

# Atmospheric Aerosol Properties and Climate Impacts

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

January 2009

## FEDERAL EXECUTIVE TEAM

Director, Climate Change Science Program: ..... William J. Brennan

Director, Climate Change Science Program Office: ..... Peter A. Schultz

Lead Agency Principal Representative to CCSP,  
Associate Director for Research, Earth Science Division,  
National Aeronautics and Space Administration: ..... Jack Kaye

Lead Agency Point of Contact, Earth Science Division,  
National Aeronautics and Space Administration: ..... Hal Maring

Product Lead, Laboratory for Atmospheres,  
Earth Science Division, Goddard Space Flight Center,  
National Aeronautics and Space Administration: ..... Mian Chin

Chair, Synthesis and Assessment Product Advisory Group  
Associate Director, National Center for Environmental  
Assessment, U.S. Environmental Protection Agency: ..... Michael W. Slimak

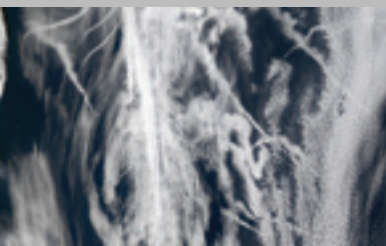
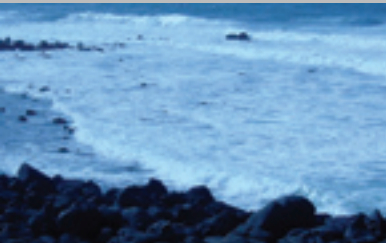
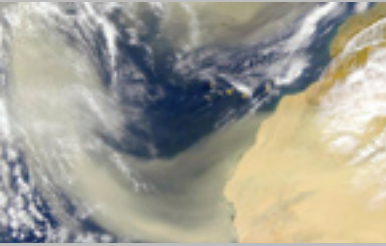
Synthesis and Assessment Product Coordinator,  
Climate Change Science Program Office: ..... Fabien J.G. Laurier

## EDITORIAL AND PRODUCTION TEAM

Editors: ..... Mian Chin, NASA  
..... Ralph A. Kahn, NASA  
..... Stephen E. Schwartz, DOE

Graphic Design: ..... Sally Bensusen, NASA  
..... Debbi McLean, NASA

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

COORDINATING LEAD AUTHOR:

Mian Chin, NASA Goddard Space Flight Center

LEAD AND CONTRIBUTING AUTHORS:

Ralph A. Kahn, Lorraine A. Remer, Hongbin Yu, NASA GSFC;

David Rind, NASA GISS;

Graham Feingold, NOAA ESRL; Patricia K. Quinn, NOAA PMEL;

Stephen E. Schwartz, DOE BNL; David G. Streets, DOE ANL;

Philip DeCola, Rangasayi Halthore, NASA HQ



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,

Carlos M. Gutierrez  
Secretary of Commerce  
Chair, Committee on Climate Change  
Science and Technology Integration

Samuel W. Bodman  
Secretary of Energy  
Vice Chair, Committee on Climate  
Change Science and Technology  
Integration

John H. Marburger III  
Director, Office of Science and  
Technology Policy  
Executive Director, Committee  
on Climate Change Science and  
Technology Integration



**Executive Summary** ..... 1

ES 1. Aerosols and Their Climate Effects ..... 1

    ES 1.1. Atmospheric Aerosols..... 1

    ES 1.2. Radiative Forcing of Aerosols..... 1

    ES 1.3. Reducing Uncertainties in Aerosol Radiative Forcing Estimates ..... 2

ES 2. Measurement-Based Assessment of Aerosol Radiative Forcing..... 2

    ES 2.1. Assessments of Aerosol Direct Radiative Forcing ..... 3

    ES 2.2. Assessments of Aerosol Indirect Radiative Forcing..... 3

ES 3. Model Estimated Aerosol Radiative Forcing and Its Climate Impact..... 4

    ES 3.1. The Importance of Aerosol Radiative Forcing in Climate Models ..... 4

    ES 3.2. Modeling Atmospheric Aerosols..... 4

    ES 3.3. Aerosol Effects on Clouds..... 5

    ES 3.4. Impacts of Aerosols on Climate Model Simulations ..... 5

ES 4. The Way Forward ..... 5

**CHAPTER**



**1** ..... 9

**Introduction**

1.1 Description of Atmospheric Aerosols ..... 9

1.2 The Climate Effects of Aerosols ..... 12

1.3. Reducing Uncertainties in Aerosol-Climate Forcing Estimates ..... 16

1.4 Contents of This Report..... 20



**2** ..... 21

**Remote Sensing and *In Situ* Measurements of Aerosol Properties, Burdens, and Radiative Forcing**

2.1. Introduction ..... 21

2.2. Overview of Aerosol Measurement Capabilities..... 22

    2.2.1. Satellite Remote Sensing..... 22

    2.2.2. Focused Field Campaigns..... 27

    2.2.3. Ground-based *In situ* Measurement Networks ..... 27

    2.2.4. *In situ* Aerosol Profiling Programs..... 28

    2.2.5. Ground-based Remote Sensing Measurement Networks ..... 29

    2.2.6. Synergy of Measurements and Model Simulations..... 32

2.3. Assessments of Aerosol Characterization and Climate Forcing ..... 34

    2.3.1. The Use of Measured Aerosol Properties to Improve Models..... 34

    2.3.2. Intercomparisons of Satellite Measurements and Model Simulation of Aerosol Optical Depth ..... 37

    2.3.3. Satellite Based Estimates of Aerosol Direct Radiative Forcing ..... 38

    2.3.4. Satellite Based Estimates of Anthropogenic Component of Aerosol Direct Radiative Forcing..... 44

    2.3.5. Aerosol-Cloud Interactions and Indirect Forcing ..... 44

2.4. Outstanding Issues ..... 49

2.5. Concluding Remarks ..... 52



**3** ..... 55

**Modeling the Effects of Aerosols on Climate Forcing**

3.1. Introduction ..... 55

3.2. Modeling of Atmospheric Aerosols ..... 56

    3.2.1. Estimates of Emissions ..... 56

    3.2.2. Aerosol Mass Loading and Optical Depth ..... 58

3.3. Calculating Aerosol Direct Radiative Forcing ..... 61

3.4. Calculating Aerosol Indirect Forcing ..... 66

    3.4.1. Aerosol Effects on Clouds ..... 66

    3.4.2. Model Experiments ..... 67

    3.4.3. Additional Aerosol Influences ..... 69

    3.4.4. High Resolution Modeling ..... 70

3.5. Aerosol in the Climate Models ..... 72

    3.5.1. Aerosol in the IPCC AR4 Climate Model Simulations ..... 72

    3.5.2. Additional considerations ..... 77

3.6. Impacts of Aerosols on Climate Model Simulations ..... 78

    3.6.1. Surface Temperature Change ..... 78

    3.6.2. Implications for Climate Model Simulations ..... 81

3.7. Outstanding Issues ..... 81

3.8. Conclusions ..... 82

**4** ..... 85

**The Way Forward**

4.1. Major Research Needs ..... 85

4.2. Priorities ..... 87

    4.2.1. Measurements ..... 87

    4.2.2. Modeling ..... 89

    4.2.3. Emissions ..... 90

4.3. Concluding Remarks ..... 90

**Glossary and Acronyms** ..... 91

**References** ..... 99

## AUTHOR TEAM FOR THIS REPORT

Executive Summary	Lorraine A. Remer, NASA GSFC; Mian Chin, NASA GSFC; Philip DeCola, NASA HQ; Graham Feingold, NOAA ESRL; Rangasayi Halthore, NASA HQ/NRL; Ralph A. Kahn, NASA GSFC; Patricia K. Quinn, NOAA PMEL; David Rind, NASA GISS; Stephen E. Schwartz, DOE BNL; David G. Streets, DOE ANL; Hongbin Yu, NASA GSFC/UMBC
Chapter 1	<b>Lead Authors:</b> Ralph A. Kahn, NASA GSFC; Hongbin Yu, NASA GSFC/UMBC <b>Contributing Authors:</b> Stephen E. Schwartz, DOE BNL; Mian Chin, NASA GSFC; Graham Feingold, NOAA ESRL; Lorraine A. Remer, NASA GSFC; David Rind, NASA GISS; Rangasayi Halthore, NASA HQ/NRL; Philip DeCola, NASA HQ
Chapter 2	<b>Lead Authors:</b> Hongbin Yu, NASA GSFC/UMBC; Patricia K. Quinn, NOAA PMEL; Graham Feingold, NOAA ESRL; Lorraine A. Remer, NASA GSFC; Ralph A. Kahn, NASA GSFC <b>Contributing Authors:</b> Mian Chin, NASA GSFC; Stephen E. Schwartz, DOE BNL
Chapter 3	<b>Lead Authors:</b> David Rind, NASA GISS; Mian Chin, NASA GSFC; Graham Feingold, NOAA ESRL; David G. Streets, DOE ANL <b>Contributing Authors:</b> Ralph A. Kahn, NASA GSFC; Stephen E. Schwartz, DOE BNL; Hongbin Yu, NASA GSFC/UMBC
Chapter 4	David Rind, NASA GISS; Ralph A. Kahn, NASA GSFC; Mian Chin, NASA GSFC; Stephen E. Schwartz, DOE BNL; Lorraine A. Remer, NASA GSFC; Graham Feingold, NOAA ESRL; Hongbin Yu, NASA GSFC/UMBC; Patricia K. Quinn, NOAA PMEL; Rangasayi Halthore, NASA HQ/NRL

## ACKNOWLEDGMENTS

First, the authors wish to acknowledge the late Yoram J. Kaufman both for his inspiration and contributions to aerosol-climate science throughout his career and for his early leadership of the activity that produced this document. His untimely passing left it to the remaining authors to complete this report. Yoram and his contributions to our community are greatly missed.

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.

We wish to thank the following individuals for their expert review of this report: Sundar Christopher (University of Alabama Huntsville), Daniel Jacob (Harvard University), Steven Ghan (Pacific Northwest National Laboratory), John Ogren (NOAA Earth System Research Laboratory), and Susan Solomon (NOAA Earth System Research Laboratory).

We also wish to thank the following individuals/group for their public/federal agency review of this report: Joel D. Scheraga (EPA), Samuel P. Williamson (NOAA/OFCM), Alan Carlin, David L. Hagen, Douglas Hoyt, Forrest M. Mims III (Geronimo Creek observatory), John Pittman, Nathan Taylor (Texas A&M University), Werner Weber (Technische University Dortmund, Germany), and the NOAA Research Council.

The work by Bates et al. (2006), Penner et al. (2006), Yu et al. (2006), Textor et al. (2006), Kinne et al. (2006), Schulz et al. (2006), and the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (2007) provided important groundwork for the material in Chapter 2 and Chapter 3.



## RECOMMENDED CITATIONS

### For the Report as a Whole:

CCSP 2009: *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, 128 pp.

### For the Executive Summary:

Remer, L. A., M. Chin, P. DeCola, G. Feingold, R. Halthore, R. A. Kahn, P. K. Quinn, D. Rind, S. E. Schwartz, D. Streets, and H. Yu, 2009: Executive Summary, 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 1:

Kahn, R. A., H. Yu, S. E. Schwartz, M. Chin, G. Feingold, L. A. Remer, D. Rind, R. Halthore, and P. DeCola, 2009: Introduction, 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 2:

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.

### For Chapter 4:

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).



## Modeling the Effects of Aerosols on Climate

**Lead Authors:** David Rind, NASA GISS; Mian Chin, NASA GSFC; Graham Feingold, NOAA ESRL; David G. Streets, DOE ANL

**Contributing Authors:** Ralph A. Kahn, NASA GSFC; Stephen E. Schwartz, DOE BNL; Hongbin Yu, NASA GSFC/UMBC

### 3.1. Introduction

The IPCC Fourth Assessment Report (AR4) (IPCC, 2007) concludes that man's influence on the warming climate is in the category of "very likely". This conclusion is based on, among other things, the ability of models to simulate the global and, to some extent, regional variations of temperature over the past 50 to 100 years. When anthropogenic effects are included, the simulations can reproduce the observed warming (primarily for the past 50 years); when they are not, the models do not get very much warming at all. In fact, all of the models runs for the IPCC AR4 assessment (more than 20) produce this distinctive result, driven by the greenhouse gas increases that have been observed to occur.

These results were produced in models whose average global warming associated with a doubled  $\text{CO}_2$  forcing of  $4 \text{ W m}^{-2}$  was about  $3^\circ\text{C}$ . This translates into a climate sensitivity (surface temperature change per forcing) of about  $0.75^\circ\text{C}/(\text{W m}^{-2})$ . The determination of climate sensitivity is crucial to projecting the future impact of increased greenhouse gases, and the credibility of this projected value relies on the ability of these models to simulate the observed temperature changes over the past century. However, in producing the observed temperature trend in the past, the models made use of very uncertain aerosol forcing. The greenhouse gas change by itself produces warming in models that exceeds that observed by some 40% on average (IPCC, 2007). Cooling associ-

ated with aerosols reduces this warming to the observed level. Different climate models use differing aerosol forcings, both direct (aerosol scattering and absorption of short and long-wave radiation) and indirect (aerosol effect on cloud cover reflectivity and lifetime), whose magnitudes vary markedly from one model to the next. Kiehl (2007) using nine of the IPCC (2007) AR4 climate models found that they had a factor of three forcing differences in the aerosol contribution for the 20th century. The differing aerosol forcing is the prime reason why models whose climate sensitivity varies by almost a factor of three can produce the observed trend. It was thus concluded that the uncertainty in IPCC (2007) anthropogenic climate simulations for the past century should really be much greater than stated (Schwartz et al., 2007; Kerr, 2007), since, in general, models with low/high sensitivity to greenhouse warming used weaker/stronger aerosol cooling to obtain the same temperature response (Kiehl, 2007). Had the situation been reversed and the low/high sensitivity models used strong/weak aerosol forcing, there would have been a greater divergence in model simulations of the past century.

Therefore, the fact that a model has accurately reproduced the global temperature change in the past does not imply that its future forecast is accurate. This state of affairs will remain until a firmer estimate of radiative forcing (RF) by aerosols, in addition to that by greenhouse gases, is available.

The uncertainty in anthropogenic climate simulation for the past century should be much greater than stated, since models with low/high sensitivity to greenhouse warming used weaker/stronger aerosol cooling to obtain the same temperature response.



