EXECUTIVE SUMMARY

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This report critically reviews current knowledge about global distributions and properties of atmospheric aerosols, as they relate to aerosol impacts on climate. It assesses possible next steps aimed at substantially reducing uncertainties in aerosol radiative forcing estimates. Current measurement techniques and modeling approaches are summarized, providing context. As a part of the Synthesis and Assessment Product in the Climate Change Science Program, this assessment builds upon recent related assessments, including the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR4, 2007) and other Climate Change Science Program reports. The objectives of this report are (1) to promote a consensus about the knowledge base for climate change decision support, and (2) to provide a synthesis and integration of the current knowledge of the climate-relevant impacts of anthropogenic aerosols for policy makers, policy analysts, and general public, both within and outside the U.S government and worldwide.

ES 1. AEROSOLS AND THEIR CLIMATE EFFECTS

ES 1.1. Atmospheric Aerosols

Atmospheric aerosols are suspensions of solid and/or liquid particles in air. Aerosols are ubiquitous in air and are often observable as dust, smoke, and haze. Both natural and human processes contribute to aerosol concentrations. On a global basis, aerosol mass derives predominantly from natural sources, mainly sea salt and dust. However, anthropogenic (manmade) aerosols, arising primarily from a variety of combustion sources, can dominate in and downwind of highly populated and industrialized regions, and in areas of intense agricultural burning.

The term "atmospheric aerosol" encompasses a wide range of particle types having different compositions, sizes, shapes, and optical properties. Aerosol loading, or amount in the atmosphere, is usually quantified by mass concentration or by an optical measure, aerosol optical depth (AOD). AOD is the vertical integral through the entire height of the atmosphere of the fraction of incident light either scattered or absorbed by airborne particles. Usually numerical models and *in situ* observations use mass concentration as the primary measure of aerosol loading, whereas most remote sensing methods retrieve AOD.

ES 1.2. Radiative Forcing of Aerosols

Aerosols affect Earth's energy budget by scattering and absorbing radiation (the "direct effect") and by modifying amounts and microphysical and radiative properties of clouds (the "indirect effects"). Aerosols influence cloud properties through their role as cloud condensation nuclei (CCN) and/or ice nuclei. Increases in aerosol particle concentrations may increase the ambient concentration of CCN and ice nuclei, affecting cloud properties. A CCN increase can lead to more cloud droplets so that, for fixed cloud liquid water content, the cloud droplet size will decrease. This effect leads to brighter clouds (the "cloud albedo effect"). Aerosols can also affect clouds by absorbing solar energy and altering the environment in which the cloud develops, thus changing cloud properties without actually serving as CCN. Such effects can change precipitation patterns as well as cloud extent and optical properties.

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The addition of aerosols to the atmosphere alters the intensity of sunlight scattered back to space, absorbed in the atmosphere, and arriving

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at the surface. Such a perturbation of sunlight by aerosols is designated aerosol radiative forcing (RF). Note that RF must be defined as a perturbation from an initial state, whether that state be the complete absence of aerosols, the estimate of aerosol loading from pre-industrial times, or an estimate of aerosol loading for today's natural aerosols. The RF calculated from the difference between today's total aerosol loading (natural plus anthropogenic) and each of the three initial states mentioned above will result in different values. Also, the aerosol RF calculated at the top of the atmosphere, the bottom of the atmosphere, or any altitude in between, will result in different values. Other quantities that need to be specified when reporting aerosol RF include the wavelength range, the temporal averaging, the cloud conditions considered for direct effects, and the aerosol-cloud interactions that are being considered for the broad classifications of indirect and semi-direct effects. Regardless of the exact definition of aerosol RF, it is characterized by large spatial and temporal heterogeneity due to the wide variety of aerosol sources and types, the spatial non-uniformity and intermittency of these sources, the short atmospheric lifetime of aerosols, and the chemical and microphysical processing that occurs in the atmosphere.

On a global average basis, the sum of direct and indirect forcing by anthropogenic aerosols at the top of the atmosphere is almost certainly negative (a cooling influence), and thus almost certainly offsets a fraction of the positive (warming) forcing due to anthropogenic greenhouse gases. However, because of the spatial and temporal non-uniformity of the aerosol RF, and likely differences in the effects of shortwave and longwave forcings, the net effect on Earth's climate is not simply a fractional offset to the effects of forcing by anthropogenic greenhouse gases.

