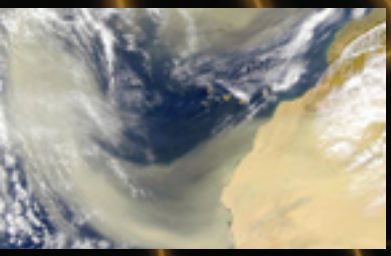

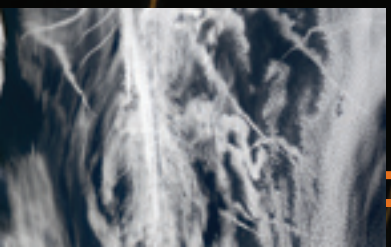

Atmospheric Aerosol Properties and Climate Impacts

U.S. Climate Change Science Program
Synthesis and Assessment Product 2.3

January 2009

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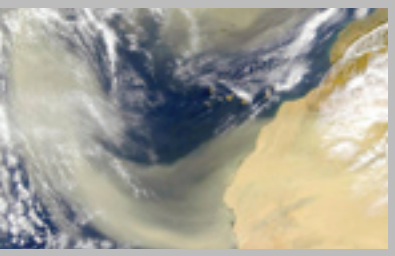
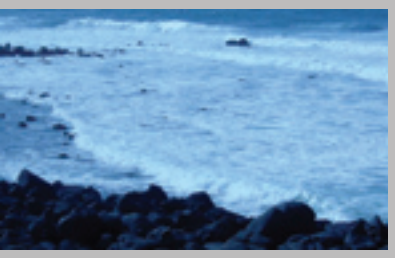
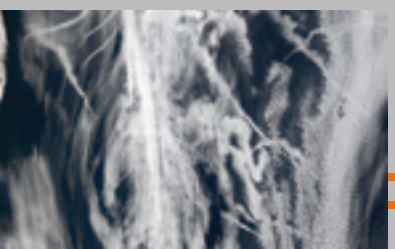
This document, part of the Synthesis and Assessment Products described in the U.S. Climate Change Science Program (CCSP) Strategic Plan, was prepared in accordance with Section 515 of the Treasury and General Government Appropriations Act for Fiscal Year 2001 (Public Law 106-554) and the information quality act guidelines issued by the National Aeronautics and Space Administration pursuant to Section 515. The CCSP Interagency Committee relies on National Aeronautics and Space Administration certifications regarding compliance with Section 515 and Agency guidelines as the basis for determining that this product conforms with Section 515. For purposes of compliance with Section 515, this CCSP Synthesis and Assessment Product is an "interpreted product" as that term is used in National Aeronautics and Space Administration guidelines and is classified as "highly influential". This document does not express any regulatory policies of the United States or any of its agencies, or provides recommendations for regulatory action.







Atmospheric Aerosol Properties and Climate Impacts

Synthesis and Assessment Product 2.3
Report by the U.S. Climate Change Science Program
and the Subcommittee on Global Change Research

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January 2009,

Members of Congress:

On behalf of the National Science and Technology Council, the U.S. Climate Change Science Program (CCSP) is pleased to transmit to the President and the Congress this Synthesis and Assessment Product (SAP) *Atmospheric Aerosol Properties and Climate Impacts*. This is part of a series of 21 SAPs produced by the CCSP aimed at providing current assessments of climate change science to inform public debate, policy, and operational decisions. These reports are also intended to help the CCSP develop future program research priorities.

The CCSP's guiding vision is to provide the Nation and the global community with the science-based knowledge needed to manage the risks and capture the opportunities associated with climate and related environmental changes. The SAPs are important steps toward achieving that vision and help to translate the CCSP's extensive observational and research database into informational tools that directly address key questions being asked of the research community.

This SAP reviews current knowledge about global distributions and properties of atmospheric aerosols, as they relate to aerosol impacts on climate. It was developed in accordance with the Guidelines for Producing CCSP SAPs, the Information Quality Act (Section 515 of the Treasury and General Government Appropriations Act for Fiscal Year 2001 (Public Law 106-554)), and the guidelines issued by the National Aeronautics and Space Administration pursuant to Section 515.

We commend the report's authors for both the thorough nature of their work and their adherence to an inclusive review process.

Sincerely,

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CHAPTER

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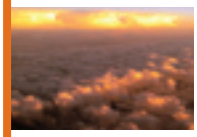

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Earth observed from space. Much of the information contained in this image came from the MODIS instrument on the NASA Terra satellite. This 2002 "Blue Marble" features land surfaces, clouds, topography, and city lights. Credit: NASA (image processed by Robert Simmon and Reto Stöckli).

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.

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").

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

Forcing by anthropogenic aerosols at the top of the atmosphere is negative (cooling) and offsets a fraction of the positive (warming) forcing by greenhouse gases. However, because of the spatial and temporal non-uniformity of aerosol forcing, the net effect is not simply a fractional offset.

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.

The way forward requires more certain estimates of aerosol radiative forcing, which in turn requires better observations, improved models, and a synergistic approach.

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.

Most importantly, greater synergy among different types of measurements, among different types of models, and especially between measurements and models is critical.

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.

GLOSSARY

(Note: Terms in *italic* in each paragraph are defined elsewhere in this glossary.)

Absorption
the process in which incident radiant energy is retained by a substance.

Absorption coefficient
fraction of incident radiant energy removed by *absorption* per length of travel of radiation through the substance.

Active remote sensing
a remote sensing system that transmits its own energy source, then measures the properties of the returned signal. Contrasted with *passive remote sensing*.

Adiabatic equilibrium
a vertical distribution of temperature and pressure in an atmosphere in hydrostatic equilibrium such that an air parcel displaced adiabatically will continue to possess the same temperature and pressure as its surroundings, so that no restoring force acts on a parcel displaced vertically.

Aerosol
a colloidal suspension of liquid or solid particles (in air).

Aerosol asymmetry factor (also called **asymmetry parameter**, ***g*)**
the mean cosine of the scattering angle, found by integration over the complete scattering *phase function* of aerosol; $g = 1$ denotes completely forward scattering and $g = 0$ denotes symmetric scattering. For spherical particles, the asymmetry parameter is related to particle size in a systematic way: the larger the particle size, the more the scattering in the forward hemisphere.

Aerosol direct radiative effect
change in radiative flux due to aerosol scattering and absorption with the presence of aerosol relative to the absence of aerosol.

Aerosol hemispheric backscatter fraction (*b*)
the fraction of the scattered intensity that is redirected into the backward hemisphere relative to the incident light; can be determined from measurements made with an integrating nephelometer. The larger the particle size, the smaller the *b*.

Aerosol indirect effects
processes referring to the influence of aerosol on cloud droplet concentration or radiative properties. Effects include the effect of aerosols on cloud droplet size and therefore its brightness (also known as the "cloud albedo effect", "first aerosol indirect effect", or "Twomey effect"); and the effect of cloud droplet size on precipitation efficiency and possibly cloud lifetime (also known as the "second aerosol indirect effect" or "Albrecht effect").

Aerosol mass extinction (scattering, absorption) efficiency
the aerosol *extinction* (*scattering*, *absorption*) *coefficient* per aerosol mass concentration, with a commonly used unit of $m^2\ g^{-1}$.

Aerosol optical depth
the (wavelength dependent) negative logarithm of the fraction of radiation (or light) that is extinguished (or *scattered* or *absorbed*) by *aerosol* particles on a vertical path, typically from the surface (or some specified altitude) to the top of the atmosphere. Alternatively and equivalently: The (dimensionless) line integral of the *absorption coefficient* (due to aerosol particles), or of the *scattering coefficient* (due to aerosol particles), or of the sum of the two (*extinction coefficient* due to aerosol particles), along such a vertical path. Indicative of the amount of aerosol in the column, and specifically relates to the magnitude of interaction between the aerosols and *shortwave* or *longwave radiation*.

Aerosol phase function
the angular distribution of radiation scattered by aerosol particle or by particles comprising an *aerosol*. In practice, the phase function is parameterized with *asymmetry factor* (or *asymmetry parameter*). Aerosol phase function is related to *aerosol hemispheric backscatter fraction* (*b*) and aerosol particle size: the larger the particle size, the more the forward *scattering* (i.e. larger *g* and smaller *b*).

Aerosol radiative forcing
the net energy flux (downwelling minus upwelling) difference between an initial and a perturbed aerosol loading state, at a specified level in the atmosphere. (Other quantities, such as solar radiation, are assumed to be the same.) This difference is defined such that a negative aerosol forcing implies that the change in aerosols relative to the initial state exerts a cooling in-

fluence, whereas a positive forcing would mean the change in aerosols exerts a warming influence. The aerosol radiative forcing must be qualified by specifying the initial and perturbed aerosol states for which the radiative flux difference is calculated, the altitude at which the quantity is assessed, the wavelength regime considered, the temporal averaging, the cloud conditions, and whether total or only human-induced contributions are considered (see Chapter 1, Section 1.2).

Aerosol radiative forcing efficiency
aerosol direct radiative forcing per *aerosol optical depth* (usually at 550 nm). It is governed mainly by aerosol size distribution and chemical composition (determining the aerosol *single-scattering albedo* and *phase function*), surface reflectivity, and solar irradiance.

Aerosol semi-direct effect
the processes by which *aerosols* change the local temperature and moisture (e.g., by direct radiative heating and changing the heat releases from surface) and thus the local relative humidity, which leads to changes in cloud liquid water and perhaps cloud cover.

Aerosol single-scattering albedo (SSA)
a ratio of the *scattering coefficient* to the *extinction coefficient* of an aerosol particle or of the particulate matter of an aerosol. More absorbing aerosols and smaller particles have lower SSA.

Aerosol size distribution
probability distribution function of the number concentration, surface area, or volume of the particles comprising an aerosol, per interval (or logarithmic interval) of radius, diameter, or volume.

Albedo
the ratio of reflected flux density to incident flux density, referenced to some surface; might be Earth surface, top of the atmosphere.

Angström exponent (*Å*)
exponent that expresses the spectral dependence of *aerosol optical depth* (τ) (or *scattering coefficient*, absorption *coefficient*, etc.) with the wavelength of light (λ) as inverse power law: $\tau \propto \lambda^{-Å}$. The Ångström exponent is inversely related to the average size of aerosol particles: the smaller the particles, the larger the exponent.

Anisotropic
not having the same properties in all directions.

Atmospheric boundary layer (abbreviated **ABL**; also called planetary boundary layer—**PBL**)
the bottom layer of the troposphere that is in contact with the surface of the earth. It is often turbulent and is capped by a statically stable layer of air or temperature inversion. The ABL depth (i.e., the inversion height) is variable in time and space, ranging from tens of meters in strongly statically stable situations, to several kilometers in convective conditions over deserts.

Bidirectional reflectance distribution function (**BRDF**)
a relationship describing the reflected radiance from a given region as a function of both incident and viewing directions. It is equal to the reflected *radiance* divided by the incident *irradiance* from a single direction.

Clear-sky radiative forcing
radiative forcing (of gases or aerosols) in the absence of clouds. Distinguished from total-sky or all-sky *radiative forcing*, which include both cloud-free and cloudy regions.

Climate sensitivity
the change in global mean near-surface temperature per unit of *radiative forcing*; when unqualified typically refers to equilibrium sensitivity; transient sensitivity denotes time dependent change in response to a specified temporal profile.

Cloud albedo
the fraction of solar radiation incident at the top of cloud that is reflected by clouds in the atmosphere or some subset of the atmosphere.

Cloud condensation nuclei (abbreviated **CCN**)
aerosol particles that can serve as seed particles of atmospheric cloud droplets, that is, particles on which water condenses (activates) at *supersaturations* typical of atmospheric cloud formation (fraction of one percent to a few percent, depending on cloud type); may be specified as function of supersaturation.

Cloud resolving model
a numerical model that resolves cloud-scale (and mesoscale) circulations in three (or sometimes two) spatial dimensions. Usually run with horizontal resolution of 5 km or less.

Coalescence
the merging of two or more droplets of precipitation (or aerosol particles; also denoted coagulation) into a single droplet or particle.

Condensation
in general, the physical process (phase transition) by which a vapor becomes a liquid or solid; the opposite of *evaporation*.

Condensation nucleus (abbreviated **CN**)
an aerosol particle forming a center for *condensation* under extremely high *supersaturations* (up to 400% for water, but below that required to activate small ions).

Data assimilation
the combining of diverse data, possibly sampled at different times and intervals and different locations, into a unified and physically consistent description of a physical system, such as the state of the atmosphere.

Diffuse radiation
radiation that comes from some continuous range of directions. This includes radiation that has been scattered at least once, and emission from nonpoint sources.

Dry deposition
the process by which atmospheric gases and particles are transferred to the surface as a result of random turbulent air, impaction, and /or gravitational settling.

Earth Observing System (abbreviated **EOS**)
a major NASA initiative to develop and deploy state-of-the-art *remote sensing* instruments for global studies of the land surface, biosphere, solid earth, atmosphere, oceans, and cryosphere. The first EOS satellite, Terra, was launched in December 1999. Other EOS satellites include Aqua, Aura, ICESat, among others.

Emission of radiation
the generation and sending out of radiant energy. The emission of radiation by natural emitters is accompanied by a loss of energy and is considered separately from the processes of *absorption* or *scattering*.

Emission of gases or particles
the introduction of gaseous or particulate matter into the atmosphere by natural or human activities, e.g., bubble bursting of *whitecaps*, agriculture or wild fires, volcanic eruptions, and industrial processes.

Equilibrium vapor pressure
the pressure of a vapor in equilibrium with its condensed phase (liquid or solid).

Evaporation (also called vaporization)
physical process (phase transition) by which a liquid is transformed to the gaseous state; the opposite of *condensation.*

External mixture (referring to an *aerosol*; contrasted with *internal mixture*)
an aerosol in which different particles (or in some usages, different particles in the same size range) exhibit different compositions.

Extinction (sometimes called attenuation)
the process of removal of radiant energy from an incident beam by the processes of *absorption* and/or *scattering* and consisting of the totality of this removal.

Extinction coefficient
fraction of incident radiant energy removed by extinction per length of travel of radiation through the substance.

General circulation model (abbreviated **GCM**)
a time-dependent numerical model of the entire global atmosphere or ocean or both. The acronym GCM is often applied to Global Climate Model.

Geostationary satellite
a satellite to be placed into a circular orbit in a plane aligned with Earth's equator, and at an altitude of approximately 36,000 km such that the orbital period of the satellite is exactly equal to Earth's period of rotation (approximately 24 hours). The satellite appears stationary with respect to a fixed point on the rotating Earth.

Hygroscopicity
the relative ability of a substance (as an *aerosol*) to adsorb water vapor from its surroundings and ultimately dissolve. Frequently reported as ratio of some property of particle or of particulate phase of an aerosol (e.g., diameter, mean diameter) as function of *relative humidity* to that at low relative humidity.

Ice nucleus (abbreviated **IN**)
any particle that serves as a nucleus leading to the formation of ice crystals without regard to the particular physical processes involved in the nucleation.

In situ
a method of obtaining information about properties of an object (e.g., *aerosol*, cloud) through direct contact with that object, as opposed to *remote sensing*.

Internal mixture (referring to an *aerosol*; contrasted with external mixture)
an aerosol consisting of a mixture of two or more substances, for which all particles exhibit the same composition (or in some usage, the requirement of identical composition is limited to all particles in a given size range). Typically an internal mixture has a higher *absorption coefficient* than an external mixture.

Irradiance (also called radiant flux density)
a radiometric term for the rate at which radiant energy in a radiation field is transferred across a unit area of a surface (real or imaginary) in a hemisphere of directions. In general, irradiance depends on the orientation of the surface. The radiant energy may be confined to a narrow range of frequencies (spectral or monochromatic irradiance) or integrated over a broad range of frequencies.

Large eddy simulation (LES)
A three dimensional numerical simulation of turbulent flow in which large eddies (with scales on the order of hundreds of meters) are resolved and the effects of the subgrid-scale eddies are parameterized. The typical model grid-size is < 100 m and modeling domains are on the order of 10 km. Because they resolve cloud-scale dynamics, large eddy simulations are powerful tools for studying the effects of aerosol on cloud microphysics and dynamics.

Lidar (light detection and ranging)
a technique for detecting and characterizing objects by transmitting pulses of laser light and analyzing the portion of the signal that is reflected and returned to the sensor.

Liquid water path
line integral of the mass concentration of the liquid water droplets in the atmosphere along a specified path, typically along the path above a point on the Earth surface to the top of the atmosphere.

Longwave radiation (also known as terrestrial radiation or thermal infrared radiation)
electromagnetic radiation at wavelengths greater than 4 μm, typically for temperatures characteristic of Earth's surface or atmosphere. In practice, radiation originating by *emission* from Earth and its atmosphere, including clouds; contrasted with *shortwave radiation*.

Low Earth orbit (LEO)
an orbit (of satellite) typically between 300 and 2000 kilometers above Earth.

Mass spectrometer
instrument that fragments and ionizes a chemical substance or mixture by and characterizes composition by amounts of ions as function of molecular weight.

Nucleation
the process of initiation of a new phase in a supercooled (for liquid) or supersaturated (for solution or vapor) environment; the initiation of a phase change of a substance to a lower thermodynamic energy state (vapor to liquid condensation, vapor to solid deposition, liquid to solid freezing).