Two different approaches are used to assess the aerosol effect on climate. “Forward modeling” studies incorporate different aerosol types and attempt to explicitly calculate the aerosol RF. From this approach, IPCC (2007) concluded that the best estimate of the global aerosol direct RF (compared with preindustrial times) is  $-0.5$  ( $-0.9$  to  $-0.1$ )  $\text{W m}^{-2}$  (see Figure 1.3, Chapter 1). The RF due to the cloud albedo or brightness effect (also referred to as first indirect or Twomey effect) is estimated to be  $-0.7$  ( $-1.8$  to  $-0.3$ )  $\text{W m}^{-2}$ . No estimate was specified for the effect associated with cloud lifetime. The total negative RF due to aerosols according to IPCC (2007) estimates (see Figure 1.3 in Chapter 1) is then  $-1.3$  ( $-2.2$  to  $-0.5$ )  $\text{W m}^{-2}$ . In comparison, the positive radiative forcing (RF) from greenhouse gases (including tropospheric ozone) is estimated to be  $+2.9 \pm 0.3$   $\text{W m}^{-2}$ ; hence tropospheric aerosols reduce the influence from greenhouse gases by about 45% (15–85%). This approach however inherits large uncertainties in aerosol amount, composition, and physical and optical properties in modeling of atmospheric aerosols. The consequences of these uncertainties are discussed in the next section.

Because of the complexity of the processes and composition, and highly inhomogeneous distribution of aerosols, accurately modeling atmospheric aerosols and their effects remains a challenge.



The other method of calculating aerosol forcing is called the “inverse approach” – it is assumed that the observed climate change is primarily the result of the known climate forcing contributions. If one further assumes a particular climate sensitivity (or a range of sensitivities), one can determine what the total forcing had to be to produce the observed temperature change. The aerosol forcing is then deduced as a residual after subtraction of the greenhouse gas forcing along with other known forcings from the total value. Studies of this nature come up with aerosol forcing ranges of  $-0.6$  to  $-1.7$   $\text{W m}^{-2}$  (Knutti et al., 2002, 2003; IPCC AR4 Chap.9);  $-0.4$  to  $-1.6$   $\text{W m}^{-2}$  (Gregory et al., 2002); and  $-0.4$  to  $-1.4$   $\text{W m}^{-2}$  (Stott et al., 2006). This approach however provides a bracket of the possible range of aerosol forcing without the assessment of current knowledge of the complexity of atmospheric aerosols.

This chapter reviews the current state of aerosol RF in the global models and assesses the uncertainties in these calculations. First representation of aerosols in the forward

global chemistry and transport models and the diversity of the model simulated aerosol fields are discussed; then calculation of the aerosol direct and indirect effects in the climate models is reviewed; finally the impacts of aerosols on climate model simulations and their implications are assessed.

### 3.2. Modeling of Atmospheric Aerosols

The global aerosol modeling capability has developed rapidly in the past decade. In the late 1990s, there were only a few global models that were able to simulate one or two aerosol components, but now there are a few dozen global models that simulate a comprehensive suite of aerosols in the atmosphere. As introduced in Chapter 1, aerosols consist of a variety of species including dust, sea salt, sulfate, nitrate, and carbonaceous aerosols (black and organic carbon) produced from natural and man-made sources with a wide range of physical and optical properties. Because of the complexity of the processes and composition, and highly inhomogeneous distribution of aerosols, accurately modeling atmospheric aerosols and their effects remains a challenge. Models have to take into account not only the aerosol and precursor emissions, but also the chemical transformation, transport, and removal processes (e.g. dry and wet depositions) to simulate the aerosol mass concentrations. Furthermore, aerosol particle size can grow in the atmosphere because the ambient water vapor can condense on the aerosol particles. This “swelling” process, called hygroscopic growth, is most commonly parameterized in the models as a function of relative humidity.

#### 3.2.1. ESTIMATES OF EMISSIONS

Aerosols have various sources from both natural and anthropogenic processes. Natural emissions include wind-blown mineral dust, aerosol and precursor gases from volcanic eruptions, natural wild fires, vegetation, and oceans. Anthropogenic sources include emissions from fossil fuel and biofuel combustion, industrial processes, agriculture practices, and human-induced biomass burning.

Following earlier attempts to quantify man-made primary emissions of aerosols (Turco et al., 1983; Penner et al., 1993) systematic work was undertaken in the late 1990s to calculate

emissions of black carbon (BC) and organic carbon (OC), using fuel-use data and measured emission factors (Liousse et al., 1996; Cooke and Wilson, 1996; Cooke et al., 1999). The work was extended in greater detail and with improved attention to source-specific emission factors in Bond et al. (2004), which provides global inventories of BC and OC for the year 1996, with regional and source-category discrimination that includes contributions from industrial, transportation, residential solid-fuel combustion, vegetation and open biomass burning (forest fires, agricultural waste burning, etc.), and diesel vehicles.

Emissions from natural sources—which include wind-blown mineral dust, wildfires, sea salt, and volcanic eruptions—are less well quantified, mainly because of the difficulties of measuring emission rates in the field and the unpredictable nature of the events. Often, emissions must be inferred from ambient observations at some distance from the actual source. As an example, it was concluded (Lewis and Schwartz, 2004) that available information on size-dependent sea salt production rates could only provide order-of-magnitude estimates. The natural emissions in general can vary dramatically over space and time.

Aerosols can be produced from trace gases in the atmospheric via chemical reactions, and those aerosols are called *secondary* aerosols, as distinct from *primary* aerosols that are directly emitted to the atmosphere as aerosol particles. For example, most sulfate and nitrate aerosols are secondary aerosols that are formed from their precursor gases, sulfur dioxide (SO<sub>2</sub>) and nitrogen oxides (NO and NO<sub>2</sub>, collectively called NO<sub>x</sub>), respectively. Those sources have been studied for many years and are relatively well known. By contrast, the sources of secondary organic aerosols (SOA) are poorly understood, including emissions of their precursor gases (called volatile organic compounds, VOC) from both natural and anthropogenic sources and the atmospheric production processes.

Globally, sea salt and mineral dust dominate the total aerosol mass emissions because of the large source areas and/or large particle sizes. However, sea salt and dust also have shorter atmospheric lifetimes because of their large

particle size, and are radiatively less active than aerosols with small particle size, such as sulfate, nitrate, BC, and particulate organic matter (POM, which includes both carbon and non-carbon mass in the organic aerosol, see Glossary), most of which are anthropogenic in origin.

Because the anthropogenic aerosol RF is usually evaluated (e.g., by the IPCC) as the anthropogenic perturbation since the pre-industrial period, it is necessary to estimate the historical emission trends, especially the emissions in the pre-industrial era. Compared to estimates of present-day emissions, estimates of historical emission have much larger uncertainties. Information for past years on the source types and strengths and even locations are difficult to obtain, so historical inventories from pre-industrial times to the present have to be based on limited knowledge and data. Several studies on historical emission inventories of BC and OC (e.g., Novakov et al., 2003; Ito and Penner 2005; Bond et al., 2007; Fernandes et al., 2007; Junker and Liousse, 2008), SO<sub>2</sub> (Stern, 2005), and various species (van Aardenne et al., 2001; Dentener et al., 2006) are available in the literature; there are some similarities and some differences among them, but the emission estimates for early times do not have the rigor of the studies for present-day emissions. One major conclusion from all these studies is that the growth of primary aerosol emissions in the 20th century was not nearly as rapid as the growth in CO<sub>2</sub> emissions. This is because in the late 19th and early 20th centuries, particle emissions such as BC and POM were relatively high due to the heavy use of biofuels and the lack of particulate controls on coal-burning facilities; however, as economic development continued, traditional biofuel use remained fairly constant and particulate emissions from coal burning were reduced by the application of technological controls (Bond et al., 2007). Thus, particle emissions in the 20th century did not grow as fast as CO<sub>2</sub> emissions, as the latter are roughly proportional to total fuel use—oil and gas included. Another challenge is estimating historical biomass burning emissions. A recent study suggested about a 40% increase in carbon emissions from biomass burning from the beginning to the end of last century (Mouillot et al., 2006), but it is difficult to verify.

Aerosols have various sources from both natural and anthropogenic processes, including dust, volcanic eruptions, fires, fossil fuel and biofuel combustion, and agricultural practices.



**Table 3.1. Anthropogenic emissions of aerosols and precursors for 2000 and 1750. Adapted from Dentener et al., 2006.**

Source	Species*	Emission# 2000 (Tg/yr)	Emission 1750 (Tg/yr)
Biomass burning	BC	3.1	1.03
	POM	34.7	12.8
	S	4.1	1.46
Biofuel	BC	1.6	0.39
	POM	9.1	1.56
	S	9.6	0.12
Fossil fuel	BC	3.0	
	POM	3.2	
	S	98.9	

# Data source for 2000 emission: biomass burning – Global Fire Emission Dataset (GFED); biofuel BC and POM – Speciated Pollutant Emission Wizard (SPEW); biofuel sulfur – International Institute for Applied System Analysis (IIASA); fossil fuel BC and POM – SPEW; fossil fuel sulfur – Emission Database for Global Atmospheric Research (EDGAR) and IIASA. Fossil fuel emission of sulfur (S) is the sum of emission from industry, power plants, and transportation listed in Dentener et al., 2006.

\* S=sulfur, including SO<sub>2</sub> and particulate sulfate. Most emitted as SO<sub>2</sub>, and 2.5% emitted as sulfate.

As an example, Table 3.1 shows estimated anthropogenic emissions of sulfur, BC and POM in the present day (year 2000) and pre-industrial time (1750) compiled by Dentener et al., 2006. These estimates have been used in the Aerosol Comparisons between Observations and Models (AeroCom) project (Experiment B, which uses the year 2000 emission; and Experiment PRE, which uses pre-industrial emissions), for simulating atmospheric aerosols and anthropogenic aerosol RF. The AeroCom results are discussed in Sections 3.2.2 and 3.3.

### 3.2.2. AEROSOL MASS LOADING AND OPTICAL DEPTH

In the global models, aerosols are usually simulated in the successive steps of sources (emission and chemical formation), transport (from source location to other area), and removal processes (dry deposition, in which particles fall onto the surface, and wet deposition by rain) that control the aerosol lifetime. Collectively, emission, transport, and removal determine the amount (mass) of aerosols in the atmosphere.

Aerosol optical depth (AOD), which is a measure of solar or thermal radiation being attenuated by aerosol particles via scattering or absorption, can be related to the atmospheric aerosol mass loading as follows:

$$AOD = MEE \cdot M \quad (3.1)$$

where M is the aerosol mass loading per unit area (g m<sup>-2</sup>), MEE is the mass extinction efficiency or specific extinction in unit of m<sup>2</sup> g<sup>-1</sup>, which is

$$MEE = \frac{3Q_{ext}}{4\pi\rho r_{eff}} \cdot f \quad (3.2)$$

where  $Q_{ext}$  is the extinction coefficient (a function of particle size distribution and refractive index),  $r_{eff}$  is the aerosol particle effective radius,  $\rho$  is the aerosol particle density, and  $f$  is the ratio of ambient aerosol mass (wet) to dry aerosol mass M. Here, M is the result from model-simulated atmospheric processes and MEE embodies the aerosol physical (including microphysical) and optical properties. Since  $Q_{ext}$  varies with radiation wavelength, so do MEE and AOD. AOD is the quantity that is most commonly obtained from remote sensing measurements and is frequently used for model evaluation (see Chapter 2). AOD is also a key parameter determining aerosol radiative effects.

Here the results from the recent multiple-global-model studies by the AeroCom project are summarized, as they represent the current assessment of model-simulated atmospheric aerosol loading, optical properties, and RF for the present-day. AeroCom aims to document differences in global aerosol models and com-

pare the model output to observations. Sixteen global models participated in the AeroCom Experiment A (AeroCom-A), for which every model used their own configuration, including their own choice of estimating emissions (Kinne et al., 2006; Textor et al., 2006). Five major aerosol types: sulfate, BC, POM, dust, and sea salt, were included in the experiments,

although some models had additional aerosol species. Of those major aerosol types, dust and sea-salt are predominantly natural in origin, whereas sulfate, BC, and POM have major anthropogenic sources.

Table 3.2 summarizes the model results from the AeroCom-A for several key parameters:

**Table 3.2. Summary of statistics of AeroCom Experiment A results from 16 global models. Data from Textor et al. (2006) and Kinne et al. (2006), and AeroCom website (<http://nansen.ipsl.jussieu.fr/AEROCOM/data.html>).**

Quantity	Mean	Median	Range	Stddev /mean*
<b>Sources (Tg yr<sup>-1</sup>)</b>				
Sulfate	179	186	98-232	22%
Black carbon	11.9	11.3	7.8-19.4	23%
Organic matter	96.6	96.0	53-138	26%
Dust	1840	1640	672-4040	49%
Sea salt	16600	6280	2180-121000	199%
<b>Removal rate (day<sup>-1</sup>)</b>				
Sulfate	0.25	0.24	0.19-0.39	18%
Black carbon	0.15	0.15	0.066-0.19	21%
Organic matter	0.16	0.16	0.09-0.23	24%
Dust	0.31	0.25	0.14-0.79	62%
Sea salt	5.07	2.50	0.95-35.0	188%
<b>Lifetime (day)</b>				
Sulfate	4.12	4.13	2.6-5.4	18%
Black carbon	7.12	6.54	5.3-15	33%
Organic matter	6.54	6.16	4.3-11	27%
Dust	4.14	4.04	1.3-7.0	43%
Sea salt	0.48	0.41	0.03-1.1	58%
<b>Mass loading (Tg)</b>				
Sulfate	1.99	1.98	0.92-2.70	25%
Black carbon	0.24	0.21	0.046-0.51	42%
Organic matter	1.70	1.76	0.46-2.56	27%
Dust	19.2	20.5	4.5-29.5	40%
Sea salt	7.52	6.37	2.5-13.2	54%
<b>MEE at 550 nm (m<sup>2</sup> g<sup>-1</sup>)</b>				
Sulfate	11.3	9.5	4.2-28.3	56%
Black carbon	9.4	9.2	5.3-18.9	36%
Organic matter	5.7	5.7	3.7-9.1	26%
Dust	0.99	0.95	0.46-2.05	45%
Sea salt	3.0	3.1	0.97-7.5	55%
<b>AOD at 550 nm</b>				
Sulfate	0.035	0.034	0.015-0.051	33%
Black carbon	0.004	0.004	0.002-0.009	46%
Organic matter	0.018	0.019	0.006-0.030	36%
Dust	0.032	0.033	0.012-0.054	44%
Sea salt	0.033	0.030	0.02-0.067	42%
<b>Total AOT at 550 nm</b>	<b>0.124</b>	<b>0.127</b>	<b>0.065-0.151</b>	<b>18%</b>

\* Stddev/mean was used as the term “diversity” in Textor et al., 2006.

