on and future needs of major aerosol measurement requirements from space is provided in **Table 4.1**.

Synergy of aerosol and radiation measurements from multiple platforms and sensors. A wealth of data has been collected from diverse platforms and sensors. Individual sensors or platforms have both strengths and limitations and no single type of observation is adequate for characterizing the complex aerosol system. As such, the best strategy is to make a synergistic use of measurements from multiple platforms/sensors with complementary capabilities. The synergy can be performed through integrating retrieved products from individual platforms and/or sensors for a better characterization of multitudes of aerosols, and/or fusing multi-satellite radiance measurements for joint retrievals of new, standalone parameters. The constellation of six afternoon-overpass spacecrafts, so-called A-Train, provides an unprecedented opportunity for such synergy because they conduct near simultaneous measurements of aerosols, clouds, and radiative fluxes in multiple dimensions with sensors with complementary capabilities, such as multi-spectral, multi-angle, and polarization measurements of aerosol column from radiometers and vertical distributions of aerosols and clouds from lidar and radar. Some promising progress made in recent years needs to be advanced with a good deal of effort when data from the most recently launched CALIPSO and CloudSat are emerging. A combination of polar-orbiting and geostationary satellites, with multi-spectral measurements from a polar-orbiting satellite providing constraints to retrievals from a geostationary satellite, would monitor the daytime cycle of aerosols with a better accuracy than a geostationary satellite alone. More coordinated suborbital measurements are also required for validating and complementing satellite observations. To digest and make the best use of a pool of measurements from different platforms, a coordinated research strategy and international collaboration need to be developed.

Determination of anthropogenic component of aerosols and their radiative forcing. This is an important question necessary to be addressed in order to gain better understanding and assessment of human influences on climate. While satellite instruments do not measure the aerosol chemical composition needed to discriminate anthropogenic from natural aerosol components, they can measure such aerosol microphysical properties as particle size and shape. Given that anthropogenic aerosol is dominated by submicron or fine-mode particles and mineral dust is largely non-spherical, the fine-mode fraction, non-spherical fraction, and depolarization of aerosol extinction from modern sensors such as MODIS, MISR, POLDER, and CALIOP have been used to estimate anthropogenic aerosol component and the direct radiative forcing. Substantial efforts are needed to further explore and improve such approaches. For example, removal of contributions of fine-mode portion of dust and maritime aerosol has been empirically determined from satellite observations in specific regions without accounting for their possible temporal and spatial variations. These issues need to be further examined. Comparisons of approaches using different microphysical properties are mutually beneficial. Satellite measurement-based assessment of direct climate forcing by anthropogenic aerosol has been applied only to oceans because of the limited capability of current satellite sensors in retrieving aerosol size information over land. The NASA Glory Mission using a multi-angle, multi-spectral polarimeter will acquire information on aerosol size distribution, absorption, and type with good accuracy that will improve estimates of the anthropogenic contribution of aerosols. Finally but not

Table 4.1 Summary of status and future needs of major aerosol measurement requirements from space for the tropospheric aerosol characterization and climate forcing research.

Requirements	Current Status	Scheduled Follow-on	Future Needs
optical depth	AVHRR (since 1981) TOMS (1979-2001) POLDER (since 1997) MODIS (since 2000) MISR (since 2000) OMI (since 2004)	VIIRS on NPP (2009) and NPOESS to maintain MODIS capabilities OMPS on NPP (2009) to maintain OMI capabilities APS on Glory (2008) to provide optical depth, particle size/shape, and absorption, but limited to sub-satellite ground track	A *multi-angle, multi-spectral polarimeter* is needed to acquire aerosol optical depth, particle size, shape, and absorption with high accuracy and adequate spatial coverage. A *multi-beam, high-spectral resolution lidar* is needed to acquire vertical profiles of aerosol extinction and size/shape information with high accuracy and adequate spatial coverage. A *coordinated research strategy* is needed to develop sub-orbital programs for evaluating and validating satellite remote sensing measurements.
particle size/shape	AVHRR (since1981) POLDER (since 1997) MODIS (since 2000) MISR (since 2000)		
absorption	TOMS (1979-2001) MISR (since 2000) OMI (since 2004)		
vertical profiles	GLAS (since 2003) CALIOP (since 2006)	N/A	

least, satellite-based estimates of anthropogenic component desperately need to be evaluated and validated with in-situ measurements. The in-situ measurements should be conducted in the context of evaluating and validating satellite remote sensing approaches, focusing on measuring aerosol microphysical properties and anthropogenic fraction in the column.