Optical depth
the *optical thickness* measured vertically above some given altitude. Optical depth is dimensionless and may be applied to Rayleigh scattering optical depth, aerosol *extinction* (or *scattering*, or *absorption*) *optical depth*.

Optical thickness
line integral of *extinction* (or *scattering* or *absorption*) *coefficient* along a path. Dimensionless.

Passive remote sensing
a remote sensing system that relies on the emission (transmission) of natural levels of radiation from (through) the target. Contrasted with *active remote sensing*.

Phase function
probability distribution function of the angular distribution of the intensity of radiation scattered (by a molecule, gas, particle or aerosol) relative to the direction of the incident beam. See also *Aerosol phase function*.

Polarization
a state in which rays of light exhibit different properties in different directions as measured azimuthially about the direction of propagation of the radiation, especially the state in which all the electromagnetic vibration takes place in a single plane (plane polarization).

Polarimeter
instrument that measures the polarization of incoming light often used in the characterization of light scattered by atmospheric aerosols.

Primary trace atmospheric gases or particles
substances which are directly emitted into the atmosphere from Earth surface, vegetation or natural or human activity, e.g., bubble bursting of *whitecaps*, fires, and industrial processes; contrasted with *secondary* substances.

Radar (radio detection and ranging)
similar to lidar, but using radiation in microwave range.

Radiance
a radiometric term for the rate at which radiant energy in a set of directions confined to a small unit solid angle around a particular direction is transferred across unit area of a surface (real or imaginary) projected onto this direction, per unit solid angle of incident direction.

Radiative forcing
the net energy flux (downwelling minus upwelling) difference between an initial and a perturbed state of atmospheric constituents, such as carbon dioxide or aerosols, at a specified level in the atmosphere; applies also to perturbation in reflected radiation at Earth's surface due to change in albedo. See also *Aerosol radiative forcing*.

Radiative heating
the process by which temperature of an object (or volume of space that encompasses a gas or aerosol) increases in response to an excess of absorbed radiation over emitted radiation.

Radiometer
instrument that measures the intensity of radiant energy radiated by an object at a given wavelength; may or may not resolve by wavelength.

Refractive index (of a medium)
the real part is a measure for how much the speed of light (or other waves such as sound waves) is reduced inside the medium relative to speed of light in vacuum, and the imaginary part is a measure of the amount of *absorption* when the electromagnetic wave propagates through the medium.

Relative humidity
the ratio of the vapor pressure of water to its saturation vapor pressure at the same temperature.

Remote sensing: a method of obtaining information about properties of an object (e.g., aerosol, cloud) without coming into physical contact with that object; opposed to *in situ*.

Saturation
the condition in which the vapor pressure (of a liquid substance; for atmospheric application, water) is equal to the *equilibrium vapor pressure* of the substance over a plane surface of the pure liquid substance, sometimes similarly for ice; similarly for a solute in contact with a solution.

Scattering
in a broad sense, the process by which matter is excited to radiate by an external source of electromagnetic radiation. By this definition, reflection, refraction, and even diffraction of electromagnetic waves are subsumed under *s*cattering. Often the term scattered radiation is applied to that radiation observed in directions other than that of the source and may also be applied to acoustic and other waves.

Scattering coefficient
fraction of incident radiant energy removed by *scattering* per length of travel of radiation through the substance.

Secondary trace atmospheric gases or particles
formed in the atmosphere by chemical reaction, new particle formation, etc.; contrasted with *primary* substances, which are directly emitted into the atmosphere.

Secondary organic aerosols (SOA)
organic *aerosol* particles formed in the atmosphere by chemical reactions from gas-phase precursors.

Shortwave radiation
radiation in the visible and near-visible portions of the electromagnetic spectrum (roughly 0.3 to 4.0 μm in wavelength) which range encompasses the great majority of solar radiation and little longwave (terrestrial thermal) radiation; contrasted with *longwave (terrestrial) radiation*.

Single scattering albedo (SSA)
the ratio of light scattering to total light extinction (sum of *scattering* and *absorption*); for *aerosols*, generally restricted to scattering and extinction by the aerosol particles. More absorbing aerosols have lower SSA; a value of unity indicates that the particles are not absorbing.

Solar zenith angle
angle between the vector of Sun and the zenith.

Spectrometer
instrument that measures light received in terms of the intensity at constituent wavelengths, used for example to determine chemical makeup, temperature profiles, and other properties of atmosphere. See also *Mass spectrometer*.

Stratosphere
the region of the atmosphere extending from the top of the *troposphere*, at heights of roughly 10-17 km, to the base of the mesosphere, at a height of roughly 50 km.

Sunglint
a phenomenon that occurs when the sun reflects off the surface of the ocean at the same angle that a satellite sensor is viewing the surface.

Supersaturation
the condition existing in a given portion of the atmosphere (or other space) when the *relative humidity* is greater than 100%, that is, when it contains more water vapor than is needed to produce *saturation* with respect to a plane surface of pure water or pure ice.

Surface albedo
the ratio, often expressed as a percentage, of the amount of electromagnetic radiation reflected by Earth's surface to the amount incident upon it. In general, surface albedo depends on wavelength and the directionality of the incident radiation; hence whether incident radiation is direct or diffuse, cf., *bidirectional reflectance distribution function* (*BRDF*). Value varies with wavelength and with the surface composition. For example, the surface albedo of snow and ice vary from 80% to 90% in the mid-visible, and that of bare ground from 10% to 20%.

Troposphere
the portion of the atmosphere from the earth's surface to the tropopause; that is, the lowest 10-20 kilometers of the atmosphere, depending on latitude and season; most weather occurs in troposphere.

Transient climate response
The time-dependent surface temperature response to a gradually evolving forcing.

Wet scavenging or wet deposition
removal of trace substances from the air by either rain or snow. May refer to in-cloud scavenging, uptake of trace substances into cloud water followed by precipitation, or to below-cloud scavenging, uptake of material below cloud by falling precipitation and subsequent delivery to Earth's surface.

Whitecap
a patch of white water formed at the crest of a wave as it breaks, due to air being mixed into the water.

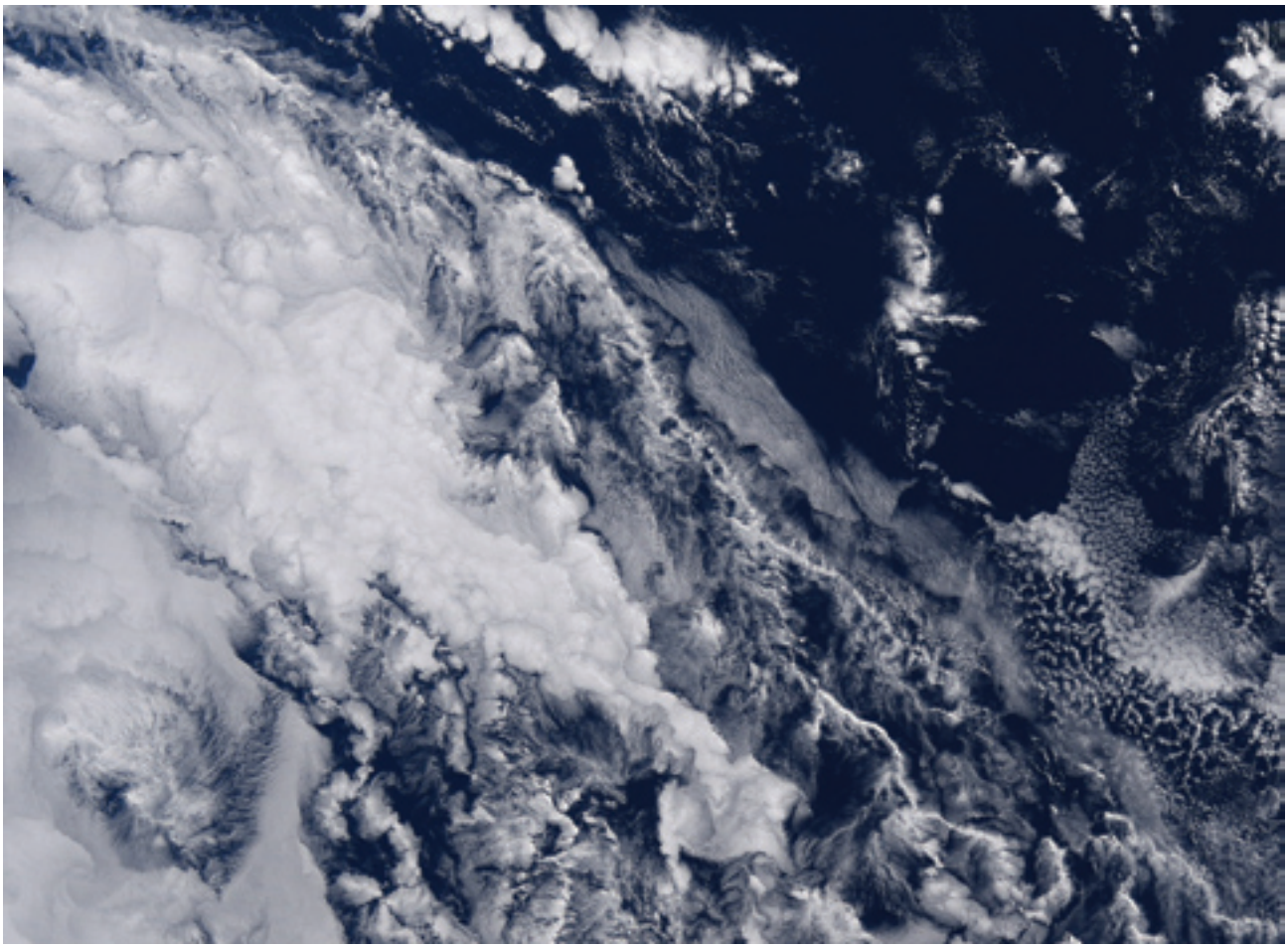
Major reference: *Glossary of Meteorology*, 2nd edition, American Meteorological Society.

ACRONYMS

A	Surface albedo (broadband)
Å	Ångström exponent
ABC	Asian Brown Cloud
ACE	Aerosol Characterization Experiment
AD-Net	Asian Dust Network
ADEOS	Advanced Earth Observation Satellite
ADM	Angular Dependence Models
AeroCom	Aerosol Comparisons between Observations and Models
AERONET	Aerosol Robotic Network
AI	Aerosol Index
AIOP	Aerosol Intensive Operative Period
ANL	Argonne National Laboratory (DOE)
AOD (τ)	Aerosol Optical Depth
AOT	Aerosol Optical Thickness
APS	Aerosol Polarimetry Sensor
AR4	Forth Assessment Report, IPCC
ARCTAS	Arctic Research of the Composition of the Troposphere from Aircraft and Satellites
ARM	Atmospheric Radiation Measurements
AVHRR	Advanced Very High Resolution Radiometer
A-Train	Constellation of six afternoon overpass satellites
BASE-A	Biomass Burning Airborne and Spaceborne Experiment Amazon and Brazil
BC	Black Carbon
BNL	Brookhaven National Laboratory (DOE)
BRDF	Bidirectional Reflectance Distribution Function
CALIOP	Cloud and Aerosol Lidar with Orthogonal Polarization
CALIPSO	Cloud Aerosol Infrared Pathfinder Satellite Observations
CAPMoN	Canadian Air and Precipitation Monitoring Network
CCN	Cloud Condensation Nuclei
CCRI	Climate Change Research Initiative
CCSP	Climate Change *Science,* Program
CDNC	Cloud Droplet Number Concentration
CERES	Clouds and the Earth's Radiant Energy System
CLAMS	Chesapeake Lighthouse and Aircraft Measurements for Satellite campaign
CTM	Chemistry and Transport Model
DABEX	Dust And Biomass-burning Experiment
DOE	Department of Energy
DRF	Direct Radiative Forcing (aerosol)
EANET	Acid Deposition Monitoring Network in East Asia
EARLINET	European Aerosol Research Lidar Network
EarthCARE	Earth Clouds, Aerosols, and Radiation Explorer

EAST-AIRE	East Asian Studies of Tropospheric Aerosols: An International Regional Experiment
EMEP	European Monitoring and Evaluation Programme
EOS	Earth Observing System
EP	Earth Pathfinder
EPA	Environmental Protection Agency
ERBE	Earth Radiation Budget Experiment
ESRL	Earth System Research Laboratory (NOAA)
Eτ	Aerosol Forcing Efficiency (RF normalized by AOD)
FAR	IPCC First Assessment Report (1990)
FT	Free Troposphere
g	Particle scattering asymmetry factor
GAW	Global Atmospheric Watch
GCM	General Circulation Model, Global Climate Model
GEOS	Goddard Earth Observing System
GFDL	Geophysical Fluid Dynamics Laboratory (NOAA)
GHGs	Greenhouse Gases
GISS	Goddard Institute for Space Studies (NASA)
GLAS	Geoscience Laser Altimeter System
GMI	Global Modeling Initiative
GOCART	Goddard Chemistry Aerosol Radiation and Transport (model)
GOES	Geostationary Operational Environmental Satellite
GoMACCS	Gulf of Mexico Atmospheric Composition and Climate Study
GSFC	Goddard Space Flight Center (NASA)
HSRL	High-Spectral-Resolution Lidar
ICARTT	International Consortium for Atmospheric Research on Transport and Transformation
ICESat	Ice, Cloud, and Land Elevation Satellite
IMPROVE	Interagency Monitoring of Protected Visual Environment
INCA	Interactions between Chemistry and Aerosol (LMDz model)
INDOEX	Indian Ocean Experiment
INTEX-NA	Intercontinental Transport Experiment - North America
INTEX-B	Intercontinental Transport Experiment - Phase B
IPCC	Intergovermental Panel on Climate Change
IR	Infrared radiation
LBA	Large-Scale Biosphere-Atmosphere Experiment in Amazon
LES	Large Eddy Simulation
LITE	Lidar In-space Technology Experiment
LMDZ	Laboratoire de Météorologie Dynamique with Zoom, France
LOA	Laboratoire d' Optique Atmosphérique, France
LOSU	Level of Scientific Understanding
LSCE	Laboratoire des Sciences du Climat et de l'Environnement, France
LWC	Liquid Water Content
LWP	Liquid Water Path
MAN	Maritime Aerosol Network
MEE	Mass Extinction Efficiency
MILAGRO	Megacity Initiative: Local and Global Research Observations
MFRSR	Multifilter Rotating Shadowband Radiometer
MINOS	Mediterranean Intensive Oxidant Study
MISR	Multi-angle Imaging SpectroRadiometer
MODIS	Moderate Resolution Imaging Spectro-radiometer
MOZART	Model for Ozone and Related chemical Tracers
MPLNET	Micro Pulse Lidar Network
NASA	National Aeronautics and Space Administration
NASDA	NAtional Space Development Agency, Japan
NEAQS	New England Air Quality Study
NOAA	National Oceanography and Atmosphere Administration
NPOESS	National Polar-orbiting Operational Environmental Satellite System
NPP	NPOESS Preparatory Project
NPS	National Park Services
NRC	National Research Council
OC	Organic Carbon
OMI	Ozone Monitoring Instrument
PARASOL	Polarization and Anisotropy of Reflectance for Atmospheric Science, coupled with Observations from a Lidar
PDF	Probability Distribution Function
PEM-West	Western Pacific Exploratory Mission
PM	Particulate Matter (aerosols)
PMEL	Pacific Marine Environmental Laboratory (NOAA)
POLDER	Polarization and Directionality of the Earth's Reflectance
POM	Particulate Organic Matter
PRIDE	Pueto Rico Dust Experiment
REALM	Regional East Atmospheric Lidar Mesonet
RF	Radiative Forcing, aerosol
RH	Relative Humidity
RTM	Radiative Transfer Model
SAFARI	South Africa Regional Science, Experiment

SAMUM	Saharan Mineral Dust Experiment
SAP	Synthesis and Assessment Product (CCSP)
SAR	IPCC Second Assessment Report (1995)
SCAR-A	Smoke, Clouds, and Radiation - America
SCAR-B	Smoke, Clouds, and Radiation - Brazil
SeaWiFS	Sea-viewing Wide Field-of-view Sensor
SGP	Southern Great Plain, ARM site in Oklahoma
SHADE	Saharan Dust Experiment
SMOCC	Smoke, Aerosols, Clouds, Rainfall and Climate
SOA	Secondary Organic Aerosol
SPRINTARS	Spectral Radiation-Transport Model for Aerosol Species
SSA	Single-Scattering Albedo
SST	Sea Surface Temperature
STEM	Sulfate Transport and Deposition Model
SURFRAD	NOAA's national surface radiation budget network
SZA	Solar Zenith Angle
TAR	Third Assessment Report, IPCC
TARFOX	Tropospheric Aerosol Radiative Forcing Observational Experiment
TCR	Transient Climate sensitivity Range
TexAQS	Texas Air Quality Study
TOA	Top of the Atmosphere
TOMS	Total Ozone Mapping Spectrometer
TRACE-A	Transport and Chemical Evolution over the Atlantic
TRACE-P	Transport and Chemical Evolution over the Pacific
UAE2	United Arab Emirates Unified Aerosol Experiment
UMBC	University of Maryland at Baltimore County
UV	Ultraviolet radiation
VOC	Volatile Organic Compounds
WMO	World Meteorological Organization



Assessing the environmental impact of cloud fields becomes even more complicated when the contributions of aerosol particles in and around the cloud particles are also considered. Image from MODIS. Credit: NASA.