ES 1.3. Reducing Uncertainties in Aerosol Radiative Forcing Estimates

The need to represent aerosol influences on climate is rooted in the larger, policy related requirement to predict the climate changes that would result from different future emission strategies. This requires that confidence in climate models be based on their ability to accurately represent not just present climate, but also the changes that have occurred over roughly the past century. Achieving such confidence depends upon adequately understanding the forcings that have occurred over this period. Although the forcing by long-lived greenhouse gases is known relatively accurately for this period, the history of total forcing is not, due mainly to the uncertain contribution of aerosols.

Present-day aerosol radiative forcing relative to preindustrial is estimated primarily using numerical models that simulate the emissions of aerosol particles and gaseous precursors and the aerosol and cloud processes in the atmosphere. The accuracy of the models is assessed primarily by comparison with observations. The key to reducing aerosol RF uncertainty estimates is to understand the contributing processes well enough to accurately reproduce them in models. This report assesses present ability to represent in models the distribution, properties and forcings of present-day aerosols, and examines the limitations of currently available models and measurements. The report identifies three specific areas where continued, focused effort would likely result in substantial reduction in present-day aerosol forcing uncertainty estimates: (1) improving quality and coverage of aerosol measurements, (2) achieving more effective use of these measurements to constrain model simulation/assimilation and to test model parameterizations, and (3) producing more accurate representation of aerosols and clouds in models.

ES 2. MEASUREMENT-BASED ASSESSMENT OF AEROSOL RADIATIVE FORCING

Over the past decade, measurements of aerosol amount, geographical distribution, and physical and chemical properties have substantially improved, and understanding of the controlling processes and the direct and indirect radiative effects of aerosols has increased. Key research activities have been:

- Development and implementation of new and enhanced satellite-borne sensors capable of observing the spatial and temporal characteristics of aerosol properties and examine aerosol effects on atmospheric radiation.
- Execution of focused field experiments examining aerosol processes and properties in various aerosol regimes around the globe;

- Establishment and enhancement of ground-based networks measuring aerosol properties and radiative effects;
- Development and deployment of new and enhanced instrumentation including devices to determine size dependent particle composition on fast timescales, and methods for determining aerosol light absorption coefficients and single scattering albedo.

ES 2.1. Assessments of Aerosol Direct Radiative Forcing

Over the past 15 years, focused field campaigns have provided detailed characterizations of regional aerosol, chemical, microphysical and radiative properties, along with relevant surface and atmospheric conditions. Studies from these campaigns provide highly reliable characterization of submicrometer spherical particles such as sulfate and carbonaceous aerosol. *In situ* characterization of larger particles such as dust are much less reliable.

For all their advantages, field campaigns are inherently limited by their relatively short duration and small spatial coverage. Surface networks and satellites provide a needed long-term view, and satellites provide additional extensive spatial coverage. Surface networks, such as the Aerosol Robotic Network (AERONET), provide observations of AOD at mid-visible wavelengths with an accuracy of 0.01 to 0.02, nearly three to five times more accurate than satellite retrievals. These same remote sensing ground networks also typically retrieve column integrated aerosol microphysical properties, but with uncertainties that are much larger than *in situ* measurements.

The satellite remote sensing capability developed over the past decades has enabled the estimate of aerosol radiative forcing on a global scale. Current satellite sensors such as the MODerate resolution Imaging Spectroradiometer (MODIS) and Multi-angle Imaging SpectroRadiometer (MISR) can retrieve AOD (τ) under cloud free conditions with an accuracy of $\pm 0.05 \pm 0.20\tau$ over land and better than $\pm 0.04 \pm 0.1\tau$ over ocean at mid-visible wavelength. In addition, these and other satellite sensors can qualitatively retrieve particle properties (size, shape and absorption), a major advance over the previous generation of satellite instruments. Much effort has gone into comparing different observational methods to estimate global oceanic cloud-free aerosol direct radiative forcing for solar wavelengths at the top of the atmosphere (TOA). Applying various methods using MODIS, MISR and the Clouds and Earth's Radiant Energy System (CERES), the aerosol direct RF at TOA derived above ocean converges to -5.5 ± 0.2 W m^{-2}, where the initial state of the forcing perturbation is a completely aerosol-free atmosphere. Here, the uncertainty is the standard deviation of the various methods, indicating close agreement between the different satellite data sets. However, regional comparisons of the various methods show greater spread than the global mean. Estimates of direct radiative forcing at the ocean surface, and at top and bottom of the atmosphere over land, are also reported, but are much less certain. All these measurement-based estimates are calculated for cloud-free conditions using an initial state of an aerosol-free atmosphere.