Detection of aerosol long-term trends and attribution of the observed radiation trends to aerosols. This is an important yet challenging issue that needs to be addressed with substantial effort in coming years. It requires a construction of consistent multi-decadal data records with climate data quality. To get as long data records as possible, it requires a use of data from historic sensors like AVHRR and TOMS that should be extended to observations from modern sensors currently on orbit and scheduled to launch. Some analyses of aerosol optical depth climatology have emerged very recently, using either historic sensors for multi-decadal trends or modern sensors for short-term tendencies of change. However the results from these studies are not always consistent. It thus requires a good understanding and reconciliation of existing differences before a merger of aerosol products from historic and modern satellite sensors. A close examination of relevant issues associated with individual sensors is urgently needed, including sensor calibration, algorithm assumptions, cloud screening, data sampling and aggregation, among others. Trend analyses on regional scales are particularly needed and should be encouraged, given the documented regional differences in the emission trends. The satellite-based trend analysis should also be performed in conjunction with long-term surface-based Sun photometer networks and a construction of aerosol emissions and multi-decadal model simulations. It is even more challenging to unambiguously establish connections between aerosol trends and the observed trends of radiation (e.g., dimming or brightening). The attribution of the observed radiation trends to aerosol changes requires the detection of trends not only for aerosol optical depth, but also aerosol compositions and sizes that determine aerosol single-scattering albedo and asymmetry factor and hence the aerosol radiative forcing. Unfortunately reliable data for the latter don’t exist. Given that current understanding of aerosol effects on clouds is far from complete, initial efforts should focus on establishing aerosol-radiation connections under cloud-free conditions.

Integration of remote sensing and in-situ measurements into models. Aerosol models provide an essential tool for estimating the past aerosol forcing and projecting future climate change. There is a need to encourage “cross pollination” between observations and models. To reduce model uncertainties, continuous efforts are required for improving the characterization of the aerosol life cycle. One of the largest uncertainties associated with the model calculations of aerosol and their radiative forcing is the emissions of aerosol and aerosol precursors and the resulting burdens. Aerosol sinks, such as wet deposition, also tend to be poorly characterized as a result of the difficulty in representing cloud and precipitation processes and lack of observations. Models should aim to improve the performance based on information provided by observational results, which include not only the measures of aerosol optical depth but also the observed relationships between parameters. Observations should be explored to aid models in determining sources and sinks of aerosols via inverse methods. It is also of great importance to integrate satellite and in-situ measurements into global models. There have been some preliminary efforts that integrate satellite retrieved columnar AOD as well as empirically determined optical properties with model simulations. A coordinated research strategy needs to be developed for integrating the emerging CALIPSO observed three-dimensional aerosol extinction into aerosol models. Schemes of surface albedo characterization in global models also need to be evaluated and constrained with emerging measurements from new-generation satellite sensors.

4.3. Requirements for Future Research - Modeling

The comparisons with aerosol observations have already led to some improvement in GCMs, particularly with respect to the realism of some sources and processes. For example, Koch et al. (2006) included species dissolution in stratiform clouds that reduced the atmospheric load of most soluble aerosols, since it increased the scavenging of these aerosols by large-scale rainfall. But as an indication of the problems encountered with such 'improvements', despite using increased natural sulfur emissions, this new process causes sulfate to be less than observed, and suggests the need for additional sulfur oxidation mechanisms (Koch et al., 2006). Due to the uncertainties in sources and removal processes, there are many degrees of freedom in the system, and changes in one component may well necessitate different choices or the inclusion of even more processes associated with other components.

The *sine qua non* for improving model simulations of aerosols is that modelers must be able to tell what constitutes an improvement. Many of the comparisons with observations shown for aerosol models in Chapter 2, and the GISS and GFDL GCMs in Chapter 3, are less than definitive because of disagreements among the observing platforms. Knowing the right answer(s) is clearly important for the aerosol characteristics themselves, but also for the associated radiative forcing. The number one priority for improving models is to obtain improved observations of aerosol component distributions and radiative forcing.

4.3.1 Required modeling improvements

The aerosol component distributions are affected primarily by sources, removal mechanisms and atmospheric transport. Calculation of the aerosol radiative forcing requires information on their radiative properties. We discuss the modeling needs in each of these areas.

Emissions. A discussion of the current status of understanding of sources was provided in Chapter 1. Improvements in specifying emissions requires better observations and laboratory studies, but the subject is included here under the modeling category since aerosol emissions are the most important factor in determining the model distribution and loading of the different aerosol components.

We need to have a systematic determination of emissions of primary particles, including size-distributed composition, and of aerosol precursor gases. Additionally emission inventories are required for the twentieth century to serve as input to models examining radiative forcing over this time period needed for input to climate models to evaluate their performance by comparison with observations. Projected future emissions are required as well as input to models providing projections of future climate change. Because of the need to represent aerosol emissions in models at locations and times for which measurements are not available, such inventories must be tied to the particular activities that produce those emissions, with the emissions calculated as a product of an emission factor (emission per activity) times the activity rate, the latter developed or projected as a function of time, economic growth, and the like.