REFERENCES

Abdou, W., D. Diner, J. Martonchik, C. Bruegge, R. Kahn, B. Gaitley, and K. Crean, 2005: Comparison of coincident MISR and MODIS aerosol optical depths over land and ocean scenes containing AERONET sites. *Journal of Geophysical Research,* **110**, D10S07, doi:10.1029/2004JD004693.

Ackerman, A.S., Toon, O. B., and P. V. Hobbs, 1994: Reassessing the dependence of cloud condensation nucleus concentration on formation rate. *Nature,* **367**, 445-447, doi:10.1038/367445a0.

Ackerman, A., O. Toon, D. Stevens, A. Heymsfield, V. Ramanathan, and E. Welton, 2000: Reduction of tropical cloudiness by soot. *Science,* **288**, 1042-1047.

Ackerman, A. S., M. P. Kirkpatrick, D. E. Stevens and O. B. Toon, 2004: The impact of humidity above stratiform clouds on indirect aerosol climate forcing. *Nature,* **432**, 1014-1017.

Ackerman, T., and G. Stokes, 2003: The Atmospheric Radiation Measurement Program. *Physics Today* **56**, 38-44.

Albrecht, B., 1989: Aerosols, cloud microphysics, and fractional cloudiness. *Science,* **245**, 1227-1230.

Alpert, P., P. Kishcha, Y. Kaufman, and R. Schwarzbard, 2005: Global dimming or local dimming? Effect of urbanization on sunlight availability. *Geophysical Research Letters,* **32**, L17802, doi: 10.1029/GL023320.

Anderson, T., R. Charlson, S. Schwartz, R. Knutti, O. Boucher, H. Rodhe, and J. Heintzenberg, 2003: Climate forcing by aerosols—A hazy picture. *Science,* **300**, 1103-1104.

Anderson, T., R. Charlson, N. Bellouin, O. Boucher, M. Chin, S. Christopher, J. Haywood, Y. Kaufman, S. Kinne, J. Ogren, L. Remer, T. Takemura, D. Tanré, O. Torres, C. Trepte, B. Wielicki, D. Winker, and H. Yu, 2005a: An "A-Train" strategy for quantifying direct aerosol forcing of climate. *Bulletin of the American Meteorological Society,* **86**, 1795-1809.

Anderson, T., Y. Wu, D. Chu, B. Schmid, J. Redemann, and O. Dubovik, 2005b: Testing the MODIS satellite retrieval of aerosol fine-mode fraction. *Journal of Geophysical Research,* **110**, D18204, doi:10.1029/2005JD005978.

Andreae, M. O., D. Rosenfeld, P. Artaxo, A. A. Costa, G. P. Frank, K. M. Longo and M. A. F. Silvas-Dias, 2004: Smoking rain clouds over the amazon. *Science,* **303**, 1337-1342.

Andrews, E., P. J. Sheridan, J. A. Ogren, R. Ferrare, 2004: *In situ* aerosol profiles over the Southern Great Plains cloud and radiation test bed site: 1. Aerosol optical properties. *Journal of Geophysical Research,* **109**, D06208, doi:10.1029/2003JD004025.

Ansmann, A., U. Wandinger, A. Wiedensohler, and U. Leiterer, 2002: Lindenberg Aerosol Characterization Experiment 1998 (LACE 98): Overview, *Journal of Geophysical Research,* **107**, 8129, doi:10.1029/2000JD000233.

Arnott, W., H. Moosmuller, and C. Rogers, 1997: Photoacoustic spectrometer for measuring light absorption by aerosol: instrument description. *Atmospheric Environment,* **33**, 2845-2852.

Atwater, M., 1970: Planetary albedo changes due to aerosols. *Science,* **170**(3953), 64-66.

Augustine, J.A., G.B. Hodges, E.G. Dutton, J.J. Michalsky, and C.R. Cornwall, 2008: An aerosol optical depth climatology for NOAA's national surface radiation budget network (SURFRAD). *Journal of Geophysical Research,* **113**, D11204, doi:10.1029/2007JD009504.

Baker, M. B., and R.J. Charlson, 1990: Bistability of CCN concentrations and thermodynamics in the cloud-topped boundary layer. *Nature,* **345**, 142-145.

Balkanski, Y., M. Schulz, T. Claquin, and S. Guibert, 2007: Reevaluation of mineral aerosol radiative forcings suggests a better agreement with satellite and AERONET data. *Atmospheric Chemistry and Physics,* **7**, 81-95.

Bates, T., B. Huebert, J. Gras, F. Griffiths, and P. Durkee (1998): The International Global Atmospheric Chemistry (IGAC) Project's First Aerosol Characterization Experiment (ACE-1)—Overview. *Journal of Geophysical Research,* **103**, 16297-16318.

Bates, T.S., P.K. Quinn, D.J. Coffman, J.E. Johnson, T.L. Miller, D.S. Covert, A. Wiedensohler, S. Leinert, A. Nowak, and C. Neusüb, 2001: Regional physical and chemical properties of the marine boundary layer aerosol across the Atlantic during Aerosols99: An overview. *Journal of Geophysical Research,* **106**, 20767-20782.

Bates T., P. Quinn, D. Coffman, D. Covert, T. Miller, J. Johnson, G. Carmichael, S. uazzotti, D. Sodeman, K. Prather, M. Rivera, L. Russell, and J. Merrill, 2004: Marine boundary layer dust and pollution transport associated with the passage of a frontal system over eastern Asia. *Journal of Geophysical Research,* **109**, doi:10.1029/2003JD004094.

Bates T., et al., 2006: Aerosol direct radiative effects over the northwestern Atlantic, northwestern Pacific, and North Indian Oceans: estimates based on *in situ* chemical and optical measurements and chemical transport modeling. *Atmospheric Chemistry and Physics,* **6**, 1657-1732.

Baynard, T., E.R. Lovejoy, A. Pettersson, S.S. Brown, D. Lack, H. Osthoff, P. Massoli, S. Ciciora, W.P. Dube, and A.R. Ravishankara, 2007: Design and application of a pulsed cavity ring-down aerosol extinction spectrometer for field measurements. *Aerosol Science and Technology,* **41**, 447-462.

Bellouin, N., O. Boucher, D. Tanré, and O. Dubovik, 2003: Aerosol absorption over the clear-sky oceans deduced from POLDER-1 and AERONET observations. *Geophysical Research Letters,* **30**, 1748, doi:10.1029/2003GL017121.

Bellouin, N., O. Boucher, J. Haywood, and M. Reddy, 2005: Global estimates of aerosol direct radiative forcing from satellite measurements. *Nature,* **438**, 1138-1140, doi:10.1038/nature04348.

Bellouin, N., A. Jones, J. Haywood, and S.A. Christopher, 2008: Updated estimate of aerosol direct radiative forcing from satellite observations and comparison against the Hadley Centre climate model. *Journal of Geophysical Research,* **113**, D10205, doi:10.1029/2007JD009385.

Bond, T.C., D.G. Streets, K.F. Yarber, S.M. Nelson, J.-H. Woo, and Z. Klimont, 2004: A technology-based global inventory of black and organic carbon emissions from combustion. *Journal of Geophysical Research,* **109**, D14203, doi:10.1029/2003JD003697.

Bond, T.C., E. Bhardwaj, R. Dong, R. Jogani, S. Jung, C. Roden, D.G. Streets, and N.M. Trautmann, 2007: Historical emissions of black and organic carbon aerosol from energy-related combustion, 1850-2000. *Global Biogeochemical Cycles,* **21**, GB2018, doi:10.1029/2006GB002840.

Boucher, O., and D. Tanré, 2000: Estimation of the aerosol perturbation to the Earth's radiative budget over oceans using POLDER satellite aerosol retrievals. *Geophysical Research Letters,* **27**, 1103-1106.

Brenguier, J. L., P. Y. Chuang, Y. Fouquart, D. W. Johnson, F. Parol, H. Pawlowska, J. Pelon, L. Schuller, F. Schroder, and J. Snider, 2000: An overview of the ACE-2 CLOUDYCOLUMN closure experiment. *Tellus,* **52B**, 815-827.

Caldeira, K., A. K. Jain, and M. I. Hoffert, 2003: Climate sensitivity uncertainty and the need for energy without CO_2 emission. *Science*, **299**, 2052-2054.

Carmichael, G., G. Calori, H. Hayami, I. Uno, S. Cho, M. Engardt, S. Kim, Y. Ichikawa, Y. Ikeda, J. Woo, H. Ueda and M. Amann, 2002: The Mics-Asia study: Model intercomparison of long-range transport and sulfur deposition in East Asia. *Atmospheric Environment,* **36**, 175-199.

Carmichael, G., Y. Tang, G. Kurata, I. Uno, D. Streets, N. Thongboonchoo, J. Woo, S. Guttikunda, A. White, T. Wang, D. Blake, E. Atlas, A. Fried, B. Potter, M. Avery, G. Sachse, S. Sandholm, Y. Kondo, R. Talbot, A. Bandy, D. Thorton and A. Clarke, 2003: Evaluating regional emission estimates using the TRACE-P observations. *Journal of Geophysical Research,* **108**, 8810, doi:10.1029/2002JD003116.

Carrico, C. et al., 2005: Hygroscopic growth behavior of a carbon-dominated aerosol in Yosemite National Park. *Atmospheric Environment,* **39**, 1393-1404.

CCSP, 2008: *Climate Projections Based on Emissions Scenarios for Long-lived and Short-lived Radiatively Active Gases and Aerosols*. A Report by the U.S. Climate Change Science, Program and the Subcommittee on Global Change Research, H. Levy II, D, T. Shindell, A. Gilliland, M. D. Schwarzkopf, L. W. Horowitz, (eds.). Department of Commerce, NOAA's National Climatic Data Center, Washington, D. C. USA, 116 pp.

Chand, D., T. Anderson, R. Wood, R. J. Charlson, Y. Hu, Z. Liu, and M. Vaughan, 2008: Quantifying above-cloud aerosol using spaceborne lidar for improved understanding of cloudy-sky direct climate forcing. *Journal of Geophysical Research,* **113**, D13206, doi:10.1029/2007JD009433.

Charlson, R. and M. Pilat, 1969: Climate: The influence of aerosols. *Journal of Applied Meteorology,* **8**, 1001-1002.

Charlson, R., J. Langner, and H. Rodhe, 1990: Sulfate aerosol and climate. *Nature,* **348**, 22.

Charlson, R., J. Langner, H. Rodhe, C. Leovy, and S. Warren, 1991: Perturbation of the Northern Hemisphere radiative balance by backscattering from anthropogenic sulfate aerosols. *Tellus,* **43AB**, 152-163.

Charlson, R., S. Schwartz, J. Hales, R. Cess, R. J. Coakley, Jr., J. Hansen, and D. Hofmann, 1992: Climate forcing by anthropogenic aerosols. *Science,* **255**, 423-430.

Chen, W-T, R. Kahn, D. Nelson, K. Yau, and J. Seinfeld, 2008: Sensitivity of multi-angle imaging to optical and microphysical properties of biomass burning aerosols. *Journal of Geophysical Research,* **113**, D10203, doi:10.1029/2007JD009414.

Chin, M., P. Ginoux, S. Kinne, O. Torres, B. Holben, B. Duncan, R. Martin, J. Logan, A. Higurashi, and T. Nakajima, 2002: Tropospheric aerosol optical thickness from the GOCART model and comparisons with satellite and sun photometer measurements. *Journal of the Atmospheric Sciences,* **59**, 461-483.

Chin, M., T. Diehl, P. Ginoux, and W. Malm, 2007: Intercontinental transport of pollution and dust aerosols: implications for regional air quality. *Atmospheric Chemistry and Physics,* **7**, 5501-5517.

Chou, M., P. Chan, and M. Wang, 2002: Aerosol radiative forcing derived from SeaWiFS-retrieved aerosol optical properties. *Journal of the Atmospheric Sciences,* **59**, 748-757.

Christopher, S., and J. Zhang, 2002: Daytime variation of shortwave direct radiative forcing of biomass burning aerosols from GEOS-8 imager. *Journal of the Atmospheric Sciences,* **59**, 681-691.

Christopher, S., J. Zhang, Y. Kaufman, and L. Remer, 2006: Satellite-based assessment of top of atmosphere anthropogenic aerosol radiative forcing over cloud-free oceans. *Geophysical Research Letters,* **33**, L15816.

Christopher, A., and T. Jones, 2008: Short-wave aerosol radiative efficiency over the global oceans derived from satellite data. *Tellus,* (B) **60(4)**, 636-640.

Chu, D., Y. Kaufman, C. Ichoku, L. Remer, D. Tanré, and B. Holben, 2002: Validation of MODIS aerosol optical depth retrieval over land. *Geophysical Research Letters,* **29**, 8007, doi:10.1029/2001/GL013205.

Chung, C., V. Ramanathan, D. Kim, and I. Podgomy, 2005: Global anthropogenic aerosol direct forcing derived from satellite and ground-based observations. *Journal of Geophysical Research,* **110**, D24207, doi:10.1029/2005JD006356.

Chung, C. E. and G. Zhang, 2004: Impact of absorbing aerosol on precipitation. *Journal of Geophysical Research,* **109**, doi:10.1029/2004JD004726.

Clarke, A.D., J.N. Porter, F.P.J. Valero, and P. Pilewskie, 1996: Vertical profiles, aerosol microphysics, and optical closure during the Atlantic Stratocumulus Transition Experiment: Measured and modeled column optical properties *Journal of Geophysical Research,* **101**, 4443-4453.

Coakley, J. Jr., R. Cess, and F. Yurevich, 1983: The effect of tropospheric aerosols on the earth's radiation budget: A parameterization for climate models. *Journal of the Atmospheric Sciences,* **40**, 116-138.

Coakley, J. A. Jr. and C. D. Walsh, 2002: Limits to the aerosol indirect radiative effect derived from observations of ship tracks. *Journal of the Atmospheric Sciences,* **59**, 668-680.

Collins, D.R., H.H. Jonsson, J.H. Seinfeld, R.C. Flagan, S. Gassó, D.A. Hegg, P.B. Russell, B. Schmid, J.M. Livingston, E. Öström, K.J. Noone, L.M. Russell, and J.P. Putaud, 2000: *In Situ* aerosol size distributions and clear column radiative closure during ACE-2. *Tellus,* **52B**, 498-525.

Collins, W., P. Rasch, B. Eaton, B. Khattatov, J. Lamarque, and C. Zender, 2001: Simulating aerosols using a chemical transport model with assimilation of satellite aerosol retrievals: Methodology for INDOEX. *Journal of Geophysical Research,* **106**, 7313-7336.

Conant, W. C., T. M. VanReken, T. A. Rissman, V. Varutbangkul, H. H. Jonsson, A. Nenes, J. L. Jimenez, A. E. Delia, R. Bahreini, G. C. Roberts, R. C. Flagan,J. H. Seinfeld, 2004: Aerosol, cloud drop concentration closure in warm cumulus. *Journal of Geophysical Research,* **109**, D13204, doi:10.1029/2003JD004324.

Cooke, W.F., and J.J.N. Wilson, 1996: A global black carbon aerosol model. *Journal of Geophysical Research,*, **101**, 19395-19409.

Cooke, W.F., C. Liousse, H. Cachier, and J. Feichter, 1999: Construction of a 1º × 1º fossil fuel emission data set for carbonaceous aerosol and implementation and radiative impact in the ECHAM4 model. *Journal of Geophysical Research,* **104**, 22137-22162.

Costa, M., A. Silva, and V. Levizzani, 2004a: Aerosol characterization and direct radiative forcing assessment over the ocean. Part I: Methodology and sensitivity analysis. *Journal of Applied Meteorology,* **43**, 1799-1817.

Costa, M., A. Silva AM, and V. Levizzani, 2004b: Aerosol characterization and direct radiative forcing assessment over the ocean. Part II: Application to test cases and validation. *Journal of Applied Meteorology,* **43**, 1818-1833.

de Gouw, J., et al., 2005: Budget of organic carbon in a polluted atmosphere: Results from the New England Air Quality Study in 2002. *Journal of Geophysical Research,* **110**, D16305, doi:10.1029/2004JD005623.

Delene, D. and J. Ogren, 2002: Variability of aerosol optical properties at four North American surface monitoring sites. *Journal of the Atmospheric Sciences,* **59**, 1135-1150.

Delworth, T. L., V. Ramaswamy and G. L. Stenchikov, 2005: The impact of aerosols on simulated ocean temperature and heat content in the 20th century. *Geophysical Research Letters,* **32**, doi:10.1029/2005GL024457.

Dentener, F., S. Kinne, T. Bond, O. Boucher, J. Cofala, S. Generoso, P. Ginoux, S. Gong, J.J. Hoelzemann, A. Ito, L. Marelli, J.E. Penner, J.-P. Putaud, C. Textor, M. Schulz, G.R. van der Werf, and J. Wilson, 2006: Emissions of primary aerosol and precursor gases in the years 2000 and 1750 prescribed datasets for AeroCom. *Atmospheric Chemistry and Physics,* **6**, 4321-4344.

