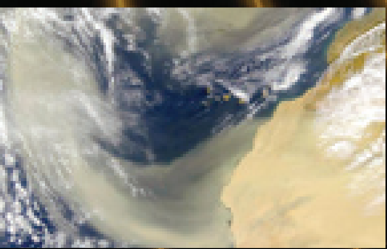
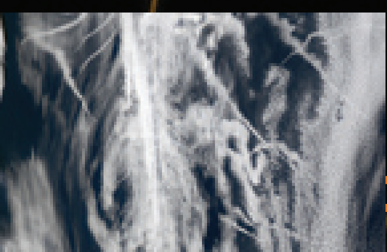
Atmospheric Aerosol Properties and Climate Impacts



U.S. Climate Change Science Program

Synthesis and Assessment Product 2.3

January 2009



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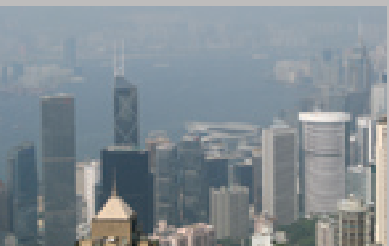
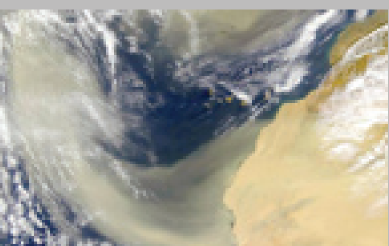
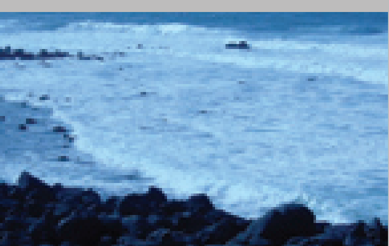


Atmospheric Aerosol Properties and Climate Impacts





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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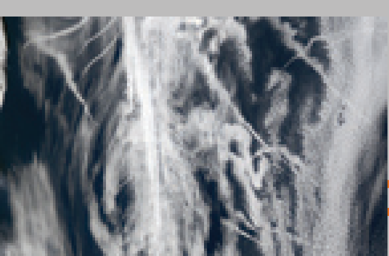

January 2009,

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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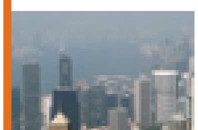

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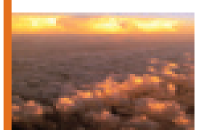

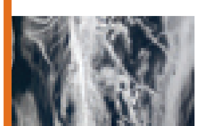

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This Climate Change Science Program Synthesis and Assessment Product (CCSP SAP) 2.3 has been reviewed by a group of experts, the public, and Federal Agencies. The purpose of these independent reviews was to assure the quality of this product.

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Yu, H., P. K. Quinn, G. Feingold, L. A. Remer, R. A. Kahn, M. Chin, and S. E. Schwartz, 2009: Remote Sensing and *In Situ* Measurements of Aerosol Properties, Burdens, and Radiative Forcing, in *Atmospheric Aerosol Properties and Climate Impacts,* A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. [Mian Chin, Ralph A. Kahn, and Stephen E. Schwartz (eds.)]. National Aeronautics and Space Administration, Washington, D.C., USA.

For Chapter 3:

Rind, D., M. Chin, G. Feingold, D. Streets, R. A. Kahn, S. E. Schwartz, and H. Yu, 2009: Modeling the Effects of Aerosols on Climate, in *Atmospheric Aerosol Properties and Climate Impacts,* A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. [Mian Chin, Ralph A. Kahn, and Stephen E. Schwartz (eds.)]. National Aeronautics and Space Administration, Washington, D.C., USA.

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Rind, D., R. A. Kahn, M. Chin, S. E. Schwartz, L. A. Remer, G. Feingold, H. Yu, P. K. Quinn, and R. Halthore, 2009: The Way Forward, in *Atmospheric Aerosol Properties and Climate Impacts,* A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. [Mian Chin, Ralph A. Kahn, and Stephen E. Schwartz (eds.)]. National Aeronautics and Space Administration, Washington, D.C., USA.