A requirement of emissions inventories of particulate matter is that they provide emissions rates of size-distributed composition. Much of the present inventory of aerosols provides only mass emissions (generally in support of achieving air quality requirements) but this is wholly inadequate to the task of determining climate influences of anthropogenic aerosols, given that aerosol optical and cloud nucleating properties depend on size distributed composition. Similarly, there is a requirement for emissions of aerosol precursor gases, of which a large component is thought, on the basis of recent work, to be biogenic organics, which interact with highly photochemically active urban plumes to produce secondary organic aerosol. Identification of precursor gases and of the pertinent chemical reactions is not firmly established, so emissions requirements will depend on identification of the pertinent precursor gases. Emissions inventories must be tied to underlying vegetation types including determination of dependence on controlling conditions, e.g., leaf area index, primary production, water stress, temperature, so that these inventories can be incorporated into global-scale models.

Aerosol production, transformation, and removal processes. We need to better understanding and model the processes of new particle formation, gas to particle conversion, and evolution of aerosol chemical and physical properties in the atmosphere based on concentrations of precursor gases and other dependences. This also includes in-cloud processes. There needs to be greater understanding of aerosol removal processes by wet and dry deposition.

Aerosol chemical transport modeling. Considering the other aspects that affect aerosol distributions, atmospheric transports in models can be tested by comparison with observations of long-lived species (e.g., Rind et al., 2007). Interhemispheric transports are strongly affected by the 'ageostrophic' circulations that are hard to detect directly, and which are generated by heat released from condensation of moisture associated with precipitation. Precipitation also functions as a primary removal mechanism for aerosols. Hence improving these processes requires improving precipitation fields – which also means improving observations of precipitation (including the vertical level of condensation) for comparison purposes. Convective precipitation and vertical transport are associated with the convective parameterization in models; its improvement, too, depends on observations and using appropriate scales in models, something that is not currently possible due to resource limitations. The 'way forward' for better aerosol transport and removal is contained in having better physical meteorological simulation capability in climate models.

Aerosol optical properties. Even were we to know the different aerosol component distributions perfectly, there would still be uncertainty concerning the aerosol optical properties (extinction coefficient, single scattering albedo, and asymmetry parameter or higher representation of the phase function) from size distributed aerosol properties. Observations have to be done locally as their generalizability in some cases is open to question; clearly, all 'organic' aerosols are not alike in terms of their reflectivity and absorption. The variation of aerosol properties with relative humidity is another parameterization models must use, and questions have arisen as to what shape it takes at high relative humidities (e.g., in the GFDL model). More observations of these factors would help modelers constrain their parameterizations and provide some degree of uniformity amongst the models.

Aerosol cloud nucleating properties. The interaction between aerosols and clouds is probably the biggest uncertainty of all climate forcing/feedback processes. As discussed in Chapter 3, the processes could well be very complicated, and are unlikely to be resolvable on the horizontal scales that are feasible to use in global climate models. This problem is usually handled by coarser-scale parameterizations, but observations of the fine-scale processes are also difficult to obtain, so it is not clear exactly what models should be parameterizing. We need to know the cloud nucleating properties for different aerosols and different size distributions (CCN concentration as function of supersaturation and any kinetic influences), which will require progress to take place simultaneously in observational and modeling capabilities.

What is true for the aerosol/cloud interaction is of course true for clouds themselves. Clouds represent the biggest uncertainty in understanding climate feedbacks and hence climate sensitivity. We need to demonstrate the capability of calculating cloud drop concentration for known (measured) updraft, humidity, and temperature conditions. As noted in Chapter 3, no improvement can be made in understanding the indirect effects of aerosols without better knowledge of cloud processes, and the ability of models to simulate clouds more realistically. Cloud resolving models, as noted in Chapter 3, are one possibility, as is the continual improvement in computing capability to allow the resolution of more appropriate scales. This latter approach, however, may take decades.