Deuzé, J., F. Bréon, C. Devaux, P. Goloub, M. Herman, B. Lafrance, F. Maignan, A. Marchand, F. Nadal, G. Perry, and D. Tanré, 2001: Remote sensing of aerosols over land surfaces from POLDER-ADEOS-1 polarized measurements. *Journal of Geophysical Research,* **106**, 4913-4926.

Diner, D., J. Beckert, T. Reilly, et al., 1998: Multiangle Imaging SptectrRadiometer (MISR) description and experiment overview. *IEEE Transactions on Geoscience and Remote Sensing,* **36**, 1072-1087.

Diner, D., J. Beckert, G. Bothwell and J. Rodriguez, 2002: Performance of the MISR instrument during its first 20 months in Earth orbit. *IEEE Transactions on Geoscience and Remote Sensing,* **40**, 1449-1466.

Diner, D., T. Ackerman, T. Anderson, et al., 2004: Progressive Aerosol Retrieval and Assimilation Global Observing Network (PARAGON): An integrated approach for characterizing aerosol climatic and environmental interactions. *Bulletin of the American Meteorological Society,* **85**, 1491-1501.

Doherty, S.J., P. Quinn, A. Jefferson, C. Carrico, T.L. Anderson, and D. Hegg, 2005: A comparison and summary of aerosol optical properties as observed *in situ* from aircraft, ship and land during ACE-Asia. *Journal of Geophysical Research,* **110**, D04201, doi: 10.1029/2004JD004964.

Dubovik, O., A. Smirnov, B. Holben, M. King, Y. Kaufman, and Slutsker, 2000: Accuracy assessments of aerosol optical properties retrieved from AERONET sun and sky radiance measurements. *Journal of Geophysical Research,* **105**, 9791-9806.

Dubovik, O., and M. King, 2000: A flexible inversion algorithm for retrieval of aerosol optical properties from Sun and sky radiance measurements. *Journal of Geophysical Research,*, **105**, 20673-20696.

Dubovik, O., B. Holben, T. Eck, A. Smirnov, Y. Kaufman, M. King, D. Tanré, and I. Slutsker, 2002: Variability of absorption and optical properties of key aerosol types observed in worldwide locations. *Journal of the Atmospheric Sciences,* **59**, 590-608.

Dubovik, O., T. Lapyonok, Y. Kaufman, M. Chin, P. Ginoux, and A. Sinyuk, 2007: Retrieving global sources of aerosols from MODIS observations by inverting GOCART model, *Atmospheric Chemistry and Physics Discussions,* **7**, 3629-3718.

Dusek, U., G. P. Frank, L. Hildebrandt, J. Curtius, S. Walter, D. Chand, F. Drewnick, S. Hings, D. Jung, S. Borrmann, and M. O. Andreae, 2006: Size matters more than chemistry in controlling which aerosol particles can nucleate cloud droplets. *Science,* **312**, 1375-1378.

Eagan, R.C., P. V. Hobbs and L. F. Radke, 1974: Measurements of cloud condensation nuclei and cloud droplet size distributions in the vicinity of forest fires. *Journal of Applied Meteorology,* **13**, 553-557.

Eck, T., B. Holben, J. Reid, O. Dubovik, A. Smirnov, N. O'Neill, I. Slutsker, and S. Kinne, 1999: Wavelength dependence of the optical depth of biomass burning, urban and desert dust aerosols. *Journal of Geophysical Research,* **104**, 31333-31350.

Eck, T., et al., 2008: Spatial and temporal variability of column-integrated aerosol optical properties in the southern Arabian Gulf and United Arab Emirates in summer. *Journal of Geophysical Research,* **113**, D01204, doi:10.1029/2007JD008944.

Ervens, B., G. Feingold, and S. M. Kreidenweis, 2005: The influence of water-soluble organic carbon on cloud drop number concentration. *Journal of Geophysical Research,* **110**, D18211, doi:10.1029/2004JD005634.

Fehsenfeld, F., et al., 2006:International Consortium for *Atmospheric Research* on Transport and Transformation (ICARTT): North America to Europe—Overview of the 2004 summer field study. *Journal of Geophysical Research,* **111**, D23S01, doi:10.1029/2006JD007829.

Feingold, G., B. Stevens, W.R. Cotton, and R.L. Walko, 1994: An explicit microphysics/LES model designed to simulate the Twomey Effect. *Atmospheric Research,* **33**, 207-233.

Feingold, G., W. R. Cotton, S. M. Kreidenweis, and J. T. Davis, 1999: The impact of giant cloud condensation nuclei on drizzle formation in stratocumulus: Implications for cloud radiative properties. *Journal of the Atmospheric Sciences*, **56**, 4100-4117.

Feingold, G., Remer, L. A., Ramaprasad, J. and Kaufman, Y. J., 2001: Analysis of smoke impact on clouds in Brazilian biomass burning regions: An extension of Twomey's approach. *Journal of Geophysical Research,* **106**, 22907-22922.

Feingold, G. W. Eberhard, D. Veron, and M. Previdi, 2003: First measurements of the Twomey aerosol indirect effect using ground-based remote sensors. *Geophysical Research Letters,* **30**, 1287, doi:10.1029/2002GL016633.

Feingold, G., 2003: Modeling of the first indirect effect: Analysis of measurement requirements. *Geophysical Research Letters,* **30**, 1997, doi:10.1029/2003GL017967.

Feingold, G., H. Jiang, and J. Harrington, 2005: On smoke suppression of clouds in Amazonia. *Geophysical Research Letters,* **32**, L02804, doi:10.1029/2004GL021369.

Feingold, G., R. Furrer, P. Pilewskie, L. A. Remer, Q. Min, H. Jonsson, 2006: Aerosol indirect effect studies at Southern Great Plains during the May 2003 Intensive Operations Period. *Journal of Geophysical Research,* **111**, D05S14, doi:10.1029/2004JD005648.

Fernandes, S.D., N.M. Trautmann, D.G. Streets, C.A. Roden, and T.C. Bond, 2007: Global biofuel use, 1850-2000. *Global Biogeochemical Cycles,* **21**, GB2019, doi:10.1029/2006GB002836.

Ferrare, R., G. Feingold, S. Ghan, J. Ogren, B. Schmid, S.E. Schwartz, and P. Sheridan, 2006: Preface to special section: Atmospheric Radiation Measurement Program May 2003 Intensive Operations Period examining aerosol properties and radiative influences. *Journal of Geophysical Research,* **111**, D05S01, doi:10.1029/2005JD006908.

Fiebig, M., and J.A. Ogren, 2006: Retrieval and climatology of the aerosol asymmetry parameter in the NOAA aerosol monitoring network. *Journal of Geophysical Research,* **111**, D21204, doi:10.1029/2005JD006545.

Fishman, J., J.M. Hoell, R.D. Bendura, R.J. McNeal, and V. Kirchhoff, 1996: NASA GTE TRACE A experiment (Septemner-October 2002): Overview. *Journal of Geophysical Research,* **101**, 23865-23880.

Fitzgerald, J. W., 1975: Approximation formulas for the equilibrium size of an aerosol particle as a function of its dry size and composition and the ambient relative humidity. *Journal of Applied Meteorology,* **14**, 1044-1049.

Fraser, R. and Y. Kaufman, 1985: The relative importance of aerosol scattering and absorption in Remote Sensing. *Transactions on Geoscience and Remote Sensing*, GE-**23**, 625-633.

Garrett, T., C. Zhao, X. Dong, G. Mace, and P. Hobbs, 2004: Effects of varying aerosol regimes on low-level Arctic stratus. *Geophysical Research Letters,* **31**, L17105, doi:10.1029/2004GL019928.

Garrett, T., and C. Zhao, 2006: Increased Arctic cloud longwave emissivity associated with pollution from mid-latitudes. *Nature,* **440**, 787-789.

Geogdzhayev, I., M. Mishchenko, W. Rossow, B. Cairns, B., and A. Lacis, 2002: Global two-channel AVHRR retrievals of aerosol properties over the ocean for the period of NOAA-9 observations and preliminary retrievals using NOAA-7 and NOAA-11 data. *Journal of the Atmospheric Sciences*, **59**, 262-278.

Ghan, S., and S.E. Schwartz, 2007: Aerosol properties and processes. *Bulletin of the American Meteorological Society,* **88**, 1059-1083.

Gillett, N.P., et al., 2002a: Reconciling two approaches to the detection of anthropogenic influence on climate. *Journal of Climate,* **15**, 326–329.

Gillett, N.P., et al., 2002b: Detecting anthropogenic influence with a multimodel ensemble. *Geophysical Research Letters,* **29**, doi:10.1029/2002GL015836.

Ginoux, P., M. Chin, I. Tegen, J. M. Prospero, B. Holben, O. Dubovik and S.-J. Lin, 2001: Sources and distributions of dust aerosols simulated with the GOCART model. *Journal of Geophysical Research,* **20**, 20255-20273.

Ginoux, P., L. W. Horowitz, V. Ramaswamy, I. V. Geogdzhayev, B. N. Holben, G. Stenchikov and X. tie, 2006: Evaluation of aerosol distribution and optical depth in the Geophysical Fluid Dynamics Laboratory coupled model CM2.1 for present climate. *Journal of Geophysical Research,* **111**, doi:10.1029/2005JD006707.

Golaz, J-C., V. E. Larson, and W. R. Cotton, 2002a: A PDF-based model for boundary layer clouds. Part I: Method and model description. *Journal of the Atmospheric Sciences,* **59**, 3540-3551.

Golaz, J-C., V. E. Larson, and W. R. Cotton, 2002b: A PDF-based model for boundary layer clouds. Part II: Model results. *Journal of the Atmospheric Sciences,* **59**, 3552-3571.

Grabowski, W.W., 2004: An improved framework for superparameterization. *Journal of the Atmospheric Sciences,* **61**, 1940-52.

Grabowski, W.W., X. Wu, and M.W. Moncrieff, 1999: Cloud resolving modeling of tropical cloud systems during Phase III of GATE. Part III: Effects of cloud microphysics. *Journal of the Atmospheric Sciences,* **56**, 2384-2402.

Gregory, J.M., et al., 2002: An observationally based estimate of the climate sensitivity. *Journal of Climate,* **15**, 3117-3121.

Gunn, R. and B. B. Phillips. 1957: An experimental investigation of the effect of air pollution on the initiation of rain. *Journal of Meteorology,* **14**, 272-280.

Han, Q., W. B. Rossow, J. Chou, and R. M. Welch, 1998: Global survey of the relationship of cloud albedo and liquid water path with droplet size using ISCCP. *Journal of Climate,* **11**, 1516-1528.

Han, Q., W.B. Rossow, J. Zeng, and R. Welch, 2002: Three different behaviors of liquid water path of water clouds in aerosol-cloud interactions. *Journal of the Atmospheric Sciences,* **59**, 726-735.

Hansen, J., M. Sato, and R. Ruedy, 1997: Radiative forcing and climate response. *Journal of Geophysical Research,* **102**, 6831-6864.

Hansen, J., et al., 2005: Efficacy of climate forcings. *Journal of Geophysical Research,* **110**, doi:10.1029/2005JD005776, 45pp.

Hansen, J. et al., 2007: Climate simulations for 1880-2003 with GISS model E. *Climate Dynamics,* **29**, 661-696.

Harrison, L., J. Michalsky, and J. Berndt, 1994: Automated multifilter rotating shadowband radiometer: An instrument for optical depth and radiation measurements. *Applied Optics,* **33**, 5118-5125.

Harvey, L.D.D., 2004: Characterizing the annual-mean climatic effect of anthropogenic CO_2 and aerosol emissions in eight coupled atmosphere-ocean GCMs. *Climate Dynamics,* **23**, 569-599.

Haywood, J. M., V. Ramaswamy, and B. J. Soden, 1999: Tropospheric aerosol climate forcing in clear-sky satellite observations over the oceans. *Science,* **283**(5406), 1299-1303.

Haywood, J., and O. Boucher, 2000: Estimates of the direct and indirect radiative forcing due to tropospheric aerosols: A review. *Reviews of Geophysics,* **38**, 513-543.

Haywood, J., P. Francis, S. Osborne, M. Glew, N. Loeb, E. Highwood, D. Tanré, E. Myhre, P. Formenti, and E. Hirst, 2003: Radiative properties and direct radiative effect of Saharan dust measured by the C-130 aircraft during SHADE: 1.Solar spectrum. *Journal of Geophysical Research,* **108**, 8577, doi:10.1029/2002JD002687.

Haywood, J., and M. Schulz, 2007: Causes of the reduction in uncertainty in the anthropogenic radiative forcing of climate between IPCC (2001) and IPCC (2007). *Geophysical Research Letters,* **34**, L20701, doi:10.1029/2007GL030749.

Haywood, J., et al., 2008: Overview of the Dust and Biomass burning Experiment and African Monsoon Multidisciplinary Analysis Special Observing Period-0. *Journal of Geophysical Research,* **113**, D00C17, doi:10.1029/2008JD010077.

Heald, C. L., D. J. Jacob, R. J. Park, L. M. Russell, B. J. Huebert, J. H. Seinfeld, H. Liao, and R. J. Weber, 2005: A large organic aerosol source in the free troposphere missing from current models. *Geophysical Research Letters,* **32**, L18809, doi:10.1029/2005GL023831.

Heintzenberg, J., et al., 2009: The SAMUM-1 experiment over Southern Morocco: Overview and introduction. *Tellus,* **61B**, in press.

Henze, D. K. and J.H. Seinfeld, 2006: Global secondary organic aerosol from isoprene oxidation. *Geophysical Research Letters,* **33**, L09812, doi:10.1029/2006GL025976.

Herman, J., P. Bhartia, O. Torres, C. Hsu, C. Seftor, and E. Celarier, 1997: Global distribution of UV-absorbing aerosols from Nimbus-7/TOMS data. *Journal of Geophysical Research,* 102, 16911-16922.

Hoell, J.M., D.D. Davis, S.C. Liu, R. Newell, M. Shipham, H. Akimoto, R.J. McNeal, R.J. Bemdura, and J.W. Drewry, 1996: Pacific Exploratory Mission-West A (PEM-WEST A): September-October, 1991. *Journal of Geophysical Research,* **101**, 1641-1653.

Hoell, J.M., D.D. Davis, S.C. Liu, R. Newell, M. Shipham, H. Akimoto, R.J. McNeal, R.J. Bemdura, and J.W. Drewry, 1997: The Pacific Exploratory Mission-West Phase B: February-March, 1994. *Journal of Geophysical Research,* **102**, 28223-28239.

Hoff, R. et al., 2002: Regional East Atmospheric Lidar Mesonet: REALM, in *Lidar Remote Sensing in Atmospheric and Earth Sciences*, edited by L. Bissonette, G. Roy, and G. Vallée, pp. 281-284, Def. R&D Can. Valcartier, Val-Bélair, Que.

Hoff, R., J. Engel-Cox, N. Krotkov, S. Palm, R. Rogers, K. McCann, L. Sparling, N. Jordan, O. Torres, and J. Spinhirne, 2004: Long-range transport observations of two large forest fire plumes to the northeastern U.S., in *22nd International Laser Radar Conference, ESA Spec. Publ.*, SP-**561**, 683-686.

Holben, B., T. Eck, I. Slutsker, et al., 1998: AERONET—A federated instrument network and data archive for aerosol characterization. *Remote Sensing of the Environment,* **66**, 1-16.

Holben, B., D. Tanré, A. Smirnov, et al., 2001: An emerging ground-based aerosol climatology: aerosol optical depth from AERONET. *Journal of Geophysical Research,* **106**, 12067-12098.

Horowitz, L. W., et al., 2003: A global simulation of tropospheric ozone and related tracers: Description and evaluation of MOZART, version 2. *Journal of Geophysical Research,* **108**, 4784, doi:10.1029/2002JD002853.

Horowitz, L., 2006: Past, present, and future concentrations of tropospheric ozone and aerosols: Methodology, ozone evaluation, and sensitivity to aerosol wet removal. *Journal of Geophysical Research,* **111**, D22211, doi:10.1029/2005JD006937.

Hoyt, D., and C. Frohlich, 1983: Atmospheric transmission at Davos, Switzerland 1909-1979. *Climatic Change,* **5**, 61-71.

Hsu, N., S. Tsay, M. King, and J. Herman, 2004: Aerosol properties over bright-reflecting source regions.*IEEE Transactions on Geoscience and Remote Sensing,* **42**, 557-569.

Huebert, B., T. Bates, P. Russell, G. Shi, Y. Kim, K. Kawamura, G. Carmichael, and T. Nakajima, 2003: An overview of ACE-Asia: strategies for quantifying the relationships between Asian aerosols and their climatic impacts. *Journal of Geophysical Research,* **108**, 8633, doi:10.1029/2003JD003550.

Huneeus, N., and O. Boucher, 2007: One-dimensional variational retrieval of aerosol extinction coefficient from synthetic LIDAR and radiometric measurements. *Journal of Geophysical Research,* **112**, D14303, doi:10.1029/2006JD007625.

Husar, R., J. Prospero, and L. Stowe, 1997: Characterization of tropospheric aerosols over the oceans with the NOAA advanced very high resolution radiometer optical thickness operational product. *Journal of Geophysical Research,* **102**, 16889-16909.