Although no proven methods exist for measuring the anthropogenic component of the observed aerosol over broad geographic regions, satellite retrievals are able to qualitatively determine aerosol type under some conditions. From observations of aerosol type, the best estimates indicate that approximately 20% of the AOD over the global oceans is a result of human activities. Following from these estimates of anthropogenic fraction, the cloud-free anthropogenic direct radiative forcing at TOA is approximated to be -1.1 ± 0.4 W m^{-2} over the global ocean, representing the anthropogenic perturbation to today's natural aerosol.

ES 2.2. Assessments of Aerosol Indirect Radiative Forcing

Remote sensing estimates of aerosol indirect forcing are still very uncertain. Even on small spatial scales, remote sensing of aerosol effects on cloud albedo do not match *in situ* observations, due to a variety of difficulties with the remote sensing of cloud properties at fine scales, the inability of satellites to observe aerosol properties beneath cloud base, and the difficulty of making aerosol retrievals in cloud fields. Key quantities such as liquid water path, cloud updraft velocity and detailed aerosol size distributions are rarely constrained by coincident observations.

Most remote sensing observations of aerosol-cloud interactions and aerosol indirect forcing

are based on simple correlations among variables, which do not establish cause-and-effect relationships. Inferring aerosol effects on clouds from the observed relationships is complicated further because aerosol loading and meteorology are often correlated, making it difficult to distinguish aerosol from meteorological effects. As in the case of direct forcing, the regional nature of indirect forcing is especially important for understanding actual climate impact.

The fact that models have reproduced the global temperature change in the past does not imply that their future forecasts are accurate. This state of affairs will remain until a firmer estimate of radiative forcing by aerosols, as well as climate sensitivity, is available.

ES 3. MODEL ESTIMATED AEROSOL RADIATIVE FORCING AND ITS CLIMATE IMPACT

Just as different types of aerosol observations serve similar purposes, diverse types of models provide a variety of approaches to understanding aerosol forcing of climate. Large-scale Chemistry and Transport Models (CTMs) are used to test current understanding of the processes controlling aerosol spatial and temporal distributions, including aerosol and precursor emissions, chemical and microphysical transformations, transport, and removal. CTMs are used to describe the global aerosol system and to make estimates of direct aerosol radiative forcing. In general, CTMs do not explore the climate response to this forcing. General Circulation Models (GCMs), sometimes called Global Climate Models, have the capability of including aerosol processes as a part of the climate system to estimate aerosol climate forcing, including aerosol-cloud interactions, and the climate response to this forcing. Another type of model represents atmospheric processes on much smaller scales, such as cloud resolving and large eddy simulation models. These small-scale models are the primary tools for improving understanding of aerosol-cloud processes, although they are not used to make estimates of aerosol-cloud radiative forcing on regional or global scales.

ES 3.1. The Importance of Aerosol Radiative Forcing in Climate Models

Calculated change of surface temperature due to forcing by anthropogenic greenhouse gases and aerosols was reported in IPCC AR4 based on results from more than 20 participating global climate modeling groups. Despite a wide range of climate sensitivity (i.e. the amount of surface temperature increase due to a change in radiative forcing, such as an increase of CO_2) exhibited by the models, they all yield a global average temperature change very similar to that observed over the past century. This agreement across models appears to be a consequence of the use of very different aerosol forcing values, which compensates for the range of climate sensitivity. For example, the direct cooling effect of sulfate aerosol varied by a factor of six among the models. An even greater disparity was seen in the model treatment of black carbon and organic carbon. Some models ignored aerosol indirect effects whereas others included large indirect effects. In addition, for those models that included the indirect effect, the aerosol effect on cloud brightness (reflectivity) varied by up to a factor of nine. Therefore, the fact that models have reproduced the global temperature change in the past does not imply that their future forecasts are accurate. This state of affairs will remain until a firmer estimate of radiative forcing by aerosols, as well as climate sensitivity, is available.