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).

The Way Forward

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4.1. Major Research Needs

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

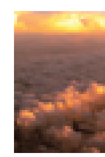
When comparing surface temperature changes calculated by climate models with those observed, the IPCC AR4 noted "broad consistency" between the modeled and observed temperature record over the industrial period. However, understanding of the degree to which anthropogenic aerosols offset the better-established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

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

1. The uncertainty in assessing anthropogenic and aerosol impacts on climate must be much reduced from its current level to allow meaningful projections of future climate. Using statistical methods, IPCC AR4 concluded that the present-day global-average anthropogenic RF is 2.9 ± 0.3 W m^{-2} for long-lived greenhouse gases plus ozone, -1.3 (-2.2 to -0.5) W m^{-2} for aerosol direct plus aerosol-cloud-albedo, and +1.6 (0.6 to 2.4) W m^{-2} for total anthropogenic forcing (Figure 1.3 in Chapter 1). As shown in Chapter 1, the current estimate of total anthropogenic RF yields the transient climate sensitivity range of 0.3 – 1.1°C/(W m^{-2}). This translates to a possible surface temperature increase from 1.2°C to 4.4°C at the time of (equivalent) doubled CO_2 forcing, which will likely occur toward the latter part of this century. Such a range is too wide to meaningfully predict the climate response to increased greenhouse gases.

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

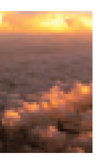
The uncertainty in assessing anthropogenic aerosol impacts on climate must be much reduced from its current level to allow meaningful projections of future climate.



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

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

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



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

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

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

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

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

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

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

4.2. Priorities

4.2.1. Measurements

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

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

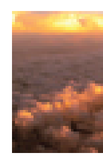


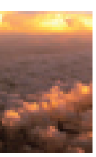
Table 4.1. Summary of current status and future needs of major aerosol measurements from space for characterization of tropospheric aerosol and determination of aerosol climate forcing.

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

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

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

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



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

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

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

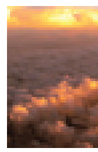
Improve measurement-based techniques for distinguishing anthropogenic from natural aerosols. Current satellite-based estimates of anthropogenic aerosol fraction rely on retrievals of aerosol type. These estimates suffer from limited information content of the data under many circumstances. More needs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

4.2.2. Modeling

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

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

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

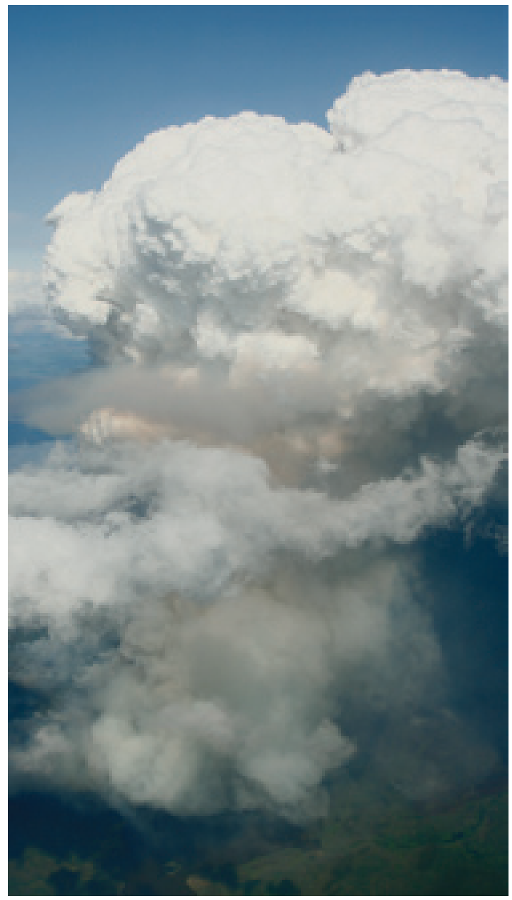


4.2.3. Emissions

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

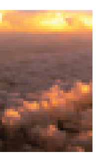
4.3. Concluding Remarks

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



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

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



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

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.