Globally, sulfate, BC, and POM make up a little over 10% of total aerosol mass in the atmosphere. However, they derive mainly from anthropogenic activity with the highest concentrations in the most populated regions.

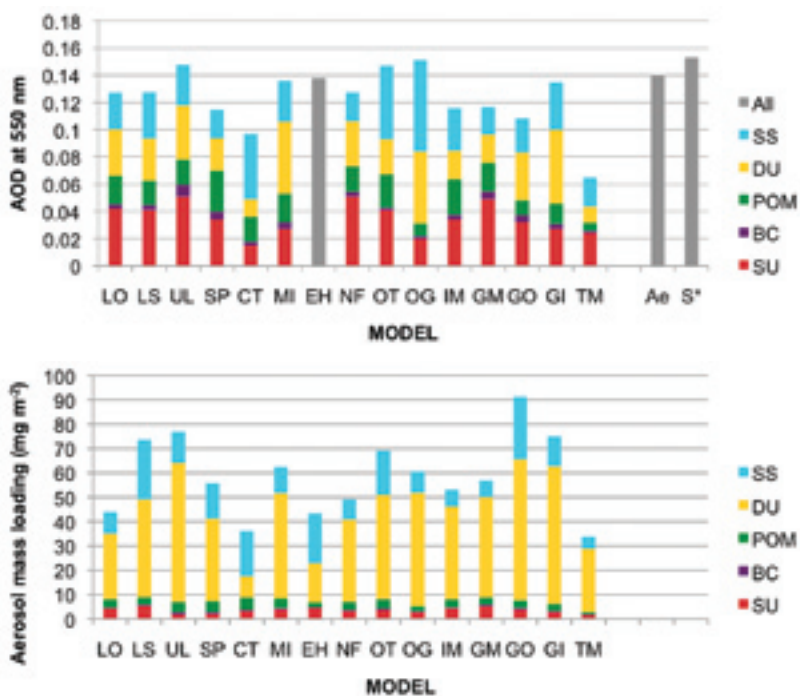
Sources (emission and chemical transformation), mass loading, lifetime, removal rates, and MEE and AOD at a commonly used, mid-visible, wavelength of 550 nanometer (nm). These are the globally averaged values for the year 2000. Major features and conclusions are:

- Globally, aerosol source (in mass) is dominated by sea salt, followed by dust, sulfate, POM, and BC. Over the non-desert land area, human activity is the major source of sulfate, black carbon, and organic aerosols.
- Aerosols are removed from the atmosphere by wet and dry deposition. Although sea salt dominates the emissions, it is quickly removed from the atmosphere because of its large particle size and near-surface distributions, thus having the shortest lifetime. The median lifetime of sea salt from the AeroCom-A models is less than half a day,

whereas dust and sulfate have similar lifetimes of 4 days and BC and POM 6-7 days.

- Globally, small-particle-sized sulfate, BC, and POM make up a little over 10% of total aerosol mass in the atmosphere. However, they are mainly from anthropogenic activity, so the highest concentrations are in the most populated regions, where their effects on climate and air quality are major concerns.
- Sulfate and BC have their highest MEE at mid-visible wavelengths, whereas dust is lowest among the aerosol types modeled. That means for the same amount of aerosol mass, sulfate and BC are more effective at attenuating (scattering or absorbing) solar radiation than dust. This is why the sulfate AOD is about the same as dust AOD even though the atmospheric amount of sulfate mass is 10 times less than that of the dust.
- There are large differences, or diversities, among the models for all the parameters listed in Table 3.2. The largest model diversity, shown as the % standard deviation from the all-model-mean and the range (minimum and maximum values) in Table 3.2, is in sea salt emission and removal; this is mainly associated with the differences in particle size range and source parameterizations in each model. The diversity of sea salt atmospheric loading however is much smaller than that of sources or sinks, because the largest particles have the shortest lifetimes even though they comprise the largest fraction of emitted and deposited mass.

- Among the key parameters compared in Table 3.2, the models agree best for simulated total AOD – the % of standard deviation from the model mean is 18%, with the extreme values just a factor of 2 apart. The median value of the multi-model simulated global annual mean total AOD, 0.127, is also in agreement with the global mean values from recent satellite measurements. However, despite the general agreement in total AOD, there are significant diversities at the individual component level for aerosol optical thickness, mass loading, and mass extinction efficiency. This indicates that uncertainties in assessing aerosol climate forcing are still large, and they depend not only on total AOD but also on aerosol absorption and scattering direction (called asymmetry factor; see next page and Glossary), both of which are determined by aerosol physical



**Figure 3.1.** Global annual averaged AOD (upper panel) and aerosol mass loading (lower panel) with their components simulated by 15 models in AeroCom-A (excluding one model which only reported mass). SU=sulfate, BC=black carbon, POM=particulate organic carbon, DU=dust, SS=sea salt. Model abbreviations: LO=LOA (Lille, Fra), LS=LSCE (Paris, Fra), UL=ULAQ (L'Aquila, Ita), SP=SPRINTARS (Kyushu, Jap), CT=ARQM (Toronto, Can), MI=MIRAGE (Richland, USA), EH=ECHAM5 (MPI-Hamburg, Ger), NF=CCM-Match (NCAR-Boulder, USA), OT=Oslo-CTM (Oslo, Nor), OG=OLSO-GCM (Oslo, Nor) [prescribed background for DU and SS], IM=IMPACT (Michigan, USA), GM=GFDL-Mozart (Princeton, NJ, USA), GO=GOCART (NASA-GSFC, Washington DC, USA), GI=GISS (NASA-GISS, New York, USA), TM=TM5 (Utrecht, Net). Also shown in the upper panel are the averaged observation data from AERONET (Ae) and the satellite composite (S\*). See Kinne et al. (2006) for details. Figure produced from data in Kinne et al. (2006).



and optical properties. In addition, even with large differences in mass loading and MEE among different models, these terms could compensate for each other (eq. 3.1) to produce similar AOD. This is illustrated in Figure 3.1. For example, model LO and LS have quite different mass loading (44 and 74 mg m<sup>-2</sup>, respectively), especially for dust and sea salt amount, but they produce nearly identical total AOD (0.127 and 0.128, respectively).

- Because of the large spatial and temporal variations of aerosol distributions, regional and seasonal diversities are even larger than the diversity for global annual means.

To further isolate the impact of the differences in emissions on the diversity of simulated aerosol mass loading, identical emissions for aerosols and their precursor were used in the AeroCom Experiment B exercise in which 12 of the 16 AeroCom-A models participated (Textor et al., 2007). The comparison of the results and diversity between AeroCom-A and -B for the same models showed that using harmonized emissions does not significantly reduce model diversity for the simulated global mass and AOD fields, indicating that the differences in atmospheric processes, such as transport, removal, chemistry, and aerosol microphysics, play more important roles than emission in creating diversity among the models. This outcome is somewhat different from another recent study, in which the differences in calculated clear-sky aerosol RF between two models (a regional model STEM and a global model MOZART) were attributed mostly to the differences in emissions (Bates et al., 2006), although the conclusion was based on only two model simulations for a few focused regions. It is highly recommended from the outcome of AeroCom-A and -B that, although more detailed evaluation for each individual process is needed, multi-model ensemble results, e.g., median values of multi-model output variables, should be used to estimate aerosol RF, due to their greater robustness, relative to individual models, when compared to observations (Textor et al., 2006, 2007; Schulz et al., 2006).

### 3.3. Calculating Aerosol Direct Radiative Forcing

The three parameters that define the aerosol direct RF are the AOD, the single scattering

albedo (SSA), and the asymmetry factor ( $g$ ), all of which are wavelength dependent. AOD is indicative of how much aerosol exists in the column, SSA is the fraction of radiation being scattered versus the total attenuation (scattered and absorbed), and the  $g$  relates to the direction of scattering that is related to the size of the particles (see Chapter 1). An indication of the particle size is provided by another parameter, the Ångström exponent ( $\text{Å}$ ), which is a measure of differences of AOD at different wavelengths. For typical tropospheric aerosols,  $\text{Å}$  tends to be inversely dependent on particle size; larger values of  $\text{Å}$  are generally associated with smaller aerosols particles. These parameters are further related; for example, for a given composition, the ability of a particle to scatter radiation decreases more rapidly with decreasing size than does its ability to absorb, so at a given wavelength varying  $\text{Å}$  can change SSA. Note that AOD, SSA,  $g$ ,  $\text{Å}$ , and all the other parameters in eq. 3.1 and 3.2 vary with space and time due to variations of both aerosol composition and relative humidity, which influence these characteristics.

In the recent AeroCom project, aerosol direct RF for the solar spectral wavelengths (or short-wave) was assessed based on the 9 models that participated in both Experiment B and PRE in which identical, prescribed emissions for present (year 2000) and pre-industrial time (year 1750) listed in Table 3.1 were used across the models (Schulz et al., 2006). The anthropogenic direct RF was obtained by subtracting AeroCom-PRE from AeroCom-B simulated results. Because dust and sea salt are predominantly from natural sources, they were not included in the anthropogenic RF assessment although the land use practice can contribute to dust emissions as “anthropogenic”. Other aerosols that were not considered in the AeroCom forcing assessment were natural sulfate (e.g. from volcanoes or ocean) and POM (e.g. from biogenic hydrocarbon oxidation), as well as nitrate. The aerosol direct forcing in the AeroCom assessment thus comprises three major anthropogenic aerosol components sulfate, BC, and POM.

The IPCC AR4 (IPCC, 2007) assessed anthropogenic aerosol RF based on the model results published after the IPCC TAR in 2001, including those from the AeroCom study discussed above. These results (adopted from IPCC

There are large differences in simulated aerosol fields among the models.



AR4) are shown in Table 3.3 for sulfate and Table 3.4 for carbonaceous aerosols (BC and POM), respectively. All values listed in Table 3.3 and 3.4 refer to anthropogenic perturbation, i.e., excluding the natural fraction of these aerosols. In addition to the mass burden, MEE,

and AOD, Table 3.3 and 3.4 also list the “normalized forcing”, also known as “forcing efficiency”, one for the forcing per unit AOD, and the other the forcing per gram of aerosol mass (dry). For some models, aerosols are externally mixed, that is, each aerosol particle contains

**Table 3.3. Sulfate mass loading, MEE and AOD at 550 nm, shortwave radiative forcing at the top of the atmosphere, and normalized forcing with respect to AOD and mass. All values refer to anthropogenic perturbation. Adapted from IPCC AR4 (2007) and Schulz et al. (2006).**

Model	Mass load (mg m <sup>-2</sup> )	MEE (m <sup>2</sup> g <sup>-1</sup> )	AOD at 550 nm	TOA Forcing (W m <sup>-2</sup> )	Forcing/AOD (W m <sup>-2</sup> )	Forcing/mass (W g <sup>-1</sup> )
<b>Published since IPCC 2001</b>						
A CCM3	2.23			-0.56		-251
B GEOSCHEM	1.53	11.8	0.018	-0.33	-18	-216
C GISS	3.30	6.7	0.022	-0.65	-30	-197
D GISS	3.27			-0.96		-294
E GISS*	2.12			-0.57		-269
F SPRINTARS	1.55	9.7	0.015	-0.21		-135
G LMD	2.76			-0.42		-152
H LOA	3.03	9.9	0.03	-0.41	-14	-135
I GATORG	3.06			-0.32		-105
J PNNL	5.50	7.6	0.042	-0.44	-10	-80
K UIO-CTM	1.79	10.6	0.019	-0.37	-19	-207
L UIO-GCM	2.28			-0.29		-127
<b>AeroCom: Identical emissions used for year 2000 and 1750</b>						
M UMI	2.64	7.6	0.02	-0.58	-29	-220
N UIO-CTM	1.70	11.2	0.019	-0.36	-19	-212
O LOA	3.64	9.6	0.035	-0.49	-14	-135
P LSCE	3.01	7.6	0.023	-0.42	-18	-140
Q ECHAM5-HAM	2.47	6.5	0.016	-0.46	-29	-186
R GISS**	1.34	4.5	0.006	-0.19	-32	-142
S UIO-GCM	1.72	7.0	0.012	-0.25	-21	-145
T SPRINTARS	1.19	10.9	0.013	-0.16	-12	-134
U ULAQ	1.62	12.3	0.02	-0.22	-11	-136
<b>Average A-L</b>	<b>2.70</b>	<b>9.4</b>	<b>0.024</b>	<b>-0.46</b>	<b>-18</b>	<b>-181</b>
<b>Average M-U</b>	<b>2.15</b>	<b>8.6</b>	<b>0.018</b>	<b>-0.35</b>	<b>-21</b>	<b>-161</b>
<b>Minimum A-U</b>	<b>1.19</b>	<b>4.5</b>	<b>0.006</b>	<b>-0.96</b>	<b>-32</b>	<b>-294</b>
<b>Maximum A-U</b>	<b>5.50</b>	<b>12.3</b>	<b>0.042</b>	<b>-0.16</b>	<b>-10</b>	<b>-80</b>
<b>Std dev A-L</b>	<b>1.09</b>	<b>1.9</b>	<b>0.010</b>	<b>0.202</b>	<b>7</b>	<b>68</b>
<b>Std dev M-U</b>	<b>0.83</b>	<b>2.6</b>	<b>0.008</b>	<b>0.149</b>	<b>8</b>	<b>35</b>
<b>%Stddev/avg A-L</b>	<b>40%</b>	<b>20%</b>	<b>41%</b>	<b>44%</b>	<b>38%</b>	<b>38%</b>
<b>%Stddev/avg M-U</b>	<b>39%</b>	<b>30%</b>	<b>45%</b>	<b>43%</b>	<b>37%</b>	<b>22%</b>

Model abbreviations: CCM3=Community Climate Model; GEOSCHEM=Goddard Earth Observing System-Chemistry; GISS=Goddard Institute for Space Studies; SPRINTARS=Spectral Radiation-Transport Model for Aerosol Species; LMD=Laboratoire de Meteorologie Dynamique; LOA=Laboratoire d’Optique Atmospherique; GATORG=Gas, Aerosol Transport and General circulation model; PNNL=Pacific Northwest National Laboratory; UIO-CTM=Univeristy of Oslo CTM; UIO-GCM=University of Oslo GCM; UMI=University of Michigan; LSCE=Laboratoire des Sciences du Climat et de l’Environnement; ECHAM5-HAM=European Centre Hamburg with Hamburg Aerosol Module; ULAQ=University of IL’Aquila.

only one aerosol type such as sulfate, whereas other models allow aerosols to mix internally to different degrees, that is, each aerosol particle can have more than one component, such as black carbon coated with sulfate. For models with internal mixing of aerosols, the compo-

nent values for AOD, MEE, and forcing were extracted (Schulz et al., 2006).