4.3.2. *Aerosol-climate modeling: the way forward*

The scientific community is poised to be able to develop a reliable representation of global and regional releases of primary aerosols throughout the time period of 1850-2050, and potentially to 2100. Emissions tasks that need to be accomplished include review and reconciliation of the extant estimates of historical trends of man-made emissions and incorporation of the best trends of open biomass burning that the science will presently allow. For further breakthroughs, the rather expensive task of testing sources in the field in developing countries would be valuable. The compilation of trends in natural-source emissions, though not so well developed, can be accomplished for some source types, and others can perhaps be held constant. In this way, it should be possible to develop a comprehensive dataset of all primary inputs of aerosols at 5- or 10- year intervals for the period 1850-2000 with a reasonable level of confidence. Such a dataset should be quickly tested within the aerosol components of climate models. We do not yet know what the effect of relatively high carbonaceous aerosol releases in the period 1850-1950 will have on the 20th century temperature reconstruction. The simulation of historical trends in secondary organic aerosol production is more difficult to accomplish and may require a special convocation of experts to design a way forward.

Climate change simulations need to be run for hundreds of years with coupled atmosphere-ocean models. The above discussion emphasizes that finer resolution is necessary to resolve the effects of aerosols and clouds, but long-term simulations and finer resolution compete for computer time. In addition, aerosol physics/chemistry is itself time-consuming, as multiple size-distributions for aerosols and multiple chemical interactions must be calculated; this too conflicts with the need for finer resolution and long-term simulations.

In the simulations that were done for IPCC (2007), aerosol properties and processes were highly simplified in GCMs. Since aerosol forcing had to be included in climate models to help produce realistic temperature changes, aerosols were just implemented as forcings. This was done basically by using 'offline' simulations to prescribe the aerosol forcings. However, this method does not allow any mutual interaction of the aerosol forcing with the meteorological variables, such as clouds, or precipitation.

A next step in aerosol-climate modeling is to have a simple representation of aerosols directly included in the climate models, incorporating the most important substances like sulfates, black and organic carbon, mineral dust and sea salt with its interactive sources and a simple scheme for sulfate chemistry. The size distribution might be described for each species and the aerosols assumed to be externally mixed. The number of aerosol particles that can nucleate to form cloud droplets can be treated as a simple autoconversion function, only considering external mixtures. Aerosol processes are in this representation highly simplified or neglected. Those kinds of models widely exist nowadays and are ready to be applied for long-term simulations, allowing first order aerosol climate feedbacks to be calculated.

The next generation of models will include various aerosol processes that allow for more realistic interactions (e.g., Ghan and Schwartz, 2007). These aerosol models will either describe aerosols in a sectional, modal or quadrature of moments scheme. Aerosol size distribution will be calculated rather than prescribed. The aerosol mixing state will be represented, so that particles forming by condensation will be capable of being internally mixed with primary particles and freshly nucleated particles. Hygroscopicity will be calculated depending on the chemical composition of a particle. Aerosol chemistry and size will determine the cloud activation and convective transport and removal will be linked to cloud microphysics. Aerosol composition, the inclusion of soluble material and aerosol water will be used to calculate the optical properties. Secondary aerosol formation will be explicitly calculated and determine the amount of organic carbon. Condensation and coagulation will determine aerosol size and mixing.

All these processes will require observations to understand them, and extensive computer time to simulate them. It is conceivable that off-line aerosol/chemistry models may incorporate many of them in the next decade, especially if the appropriate observations are obtainable. But it is unlikely that most of these can be included directly in GCMs on that time frame. More likely, the off-line aerosol/chemistry models could be used to calculate the difference these processes make in simulations, both for aerosols and radiative forcing, which might provide a zeroth-order estimate of the effect they would have in GCMs. This approach, however, would fail to provide much of the necessary information, for aerosol-climate interactions are highly interactive, and the interaction likely produces unique results. Furthermore, some of these interactions will likely change as climate does.

4.4. Concluding Remarks

Resolving the past and future aerosol effects on climate, both direct and indirect, is essential to gaining the requisite understanding of climate forcing necessary for informed decision making on CO_2 emissions and energy policy. In view of the multi-faceted nature of the scientific problem and the approaches to resolve it, a level of effort is required that is commensurate with the task. Extensive observational improvements will be necessary along with increased computational resources for the 'forward modeling' approach to produce more confident quantitative results. The continuing record of temperature and trace gas changes will also provide more data for the inverse approach to deduce the influence of aerosols (and clouds). Application of sufficient resources (including manpower) to this problem will be necessary to provide useful error bounds on aerosol forcing and thus climate sensitivity.

Finally, *aerosol-cloud interactions* continue to be an enormous challenge from both the observational and modeling perspectives, and progress is crucial to improving our ability to project climate change for various emission scenarios. The relatively short lifetimes of aerosol particles (order days), in addition to the even shorter timescales for cloud formation and dissipation (10s of minutes) make this a particularly difficult challenge. Moreover, the problem requires addressing an enormous range of spatial scales, from the microscale to the global scale. A methodology for integrating observations (in-situ and remote) and models at the range of relevant temporal/spatial scales is crucial if progress is to be made on this problem.

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