ES 3.2. Modeling Atmospheric Aerosols

Simulations of the global aerosol distribution by different models show good agreement in their representation of the global mean AOD, which in general also agrees with satellite-observed values. However, large differences exist in model simulations of regional and seasonal distributions of AOD, and in the proportion of aerosol mass attributed to individual species. Each model uses its own estimates of aerosol and precursor emissions and configurations for chemical transformations, microphysical properties, transport, and deposition. Multi-model experiments indicate that differences in the models' atmospheric processes play a more important role than differences in emissions in creating the diversity among model results. Although aerosol mass concentration is the basic measure of aerosol loading in the models, this quantity is translated to AOD via mass extinction efficiency in order to compare with observations and then to estimate aerosol direct RF. Each model employs its own mass extinction efficiency based on limited knowledge of optical and physical properties of each aerosol type. Thus, it is possible for the models to produce different distributions of aerosol loading as mass concentrations but agree in their distributions of AOD, and vice-versa.

Model calculated total global mean direct anthropogenic aerosol RF at TOA, based on the difference between pre-industrial and current

aerosol fields, is -0.22 W m^{-2}, with a range from -0.63 to +0.04 W m^{-2}. This estimate does not include man-made contributions of nitrate and dust, which could add another -0.2 W m^{-2} estimated by IPCC AR4. The mean value is much smaller than the estimates of total greenhouse gas forcing of +2.9 W m^{-2}, but the comparison of global average values does not take into account immense regional variability. Over the major sources and their downwind regions, the model-calculated negative forcing from aerosols can be comparable to or even larger than the positive forcing by greenhouse gases.

ES 3.3. Aerosol Effects on Clouds

Large-scale models are increasingly incorporating aerosol indirect effects into their calculations. Published large-scale model studies report calculated global cloud albedo effect RF at top-of-atmosphere, based on the perturbation from pre-industrial aerosol fields, ranging from -0.22 to -1.85 W m^{-2} with a central value of -0.7 W m^{-2}. Numerical experiments have shown that the cloud albedo effect is not a strong function of a model's cloud or radiation scheme, and that although model representations of cloud physics are important, the differences in modeled aerosol concentrations play a strong role in inducing differences in the indirect as well as the direct effect. Although small-scale models, such as cloud-resolving or large eddy simulation models, do not attempt to estimate global aerosol RF, they are essential for understanding the fundamental processes occurring in clouds, which then leads to better representation of these processes in larger-scale models.

ES 3.4. Impacts of Aerosols on Climate Model Simulations

The current aerosol modeling capability demonstrated by chemical transport models has not been fully incorporated into GCM simulations. Of the 20+ models used in the IPCC AR4 assessment, most included sulfate direct RF, but only a fraction considered other aerosol types, and only less than a third included aerosol indirect effects. The lack of a comprehensive representation of aerosols in climate models makes it difficult to determine climate sensitivity, and thus to make climate change predictions.

Although the nature and geographical distribution of forcings by greenhouse gases and aerosols are quite different, it is often assumed that to first approximation the effects of these forcings on global mean surface temperature are additive, so that the negative forcing by anthropogenic aerosols has partially offset the positive forcing by incremental greenhouse gas increases over the industrial period. The IPCC AR4 estimates the total global average TOA forcing by incremental greenhouse gases to be 2.9 ± 0.3 W m^{-2}, where the uncertainty range is meant to encompass the 90% probability that the actual value will be within the indicated range. The corresponding value for aerosol forcing at TOA (direct plus enhanced cloud albedo effects), defined as the perturbation from pre-industrial conditions, is -1.3 (-2.2 to -0.5) W m^{-2}. The total forcing, 1.6 (0.6 to 2.4) W m^{-2}, reflects the offset of greenhouse gas forcing by aerosols, where the uncertainty in total anthropogenic RF is dominated by the uncertainty in aerosol RF.

The uncertainty in total anthropogenic radiative forcing (greenhouse gases + aerosols) is dominated by the uncertainty in aerosol radiative forcing.

However, since aerosol forcing is much more pronounced on regional scales than on the global scale because of the highly variable aerosol distributions, it would be insufficient or even misleading to place too much emphasis on the global average. Also, aerosol RF at the surface is stronger than that at TOA, exerting large impacts within the atmosphere to alter the atmospheric circulation patterns and water cycle. Therefore, impacts of aerosols on climate should be assessed beyond the limted aspect of globally averaged radiative forcing at TOA.

Impacts of aerosols on climate should be assessed beyond the limited aspect of globally-averaged radiative forcing at top-of-atmosphere.

ES 4. THE WAY FORWARD

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. This uncertainty is currently dominated by the aerosol component. In addition, evaluation of aerosol effects on climate must take into account high spatial and temporal variation of aerosol amounts and properties as well as the aerosol interactions with clouds and precipitation. Thus, the way forward requires more certain estimates of aerosol radiative forcing, which in turn requires better observations, improved models, and a synergistic approach.