Considerable variation exists among these models for all quantities in Table 3.3 and 3.4. The RF for all the components varies by a factor of

**Table 3.4. Particulate organic matter (POM) and black carbon (BC) mass loading, AOD at 550 nm, shortwave radiative forcing at the top of the atmosphere, and normalized forcing with respect to AOD and mass. All values refer to anthropogenic perturbation. Based on IPCC AR4 (2007) and Schulz et al. (2006).**

Model	POM						BC					
	Mass load (mg m <sup>-2</sup> )	MEE (m <sup>2</sup> g <sup>-1</sup> )	AOD at 550 nm	TOA Forcing (W m <sup>-2</sup> )	Forcing/AOD (W m <sup>-2</sup> )	Forcing/mass (W g <sup>-1</sup> )	Mass load (mg m <sup>-2</sup> )	MEE (m <sup>2</sup> g <sup>-1</sup> )	AOD at 550 nm x1000	TOA Forcing (W m <sup>-2</sup> )	Forcing/AOD (W m <sup>-2</sup> )	Forcing/mass (W g <sup>-1</sup> )
<b>Published since IPCC 2001</b>												
A SPRINTARS				-0.24		-107				0.36		
B LOA	2.33	6.9	0.016	-0.25	-16	-140	0.37			0.55		
C GISS	1.86	9.1	0.017	-0.26	-15	-161	0.29			0.61		
D GISS	1.86	8.1	0.015	-0.30	-20	-75	0.29			0.35		
E GISS*	2.39			-0.18		-92	0.39			0.50		
F GISS	2.49			-0.23		-101	0.43			0.53		
G SPRINTARS	2.67	10.9	0.029	-0.27	-9	-23	0.53			0.42		
H GATORG	2.56			-0.06		-112	0.39			0.55		
I MOZGN	3.03	5.9	0.018	-0.34	-19							
J CCM							0.33			0.34		
K UIO-GCM							0.30			0.19		
<b>AeroCom: Identical emissions for year 2000 &amp; 1750</b>												
L UMI	1.16	5.2	0.0060	-0.23	-38	-198	0.19	6.8	1.29	0.25	194	1316
M UIO-CTM	1.12	5.2	0.0058	-0.16	-28	-143	0.19	7.1	1.34	0.22	164	1158
N LOA	1.41	6.0	0.0085	-0.16	-19	-113	0.25	7.9	1.98	0.32	162	1280
O LSCE	1.50	5.3	0.0079	-0.17	-22	-113	0.25	4.4	1.11	0.30	270	1200
P ECHAM5-HAM	1.00	7.7	0.0077	-0.10	-13	-100	0.16	7.7	1.23	0.20	163	1250
Q GISS**	1.22	4.9	0.0060	-0.14	-23	-115	0.24	7.6	1.83	0.22	120	917
R UIO-GCM	0.88	5.2	0.0046	-0.06	-13	-68	0.19	10.3	1.95	0.36	185	1895
S SPRINTARS	1.84	10.9	0.0200	-0.10	-5	-54	0.37	9.5	3.50	0.32	91	865
T ULAQ	1.71	4.4	0.0075	-0.09	-12	-53	0.38	7.6	2.90	0.08	28	211
<b>Average A-K</b>	<b>2.40</b>	<b>8.2</b>	<b>0.019</b>	<b>-0.24</b>	<b>-16</b>	<b>-102</b>	<b>0.37</b>			<b>0.44</b>		<b>1242</b>
<b>Average L-T</b>	<b>1.32</b>	<b>6.1</b>	<b>0.008</b>	<b>-0.13</b>	<b>-19</b>	<b>-106</b>	<b>0.25</b>	<b>7.7</b>	<b>1.90</b>	<b>0.25</b>	<b>153</b>	<b>1121</b>
<b>Minimum A-T</b>	<b>0.88</b>	<b>4.4</b>	<b>0.005</b>	<b>-0.34</b>	<b>-38</b>	<b>-198</b>	<b>0.16</b>	<b>4.4</b>	<b>1.11</b>	<b>0.08</b>	<b>28</b>	<b>211</b>
<b>Maximum A-T</b>	<b>3.03</b>	<b>10.9</b>	<b>0.029</b>	<b>-0.06</b>	<b>-5</b>	<b>-23</b>	<b>0.53</b>	<b>10.3</b>	<b>3.50</b>	<b>0.61</b>	<b>270</b>	<b>2103</b>
<b>Std dev A-K</b>	<b>0.39</b>	<b>1.7</b>	<b>0.006</b>	<b>0.09</b>	<b>4</b>	<b>41</b>	<b>0.08</b>			<b>0.06</b>		<b>384</b>
<b>Std dev L-T</b>	<b>0.32</b>	<b>2.0</b>	<b>0.005</b>	<b>0.05</b>	<b>10</b>	<b>46</b>	<b>0.08</b>	<b>1.6</b>	<b>0.82</b>	<b>0.09</b>	<b>68</b>	<b>450</b>
<b>%Stddev/avg A-K</b>	<b>16%</b>	<b>21%</b>	<b>30%</b>	<b>36%</b>	<b>26%</b>	<b>41%</b>	<b>22%</b>			<b>23%</b>		<b>31%</b>
<b>%Stddev/avg L-T</b>	<b>25%</b>	<b>33%</b>	<b>56%</b>	<b>39%</b>	<b>52%</b>	<b>43%</b>	<b>32%</b>	<b>21%</b>	<b>43%</b>	<b>34%</b>	<b>45%</b>	<b>40%</b>

Although black carbon has the lowest mass loading and optical depth, it is the only aerosol species that absorbs strongly, causing positive forcing to warm the atmosphere, in contrast to other aerosols that impose negative forcing to cool the atmosphere.

6 or more: Sulfate from 0.16 to 0.96  $W m^{-2}$ , POM from -0.06 to -0.34  $W m^{-2}$ , and BC from +0.08 to +0.61  $W m^{-2}$ , with the standard deviation in the range of 30 to 40% of the ensemble mean. It should be noted that although BC has the lowest mass loading and AOD, it is the only aerosol species that absorbs strongly, causing positive forcing to warm the atmosphere, in contrast to other aerosols that impose negative forcing to cool the atmosphere. As a result, the net anthropogenic aerosol forcing as a whole becomes less negative when BC is included. The global average anthropogenic aerosol direct RF at the top of the atmosphere (TOA) from the models, together with observation-based estimates (see Chapter 2), is presented in Figure 3.2. Note the wide range for forcing in Figure 3.2. The comparison with observation-based estimates shows that the model estimated forcing is in general lower, partially because the forcing value from the model is the difference between present-day and pre-industrial time, whereas the observation-derived quantity is the difference between an atmosphere with and without anthropogenic aerosols, so the “background” value that is subtracted from the total forcing is higher in the models.

The discussion so far has dealt with global average values. The geographic distributions of multi-model aerosol direct RF has been evaluated among the AeroCom models, which are shown in Figure 3.3 for total and anthropogenic AOD at 550 nm and anthropogenic aerosol RF at TOA, within the atmospheric column, and at the surface. Globally, anthropogenic AOD is about 25% of total AOD (Figure 3.3a and b) but is more concentrated over polluted regions in Asia, Europe, and North America and biomass burning regions in tropical southern Africa and South America. At TOA, anthropogenic aerosol causes negative forcing over mid-latitude continents and oceans with the most negative values (-1 to -2  $W m^{-2}$ ) over polluted regions (Figure 3.3c). Although anthropogenic aerosol has a cooling effect at the surface with surface forcing values down to -10  $W m^{-2}$  over China, India, and tropical Africa (Figure 3.3e), it warms the atmospheric column with the largest effects again over the polluted and biomass burning regions over the polluted and biomass burning regions. This heating effect will change the atmospheric circulation and can affect the weather and precipitation (e.g., Kim et al., 2006).

Basic conclusions from forward modeling of aerosol direct RF are:

- The most recent estimate of all-sky short-wave aerosol direct RF at TOA from anthropogenic sulfate, BC, and POM (mostly from fossil fuel/biofuel combustion and biomass burning) is  $-0.22 \pm 0.18 W m^{-2}$  averaged globally, exerting a net cooling effect. This value would represent the low-end of the forcing magnitude, since some potentially significant anthropogenic aerosols, such as nitrate and dust from human activities are not included because of their highly uncertain sources and processes. IPCC AR4 had adjusted the total anthropogenic aerosol direct RF to  $-0.5 \pm 0.4 W m^{-2}$  by adding estimated anthropogenic nitrate and dust forcing values based on limited modeling studies and by considering the observation-based estimates (see Chapter 2).
- Both sulfate and POM negative forcing whereas BC causes positive forcing because of its highly absorbing nature. Although BC comprises only a small fraction of anthropogenic aerosol mass load and AOD, its forcing efficiency (with respect to either AOD or mass) is an order of magnitude stronger than sulfate and POM, so its positive shortwave forcing largely offsets the negative forcing

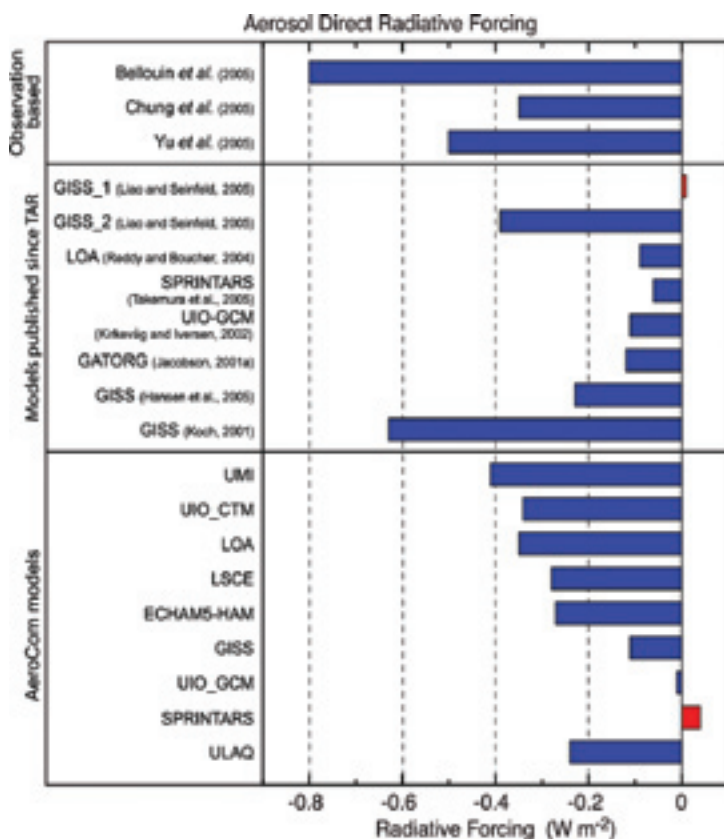
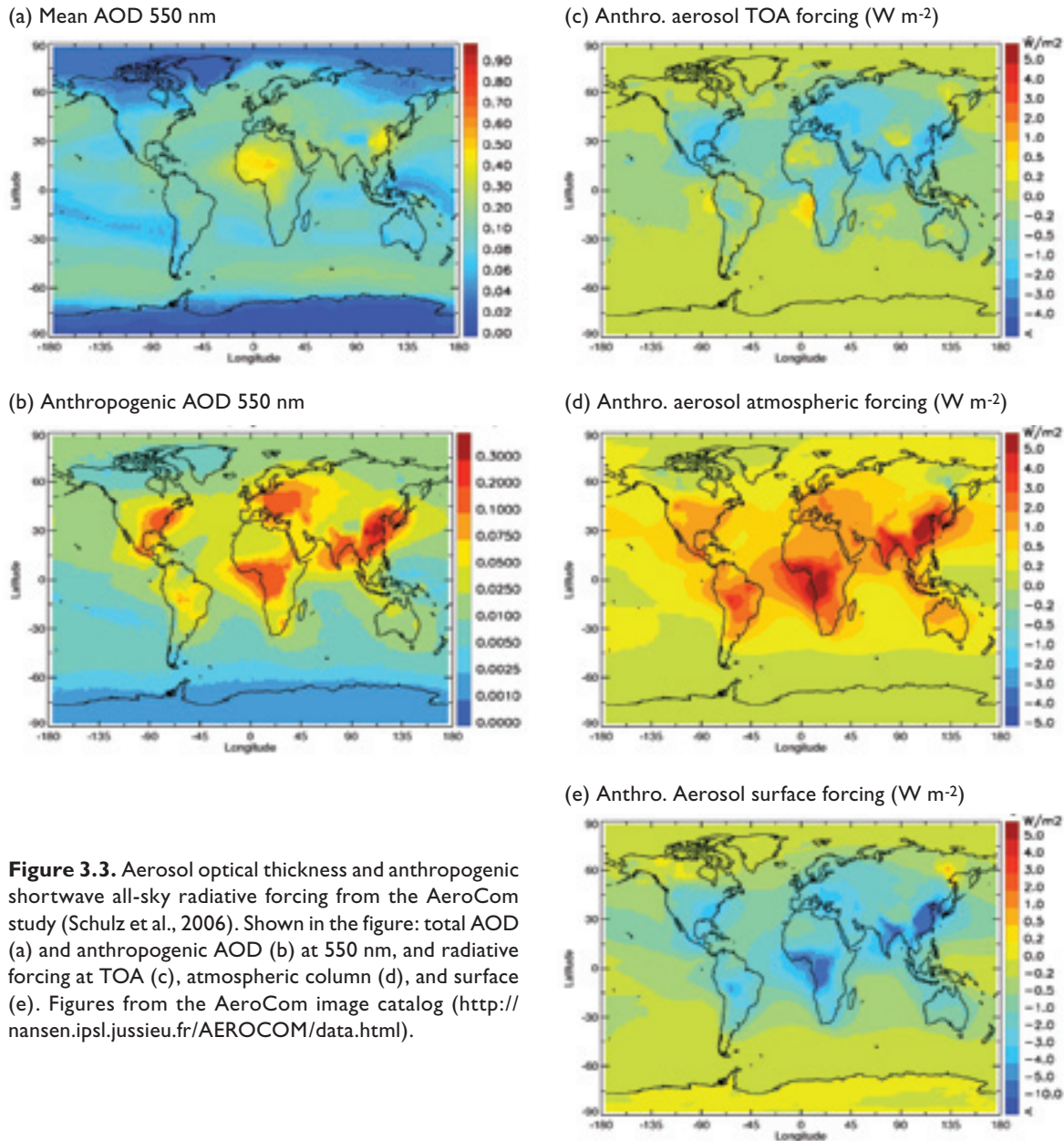


Figure 3.2. Aerosol direct radiative forcing in various climate and aerosol models. Observed values are shown in the top section. From IPCC (2007).