IPCC, 1992: *Climate Change 1992: The Supplementary Report to the IPCC Scientific Assessment*. J. T. Houghton, B. A. Callander and S. K. Varney (eds). Cambridge University Press, Cambridge, UK, 198 pp.

IPCC (Intergovernmental Panel on Climate Change), 1995: *Radiative forcing of climate change and an evaluation of the IPCC IS92 emission scenarios, in Climate Change 1994*, Cambridge Univ. Press, New York, Cambridge University Press, 1995.

IPCC (Intergovernmental Panel on Climate Change), 1996: *Radiative forcing of climate change, in Climate Change 1995,* Cambridge Univ. Press, New York, Cambridge University Press, 1996.

IPCC (Intergovernmental Panel on Climate Change), 2001: *Radiative forcing of climate change, in Climate Change 2001,* Cambridge Univ. Press, New York, Cambridge University Press, 2001.

IPCC (Intergovernmental Panel on Climate Change), 2007: *Changes in Atmospheric Constituents and in Radiative forcing, in Climate Change 2007*, Cambridge University Press, New York, Cambridge University Press, 2007.

Ito, A., and J.E. Penne, 2005: Historical estimates of carbonaceous aerosols from biomass and fossil fuel burning for the period 1870-2000. *Global Biogeochemical Cycles,* **19**, GB2028, doi:10.1029/2004GB002374.

Jacob, D., J. Crawford, M. Kleb, V. Connors, R.J. Bendura, J. Raper, G. Sachse, J. Gille, L. Emmons, and C. Heald, 2003: The Transport and Chemical Evolution over the Pacific (TRACE-P) aircraft mission: design, execution, and first results. *Journal of Geophysical Research,* **108**, 9000, 10.1029/2002JD003276.

Jayne, J. T., D. C. Leard, X. Zhang, P. Davidovits, K. A. Smith, C. E. Kolb,and D. R. Worsnop, 2000: Development of an aerosol mass spectrometer for size and composition analysis of submicron particles. *Aerosol Science and Technology,* **33**, 49-70.

Jeong, M., Z. Li, D. Chu, and S. Tsay, 2005: Quality and Compatibility Analyses of Global Aerosol Products Derived from the Advanced Very High Resolution Radiometer and Moderate Resolution Imaging Spectroradiometer. *Journal of Geophysical Research,* **110**, D10S09, doi:10.1029/2004JD004648.

Jiang, H., and G. Feingold, 2006: Effect of aerosol on warm convective clouds: Aerosol-cloud-surface flux feedbacks in a new coupled large eddy model. *Journal of Geophysical Research,* **111**, D01202, doi:10.1029/2005JD006138.

Jiang, H., H. Xue, A. Teller, G. Feingold, and Z. Levin, 2006: Aerosol effects on the lifetime of shallow cumulus. *Geophysical Research Letters,* **33**, doi: **10**.1029/2006GL026024.

Jiang, H., G. Feingold, H. H. Jonsson, M.-L. Lu, P. Y. Chuang, R. C. Flagan, J. H. Seinfeld, 2008: Statistical comparison of properties of simulated and observed cumulus clouds in the vicinity of Houston during the Gulf of Mexico Atmospheric Composition and Climate Study (GoMACCS). *Journal of Geophysical Research,* **113**, D13205, doi:10.1029/2007JD009304.

Johnson, D. B., 1982: The role of giant and ultragiant aerosol particles in warm rain initiation. *Journal of the Atmospheric Sciences,* **39**, 448-460.

Jones, G.S., et al., 2005: Sensitivity of global scale attribution results to inclusion of climatic response to black carbon. *Geophysical Research Letters,* **32**:L14701, doi:10.1029/2005GL023370.

Junker, C., and C. Liousse, 2008: A global emission inventory of carbonaceous aerosol from historic records of fossil fuel and biofuel consumption for the period 1860-1997. *Atmospheric Chemistry and Physics,* **8**, 1195-1207.

Kahn, R., P. Banerjee, D. McDonald, and D. Diner, 1998: Sensitivity of multiangle imaging to aerosol optical depth, and to pure-particle size distribution and composition over ocean. *Journal of Geophysical Research,* **103**, 32195-32213.

Kahn, R., P. Banerjee, and D. McDonald, 2001: The sensitivity of multiangle imaging to natural mixtures of aerosols over ocean. *Journal of Geophysical Research,* **106**, 18219-18238.

Kahn, R., J. Ogren, T. Ackerman, et al., 2004: Aerosol data sources and their roles within PARAGON. *Bulletin of the American Meteorological Society,* **85**, 1511-1522.

Kahn, R., R. Gaitley, J. Martonchik, D. Diner, K. Crean, and B. Holben, 2005a: MISR global aerosol optical depth validation based on two years of coincident AERONET observations. *Journal of Geophysical Research,* **110**, D10S04, doi:10.1029/2004JD004706.

Kahn, R., W. Li, J. Martonchik, C. Bruegge, D. Diner, B. Gaitley, W. Abdou, O. Dubovik, B. Holben, A. Smirnov, Z. Jin, and D. Clark, 2005b: MISR low-light-level calibration, and implications for aerosol retrieval over dark water. *Journal of the Atmospheric Sciences,* **62**, 1032-1052.

Kahn, R., W. Li, C. Moroney, D. Diner, J. Martonchik, and E. Fishbein, 2007a: Aerosol source plume physical characteristics from space-based multiangle imaging. *Journal of Geophysical Research,* **112**, D11205, doi:10.1029/2006JD007647.

Kahn, R., et al., 2007b: Satellite-derived aerosol optical depth over dark water from MISR and MODIS: Comparisons with AERONET and implications for climatological studies. *Journal of Geophysical Research,* **112**, D18205, doi:10.1029/2006JD008175.

Kalashnikova, O., and R. Kahn, 2006: Ability of multiangle remote sensing observations to identify and distinguish mineral dust types: Part 2. Sensitivity over dark water. *Journal of Geophysical Research,* **111**:D11207, doi:10.1029/2005JD006756.

Kapustin, V.N., A.D. Clarke, Y. Shinozuka, S. Howell, V. Brekhovskikh, T. Nakajima, and A. Higurashi, 2006: On the determination of a cloud condensation nuclei from satellite: Challenges and possibilities. *Journal of Geophysical Research,* **111**, D04202, doi:10.1029/2004JD005527.

Kaufman, Y., 1987: Satellite sensing of aerosol absorption. *Journal of Geophysical Research,* **92**, 4307-4317.

Kaufman, Y.J., A. Setzer, D. Ward, D. Tanre, B. N. Holben, P. Menzel, M. C. Pereira, and R. Rasmussen, 1992: Biomass Burning Airborne and Spaceborne Experiment in the Amazonas (BASE-A). *Journal of Geophysical Research,* **97**, 14581-14599.

Kaufman, Y. J. and Nakajima, T., 1993: Effect of Amazon smoke on cloud microphysics and albedo—Analysis from satellite imagery. *Journal of Applied Meteorology,* **32**, 729-744.

Kaufman, Y. and R. Fraser, 1997: The effect of smoke particles on clouds and climate forcing. *Science,* **277**, 1636-1639.

Kaufman, Y., D. Tanré, L. Remer, E. Vermote, A. Chu, and B. Holben, 1997: Operational remote sensing of tropospheric aerosol over land from EOS moderate resolution imaging spectroradiometer. *Journal of Geophysical Research,* **102**, 17051-17067.

Kaufman, Y.J., P. V. Hobbs, V. W. J. H. Kirchhoff, P. Artaxo, L. A. Remer, B. N. Holben, M. D. King, D. E. Ward, E. M. Prins, K. M. Longo, L. F. Mattos, C. A. Nobre, J. D. Spinhirne, Q. Ji, A. M. Thompson, J. F. Gleason, and S. A. Christopher, 1998: Smoke, clouds, and radiation—Brazil (SCAR-B) experiment. *Journal of Geophysical Research,* **103**, 31783-31808.

Kaufman, Y., D. Tanré, and O. Boucher, 2002a: A satellite view of aerosols in the climate system. *Nature,* **419**, doi:10.1038/nature01091.

Kaufman, Y., J. Martins, L. Remer, M. Schoeberl, and M. Yamasoe, 2002b: Satellite retrieval of aerosol absorption over the oceans using sunglint. *Geophysical Research Letters,* **29**, 1928, doi:10.1029/2002GL015403.

Kaufman, Y., J. Haywood, P. Hobbs, W. Hart, R. Kleidman, and B. Schmid, 2003: Remote sensing of vertical distributions of smoke aerosol off the coast of Africa. *Geophysical Research Letters,* **30**, 1831, doi:10.1029/2003GL017068.

Kaufman, Y., O. Boucher, D. Tanré, M. Chin, L. Remer, and T. Takemura, 2005a: Aerosol anthropogenic component estimated from satellite data. *Geophysical Research Letters,* **32**, L17804, doi:10.1029/2005GL023125.

Kaufman, Y., L. Remer, D. Tanré, R. Li, R. Kleidman, S. Mattoo, R. Levy, T. Eck, B. Holben, C. Ichoku, J. Martins, and I. Koren, 2005b: A critical examination of the residual cloud contamination and diurnal sampling effects on MODIS estimates of aerosol over ocean. *IEEE Transactions on Geoscience and Remote Sensing* **43**, 2886-2897.

Kaufman, Y. J., I. Koren, L. A. Remer, D. Rosenfeld and Y. Rudich, 2005c: The effect of smoke, dust, and pollution aerosol on shallow cloud development over the Atlantic Ocean. *Proceedings of the National Academy of Sciences,* **102**, 11207-11212.

Kaufman, Y. J. and Koren, I., 2006: Smoke and pollution aerosol effect on cloud cover. *Science,* **313**, 655-658.

Kerr, R., 2007: Another global warming icon comes under attack. *Science,* **317**, 28.

Kiehl, J. T., 2007: Twentieth century climate model response and climate sensitivity. *Geophysical Research Letters,* **34**, doi:10.1029/2007GL031383.

Kim, B.-G., S. Schwartz, M. Miller, and Q. Min, 2003: Effective radius of cloud droplets by ground-based remote sensing: Relationship to aerosol. *Journal of Geophysical Research,* **108**, 4740, doi:10.1029/2003JD003721.

Kim, B.-G., M. A. Miller, S. E. Schwartz, Y. Liu, and Q. Min, 2008: The role of adiabaticity in the aerosol first indirect effect. *Journal of Geophysical Research,* **113**, D05210, doi:10.1029/2007JD008961.

Kim, M.-K., K.-M. Lau, M. Chin, K.-M. Kim, Y. Sud, and G. K. Walker, 2006: Atmospheric teleconnection over Eurasia induced by aerosol radiative forcing during boreal spring. *Proceedings of the National Academy of Sciences,* **19**, 4700-4718.

King, M., Y. Kaufman, D. Tanré, and T. Nakajima, 1999: Remote sensing of tropospheric aerosols: Past, present, and future. *Bulletin of the American Meteorological Society,* **80**, 2229-2259.

King, M., S. Platnick, C. Moeller, Revercomb, and D. Chu, 2003: Remote sensing of smoke, land, and clouds from the NASA ER-2 during SAFARI 2000. *Journal of Geophysical Research,* **108**, 8502, doi:10.1029/2002JD003207.

Kinne, S., M. Schulz, C. Textor, et al., 2006: An AeroCom initial assessment—optical properties in aerosol component modules of global models. *Atmospheric Chemistry and Physics,* **6**, 1815-1834.

Kirchstetter, T.W., R.A. Harley, N.M. Kreisberg, M.R. Stolzenburg, and S.V. Hering, 1999: On-road measurement of fine particle and nitrogen oxide emissions from light- and heavy-duty motor vehicles. *Atmospheric Environment,* **33**, 2955-2968.

Kristjánsson, J. E., Stjern, C. W., Stordal, F., Fjæraa, A. M., Myhre, G., and Jónasson, K., 2008: Cosmic rays, cloud condensation nuclei and clouds—a reassessment using MODIS data, *Atmospheric Chemistry and Physics,* **8**, 7373-7387.

Kleinman, L.I. et al., 2008: The time evolution of aerosol composition over the Mexico City plateau. *Atmospheric Chemistry and Physics,* **8**, 1559-1575.

Kleidman, R., N. O'Neill, L. Remer, Y. Kaufman, T. Eck, D. Tanré, O. Dubovik, and B. Holben, 2005: Comparison of Moderate Resolution Imaging Spectroradiometer (MODIS) and Aerosol Robotic Network (AERONET) remote-sensing retrievals of aerosol fine mode fraction over ocean. *Journal of Geophysical Research,* **110**, D22205, doi:10.1029/2005JD005760.

Knutti, R., T.F. Stocker, F. Joos, and G.-K. Plattner, 2002: Constraints on radiative forcing and future climate change from observations and climate model ensembles. *Nature,* **416**, 719-723.

Knutti, R., T.F. Stocker, F. Joos, and G.-K. Plattner, 2003: Probabilistic climate change projections using neural networks. *Climate Dynamics,* **21**, 257-272.

Koch, D., and J. Hansen, 2005: Distant origins of Arctic black carbon: A Goddard Institute for Space Studies ModelE experiment. *Journal of Geophysical Research,* **110**, D04204, doi:10.1029/2004JD005296.

Koch, D., G. Schmidt, and C. Field, 2006: Sulfur, sea salt and radionuclide aerosols in GISS ModelE. *Journal of Geophysical Research,* **111**, D06206, doi:10.1029/2004JD005550.

Koch, D., T.C. Bond, D. Streets, N. Unger, G.R. van der Werf, 2007: Global impact of aerosols from particular source regions and sectors, *Journal of Geophysical Research,* **112**, D02205, doi:10.1029/2005JD007024.

Kogan, Y. L., D. K. Lilly, Z. N. Kogan, and V. Filyushkin, 1994: The effect of CCN regeneration on the evolution of stratocumulus cloud layers. *Atmospheric Research,* **33**, 137-150.

Koren, I., Y. Kaufman, L. Remer, and J. Martins, 2004: Measurement of the effect of Amazon smoke on inhibition of cloud formation. *Science,* **303**, 1342.

Koren, I., Y.J. Kaufman, D. Rosenfeld, L.A. Remer, and Y. Rudich, 2005: Aerosol invigoration and restructuring of Atlantic convective clouds. *Geophysical Research Letters*, **32**, doi:10.1029/2005GL023187.

Koren, I., L.A. Remer, and K. Longo, 2007a: Reversal of trend of biomass burning in the Amazon. *Geophysical Research Letters,* **34**, L20404, doi:10.1029/2007GL031530.

Koren, I., L.A. Remer, Y.J. Kaufman, Y. Rudich, and J.V. Martins, 2007b: On the twilight zone between clouds and aerosols. *Geophysical Research Letters,* **34**, L08805, doi:10.1029/2007GL029253.

Koren, I., J. V. Martins, L. A. Remer, and H. Afargan, 2008: Smoke invigoration versus inhibition of clouds over the Amazon. *Science,* **321**, 946, doi: 10.1126/science.1159185.

Kroll, J. H., N.L. Ng, S.M. Murphy, R.C. Flagan, and J.H. Seinfeld, 2006: Secondary organic aerosol formation from isoprene photooxidation. *Environmental Science and Technology,* **40**, 1869-1877.

Kruger, O. and H. Grasl, 2002: The indirect aerosol effect over Europe. *Geophysical Research Letters,* **29**, doi:10.1029/2001GL014081.

Lack, D., E. Lovejoy, T. Baynard, A. Pettersson, and A. Ravishankara, 2006: Aerosol absorption measurements using photoacoustic spectroscopy: sensitivity, calibration, and uncertainty developments. *Aerosol Science and Technology,* **40**, 697-708.

Larson, V. E., R. Wood, P. R. Field, J.-C. Golaz, T. H. Vonder Haar, and W. R. Cotton, 2001: Small-scale and mesoscale variability of scalars in cloudy boundary layers: One-dimensional probability density functions. *Journal of the Atmospheric Sciences,* **58**, 1978-1996.

Larson, V.E., J.-C. Golaz, H. Jiang and W.R. Cotton, 2005: Supplying local microphysics parameterizations with information about subgrid variability: Latin hypercube sampling. *Journal of the Atmospheric Sciences,* **62**, 4010-4026.

Lau, K., M. Kim, and K. Kim, 2006: Asian summer monsoon anomalies induced by aerosol direct forcing—the role of the Tibetan Plateau. *Climate Dynamics,* **36**, 855-864, doi:10.1007/s00382-006-10114-z.

Lau, K.-M., and K.-M. Kim, 2006: Observational relationships between aerosol and Asian monsoon rainfall, and circulation. *Geophysical Research Letters,* **33**, L21810, doi:10.1029/2006GL027546.

Lau, K.-M., K.-M. Kim, G. Walker, and Y. C. Sud, 2008: A GCM study of the possible impacts of Saharan dust heating on the water cycle and climate of the tropical Atlantic and Caribbean regions. *Proceedings of the National Academy of Sciences,* (submitted).

Leahy, L., T. Anderson, T. Eck, and R. Bergstrom, 2007: A synthesis of single scattering albedo of biomass burning aerosol over southern Africa during SAFARI 2000. *Geophysical Research Letters,* **34**, L12814, doi:10.1029/2007GL029697.