From the observational perspective, the high priority tasks are:

- **Maintain current and enhance future satellite capabilities** for measuring geographical and vertical distribution of aerosol

amount and optical properties, suitable for estimating aerosol forcing over multi-decadal time scales and for evaluating global models.

- **Maintain, enhance, and expand the surface observation networks** measuring aerosol optical properties for satellite retrieval validation, model evaluation, and climate change assessments. Observation should be augmented with routine measurements of other key parameters with state-of-art techniques.
- **Execute a continuing series of coordinated field campaigns** aiming to study the atmospheric processes, to broaden the database of detailed aerosol chemical, physical, and optical/radiative characteristics, to validate remote-sensing retrieval products, and to evaluate chemistry transport models.
- **Initiate and carry out a systematic program of simultaneous measurement of aerosol** composition and size distribution, cloud microphysical properties, and precipitation variables.
- **Fully exploit the existing information in satellite observations of AOD and particle type** by refining retrieval algorithms, quantifying data quality, extracting greater aerosol information from joint multi-sensor products, and generating uniform, climate-quality data records.
- **Measure the formation, evolution, and properties of aerosols under controlled laboratory conditions** to develop mechanistic and quantitative understanding of aerosol formation, chemistry, and dynamics.
- **Improve measurement-based techniques for distinguishing anthropogenic from natural aerosols** by combining satellite data analysis with *in situ* measurements and modeling methods.

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Individual sensors or instruments have both strengths and limitations, and no single strategy is adequate for characterizing the complex aerosol system. The best approach is to make synergistic use of measurements from multiple platforms, sensors and instruments having complementary capabilities. The wealth of information coming from the variety of today's sensors has not yet been fully exploited. Advances in measurement-based estimates of aerosol radiative forcing are expected in the near future, as existing data sets are more fully explored. Even so, the long-term success in reducing climate-change prediction uncertainties rests with improving modeling capabilities, and today's suite of observations can only go so far towards that goal.

From the modeling perspective, the high priority tasks are:

- **Improve the accuracy and capability of model simulation of aerosols** (including components and atmospheric processes) and aerosol direct radiative forcing. Observational strategies described above must be developed to constrain and validate the key parameters in the model.
- **Advance the ability to model aerosol-cloud-precipitation interaction in climate models, particularly the simulation of clouds**, in order to reduce the largest uncertainty in the climate forcing/feedback processes.
- **Incorporate improved representation of aerosol processes in coupled aerosol-climate system models** and evaluate the ability of these models to simulate present climate and past (twentieth century) climate change.
- **Apply coupled aerosol-climate system models to assess the climate change** that would result from alternative scenarios of prospective future emissions of greenhouse gases and aerosols and aerosol precursors.

In addition to the above priorities in measurements and modeling, there is a critical need to:

- **Develop and evaluate emission inventories of aerosol particles and precursor gases**. Continuous development and improvement of current emissions, better estimates of past emissions, and projection of future emissions should be maintained.

Progress in improving modeling capabilities requires effort on the observational side, to reduce uncertainties and disagreements among observational data sets. The way forward will require integration of satellite and *in situ* measurements into global models. However, understanding the strengths and weaknesses of each observational data set must be clear in order for the constraints they provide to improve confidence in the models, and for efforts at data assimilation to succeed.

Narrowing the gap between the current understanding of long-lived greenhouse gas and that of anthropogenic aerosol contributions to RF 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, among different types of models, and especially between measurements and models is critical. Aerosol-climate science will naturally 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 in different atmospheric science disciplines will increasingly find common ground in addressing the challenges ahead.

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Several massive wildfires were across southern California during October 2003. MODIS, on the NASA Terra satellite, captured smoke spreading across the region and westward over the Pacific Ocean on October 26, 2003. Credit: NASA.

Mexico city, located in a basin surrounded by mountains, often accumulates air pollution—anthropogenic combustion particles, sometimes mixed with wildfire smoke and mineral dust from the surrounding region. Photo taken from the NASA DC-8 aircraft during the INTEX-B field experiment in spring 2006. Credit: Cameron McNaughton, University of Hawaii.

Los Angeles in the haze at sunset. Pollution aerosols scatter sunlight, shrouding the region in an intense orange-brown glow, as seen through an airplane window, looking west across the LA River, with the city skyline in the background. Credit: Barbara Gaitley, JPL/NASA.