**Figure 3.3.** Aerosol optical thickness and anthropogenic shortwave all-sky radiative forcing from the AeroCom study (Schulz et al., 2006). Shown in the figure: total AOD (a) and anthropogenic AOD (b) at 550 nm, and radiative forcing at TOA (c), atmospheric column (d), and surface (e). Figures from the AeroCom image catalog (<http://nansen.ipsl.jussieu.fr/AEROCOM/data.html>).

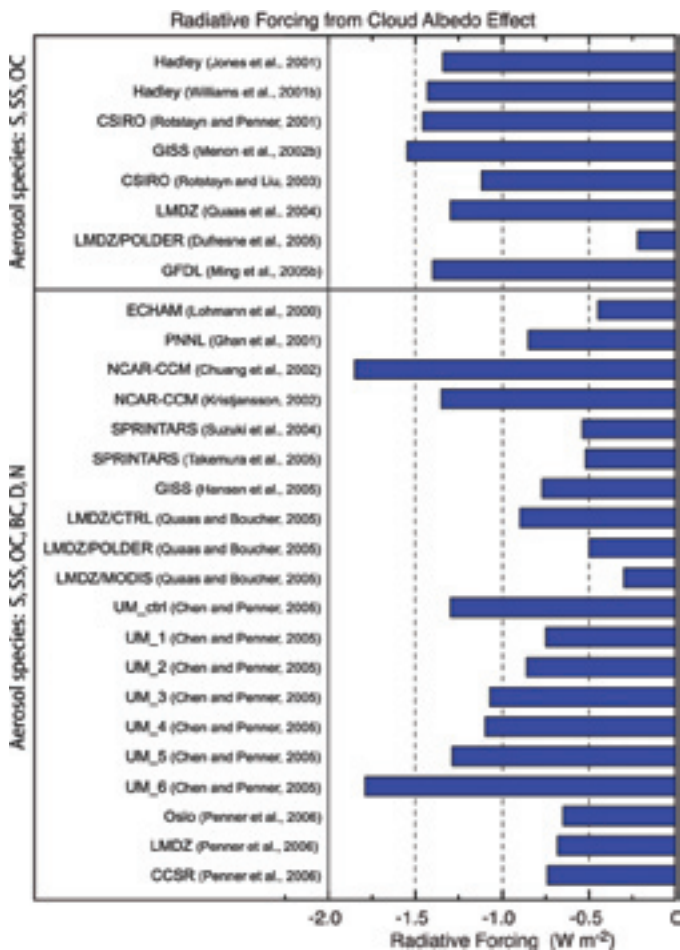
from sulfate and POM. This points out the importance of improving the model ability to simulate each individual aerosol components more accurately, especially black carbon. Separately, it is estimated from recent model studies that anthropogenic sulfate, POM, and BC forcings at TOA are  $-0.4$ ,  $-0.18$ ,  $+0.35 W m^{-2}$ , respectively. The anthropogenic nitrate and dust forcings are estimated at  $-0.1 W m^{-2}$  for each, with uncertainties exceeds 100% (IPCC AR4, 2007).

- In contrast to long-lived greenhouse gases, anthropogenic aerosol RF exhibits significant regional and seasonal variations. The forcing magnitude is the largest over the industrial and biomass burning source regions, where the magnitude of the negative aerosol forcing

can be of the same magnitude or even stronger than that of positive greenhouse gas forcing.

- There is a large spread of model-calculated aerosol RF even in the global annual averaged values. The AeroCom study shows that the model diversity at some locations (mostly East Asia and African biomass burning regions) can reach  $\pm 3 W m^{-2}$ , which is an order of magnitude above the global averaged forcing value of  $-0.22 W m^{-2}$ . The large diversity reflects the low level of current understanding of aerosol radiative forcing, which is compounded by uncertainties in emissions, transport, transformation, removal, particle size, and optical and microphysical (including hygroscopic) properties.

In contrast to long-lived greenhouse gases, anthropogenic aerosol radiative forcing exhibits significant regional and seasonal variations.



**Fig. 3.4.** Radiative forcing from the cloud albedo effect (1<sup>st</sup> aerosol indirect effect) in the global climate models used in IPCC 2007 (IPCC Fig. 2.14). For additional model designations and references, see IPCC 2007, chapter 2. Species included in the lower panel are sulfate, sea salt, organic and black carbon, dust and nitrates; in the top panel, only sulfate, sea salt and organic carbon are included.

Anthropogenic aerosols cool the surface but heat the atmosphere.

- In spite of the relatively small value of forcing at TOA, the magnitudes of anthropogenic forcing at the surface and within the atmospheric column are considerably larger: -1 to -2 W m<sup>-2</sup> at the surface and +0.8 to +2 W m<sup>-2</sup> in the atmosphere. Anthropogenic aerosols thus cool the surface but heat the atmosphere, on average. Regionally, the atmospheric heating can reach annually averaged values exceeding 5 W m<sup>-2</sup> (Figure 3.3d). These regional effects and the negative surface forcing are expected to exert an important effect on climate through alteration of the hydrological cycle.

### 3.4. Calculating Aerosol Indirect Forcing

#### 3.4.1. AEROSOL EFFECTS ON CLOUDS

A subset of the aerosol particles can act as cloud condensation nuclei (CCN) and/or ice nuclei (IN). Increases in aerosol particle con-

centrations, therefore, may increase the ambient concentrations of CCN and IN, affecting cloud properties. For a fixed cloud liquid water content, a CCN increase will lead to more cloud droplets so that the cloud droplet size will decrease. That effect leads to brighter clouds, the enhanced albedo then being referred to as the “cloud albedo effect” (Twomey, 1977), also known as the first indirect effect. If the droplet size is smaller, it may take longer to rainout, leading to an increase in cloud lifetime, hence the “cloud lifetime” effect (Albrecht, 1989), also called the second indirect effect. Approximately one-third of the models used for the IPCC 20th century climate change simulations incorporated an aerosol indirect effect, generally (though not exclusively) considered only with sulfates.

Shown in Figure 3.4 are results from published model studies indicating the different RF values from the cloud albedo effect. The cloud albedo effect ranges from -0.22 to -1.85 W m<sup>-2</sup>; the lowest estimates are from simulations that constrained representation of aerosol effects on clouds with satellite measurements of drop size vs. aerosol index. In view of the difficulty of quantifying this effect remotely (discussed later), it is not clear whether this constraint provides an improved estimate. The estimate in the IPCC AR4 ranges from +0.4 to -1.1 W m<sup>-2</sup>, with a “best-guess” estimate of 0.7 W m<sup>-2</sup>.

The representation of cloud effects in GCMs is considered below. However, it is becoming increasingly clear from studies based on high resolution simulations of aerosol-cloud interactions that there is a great deal of complexity that is unresolved in climate models. This point is examined again in section 3.4.4.

Most models did not incorporate the “cloud lifetime effect”. Hansen et al. (2005) compared this latter influence (in the form of time-averaged cloud area or cloud cover increase) with the cloud albedo effect. In contrast to the discussion in IPCC (2007), they argue that the cloud cover effect is more likely to be the dominant one, as suggested both by cloud-resolving model studies (Ackerman et al., 2004) and satellite observations (Kaufman et al., 2005c). The cloud albedo effect may be partly offset by reduced cloud thickness accompanying aerosol pollutants, producing a meteorological (cloud)

rather than aerosol effect (see the discussion in Lohmann and Feichter, 2005). (The distinction between meteorological feedback and aerosol forcing can become quite opaque; as noted earlier, the term feedback is restricted here to those processes that are responding to a change in temperature.) Nevertheless, both aerosol indirect effects were utilized in Hansen et al. (2005), with the second indirect effect calculated by relating cloud cover to the aerosol number concentration, which in turn is a function of sulfate, nitrate, black carbon and organic carbon concentration. Only the low altitude cloud influence was modeled, principally because there are greater aerosol concentrations at low levels, and because low clouds currently exert greater cloud RF. The aerosol influence on high altitude clouds, associated with IN changes, is a relatively unexplored area for models and as well for process-level understanding.

Hansen et al. (2005) used coefficients to normalize the cooling from aerosol indirect effects to between  $-0.75$  and  $-1 \text{ W m}^{-2}$ , based on comparisons of modeled and observed changes in the diurnal temperature range as well as some satellite observations. The response of the GISS model to the direct and two indirect effects is shown in Figure 3.5. As parameterized, the cloud lifetime effect produced somewhat

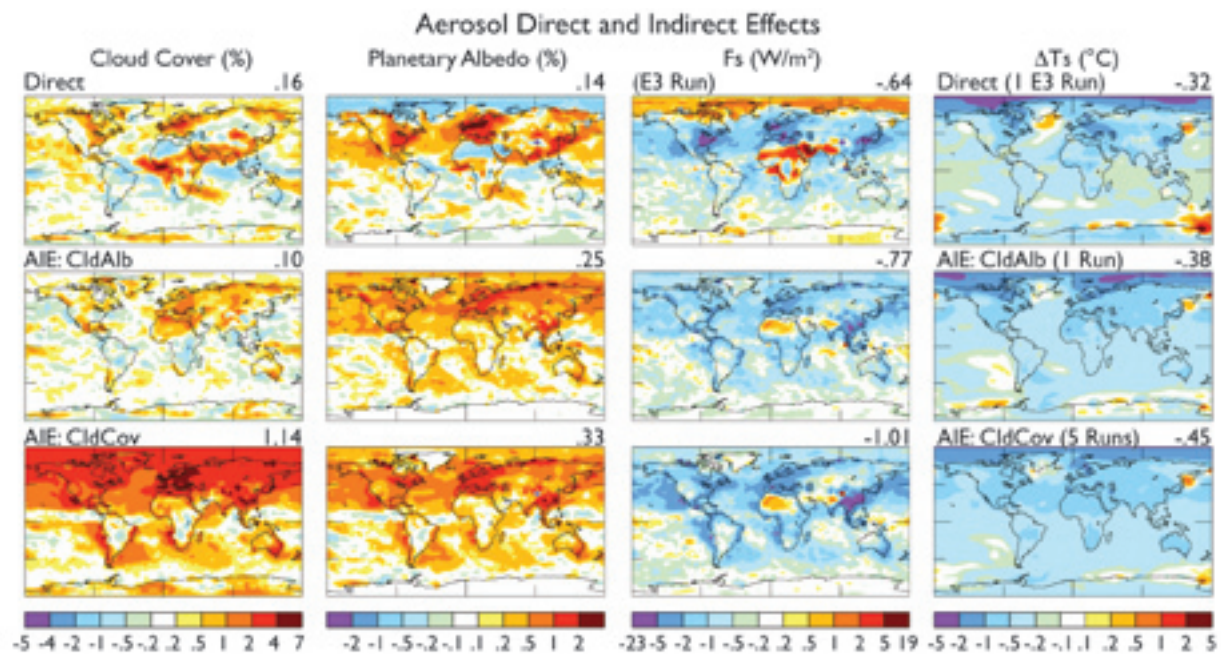
greater negative RF (cooling), but this was the result of the coefficients chosen. Geographically, it appears that the “cloud cover” effect produced slightly more cooling in the Southern Hemisphere than did the “cloud albedo” response, with the reverse being true in the Northern Hemisphere (differences on the order of a few tenths  $^{\circ}\text{C}$ ).

### 3.4.2. MODEL EXPERIMENTS

There are many different factors that can explain the large divergence of aerosol indirect effects in models (Fig. 3.4). To explore this in more depth, Penner et al. (2006) used three general circulation models to analyze the differences between models for the first indirect effect, as well as a combined first plus second indirect effect. The models all had different cloud and/or convection parameterizations.

In the first experiment, the monthly average aerosol mass and size distribution of, effectively, sulfate aerosol were prescribed, and all models followed the same prescription for parameterizing the cloud droplet number concentration (CDNC) as a function of aerosol concentration. In that sense, the only difference among the models was their separate cloud formation and radiation schemes. The different models all produced similar droplet

There are many different factors that can explain the large divergence of indirect effects in models.



**Fig. 3.5.** Anthropogenic impact on cloud cover, planetary albedo, radiative flux at the surface (while holding sea surface temperatures and sea ice fixed) and surface air temperature change from the direct aerosol forcing (top row), the 1<sup>st</sup> indirect effect (second row) and the second indirect effect (third row). The temperature change is calculated from years 81-120 of a coupled atmosphere simulation with the GISS model. From Hansen et al. (2005).

effective radii, and therefore shortwave cloud forcing, and change in net outgoing whole sky radiation between pre-industrial times and the present. Hence the first indirect effect was not a strong function of the cloud or radiation scheme. The results for this and the following experiments are presented in Figure 3.6, where the experimental results are shown sequentially from left to right for the whole sky effect, and in Table 3.5 for the clear-sky and cloud forcing response as well.

The change in cloud forcing is the difference between whole sky and clear sky outgoing radiation in the present day minus pre-industrial simulation. The large differences seen between experiments 5 and 6 are due to the inclusion of the clear sky component of aerosol scattering and absorption (the direct effect) in experiment 6.

In the second experiment, the aerosol mass and size distribution were again prescribed, but now each model used its own formulation for relating aerosols to droplets. In this case one of the models produced larger effective radii and therefore a much smaller first indirect aerosol

effect (Figure 3.6, Table 3.5). However, even in the two models where the effective radius change and net global forcing were similar, the spatial patterns of cloud forcing differ, especially over the biomass burning regions of Africa and South America.