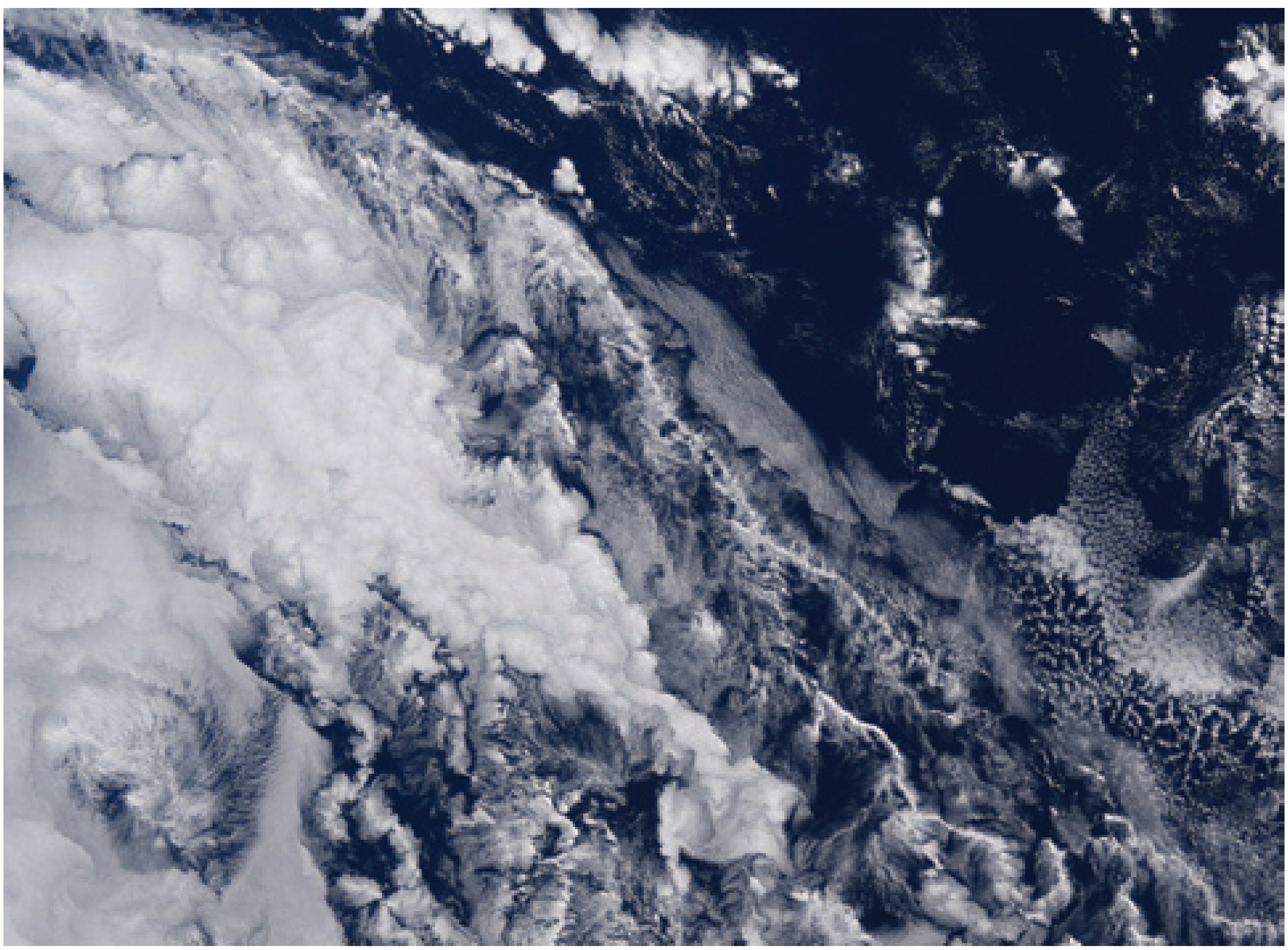
Major reference: *Glossary of Meteorology*, 2nd edition, American Meteorological Society.

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)
$E\tau$	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.

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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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