Leaitch, W. R., G.A. Isaac, J.W. Strapp, C.M. Banic and H.A. Wiebe, 1992: The Relationship between Cloud Droplet Number Concentrations and Anthropogenic Pollution—Observations and Climatic Implications. *Journal of Geophysical Research,* **97**, 2463-2474.

Leaitch, W. R., C. M. Banic, G. A. Isaac, M. D. Couture, P. S. K. Liu, I. Gultepe, S.-M. Li, L. Kleinman, J. I. MacPherson, and P. H. Daum, 1996: Physical and chemical observations in marine stratus during the 1993 North Atlantic Regional Experiment: Factors controlling cloud droplet number concentrations. *Journal of Geophysical Research,* **101**, 29123-29135.

Lee, T., et al., 2006: The NPOESS VIIRS day/night visible sensor. *Bulletin of the American Meteorological Society,* **87**, 191-199.

Lelievel, J., H. Berresheim, S. Borrmann, S., et al., 2002: Global air pollution crossroads over the Mediterranean. *Science,* **298**, 794-799.

Léon, J., D. Tanré, J. Pelon, Y. Kaufman, J. Haywood, and B. Chatenet, 2003: Profiling of a Saharan dust outbreak based on a synergy between active and passive remote sensing. *Journal of Geophysical Research,* **108**, 8575, doi:10.1029/2002JD002774.

Levin, Z. and W. R. Cotton, 2008: *Aerosol pollution impact on precipitation: A scientific review.* Report from the WMO/IUGG International Aerosol Precipitation Science, Assessment Group (IAPSAG), World Meteorological Organization, Geneva, Switzerland, 482 pp.

Levy, R., L. Remer, and O. Dubovik, 2007a: Global aerosol optical properties and application to MODIS aerosol retrieval over land. *Journal of Geophysical Research,* **112**, D13210, doi:10.1029/2006JD007815.

Levy, R., L. Remer, S. Mattoo, E. Vermote, and Y. Kaufman, 2007b: Second-generation algorithm for retrieving aerosol properties over land from MODIS spectral reflectance. *Journal of Geophysical Research,* **112**, D13211, doi:10.1029/2006JD007811.

Lewis, E.R. and S.E. Schwartz, 2004: *Sea Salt Aerosol Production: Mechanisms, Methods, Measurements, and Models—A Critical Review*. Geophysical Monograph Series Vol. **152**, (American Geophysical Union, Washington, 2004), 413 pp. ISBN: 0-87590-417-3.

Li, R., Y. Kaufman, W. Hao, I. Salmon, and B. Gao, 2004: A technique for detecting burn scars using MODIS data. *IEEE Transactions on Geoscience and Remote Sensing,* **42**, 1300-1308.

Li, Z., et al., 2007: Preface to special section on East Asian studies of tropospheric aerosols: An international regional experiment (EAST-AIRE). *Journal of Geophysical Research,* **112**, D22s00, doi:10.0129/2007JD008853.

Lindesay, J. A., M.O. Andreae, J.G. Goldammer, G. Harris, H.J. Annegarn, M. Garstang, R.J. Scholes, and B.W. van Wilgen, 1996: International Geosphere Biosphere Programme/International Global Atmospheric Chemistry SAFARI-92 field experiment: Background and overview. *Journal of Geophysical Research,* **101**, 23521-23530.

Liou, K. N. and S-C. Ou, 1989: The Role of Cloud Microphysical Processes in Climate: An Assessment From a One-Dimensional Perspective. *Journal of Geophysical Research,* **94**, 8599-8607.

Liousse, C., J. E. Penner, C. Chuang, J. J. Walton, H. Eddleman and H. Cachier, 1996: A three-dimensional model study of carbonaceous aerosols. *Journal of Geophysical Research,* **101**, 19411-19432.

Liu, H., R. Pinker, and B. Holben, 2005: A global view of aerosols from merged transport models, satellite, and ground observations. *Journal of Geophysical Research,* **110**, D10S15, doi:10.1029/2004JD004695.

Liu, L., A. A. Lacis, B. E. Carlson, M. I. Mishchenko, and B. Cairns, 2006: Assessing Goddard Institute for Space Studies ModelE aerosol climatology using satellite and ground-based measurements: A comparison study. *Journal of Geophysical Research,* **111**, doi:10.1029/2006JD007334.

Liu, X., J. Penner, B. Das, D. Bergmann, J. Rodriguez, S. Strahan, M. Wang, and Y. Feng, 2007: Uncertainties in global aerosol simulations: Assessment using three meteorological data sets. *Journal of Geophysical Research,* **112**, D11212, doi: **10**.1029/2006JD008216.

Liu, Z., A. Omar, M. Vaughan, J. Hair, C. Kittaka, Y. Hu, K. Powell, C. Trepte, D. Winker, C. Hostetler, R. Ferrare, and R. Pierce, 2008: CALIPSO lidar observations of the optical properties of Saharan dust: A case study of long-range transport. *Journal of Geophysical Research,* **113**, D07207, doi:10.1029/2007JD008878.

Lockwood, M., and C. Frohlich, 2007: Recent oppositely directed trends in solar climate forcings and the global mean surface air temperature. *Proceedings of the Royal Society A*, 1-14, doi:10.1098/rspa.2007.1880.

Loeb, N., and S. Kato, 2002: Top-of-atmosphere direct radiative effect of aerosols over the tropical oceans from the Clouds and the Earth's Radiant Energy System (CERES) satellite instrument. *Proceedings of the National Academy of Sciences,* **15**, 1474-1484.

Loeb, N., and N. Manalo-Smith, 2005: Top-of-Atmosphere direct radiative effect of aerosols over global oceans from merged CERES and MODIS observations. *Journal of Climate,* **18**, 3506-3526.

Loeb, N. G., S. Kato, K. Loukachine, and N. M. Smith, 2005: Angular distribution models for top-of-atmosphere radiative flux estimation from the Clouds and the Earth's Radiant Energy System instrument on the Terra Satellite. part I: Methodology. *Journal of Atmospheric and Oceanic Technology,* **22**, 338–351.

Lohmann, U., J. Feichter, C. C. Chuang, and J. E. Penner, 1999: Prediction of the number of cloud droplets in the ECHAM GCM. *Journal of Geophysical Research,* **104**, 9169-9198.

Lohmann, U., et al., 2001: Vertical distributions of sulfur species simulated by large scale atmospheric models in COSAM: Comparison with observations. *Tellus,* **53B**, 646-672.

Lohmann, U. and J. Feichter, 2005: Global indirect aerosol effects: a review. *Atmospheric Chemistry and Physics,* **5**, 715-737.

Lohmann, U., I. Koren and Y.J. Kaufman, 2006: Disentangling the role of microphysical and dynamical effects in determining cloud properties over the Atlantic. *Geophysical Research Letters,* **33**, L09802, doi:10.1029/2005GL024625.

Lu, M.-L., G. Feingold, H. Jonsson, P. Chuang, H. Gates, R. C. Flagan, J. H. Seinfeld, 2008: Aerosol-cloud relationships in continental shallow cumulus. *Journal of Geophysical Research,* **113**, D15201, doi:10.1029/2007JD009354.

Lubin, D., S. Satheesh, G. McFarquar, and A. Heymsfield, 2002: Longwave radiative forcing of Indian Ocean tropospheric aerosol. *Journal of Geophysical Research,* **107**, 8004, doi:10.1029/2001JD001183.

Lubin, D. and A. Vogelmann, 2006: A climatologically significant aerosol longwave indirect effect in the Arctic. *Nature,* **439**, 453-456.

Luo, Y., D. Lu, X. Zhou, W. Li, and Q. He, 2001: Characteristics of the spatial distribution and yearly variation of aerosol optical depth over China in last 30 years. *Journal of Geophysical Research,* **106**, 14501, doi:10.1029/2001JD900030.

Magi, B., P. Hobbs, T. Kirchstetter, T. Novakov, D. Hegg, S. Gao, J. Redemann, and B. Schmid, 2005: Aerosol properties and chemical apportionment of aerosol optical depth at locations off the United States East Coast in July and August 2001. *Journal of the Atmospheric Sciences,* **62**, 919-933.

Malm, W., J. Sisler, D. Huffman, R. Eldred, and T. Cahill, 1994: Spatial and seasonal trends in particle concentration and optical extinction in the United States. *Journal of Geophysical Research,* **99**, 1347-1370.

Martins, J., D. Tanré, L. Remer, Y. Kaufman, S. Mattoo, and R. Levy, 2002: MODIS cloud screening for remote sensing of aerosol over oceans using spatial variability. *Geophysical Research Letters,* **29**, 10.1029/2001GL013252.

Martonchik, J., D. Diner,R. Kahn, M. Verstraete, B. Pinty, H. Gordon, and T. Ackerman, 1998a: Techniques for the Retrieval of aerosol properties over land and ocean using multiangle data. *IEEE Transactions on Geoscience and Remote Sensing,* **36**, 1212-1227

Martonchik, J., D. Diner, B. Pinty, M. Verstraete, R. Myneni, Y. Knjazikhin, and H. Gordon, 1998b: Determination of land and ocean reflective, radiative, and biophysical properties using multiangle imaging. *IEEE Transactions on Geoscience and Remote Sensing,* **36**, 1266-1281.

Martonchik, J., D. Diner, K. Crean, and M. Bull, 2002: Regional aerosol retrieval results from MISR. *IEEE Transactions on Geoscience and Remote Sensing,* **40**, 1520-1531.

Massie, S., O. Torres, and S. Smith, 2004: Total ozone mapping spectrometer (TOMS) observations of increases in Asian aerosol in winter from 1979 to 2000. *Journal of Geophysical Research,* **109**, D18211, doi:10.1029/2004JD004620.

Matheson, M. A., J. A. Coakley Jr., W. R. Tahnk, 2005: Aerosol and cloud property relationships for summertime stratiform clouds in the northeastern Atlantic from Advanced Very High Resolution Radiometer observations. *Journal of Geophysical Research,* **110**, D24204, doi:10.1029/2005JD006165.

Matsui, T., and R. Pielke, Sr., 2006: Measurement-based estimation of the spatial gradient of aerosol radiative forcing. *Geophysical Research Letters,* **33**, L11813, doi:10.1029/2006GL025974.

Matsui, T., H. Masunaga, S. M. Kreidenweis, R. A. Pielke Sr., W.-K. Tao, M. Chin, Y. J. Kaufman, 2006: Satellite-based assessment of marine low cloud variability associated with aerosol, atmospheric stability, and the diurnal cycle. *Journal of Geophysical Research,* **111**, D17204, doi:10.1029/2005JD006097.

Matthis, I., A. Ansmann, D. Müller, U. Wandinger, and D. Althausen, 2004: Multiyear aerosol observations with dual-wavelength Raman lidar in the framework of EARLINET. *Journal of Geophysical Research,* **109**, D13203, doi:10.1029/2004JD004600.

McComiskey, A., and G. Feingold, 2008: Quantifying error in the radiative forcing of the first aerosol indirect effect, *Geophysical Research Letters*, **35**, L02810, doi:10.1029/2007GL032667.

McComiskey, A., S.E. Schwartz, B. Schmid, H. Guan, E.R. Lewis, P. Ricchiazzi, and J.A. Ogren, 2008a: Direct aerosol forcing: Calculation from observables and sensitivity to inputs. *Journal of Geophysical Research,* **113**, D09202, doi:10.1029/2007JD009170.

McComiskey, A, G. Feingold, A. S. Frisch, D. Turner, M. Miller, J. C. Chiu, Q. Min, and J. Ogren, 2008b: An assessment of aerosol-cloud interactions in marine stratus clouds based on surface remote sensing. *Journal of Geophysical Research*, submitted.

McCormick, R., and J. Ludwig, 1967: Climate modification by atmospheric aerosols. *Science,* **156**, 1358-1359.

McCormick, M. P., L. W. Thomason, and C. R. Trepte 1995: Atmospheric effects of the Mt. Pinatubo eruption. *Nature,* **373**, 399-404.

McFiggans, G., P. Artaxo, U. Baltensberger, H. Coe, M.C. Facchini, G. Feingold, S. Fuzzi, M. Gysel, A. Laaksonen, U. Lohmann, T. F. Mentel, D. M. Murphy, C. D. O'Dowd, J. R. Snider, E. Weingartner, 2006: The effect of physical and chemical aerosol properties on warm cloud droplet activation. *Atmospheric Chemistry and Physics,* **6**, 2593-2649.

Menon, S., A.D. Del Genio, Y. Kaufman, R. Bennartz, D. Koch, N. Loeb, and D. Orlikowski, 2008: Analyzing signatures of aerosol-cloud interactions from satellite retrievals and the GISS GCM to constrain the aerosol indirect effect. *Journal of Geophysical Research,* **113**, D14S22, doi:10.1029/2007JD009442.

Michalsky, J., J. Schlemmer, W. Berkheiser, et al., 2001: Multiyear measurements of aerosol optical depth in the Atmospheric Radiation Measurement and Quantitative Links program. *Journal of Geophysical Research,* **106**, 12099-12108.

Min, Q., and L.C. Harrison, 1996: Cloud properties derived from surface MFRSR measurements and comparison with GEOS results at the ARM SGP site. *Geophysical Research Letters,* **23**, 1641- 1644.

Minnis P., E. F. Harrison, L. L. Stowe, G. G. Gibson, F. M. Denn, D. R. Doelling. and W. L. Smith. Jr., 1993: Radiative climate forcing by the Mount Pinatubo eruption. *Science,* **259**, 411-1415.

Mishchenko, M., I. Geogdzhayev, B. Cairns, W. Rossow, and A. Lacis, 1999: Aerosol retrievals over the ocean by use of channels 1 and 2 AVHRR data: Sensitivity analysis and preliminary results. *Applied Optics,* **38**, 7325-7341.

Mishchenko, M., et al., 2007a: Long-term satellite record reveals likely recent aerosol trend. *Science,* **315**, 1543.

Mishchenko, M., et al., 2007b: Accurate monitoring of terrestrial aerosols and total solar irradiance. *Bulletin of the American Meteorological Society,* **88**, 677-691.

Mishchenko, M., and I. V. Geogdzhayev, 2007: Satellite remote sensing reveals regional tropospheric aerosol trends. *Optics Express,* **15**, 7423-7438.

Mitchell, J. Jr., 1971: The effect of atmospheric aerosols on climate with special reference to temperature near the Earth's surface. *Journal of Applied Meteorology,* **10**, 703-714.

Molina, L. T., S. Madronich, J.S. Gaffney, and H.B. Singh, 2008: Overview of MILAGRO/INTEX-B Campaign. IGAC activities, *Newsletter of International Global Atmospheric Chemistry Project* **38**, 2-15, April, 2008.

Moody, E., M. King, S. Platnick, C. Schaaf, and F. Gao, 2005: Spatially complete global spectral surface albedos: value-added datasets derived from Terra MODIS land products. *IEEE Transactions on Geoscience and Remote Sensing,* **43**, 144-158.

Mouillot, F., A. Narasimha, Y. Balkanski, J.-F. Lamarque, and C.B. Field, 2006: Global carbon emissions from biomass burning in the 20th century. *Geophysical Research Letters,* **33**, L01801, doi:10.1029/2005GL024707.

Murayama, T., N. Sugimoto, I. Uno, I., et al., 2001: Ground-based network observation of Asian dust events of April 1998 in East Asia. *Journal of Geophysical Research,* **106**, 18346-18359.

NRC (National Research Council), 2001: *Climate Change Sciences: An analysis of some key questions*, 42pp., National Academy Press, Washington D.C..

NRC (National Research Council), 2005: *Radiative Forcing of Climate Change: Expanding the Concept and Addessing Uncertainties*, National Academy Press, Washington D.C. (Available at http://www.nap.edu/openbook/0309095069/html).

Nakajima, T., Higurashi, A., Kawamoto, K. and Penner, J. E., 2001: A possible correlation between satellite-derived cloud and aerosol microphysical parameters. *Geophysical Research Letters,* **28**, 1171-1174.

Norris, J., and M. Wild, 2007: Trends in aerosol radiative effects over Europe inferred from observed cloud cover, solar "dimming", and solar "brightening". *Journal of Geophysical Research,* **112**, D08214, doi:10.1029/2006JD007794.

Novakov, T., V. Ramanathan, J. Hansen, T. Kirchstetter, M. Sato, J. Sinton, and J. Sathaye, 2003: Large historical changes of fossil-fuel black carbon emissions. *Geophysical Research Letters,* **30**, 1324, doi:10.1029/2002GL016345.

O'Dowd, C. D., et al. 1999: The relative importance of sea-salt and nss-sulphate aerosol to the marine CCN population: An improved multi-component aerosol-droplet parameterization. *Quarterly Journal of the Royal Meteorological Society,* **125**, 1295-1313.

O'Neill, N., T. Eck, A. Smirnov, B. Holben, and S. Thulasiraman, 2003: Spectral discrimination of coarse and fine mode optical depth. *Journal of Geophysical Research,* **108**(D17), 4559, doi:10.1029/2002JD002975.