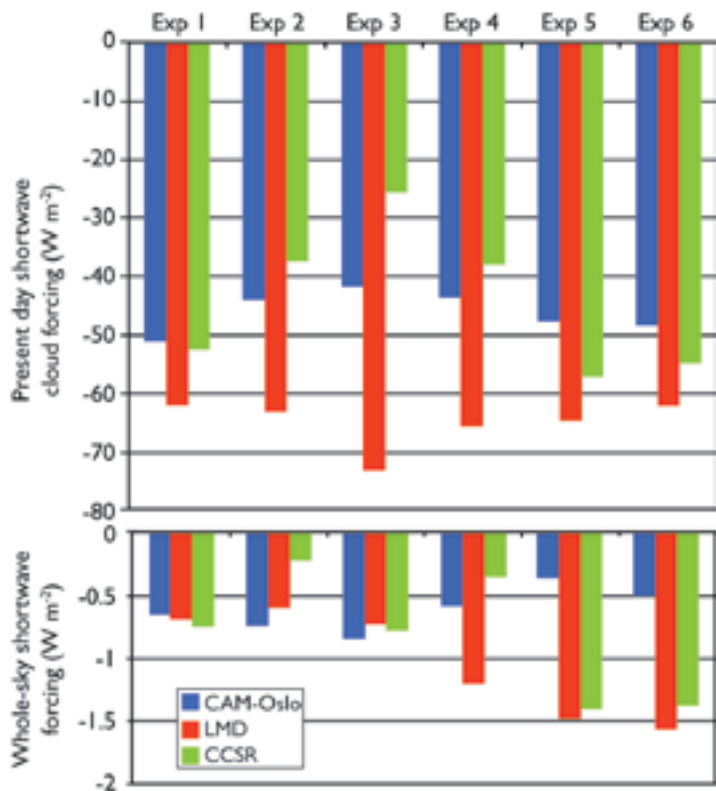
The third experiment allowed the models to relate the change in droplet size to change in precipitation efficiency (i.e., they were now also allowing the second indirect effect - smaller droplets being less efficient rain producers – as well as the first). The models utilized the same relationship for autoconversion of cloud droplets to precipitation. Changing the precipitation efficiency results in all models producing an increase in cloud liquid water path, although the effect on cloud fraction was smaller than in the previous experiments. The net result was to increase the negative radiative forcing in all three models, albeit with different magnitudes: for two of the models the net impact on outgoing shortwave radiative increased by about 20%, whereas in the third model (which had the much smaller first indirect effect), it was magnified by a factor of three.

In the fourth experiment, the models were now each allowed to use their own formulation to relate aerosols to precipitation efficiency. This introduced some additional changes in the whole sky shortwave forcing (Figure 3.6).

In the fifth experiment, models were allowed to produce their own aerosol concentrations, but were given common sources. This produced the largest changes in the RF in several of the models. Within any one model, therefore, the change in aerosol concentration has the largest effect on droplet concentrations and effective radii. This experiment too resulted in large changes in RF.

In the last experiment, the aerosol direct effect was included, based on the full range of aerosols used in each model. While the impact on the whole-sky forcing was not large, the addition of aerosol scattering and absorption primarily affected the change in clear sky radiation (Table 3.5).

The results of this study emphasize that in addition to questions concerning cloud physics, the differences in aerosol concentrations among the



**Fig. 3.6.** Global average present-day short wave cloud forcing at TOA (top) and change in whole sky net outgoing shortwave radiation (bottom) between the present-day and pre-industrial simulations for each model in each experiment. Adapted from Penner et al. (2006).



**Table 3.5. Differences in present day and pre-industrial outgoing solar radiation ( $\text{W m}^{-2}$ ) in the different experiments. Adapted from Penner et al. (2006).**

MODEL	EXP 1	EXP 2	EXP 3	EXP 4	EXP 5	EXP 6
<b>Whole-sky</b>						
CAM-Oslo	-0.648	-0.726	-0.833	-0.580	-0.365	-0.518
LMD-Z	-0.682	-0.597	-0.722	-1.194	-1.479	-1.553
CCSR	-0.739	-0.218	-0.733	-0.350	-1.386	-1.386
<b>Clear-sky</b>						
CAM-Oslo	-0.063	-0.066	-0.026	0.014	-0.054	-0.575
LMD-Z	-0.054	0.019	0.030	-0.066	-0.126	-1.034
CCSR	0.018	-0.007	-0.045	-0.008	0.018	-1.160
<b>Cloud-forcing</b>						
CAM-Oslo	-0.548	-0.660	-0.807	-0.595	-0.311	0.056
LMD-Z	-0.628	-0.616	-0.752	-1.128	-1.353	-0.518
CCSR	-0.757	-0.212	-0.728	-0.345	-1.404	-0.200

EXP1: tests cloud formation and radiation schemes

EXP2: tests formulation for relating aerosols to droplets

EXP3: tests inclusion of droplet size influence on precipitation efficiency

EXP4: tests formulation of droplet size influence on precipitation efficiency

EXP5: tests model aerosol formulation from common sources

EXP6: added the direct aerosol effect

models play a strong role in inducing differences in the indirect effect(s), as well as the direct one.

Observational constraints on climate model simulations of the indirect effect with satellite data (e.g., MODIS) have been performed previously in a number of studies (e.g., Storelvmo et al., 2006, Lohmann et al., 2006, Quaas et al., 2006, Menon et al., 2008). These have been somewhat limited since the satellite retrieved data used do not have the vertical profiles needed to resolve aerosol and cloud fields (e.g., cloud droplet number and liquid water content); the temporal resolution of simultaneous aerosol and cloud product retrievals are usually not available at a frequency of more than one a day; and higher level clouds often obscure low clouds and aerosols. Thus, the indirect effect, especially the second indirect effect, remains, to a large extent, unconstrained by satellite observations. However, improved measurements of aerosol vertical distribution from the newer generation of sensors on the A-train platform may provide a better understanding of changes to cloud properties from aerosols. Simulating the top-of-atmosphere reflectance for comparison to satellite measured values

could be another way to compare model with observations, which would eliminate the inconsistent assumptions of aerosol optical properties and surface reflectance encountered when compared the model calculated and satellite retrieved AOD values.

### 3.4.3. ADDITIONAL AEROSOL INFLUENCES

Various observations have empirically related aerosols injected from biomass burning or industrial processes to reductions in rainfall (e.g., Warner, 1968; Eagan et al., 1974; Andreae et al., 2004; Rosenfeld, 2000). There are several potential mechanisms associated with this response.

In addition to the two indirect aerosol effects noted above, a process denoted as the “semi-direct” effect involves the absorption of solar radiation by aerosols such as black carbon and dust. The absorption increases the temperature, thus lowering the relative humidity and producing evaporation, hence a reduction in cloud liquid water. The impact of this process depends strongly on what the effective aerosol absorption actually is; the more absorbing the aerosol, the larger the potential positive forcing

on climate (by reducing low level clouds and allowing more solar radiation to reach the surface). This effect is responsible for shifting the critical value of SSA (separating aerosol cooling from aerosol warming) from 0.86 with fixed clouds to 0.91 with varying clouds (Hansen et al., 1997). Reduction in cloud cover and liquid water is one way aerosols could reduce rainfall.

More generally, aerosols can alter the location of solar radiation absorption within the system, and this aspect alone can alter climate and precipitation even without producing any change in net radiation at the top of the atmosphere (the usual metric for climate impact). By decreasing solar absorption at the surface, aerosols (from both the direct and indirect effects) reduce the energy available for evapotranspiration, potentially resulting in a decrease in precipitation. This effect has been suggested as the reason for the decrease in pan evaporation over the last 50 years (Roderick and Farquhar, 2002). The decline in solar radiation at the surface appears to have ended in the 1990s (Wild et al., 2005), perhaps because of reduced aerosol emissions in industrial areas (Kruger and Grasl, 2002), although this issue is still not settled.

Energy absorption by aerosols above the boundary layer can also inhibit precipitation by warming the air at altitude relative to the surface, i.e., increasing atmospheric stability. The increased stability can then inhibit convection, affecting both rainfall and atmospheric circulation (Ramanathan et al., 2001a; Chung and Zhang, 2004). To the extent that aerosols decrease droplet size and reduce precipitation efficiency, this effect by itself could result in lowered rainfall values locally.

In their latest simulations, Hansen et al. (2007) did find that the indirect aerosol effect reduced tropical precipitation; however, the effect is similar regardless of which of the two indirect effects is used, and also similar to the direct effect. So it is likely that the reduction of tropical precipitation is because of aerosol induced cooling at the surface and the consequent reduced evapotranspiration. Similar conclusions were reached by Yu et al. (2002) and Feingold et al. (2005). In this case, the effect is a feedback and not a forcing.

The local precipitation change, through its impacts on dynamics and soil moisture, can have

large positive feedbacks. Harvey (2004) concluded from assessing the response to aerosols in eight coupled models that the aerosol impact on precipitation was larger than on temperature. He also found that the precipitation impact differed substantially among the models, with little correlation among them.

Recent GCM simulations have further examined the aerosol effects on hydrological cycle. Ramanathan et al. (2005) showed from fully coupled ocean–atmosphere GCM experiments that the “solar dimming” effect at the surface, i.e., the reduction of solar radiation reaching the surface, due to the inclusion of absorbing aerosol forcing causes a reduction in surface evaporation, a decrease in meridional sea surface temperature (SST) gradient and an increase in atmospheric stability, and a reduction in rainfall over South Asia. Lau and Kim (2006) examined the direct effects of aerosol on the monsoon water cycle variability from GCM simulations with prescribed realistic global aerosol forcing and proposed the “elevated heat pump” effect, suggesting that atmospheric heating by absorbing aerosols (dust and black carbon), through water cycle feedback, may lead to a strengthening of the South Asia monsoon. These model results are not necessarily at odds with each other, but rather illustrate the complexity of the aerosol–monsoon interactions that are associated with different mechanisms, whose relative importance in affecting the monsoon may be strongly dependent on spatial and temporal scales and the timing of the monsoon. These results may be model dependent and should be further examined.

#### 3.4.4. HIGH RESOLUTION MODELING

Largely by its nature, the representation of the interaction between aerosol and clouds in GCMs is poorly resolved. This stems in large part from the fact that GCMs do not resolve convection on their large grids (order of several hundred km), that their treatment of cloud microphysics is rather crude, and that as discussed previously, their representation of aerosol needs improvement. Superparametrization efforts (where standard cloud parameterizations in the GCM are replaced by resolving clouds in each grid column of the GCM via a cloud resolving model, e.g., Grabowski, 2004) could lead the way for the development of more realistic cloud fields and thus improved treatments of aerosol–cloud interactions in large-scale models. How-

Aerosols can alter the location of solar radiation absorption within the system, and this aspect alone can alter climate and precipitation.



ever, these are just being incorporated in models that resolve both cloud and aerosols. Detailed cloud parcel models have been developed to focus on the droplet activation problem (that asks under what conditions droplets actually start forming) and questions associated with the first indirect effect. The coupling of aerosol and cloud modules to dynamical models that resolve the large turbulent eddies associated with vertical motion and clouds [large eddy simulations (LES) models, with grid sizes of ~100 m and domains ~10 km] has proven to be a powerful tool for representing the details of aerosol-cloud interactions together with feedbacks (e.g., Feingold et al., 1994; Kogan et al., 1994; Stevens et al., 1996; Feingold et al., 1999; Ackerman et al., 2004). This section explores some of the complexity in the aerosol indirect effects revealed by such studies to illustrate how difficult parameterizing these effects properly in GCMs could really be.

#### 3.4.4A. THE FIRST INDIRECT EFFECT

The relationship between aerosol and drop concentrations (or drop sizes) is a key piece of the first indirect effect puzzle. (It should not, however, be equated to the first indirect effect which concerns itself with the resultant RF). A huge body of measurement and modeling work points to the fact that drop concentrations increase with increasing aerosol. The main unresolved questions relate to the degree of this effect, and the relative importance of aerosol size distribution, composition and updraft velocity in determining drop concentrations (for a review, see McFiggans et al., 2006). Studies indicate that the aerosol number concentration and size distribution are the most important aerosol factors. Updraft velocity (unresolved by GCMs) is particularly important under conditions of high aerosol particle number concentration.

Although it is likely that composition has some effect on drop number concentrations, composition is generally regarded as relatively unimportant compared to the other parameters (Fitzgerald, 1975; Feingold, 2003; Ervens et al., 2005; Dusek et al., 2006). Therefore, it has been stated that the significant complexity in aerosol composition can be modeled, for the most part, using fairly simple parameterizations that reflect the soluble and insoluble fractions (e.g., Rissler et al., 2004). However, composition cannot be simply dismissed. Furthermore, chemical interactions also cannot be overlooked. A large

uncertainty remains concerning the impact of organic species on cloud droplet growth kinetics, thus cloud droplet formation. Cloud drop size is affected by wet scavenging, which depends on aerosol composition especially for freshly emitted aerosol. And future changes in composition will presumably arise due to biofuels/biomass burning and a reduction in sulfate emissions, which emphasizes the need to include composition changes in models when assessing the first indirect effect. The simple soluble/insoluble fraction model may become less applicable than is currently the case.

The updraft velocity, and its change as climate warms, may be the most difficult aspect to simulate in GCMs because of the small scales involved. In GCMs it is calculated in the dynamics as a grid box average, and parameterized on the small scale indirectly because it is a key part of convection and the spatial distribution of condensate, as well as droplet activation. Numerous solutions to this problem have been sought, including estimation of vertical velocity based on predicted turbulent kinetic energy from boundary layer models (Lohmann et al., 1999; Larson et al., 2001) and PDF representations of subgrid quantities, such as vertical velocity and the vertically-integrated cloud liquid water ('liquid water path', or LWP) (Pincus and Klein, 2000; Golaz et al., 2002a,b; Larson et al., 2005). Embedding cloud-resolving models within GCMs is also being actively pursued (Grabowski et al., 1999; Randall et al., 2003). Numerous other details come into play; for example, the treatment of cloud droplet activation in GCM frameworks is often based on the assumption of adiabatic conditions, which may overestimate the sensitivity of cloud to changes in CCN (Sotiropoulou et al., 2006, 2007). This points to the need for improved theoretical understanding followed by new parameterizations.

#### 3.4.4B. OTHER INDIRECT EFFECTS

The second indirect effect is often referred to as the "cloud lifetime effect", based on the premise that non-precipitating clouds will live longer. In GCMs the "lifetime effect" is equivalent to changing the representation of precipitation production and can be parameterized as an increase in cloud area or cloud cover (e.g., Hansen et al., 2005). The second indirect effect hypothesis states that the more numerous and smaller drops associated with aerosol perturbations, suppress



A better representation of aerosol-cloud interactions in climate models depends on the ability to improve representation of aerosols and clouds, as well as their interaction, in the hydrologic cycle.



collision-induced rain, and result in a longer cloud lifetime. Observational evidence for the suppression of rain in warm clouds exists in the form of isolated studies (e.g. Warner, 1968) but to date there is no statistically robust proof of surface rain suppression (Levin and Cotton, 2008). Results from ship-track studies show that cloud water may increase or decrease in the tracks (Coakley and Walsh, 2002) and satellite studies suggest similar results for warm boundary layer clouds (Han et al., 2002). Ackerman et al. (2004) used LES to show that in stratocumulus, cloud water may increase or decrease in response to increasing aerosol depending on the relative humidity of the air overlaying the cloud. Wang et al. (2003) showed that all else being equal, polluted stratocumulus clouds tend to have lower water contents than clean clouds because the small droplets associated with polluted clouds evaporate more readily and induce an evaporation-entrainment feedback that dilutes the cloud. This result was confirmed by Xue and Feingold (2006) and Jiang and Feingold (2006) for shallow cumulus, where pollution particles were shown to decrease cloud fraction. Furthermore, Xue et al. (2008) suggested that there may exist two regimes: the first, a precipitating regime at low aerosol concentrations where an increase in aerosol will suppress precipitation and increase cloud cover (Albrecht, 1989); and a second, non precipitating regime where the enhanced evaporation associated with smaller drops will decrease cloud water and cloud fraction.

The possibility of bistable aerosol states was proposed earlier by Baker and Charlson (1990) based on consideration of aerosol sources and sinks. They used a simple numerical model to suggest that the marine boundary layer prefers two aerosol states: a clean, oceanic regime characterized by a weak aerosol source and less reflective clouds; and a polluted, continental regime characterized by more reflective clouds. On the other hand, study by Ackerman et al. (1994) did not support such a bistable system using a somewhat more sophisticated model. Further observations are needed to clarify the nature of cloud/aerosol interactions under a variety of conditions.

Finally, the question of possible effects of aerosol on cloud lifetime was examined by Jiang et al. (2006), who tracked hundreds of cumulus

clouds generated by LES from their formative stages until they dissipated. They showed that in the model there was no effect of aerosol on cloud lifetime, and that cloud lifetime was dominated by dynamical variability.

It could be argued that the representation of these complex feedbacks in GCMs is not warranted until a better understanding of the processes is at hand. Moreover, until GCMs are able to represent cloud scales, it is questionable what can be obtained by adding microphysical complexity to poorly resolved clouds. A better representation of aerosol-cloud interactions in GCMs therefore depends on the ability to improve representation of aerosols and clouds, as well as their interaction, in the hydrologic cycle. This issue is discussed further in the next chapter.

### 3.5. Aerosol in the Climate Models

#### 3.5.1. AEROSOL IN THE IPCC AR4 CLIMATE MODEL SIMULATIONS

To assess the atmospheric and climate response to aerosol forcing, e.g., changes in surface temperature, precipitation, or atmospheric circulation, aerosols, together with greenhouse gases should be an integrated part of climate model simulation under the past, present, and future conditions. Table 3.6 lists the forcing species that were included in 25 climate modeling groups used in the IPCC AR4 (2007) assessment. All the models included long-lived greenhouse gases, most models included sulfate direct forcing, but only a fraction of those climate models considered other aerosol types. In other words, aerosol RF was not adequately accounted for in the climate simulations for the IPCC AR4. Put still differently, the current aerosol modeling capability has not been fully incorporated into the climate model simulations. As pointed out in Section 3.4, fewer than one-third of the models incorporated an aerosol indirect effect, and most considered only sulfates.

The following discussion compares two of the IPCC AR4 climate models that include all major forcing agencies in their climate simulation: the model from the NASA Goddard Institute for Space Studies (GISS) and from the NOAA Geophysical Fluid Dynamics Laboratory (GFDL). The purpose in presenting these comparisons is to help elucidate how modelers go about assessing their aerosol components,

**Table 3.6. Forcings used in IPCC AR4 simulations of 20th century climate change. This table is adapted from SAP I.1 Table 5.2 (compiled using information provided by the participating modeling centers, see [http://www-pcmdi.llnl.gov/ipcc/model\\_documentation/ipcc\\_model\\_documentation.php](http://www-pcmdi.llnl.gov/ipcc/model_documentation/ipcc_model_documentation.php)) plus additional information from that website. Eleven different forcings are listed: well-mixed greenhouse gases (G), tropospheric and stratospheric ozone (O), sulfate aerosol direct (SD) and indirect effects (SI), black carbon (BC) and organic carbon aerosols (OC), mineral dust (MD), sea salt (SS), land use/land cover (LU), solar irradiance (SO), and volcanic aerosols (V). Check mark denotes inclusion of a specific forcing. As used here, “inclusion” means specification of a time-varying forcing, with changes on interannual and longer timescales.**

	MODEL	COUNTRY	G	O	SD	SI	BC	OC	MD	SS	LU	SO	V
1	BCC-CMI	China	√	√	√								
2	BCCR-BCM2.0	Norway	√		√				√	√			
3	CCSM3	USA	√	√	√		√	√				√	√
4	CGCM3.1(T47)	Canada	√		√								
5	CGCM3.1(T63)	Canada	√		√								
6	CNRM-CM3	France	√	√	√		√						
7	CSIRO-Mk3.0	Australia	√		√								
8	CSIRO-Mk3.5	Australia	√		√								
9	ECHAM5/MPI-OM	Germany	√	√	√	√							
10	ECHO-G	Germany/ Korea	√	√	√	√						√	√
11	FGOALS-g1.0	China	√		√								
12	GFDL-CM2.0	USA	√	√	√		√	√			√	√	√
13	GFDL-CM2.1	USA	√	√	√		√	√			√	√	√
14	GISS-AOM	USA	√		√					√			
15	GISS-EH	USA	√	√	√	√	√	√	√	√	√	√	√
16	GISS-ER	USA	√	√	√	√	√	√	√	√	√	√	√
17	INGV-SXG	Italy	√	√	√								
18	INM-CM3.0	Russia	√		√							√	
19	IPSL-CM4	France	√		√	√							
20	MIROC3.2(hires)	Japan	√	√	√		√	√	√	√	√	√	√
21	MIROC3.2(medres)	Japan	√	√	√		√	√	√	√	√	√	√
22	MRI-CGCM2.3.2	Japan	√		√							√	√
23	PCM	USA	√	√	√							√	√
24	UKMO-HadCM3	UK	√	√	√	√							
25	UKMO-HadGEM1	UK	√	√	√	√	√	√			√	√	√

and the difficulties that entail. A particular concern is how aerosol forcings were obtained in the climate model experiments for IPCC AR4. Comparisons with observations have already led to some improvements that can be implemented in climate models for subsequent climate change experiments (e.g., Koch et al., 2006, for GISS model). This aspect is discussed further in chapter 4.

### 3.5.1A. THE GISS MODEL

There have been many different configurations of aerosol simulations in the GISS model over the years, with different emissions, physics packages, etc., as is apparent from the multiple GISS entries in the preceding figures and tables. There were also three different GISS GCM submissions to IPCC AR4, which varied in their model physics and ocean formulation.



(Note that the aerosols in these three GISS versions are different from those in the AeroCom simulations described in section 3.2 and 3.3.) The GCM results discussed below all relate to the simulations known as GISS model ER (Schmidt et al., 2006, see Table 3.6).

Although the detailed description and model evaluation have been presented in Liu et al. (2006), below are the general characteristics of aerosols in the GISS ER:

*Aerosol fields:* The aerosol fields used in the GISS ER is a prescribed “climatology” which is obtained from chemistry transport model simulations with monthly averaged mass concentrations representing conditions up to 1990. Aerosol species included are sulfate, nitrate, BC, POM, dust, and sea salt. Dry size effective radii are specified for each of the aerosol types, and laboratory-measured phase functions are employed for all solar and thermal wavelengths. For hygroscopic aerosols (sulfate, nitrate, POM, and sea salt), formulas are used for the particle growth of each aerosol as a function of relative humidity, including the change in density and optical parameters. With these specifications, the AOD, single scattering albedo, and phase function of the various aerosols are calculated. While the aerosol distribution is prescribed as monthly mean values, the relative humidity component of the extinction is updated each hour. The global averaged AOD at 550 nm is about 0.15.

*Global distribution:* When comparing with AOD from observations by multiple satellite sensors of MODIS, MISR, POLDER, and AVHRR and surface based sunphotometer network AERONET (see Chapter 2 for detailed information about data), qualitative agreement is apparent, with generally higher burdens in Northern Hemisphere summer, and seasonal variations of smoke over southern Africa and South America, as well as wind blown dust over northern African and the Persian Gulf. Aerosol optical depth in both model and observations is smaller away from land. There are, however, considerable discrepancies between the model and observations. Overall, the GISS GCM has reduced aerosol optical depths compared with the satellite data (a global, clear-sky average of about 80% compared with MODIS and MISR data), although it is in better agreement with

AERONET ground-based measurements in some locations (note that the input aerosol values were calibrated with AERONET data). The model values over the Sahel in Northern Hemisphere winter and the Amazon in Southern Hemisphere winter are excessive, indicative of errors in the biomass burning distributions, at least partially associated with an older biomass burning source used (the source used here was from Liousse et al., 1996).

*Seasonal variation:* A comparison of the seasonal distribution of the global AOD between the GISS model and satellite data indicates that the model seasonal variation is in qualitative agreement with observations for many of the locations that represent major aerosol regimes, although there are noticeable differences. For example, in some locations the seasonal variations are different from or even opposite to the observations.

*Particle size parameter:* The Ångström exponent ( $\mathring{A}$ ), which is determined by the contrast between the AOD at two or more different wavelengths and is related to aerosol particle size (discussed in section 3.3). This parameter is important because the particle size distribution affects the efficiency of scattering of both short and long wave radiation, as discussed earlier.  $\mathring{A}$  from the GISS model is biased low compared with AERONET, MODIS, and POLDER data, although there are technical differences in determining the  $\mathring{A}$ . This low bias suggests that the aerosol particle size in the GISS model is probably too large. The average effective radius in the GISS model appears to be 0.3-0.4  $\mu\text{m}$ , whereas the observational data indicates a value more in the range of 0.2-0.3  $\mu\text{m}$  (Liu et al., 2006).

*Single scattering albedo:* The model-calculated SSA (at 550 nm) appears to be generally higher than the AERONET data at worldwide locations (not enough absorption), but lower than AERONET data in Northern Africa, the Persian Gulf, and the Amazon (too much absorption). This discrepancy reflects the difficulties in modeling BC, which is the dominant absorbing aerosol, and aerosol sizes. Global averaged SSA at 550 nm from the GISS model is at about 0.95.

*Aerosol direct RF:* The GISS model calculated anthropogenic aerosol direct shortwave RF



is  $-0.56 \text{ W m}^{-2}$  at TOA and  $-2.87 \text{ W m}^{-2}$  at the surface. The TOA forcing (upper left, Figure 3.7) indicates that, as expected, the model has larger negative values in polluted regions and positive forcing at the highest latitudes. At the surface (lower left, Figure 3.7) GISS model values exceed  $-4 \text{ W m}^{-2}$  over large regions. Note there is also a longwave RF of aerosols (right column), although they are much weaker than the shortwave RF.

There are several concerns for climate change simulations related to the aerosol trend in the GISS model. One is that the aerosol fields in the GISS AR4 climate simulation (version ER) are kept fixed after 1990. In fact, the observed trend shows a reduction in tropospheric aerosol optical thickness from 1990 through the present, at least over the oceans (Mishchenko and Geogdzhayev, 2007). Hansen et al. (2007) suggested that the deficient warming in the GISS model over Eurasia post-1990 was due to the lack of this trend. Indeed, a possible conclusion from the Penner et al. (2002) study was that the GISS model overestimated the AOD (presumably associated with anthropogenic aerosols) poleward of  $30^\circ\text{N}$ . However, when an alternate experiment reduced the aerosol optical depths, the polar warming became excessive (Hansen et al., 2007). The other concern is that the GISS model may underestimate the organic and sea salt AOD, and overestimate the influence of black carbon aerosols in the biomass burning regions (deduced from Penner et al., 2002; Liu

et al., 2006). To the extent that is true, it would indicate the GISS model underestimates the aerosol direct cooling effect in a substantial portion of the tropics, outside of biomass burning areas. Clarifying those issues requires numerous modeling experiments and various types of observations.