Patadia, F., P. Gupta, and S.A. Christopher, 2008: First observational estimates of global clear-sky shortwave aerosol direct radiative effect over land. *Journal of Geophysical Research,* **35**, L04810, doi:10.0129/2007GL032314.

Penner, J., R. Dickinson, and C. O'Neill, 1992: Effects of aerosol from biomass burning on the global radiation budget. *Science,* **256**, 1432-1434.

Penner, J., R. Charlson, J. Hales, et al., 1994: Quantifying and minimizing uncertainty of climate forcing by anthropogenic aerosols, *Bulletin of the American Meteorological Society,* **75**, 375-400.

Penner, J.E., H. Eddleman, and T. Novakov, 1993: Towards the development of a global inventory for black carbon emissions. *Atmospheric Environment,* **27**, 1277-1295.

Penner, J. E. et al., 2002: A comparison of model- and satellite-derived aerosol optical depth and reflectivity. *Journal of the Atmospheric Sciences,* **59**, 441-460.

Penner, J. E., et al. 2006: Model intercomparison of indirect aerosol effects. *Atmospheric Chemistry and Physics,* **6**, 3391-3405.

Pincus, R., and S.A. Klein, 2000: Unresolved spatial variability and microphysical process rates in large-scale models. *Journal of Geophysical Research,* **105**, 27059-27065.

Pinker, R., B. Zhang, and E. Dutton, 2005: Do satellites detect trends in surface solar radiation? *Science,* **308**, 850-854.

Procopio, A. S., P. Artaxo, Y. J. Kaufman, L. A. Remer, J. S. Schafer, and B. N. Holben, 2004: Multiyear analysis of Amazonian biomass burning smoke radiative forcing of climate. *Journal of Geophysical Research,* 31, L03108, doi: 10.1029/2003GL018646.

Qian, Y., W. Wang, L Leung, and D. Kaiser, 2007: Variability of solar radiation under cloud-free skies in China: The role of aerosols. *Geophysical Research Letters,* **34**, L12804, doi:10.1029/2006GL028800.

Quaas, J., and O. Boucher, 2005: Constraining the first aerosol indirect radiative forcing in the LMDZ GCM using POLDER and MODIS satellite data. *Geophysical Research Letters*, **32**, L17814.

Quaas, J., O. Boucher and U. Lohmann, 2006: Constraining the total aerosol indirect effect in the LMDZ GCM and ECHAM4 GCMs using MODIS satellite data. *Atmospheric Chemistry and Physics Discussions,* **5**, 9669-9690.

Quaas, J., O. Boucher, N. Bellouin, and S. Kinne, 2008: Satellite-based estimate of the direct and indirect aerosol climate forcing. *Journal of Geophysical Research,* **113**, D05204, doi:10.1029/2007JD008962.

Quinn, P.K., T. Anderson, T. Bates, R. Dlugi, J. Heintzenberg, W. Von Hoyningen-Huene, M. Kumula, P. Russel, and E. Swietlicki, 1996: Closure in tropospheric aerosol-climate research: A review and future needs for addressing aerosol direct shortwave radiative forcing. *Contributions to Atmospheric Physics,* **69**, 547-577.

Quinn, P.K., D. Coffman, V. Kapustin, T.S. Bates and D.S. Covert, 1998: Aerosol optical properties in the marine boundary layer during ACE 1 and the underlying chemical and physical aerosol properties. *Journal of Geophysical Research,* **103**, 16547-16563.

Quinn P.K., T. Bates, T. Miller, D. Coffman, J. Johnson, J. Harris, J. Ogren, G. Forbes, G., T. Anderson, D. Covert, and M. Rood, 2000: Surface submicron aerosol chemical composition: What fraction is not sulfate? *Journal of Geophysical Research,* **105**, 6785-6806.

Quinn, P.K., T.L. Miller, T.S. Bates, J.A. Ogren, E. Andrews, and G.E. Shaw, 2002: A three-year record of simultaneously measured aerosol chemical and optical properties at Barrow, Alaska. *Journal of Geophysical Research,* **107**(D11), doi:10.1029/2001JD001248.

Quinn, P.K., and T. Bates, 2003: North American, Asian, and Indian haze: Similar regional impacts on climate? *Geophysical Research Letters,* **30**, 1555, doi:10.1029/2003GL016934.

Quinn, P.K., D.J. Coffman, T.S. Bates, E.J. Welton, D.S. Covert, T.L. Miller, J.E. Johnson, S. Maria, L. Russell, R. Arimoto, C.M. Carrico, M.J. Rood, and J. Anderson, 2004: Aerosol optical properties measured aboard the Ronald H. Brown during ACE-Asia as a function of aerosol chemical composition and source region. *Journal of Geophysical Research,* **109**, doi:10.1029/2003JD004010.

Quinn, P.K. and T. Bates, 2005: Regional Aerosol Properties: Comparisons from ACE 1, ACE 2, Aerosols99, INDOEX, ACE Asia, TARFOX, and NEAQS. *Journal of Geophysical Research,* **110**, D14202, doi:10.1029/2004JD004755.

Quinn, P.K., et al., 2005: Impact of particulate organic matter on the relative humidity dependence of light scattering: A simplified parameterization. *Geophysical Research Letters*, **32**, L22809, doi:101029/2005GL024322.

Quinn, P.K., G. Shaw, E. Andrews, E.G. Dutton, T. Ruoho-Airola, S.L. Gong, 2007: Arctic Haze: Current trends and knowledge gaps. *Tellus,* **59B**, 99-114.

Radke, L.F., J.A. Coakley Jr., and M.D. King, 1989: Direct and remote sensing observations of the effects of ship tracks on clouds. *Science,* **246**, 1146-1149.

Raes, F., T. Bates, F. McGovern, and M. van Liedekerke, 2000: The 2nd Aerosol Characterization Experiment (ACE-2): General overview and main results. *Tellus,* **52B**, 111-125.

Ramanathan, V., P. Crutzen, J. Kiehl, and D. Rosenfeld, 2001a: Aerosols, Climate, and the Hydrological Cycle. *Science,* **294**, 2119-2124.

Ramanathan, V., P. Crutzen, J. Lelieveld, et al., 2001b: Indian Ocean Experiment: An integrated analysis of the climate forcing and effects of the great Indo-Asian haze. *Journal of Geophysical Research,* **106**, 28371-28398.

Ramanathan, V., and P. Crutzen, 2003: Atmospheric Brown "Clouds". *Atmospheric Environment,* **37**, 4033-4035.

Ramanathan, V., et al., 2005: Atmospheric brown clouds: Impact on South Asian climate and hydrologic cycle. *Proceedings of the National Academy of Sciences,* USA, **102**, 5326-5333.

Randall, D., M. Khairoutdinov, A. Arakawa, and W. Grabowski, 2003: Breaking the cloud parameterization deadlock. *Bulletin of the American Meteorological Society,* **84**, 1547-1564.

Rao, S., K. Riahi, K. Kupiainen, and Z. Klimont, 2005: Long-term scenarios for black and organic carbon emissions. *Environmental Science,* **2**, 205-216.

Reddy, M., O. Boucher, N. Bellouin, M. Schulz, Y. Balkanski, J. Dufresne, and M. Pham, 2005a: Estimates of multi-component aerosol optical depth and direct radiative perturbation in the LMDZT general circulation model. *Journal of Geophysical Research,* **110**, D10S16, doi:10.1029/2004JD004757.

Reddy, M., O. Boucher, Y. Balkanski, and M. Schulz, 2005b: Aerosol optical depths and direct radiative perturbations by species and source type. *Geophysical Research Letters,* **32**, L12803, doi:10.1029/2004GL021743.

Reid, J., J. Kinney, and D. Wesphal, et al., 2003: Analysis of measurements of Saharan dust by airborne and ground-based remote sensing methods during the Puerto Rico Dust Experiment (PRIDE). *Journal of Geophysical Research,* **108**, 8586, doi:10.1029/2002JD002493.

Reid, J., et al., 2008: An overview of UAE2 flight operations: Observations of summertime atmospheric thermodynamic and aerosol profiles of the southern Arabian Gulf. *Journal of Geophysical Research,* **113**, D14213, doi:10.1029/2007JD009435.

Remer, L., S. Gassó, D. Hegg, Y. Kaufman, and B. Holben, 1997: Urban/industrial aerosol: ground based sun/sky radiometer and airborne *in situ* measurements. *Journal of Geophysical Research,* **102**, 16849-16859.

Remer, L., D. Tanré, Y. Kaufman, C. Ichoku, S. Mattoo, R. Levy, D. Chu, B. Holben, O. Dubovik, A. Smirnov, J. Martins, R. Li, and Z. Ahman, 2002: Validation of MODIS aerosol retrieval over ocean. *Geophysical Research Letters,* **29**, 8008, doi:10.1029/2001/GL013204.

Remer, L., Y. Kaufman, D. Tanré, S. Mattoo, D. Chu, J. Martins, R. Li, C. Ichoku, R. Levy, R. Kleidman, T. Eck, E. Vermote, and B. Holben, 2005: The MODIS aerosol algorithm, products and validation. *Journal of the Atmospheric Sciences,* **62**, 947-973.

Remer, L., and Y. Kaufman, 2006: Aerosol direct radiative effect at the top of the atmosphere over cloud free ocean derived from four years of MODIS data. *Atmospheric Chemistry and Physics,* **6**, 237-253.

Remer, L., et al., 2008: An emerging aerosol climatology from the MODIS satellite sensors, *Journal of Geophysical Research,* **113**, D14S01, doi:10.1029/2007JD009661.

Rissler, J., E. Swietlicki, J. Zhou, G. Roberts, M. O. Andreae, L. V. Gatti, and P. Artaxo 2004: Physical properties of the sub-micrometer aerosol over the Amazon rain forest during the wet-to-dry season transition—comparison of modeled and measured CCN concentrations. *Atmospheric Chemistry and Physics,* **4**, 2119-2143.

Robock, A., 2000: Volcanic eruptions and climate. *Reviews of Geophysics,* **38**(2), 191-219.

Robock, A., 2002: Pinatubo eruption: The climatic aftermath. *Science*, **295**, 1242-1244.

Roderick, M. L. and G. D. Farquhar, 2002: The cause of decreased pan evaporation over the past 50 years. *Science,* **298**, 1410-1411.

Rosenfeld, D., and I. Lansky, 1998: Satellite-based insights into precipitation formation processes in continental and maritime convective clouds. *Bulletin of the American Meteorological Society,* **79**, 2457-2476.

Rosenfeld, D., 2000: Suppression of rain and snow by urban and industrial air pollution. *Science,* **287**, 1793-1796.

Rosenfeld, D., 2006: Aerosols, clouds, and climate. *Science,* **312**, 10.1126/science.1128972.

Ruckstuhl, C., et al., 2008: Aerosol and cloud effects on solar brightening and recent rapid warming. *Geophysical Research Letters,* **35**, L12708, doi:10.1029/2008GL034228.

Russell, P., S. Kinne, and R. Bergstrom, 1997: Aerosol climate effects: local radiative forcing and column closure experiments. *Journal of Geophysical Research,* **102**, 9397-9407.

Russell, P., J. Livingston, P. Hignett, S. Kinne, J. Wong, A. Chien, R. Bergstrom, P. Durkee, and P. Hobbs, 1999: Aerosol-induced radiative flux changes off the United States mid-Atlantic coast: comparison of values calculated from sun photometer and *in situ* data with those measured by airborne pyranometer. *Journal of Geophysical Research,* **104**, 2289-2307.

Saxena, P., L. Hildemann, P. McMurry, and J. Seinfeld, 1995: Organics alter hygroscopic behavior of atmospheric particles. *Journal of Geophysical Research,* **100**, 18755-18770.

Schmid, B., J.M. Livingston, P.B. Russell, P.A. Durkee, H.H. Jonsson, D.R. Collins, R.C. Flagan, J.H. Seinfeld, S. Gasso, D.A. Hegg, E. Ostrom, K.J. Noone, E.J. Welton, K.J. Voss, H.R. Gordon, P. Formenti, and M.O. Andreae, 2000: Clear-sky closure studies of lower tropospheric aerosol and water vapor during ACE-2 using airborne sunphotometer, airborne *in situ*, space-borne, and ground-based measurements. *Tellus,* **52**, 568-593.

Schmid, B., R. Ferrare, C. Flynn, et al., 2006: How well do state-of-the-art techniques measuring the vertical profile of tropospheric aerosol extinction compare? *Journal of Geophysical Research,* **111**, doi:10.1029/2005JD005837, 2006.

Schmidt, G. A., et al., 2006: Present-day atmospheric simulations using GISS Model E: Comparison to *in situ*, satellite and reanalysis data. *Journal of Climate,* **19**, 153-192.

Schulz, M., C. Textor, S. Kinne, et al., 2006: Radiative forcing by aerosols as derived from the AeroCom present-day and pre-industrial simulations. *Atmospheric Chemistry and Physics,* **6**, 5225-5246.

Schwartz, S. E., R. J. Charlson and H. Rodhe, 2007: Quantifying climate change—too rosy a picture? *Nature Reports Climate Change* **2**, 23-24.

Sekiguchi, M., T. Nakajima, K. Suzuki, et al., A study of the direct and indirect effects of aerosols using global satellite data sets of aerosol and cloud parameters. *Journal of Geophysical Research,* **108**, D22, 4699, doi:10.1029/2002JD003359, 2003

Seinfeld, J.H., et al., 1996. *A Plan for a Research Program on Aerosol Radiative Forcing and Climate Change*. National Research Council. 161 pp.

Seinfeld, J. H., G.R. Carmichael, R. Arimoto, et al. 2004: ACE-Asia: Regional climatic and atmospheric chemical effects of Asian dust and pollution. *Bulletin of the American Meteorological Society,* **85**, 367-380.

Sheridan, P., and J. Ogren, 1999: Observations of the vertical and regional variability of aerosol optical properties over central and eastern North America. *Journal of Geophysical Research,* **104**, 16793-16805.

Shindell, D.T., M. Chin, F. Dentener, et al., 2008a: A multi-model assessment of pollution transport to the Arctic. *Atmospheric Chemistry and Physics,* 8, 5353-5372.

Shindell, D.T., H. Levy, II, M.D. Schwarzkopf, L.W. Horowitz, J.-F. Lamarque, and G. Faluvegi, 2008b: Multimodel projections of climate change from short-lived emissions due to human activities. *Journal of Geophysical Research,* **113**, D11109, doi:10.1029/2007JD009152.

Singh, H.B., W.H. Brune, J.H. Crawford, F. Flocke, and D.J. Jacob, 2008: Chemistry and Transport of Pollution over the Gulf of Mexico and the Pacific: Spring 2006 INTEX-B Campaign Overview and First Results. *Atmospheric Chemistry and Physics Discussions*, submitted.

Sinyuk, A., O. Dubovik, B. Holben, T. F. Eck, F.-M. Breon, J. Martonchik, R. A. Kahn, D. Diner, E. F. Vermote, Y. J. Kaurman, J. C. Roger, T. Lapyonok, and I. Slutsker, 2007: Simultaneous retrieval of aerosol and surface properties from a combination of AERONET and satellite data. *Remote Sensing of the Environment,* **107**, 90-108, doi: 10.1016/j.rse.2006.07.022.

Smirnov, A., B. Holben, T. Eck, O. Dubovik, and I. Slutsker, 2000: Cloud screening and quality control algorithms for the AERONET database. *Remote Sensing of the Environment,* **73**, 337-349.

Smirnov, A., B. Holben, T. Eck, I. Slutsker, B. Chatenet, and R. Pinker, 2002: Diurnal variability of aerosol optical depth observed at AERONET (Aerosol Robotic Network) sites. *Geophysical Research Letters,* **29**, 2115, doi:10.1029/2002GL016305.

Smirnov, A., B. Holben, S. Sakerin, et al., 2006: Ship-based aerosol optical depth measurements in the Atlantic Ocean, comparison with satellite retrievals and GOCART model. *Geophysical Research Letters,* **33**, L14817, doi: 10.1029/2006GL026051.

Smith Jr., W.L., et al., 2005: EOS Terra aerosol and radiative flux validation: An overview of the Chesapeake Lighthouse and aircraft measurements from satellites (CLAMS) experiment. *Journal of the Atmospheric Sciences,* **62**, 903-918.

Sokolik, I., D. Winker, G. Bergametti, et al., 2001: Introduction to special section: outstanding problems in quantifying the radiative impacts of mineral dust. *Journal of Geophysical Research,* **106**, 18015-18027.

Sotiropoulou, R.E.P, A. Nenes, P.J. Adams, and J.H. Seinfeld, 2007: Cloud condensation nuclei prediction error from application of Kohler theory: Importance for the aerosol indirect effect. *Journal of Geophysical Research,* **112**, D12202, doi:10.1029/2006JD007834.

Sotiropoulou, R.E.P, J. Medina, and A. Nenes, 2006: CCN predictions: is theory sufficient for assessments of the indirect effect? *Geophysical Research Letters,* **33**, L05816, doi:10.1029/2005GL025148

Spinhirne, J., S. Palm, W. Hart, D. Hlavka, and E. Welton, 2005: Cloud and Aerosol Measurements from the GLAS Space Borne Lidar: initial results. *Geophysical Research Letters,* **32**, L22S03, doi:10.1029/2005GL023507.

Squires, P., 1958: The microstructure and colloidal stability of warm clouds. I. The relation between structure and stability. *Tellus,* **10**, 256-271.

Stanhill, G., and S. Cohen, 2001: Global dimming: a review of the evidence for a widespread and significant reduction in global radiation with discussion of its probable causes and possible agricultural consequences. *Agricultural and Forest Meteorology,* **107**, 255-278.

Stephens, G., D. Vane, R. Boain, G. Mace, K. Sassen, Z. Wang, A. Illingworth, E. O'Conner, W. Rossow, S. Durden, S. Miller, R. Austin, A. Benedetti, and C. Mitrescu, 2002: The CloudSat mission and the A-Train. *Bulletin of the American Meteorological Society,* **83**, 1771-1790.

Stephens, G. L. and J. M. Haynes, 2007: Near global observations of the warm rain coalescence process. *Geophysical Research Letters*, **34**, L20805, doi:10.1029/2007GL030259.

Stern, D.I., 2005: Global sulfur emissions from 1850 to 2000. *Chemosphere,* **58**, 163-175.

Stevens, B., G. Feingold, R. L. Walko and W. R. Cotton, 1996: On elements of the microphysical structure of numerically simulated non-precipitating stratocumulus. *Journal of the Atmospheric Sciences,* **53**, 980-1006.

Storlevmo, T., J.E. Kristjansson, G. Myhre, M. Johnsud, and F. Stordal, 2006: Combined observational and modeling based study of the aerosol indirect effect. *Atmospheric Chemistry and Physics,* **6**, 3583-3601.

Stott, P.A., et al., 2006: Observational constraints on past attributable warming and predictions of future global warming. *Journal of Climate,* **19**, 3055-3069.

Strawa, A., R. Castaneda, T. Owano, P. Baer, and B. Paldus, 2002: The measurement of aerosol optical properties using continuous wave cavity ring-down techniques. *Journal of Atmospheric and Oceanic Technology,***20**, 454-465.

Streets, D., T. Bond, T. Lee, and C. Jang, 2004: On the future of carbonaceous aerosol emissions. *Journal of Geophysical Research,* **109**, D24212, doi:10.1029/2004JD004902.

Streets, D., and K. Aunan, 2005: The importance of China's household sector for black carbon emissions. *Geophysical Research Letters,* **32**, L12708, doi:10.1029/2005GL022960.

Streets, D., Y. Wu, and M. Chin, 2006a: Two-decadal aerosol trends as a likely explanation of the global dimming/brightening transition. *Geophysical Research Letters,* **33**, L15806, doi:10.1029/2006GL026471.

Streets, D., Q. Zhang, L. Wang, K. He, J. Hao, Y. Tang, and G. Carmichael, 2006b: Revisiting China's CO emissions after TRACE-P: Synthesis of inventories, atmospheric modeling and observations *Journal of Geophysical Research,* **111**, D14306, doi:10.1029/2006JD007118.

Svensmark, H. and E. Friis-Christensen, 1997: Variation of cosmic ray flux and global cloud coverage—a missing link in solar-climate relationships. *Journal of Atmospheric and Solar-Terrestrial Physics,* **59**, 1225-1232.

Takemura, T., T. Nakajima, O. Dubovik, B. Holben, and S. Kinne, 2002: Single-scattering albedo and radiative forcing of various aerosol species with a global three-dimensional model. *Proceedings of the National Academy of Sciences*, **15**, 333-352.

Takemura, T., T. Nozawa,S. Emori, T. Nakajima, and T. Nakajima, 2005: Simulation of climate response to aerosol direct and indirect effects with aerosol transport-radiation model. *Journal of Geophysical Research,* **110**, D02202, doi:10.1029/2004JD005029.

Tang, Y., G. Carmichael, I. Uno, J. Woo, G. Kurata, B. Lefer, R. Shetter, H. Huang, B. Anderson, M. Avery, A. Clarke and D. Blake, 2003: Influences of biomass burning during the Transport and Chemical Evolution Over the Pacific (TRACE-P) experiment identified by the regional chemical transport model. *Journal of Geophysical Research,* **108**, 8824, doi:10.1029/2002JD003110.

Tang, Y., G. Carmichael, J. Seinfeld, D. Dabdub, R. Weber, B. Huebert, A. Clarke, S. Guazzotti, D. Sodeman, K. Prather, I. Uno, J. Woo, D. Streets, P. Quinn, J. Johnson, C. Song, A. Sandu, R. Talbot and J. Dibb, 2004: Three-dimensional simulations of inorganic aerosol distributions in East Asia during spring 2001. *Journal of Geophysical Research,* **109**, D19S23, doi:10.1029/2003JD004201.

Tanré, D., Y. Kaufman, M. Herman, and S. Mattoo, 1997: Remote sensing of aerosol properties over oceans using the MODIS/EOS spectral radiances. *Journal of Geophysical Research*, **102**, 16971-16988.

Tanré, D., J. Haywood, J. Pelon, J. Léon, B. Chatenet, P. Formenti, P. Francis, P. Goloub, E. Highwood, and G. Myhre, 2003: Measurement and modeling of the Saharan dust radiative impact: Overview of the Saharan Dust Experiment (SHADE). *Journal of Geophysical Research,* **108**, 8574, doi:10.1029/2002JD003273.

Textor, C., M. Schulz, S. Guibert, et al., 2006: Analysis and quantification of the diversities of aerosol life cycles within AEROCOM. *Atmospheric Chemistry and Physics,* **6**, 1777-1813.

Textor, C., et al., 2007: The effect of harmonized emissions on aerosol properties in global models—an AeroCom experiment. *Atmospheric Chemistry and Physics,* **7**, 4489-4501.

Tie, X. et al., 2005: Assessment of the global impact of aerosols on tropospheric oxidants. *Journal of Geophysical Research,* **110**, doi:10.1029/2004JD005359.

Torres, O., P. Bhartia, J. Herman, Z. Ahmad, and J. Gleason, 1998: Derivation of aerosol properties from satellite measurements of backscattered ultraviolet radiation: Theoretical bases. *Journal of Geophysical Research,* **103**, 17009-17110.

Torres, O., P. Bhartia, J. Herman, A. Sinyuk, P. Ginoux, and B. Holben, 2002: A long-term record of aerosol optical depth from TOMS observations and comparison to AERONET measurements. *Journal of the Atmospheric Sciences,* **59**, 398-413.

Torres, O., P. Bhartia, A. Sinyuk, E. Welton, and B. Holben, 2005: Total Ozone Mapping Spectrometer measurements of aerosol absorption from space: Comparison to SAFARI 2000 ground-based observations. *Journal of Geophysical Research,* **110**, D10S18, doi:10.1029/2004JD004611.

Turco, R.P., O.B. Toon, R.C. Whitten, J.B. Pollack, and P. Hamill, 1983: The global cycle of particulate elemental carbon: a theoretical assessment, in *Precipitation Scavenging, Dry Deposition, and Resuspension*, ed. H.R. Pruppacher et al., pp. 1337-1351, Elsevier Science, New York.

Twomey, S., 1977: The influence of pollution on the shortwave albedo of clouds. *Journal of the Atmospheric Sciences,* 34, 1149-1152.

van Ardenne, J. A., F.J. Dentener, J. Olivier, J. Klein, C.G.M. Goldewijk, and J. Lelieveld, 2001: A 1° x 1° resolution data set of historical anthropogenic trace gas emissions for the period 1890–1990. *Global Biogeochemical Cycles,* **15**, 909-928.

Veihelmann, B., P. F. Levelt, P. Stammes, and J. P. Veefkind, 2007: Simulation study of the aerosol information content in OMI spectral reflectance measurements. *Atmospheric Chemistry and Physics,* **7**, 3115-3127.

Wang, J., S. Christopher, F. Brechtel, J. Kim, B. Schmid, J. Redemann, P. Russell, P. Quinn, and B. Holben, 2003: Geostationary satellite retrievals of aerosol optical thickness during ACE-Asia. *Journal of Geophysical Research,* **108**, 8657, 10.1029/2003JD003580.

Wang, S., Q. Wang, and G. Feingold, 2003: Turbulence, condensation and liquid water transport in numerically simulated non-precipitating stratocumulus clouds. *Journal of the Atmospheric Sciences,* **60**, 262-278.

Warner, J., and S. Twomey, 1967: The production of cloud nuclei by cane fires and the effect on cloud droplet concentration. *Journal of the Atmospheric Sciences,* **24**, 704-706.

Warner, J., 1968: A reduction of rain associated with smoke from sugar-cane fires—An inadvertent weather modification. *Journal of Applied Meteorology,* **7**, 247-251.

Welton, E., K. Voss, P. Quinn, P. Flatau, K. Markowicz, J. Campbell, J. Spinhirne, H. Gordon, and J. Johnson, 2002: Measurements of aerosol vertical profiles and optical properties during INDOEX 1999 using micro-pulse lidars. *Journal of Geophysical Research,* **107**, 8019, doi:10.1029/2000JD000038.

Welton, E., J. Campbell, J. Spinhirne, and V. Scott, 2001: Global monitoring of clouds and aerosols using a network of micro-pulse lidar systems, in Lidar Remote Sensing for Industry and Environmental Monitoring, U. N. Singh, T. Itabe, N. Sugimoto, (eds.), *Proceedings of SPIE*, **4153**, 151-158.

Wen, G., A. Marshak, and R. Cahalan, 2006: Impact of 3D clouds on clear sky reflectance and aerosol retrieval in a biomass burning region of Brazil. *IEEE Geoscience and Remote Sensing Letters*, **3**, 169-172.

Wetzel, M. A. and Stowe, L. L.: Satellite-observed patterns in stratus microphysics, aerosol optical thickness, and shortwave radiative forcing. 1999: *Journal of Geophysical Research,*, **104**, 31287-31299.

Wielicki, B., B. Barkstrom, E. Harrison, R. Lee, G. Smith, and J. Cooper, 1996: Clouds and the Earth's radiant energy system (CERES): An Earth observing system experiment. *Bulletin of the American Meteorological Society,* **77**, 853-868.

Wild, M., H. Gilgen, A. Roesch, et al., 2005: From dimming to brightening: Decadal changes in solar radiation at Earth's surface. *Science,* **308**, 847-850.

Winker, D., R. Couch, and M. McCormick, 1996: An overview of LITE: NASA's Lidar In-Space Technology Experiment. *Proceedings of IEEE,* **84**(2), 164-180.

Winker, D., J. Pelon, and M. McCormick, 2003: The CALIPSO mission: spaceborne lidar for observation of aerosols and clouds. *Proceedings of SPIE,* **4893**, 1-11.

Xue, H., and G. Feingold, 2006: Large eddy simulations of trade-wind cumuli: Investigation of aerosol indirect effects. *Journal of the Atmospheric Sciences,* **63**, 1605-1622.

Xue, H., G. Feingold, and B. Stevens, 2008: Aerosol effects on clouds, precipitation, and the organization of shallow cumulus convection. *Journal of the Atmospheric Sciences,* **65**, 392-406.

Yu, H., S. Liu, and R. Dickinson, 2002: Radiative effects of aerosols on the evolution of the atmospheric boundary layer. *Journal of Geophysical Research,* **107**, 4142, doi:10.1029/2001JD000754.

Yu, H., R. Dickinson, M. Chin, Y. Kaufman, B. Holben, I. Geogdzhayev, and M. Mishchenko, 2003: Annual cycle of global distributions of aerosol optical depth from integration of MODIS retrievals and GOCART model simulations. *Journal of Geophysical Research,* **108**, 4128, doi:10.1029/2002JD002717.

Yu, H., R. Dickinson, M. Chin, Y. Kaufman, M. Zhou, L. Zhou, Y. Tian, O. Dubovik, and B. Holben, 2004: The direct radiative effect of aerosols as determined from a combination of MODIS retrievals and GOCART simulations. *Journal of Geophysical Research,* **109**, D03206, doi:10.1029/2003JD003914.

Yu, H., Y. Kaufman, M. Chin, G. Feingold, L. Remer, T. Anderson, Y. Balkanski, N. Bellouin, O. Boucher, S. Christopher, P. DeCola, R. Kahn, D. Koch, N. Loeb, M. S. Reddy, M. Schulz, T. Takemura, and M. Zhou, 2006: A review of measurement-based assessments of aerosol direct radiative effect and forcing. *Atmospheric Chemistry and Physics,* **6**, 613-666.

Yu, H., R. Fu, R. Dickinson, Y. Zhang, M. Chen, and H. Wang, 2007: Interannual variability of smoke and warm cloud relationships in the Amazon as inferred from MODIS retrievals. *Remote Sensing of the Environment,* **111**, 435-449.

Yu, H., L.A. Remer, M. Chin, H. Bian, R. Kleidman, and T. Diehl, 2008: A satellite-based assessment of trans-Pacific transport of pollution aerosol. *Journal of Geophysical Research,* **113**, D14S12, doi:10.1029/2007JD009349.

Zhang, J., and S. Christopher, 2003: Longwave radiative forcing of Saharan dust aerosols estimated from MODIS, MISR, and CERES observations on Terra. *Geophysical Research Letters,* **30**, 2188, doi:10.1029/2003GL018479.

Zhang, J., S. Christopher, L. Remer, and Y. Kaufman, 2005a: Shortwave aerosol radiative forcing over cloud-free oceans from Terra. I: Angular models for aerosols. *Journal of Geophysical Research,* **110**, D10S23, doi:10.1029/2004JD005008.

Zhang, J., S. Christopher, L. Remer, and Y. Kaufman, 2005b: Shortwave aerosol radiative forcing over cloud-free oceans from Terra. II: Seasonal and global distributions. *Journal of Geophysical Research,* **110**, D10S24, doi:10.1029/2004JD005009.

Zhang, J., J. S. Reid, and B. N. Holben, 2005c: An analysis of potential cloud artifacts in MODIS over ocean aerosol optical thickness products. *Geophysical Research Letters,* **32**, L15803, doi:10.1029/2005GL023254.

Zhang, J., J.S. Reid, D.L. Westphal, N.L. Baker, and E.J. Hyer, 2008: A system for operational aerosol optical depth data assimilation over global oceans. *Journal of Geophysical Research,* **113**, doi:10.1029/2007JD009065.

Zhang, Q. et al., 2007: Ubiquity and dominance of oxygenated species in organic aerosols in anthropogenically-influenced Northern Hemisphere midlatitudes. *Geophysical Research Letters,* **34**, L13801, doi:10.1029/2007GL029979.

Zhang, X., F.W. Zwiers, and P.A. Stott, 2006: Multi-model multi-signal climate change detection at regional scale. *Journal of Climate,* **19**, 4294-4307.

Zhang, X., F.W. Zwiers, G.C. Hegerl, F.H. Lambert, N.P. Gillett, S. Solomon, P.A. Stott, T. Nozawa, 2006: Detection of human influence on twentieth-century precipitation trends. *Nature,* **448**, 461-465, doi:10.1038/nature06025.

Zhao, T. X.-P., I. Laszlo, W. Guo, A. Heidinger, C. Cao, A. Jelenak, D. Tarpley, and J. Sullivan, 2008a: Study of long-term trend in aerosol optical thickness observed from operational AVHRR satellite instrument. *Journal of Geophysical Research,* **113**, D07201, doi:10.1029/2007JD009061.

Zhao, T. X.-P., H. Yu, I. Laszlo, M. Chin, and W.C. Conant, 2008b: Derivation of component aerosol direct radiative forcing at the top of atmosphere for clear-sky oceans. *Journal of Quantitative Spectroscopy and Radiative Transfer,* **109**, 1162-1186.

Zhou, M., H. Yu, R. Dickinson, O. Dubovik, and B. Holben, 2005: A normalized description of the direct effect of key aerosol types on solar radiation as estimated from AERONET aerosols and MODIS albedos. *Journal of Geophysical Research,* **110**, D19202, doi:10.1029/2005JD005909.

Agricultural practices also affect air quality, such as leaving bare soil exposed to wind erosion, and burning agricultural waste. Photo taken from the NASA DC-8 aircraft during ARCTAS-CARB field experiment in June 2008 over California. Credit: Mian Chin, NASA.

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Image 1: Fire in the savanna grasslands of Kruger National Park, South Africa, during the international Southern African Fire-Atmosphere Research Initiative (SAFARI) Experiment, September 1992. Due to extensive and frequent burning of the savanna grass, Africa is the "fire center" of the world. Credit: Joel S. Levine, NASA.

Image 2: Urban pollution in Hong Kong, May 2007. The persistent pollution haze significantly reduces the visibility. Credit: Mian Chin, NASA.

Image 3: Dust storms of northwest Africa captured by Sea-viewing Wide Field-of-view Sensor (SeaWiFS) on February 28, 2000. Credit: SeaWiFS Project at NASA Goddard Space Flight Center.

Image 4: Breaking ocean waves – a source of sea salt aerosols. Credit: Mian Chin, NASA.

Image 5: Clouds at sunset. Clouds and aerosols scatter the sun's rays very effectively when the sun is low in the sky, creating the bright colors of sunrise and sunset. Credit: Mian Chin, NASA.

Image 6: Ship tracks appear when clouds are formed or modified by aerosols released in exhaust from ship smokestacks. Image from MODIS. Credit: NASA.

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