3.5.1B. THE GFDL MODEL

A comprehensive description and evaluation of the GFDL aerosol simulation are given in Ginoux et al. (2006). Below are the general characteristics:

*Aerosol fields:* The aerosols used in the GFDL climate experiments are obtained from simulations performed with the MOZART 2 model (Model for Ozone and Related chemical Tracers) (Horowitz et al., 2003; Horowitz, 2006). The exceptions were dust, which was generated with a separate simulation of MOZART 2, using sources from Ginoux et al. (2001) and wind fields from NCEP/NCAR reanalysis data; and sea salt, whose monthly mean concentrations were obtained from a previous study by Haywood et al. (1999). It includes most of the same aerosol species as in the GISS model (although it does not include nitrates), and, as in the GISS model, relates the dry aerosol to wet aerosol optical depth via the model's relative humidity for sulfate (but not for organic carbon); for sea salt, a constant relative humidity of 80% was used. Although the parameterizations come from different sources, both models maintain a

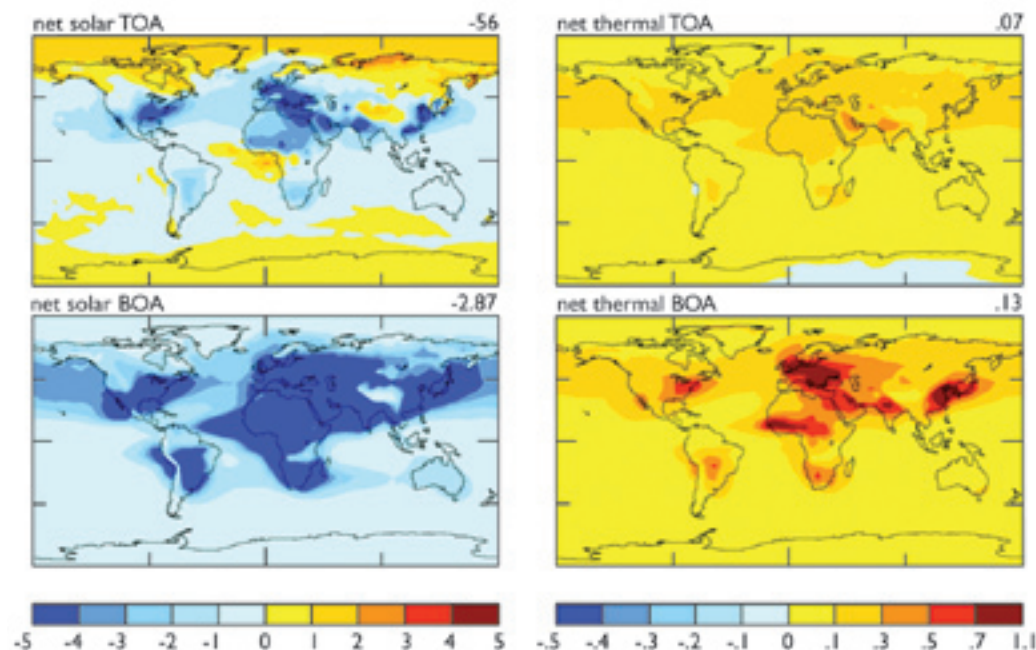


Fig. 3.7. Direct radiative forcing by anthropogenic aerosols in the GISS model (including sulfates, BC, OC and nitrates). Short wave forcing at TOA and surface are shown in the top left and bottom left panels. The corresponding thermal forcing is indicated in the right hand panels. Figure provided by A. Lacis, GISS.

very large growth in sulfate particle size when the relative humidity exceeds 90%.

*Global distributions:* Overall, the GFDL global mean aerosol mass loading is within 30% of that of other studies (Chin et al., 2002; Tie et al., 2005; Reddy et al., 2005a), except for sea salt, which is 2 to 5 times smaller. However, the sulfate AOD (0.1) is 2.5 times that of other studies, whereas the organic carbon value is considerably smaller (on the order of 1/2). Both of these differences are influenced by the relationship with relative humidity. In the GFDL model, sulfate is allowed to grow up to 100% relative humidity, but organic carbon does not increase in size as relative humidity increases. Comparison of AOD with AVHRR and MODIS data for the time period 1996-2000 shows that the global mean value over the ocean (0.15) agrees with AVHRR data (0.14) but there are significant differences regionally, with the model overestimating the value in the northern mid latitude oceans and underestimating it in the southern ocean. Comparison with MODIS also shows good agreement globally (0.15), but in this case indicates large disagreements over land, with the model producing excessive AOD over industrialized countries and underestimating the effect over biomass burning regions. Overall, the global averaged AOD at 550 nm is 0.17, which is higher than the maximum values in the AeroCom-A experiments (Table 3.2) and exceeds the observed value too ( $A_e$  and  $S^*$  in Figure 3.1).

*Composition:* Comparison of GFDL modeled species with *in situ* data over North America, Europe, and over oceans has revealed that the sulfate is overestimated in spring and summer and underestimated in winter in many regions, including Europe and North America. Organic and black carbon aerosols are also overestimated in polluted regions by a factor of two, whereas organic carbon aerosols are elsewhere underestimated by factors of 2 to 3. Dust concentrations at the surface agree with observations to within a factor of 2 in most places where significant dust exists, although over the southwest U.S. it is a factor of 10 too large. Surface concentrations of sea salt are underestimated by more than a factor of 2. Over the oceans, the excessive sulfate AOD compensates for the low sea salt values except in the southern oceans.

*Size and single-scattering albedo:* No specific comparison was given for particle size or single-scattering albedo, but the excessive sulfate would likely produce too high a value of reflectivity relative to absorption except in some polluted regions where black carbon (an absorbing aerosol) is also overestimated.

As in the case of the GISS model, there are several concerns with the GFDL model. The good global-average agreement masks an excessive aerosol loading over the Northern Hemisphere (in particular, over the northeast U.S. and Europe) and an underestimate over biomass burning regions and the southern oceans. Several model improvements are needed, including better parameterization of hygroscopic growth at high relative humidity for sulfate and organic carbon; better sea salt simulations; correcting an error in extinction coefficients; and improved biomass burning emissions inventory (Ginoux et al., 2006).

### 3.5.1C. COMPARISONS BETWEEN GISS AND GFDL MODEL

Both GISS and GFDL models were used in the IPCC AR4 climate simulations for climate sensitivity that included aerosol forcing. It would be constructive, therefore, to compare the similarities and differences of aerosols in these two models and to understand what their impacts are in climate change simulations. Figure 3.8 shows the percentage AOD from different aerosol components in the two models.

*Sulfate:* The sulfate AOD from the GISS model is within the range of that from all other models (Table 3.3), but that from the GFDL model exceeds the maximum value by a factor of 2.5. An assessment in SAP 3.2 (CCSP 2008; Shindell et al., 2008b) also concludes that GFDL had excessive sulfate AOD compared with other models. The sulfate AOD from GFDL is nearly a factor of 4 large than that from GISS, although the sulfate burden differs only by about 50% between the two models. Clearly, this implies a large difference in sulfate MEE between the two models.

*BC and POM:* Compared to observations, the GISS model appears to overestimate the influence of BC and POM in the biomass burning regions and underestimate it elsewhere, whereas the GFDL model is somewhat the reverse: it overestimates it in polluted regions, and un-





derestimates it in biomass burning areas. The global comparison shown in Table 3.4 indicates the GISS model has values similar to those from other models, which might be the result of such compensating errors. The GISS and GFDL models have relatively similar global-average black carbon contributions, and the same appears true for POM.

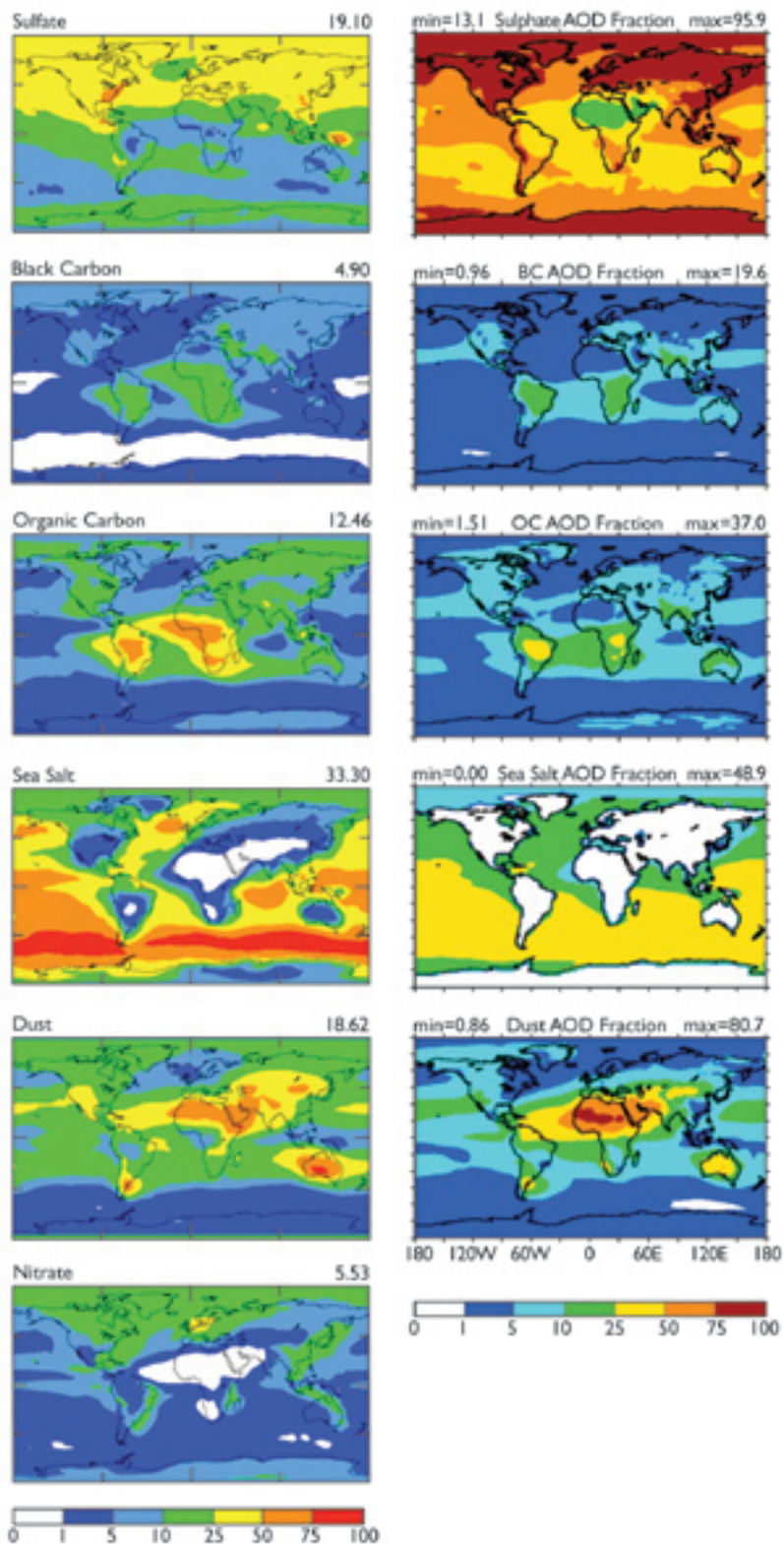
*Sea salt:* The GISS model has a much larger sea salt contribution than does GFDL (or indeed other models).

*Global and regional distributions:* Overall, the global averaged AOD is 0.15 from the GISS model and 0.17 from GFDL. However, as shown in Figure 3.8, the contribution to this AOD from different aerosol components shows greater disparity. For example, over the Southern Ocean where the primary influence is due to sea salt in the GISS model, but in the GFDL it is sulfate. The lack of satellite observations of the component contributions and the limited available *in situ* measurements make the model improvements at aerosol composition level difficult.

*Climate simulations:* With such large differences in aerosol composition and distribution between the GISS and GFDL models, one might expect that the model simulated surface temperature might be quite different. Indeed, the GFDL model was able to reproduce the observed temperature change during the 20th century without the use of an indirect aerosol effect, whereas the GISS model required a substantial indirect aerosol contribution (more than half of the total aerosol forcing; Hansen et al., 2007). It is likely that the reason for this difference was the excessive direct effect in the GFDL model caused by its overestimation of the sulfate optical depth. The GISS model direct aerosol effect (see Section 3.6) is close to that derived from observations (Chapter 2); this suggests that for models with climate sensitivity close to  $0.75^{\circ}\text{C}/(\text{W m}^{-2})$  (as in the GISS and GFDL models), an indirect effect is needed.

### 3.5.2. ADDITIONAL CONSIDERATIONS

*Long wave aerosol forcing:* So far only the aerosol RF in the shortwave (solar) spectrum has been discussed. Figure 3.7 (right column) shows that compared to the shortwave forcing, the values of anthropogenic aerosol long wave (thermal) forcing in the GISS model are on the



**Fig. 3.8.** Percentage of aerosol optical depth in the GISS (left, based on Liu et al., 2006, provided by A. Lacis, GISS) and GFDL (right, from Ginoux et al., 2006) models associated with the different components: Sulfate (1st row), BC (2nd row), OC (3rd row), sea-salt (4th row), dust (5th row), and nitrate (last row. Nitrate not available in GFDL model). Numbers on the GISS panels are global average, but on the GFDL panels are maximum and minimum.

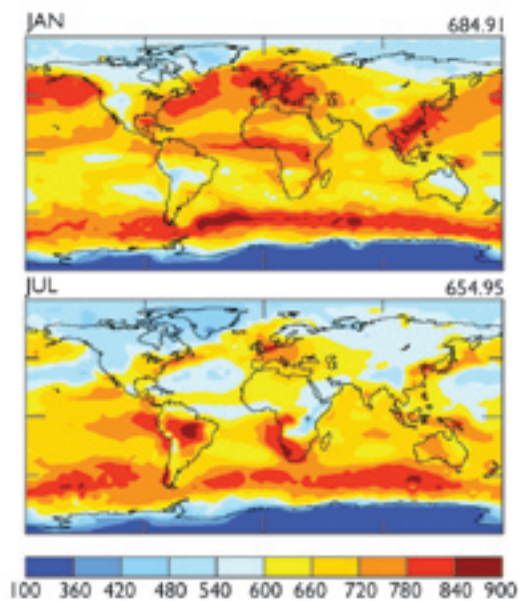
order of 10%. Like the shortwave forcing, these values will also be affected by the particular aerosol characteristics used in the simulation.

*Aerosol vertical distribution:* Vertical distribution is particularly important for absorbing aerosols, such as BC and dust in calculating the RF, particularly when longwave forcing is considered (e.g. Figure 3.7) because the energy they reradiate depends on the temperature (and hence altitude), which affects the calculated forcing values. Several model inter-comparison studies have shown that the largest difference among model simulated aerosol distributions is the vertical profile (e.g. Lohmann et al., 2001; Penner et al., 2002; Textor et al., 2006), due to the significant diversities in atmospheric processes in the models (e.g., Table 3.2). In addition, the vertical distribution also varies with space and time, as illustrated in Figure 3.9 from the GISS ER simulations for January and July showing the most probable altitude of aerosol vertical locations. In general, aerosols in the northern hemisphere are located at lower altitudes in January than in July, and vice versa for the southern hemisphere.

*Mixing state:* Most climate model simulations incorporating different aerosol types have been made using external mixtures, i.e., the evaluation of the aerosols and their radiative properties are calculated separately for each aerosol type (assuming no mixing between different components within individual particles). Observations indicate that aerosols commonly consist of internally mixed particles, and these “internal

mixtures” can have very different radiative impacts. For example, the GISS-1 (internal mixture) and GISS-2 (external mixture) model results shows very different magnitude and sign of aerosol forcing from slightly positive (implying slight warming) to strong negative (implying significant cooling) TOA forcing (Figure 3.2), due to changes in both radiative properties of the mixtures, and in aerosol amount. The more sophisticated aerosol mixtures from detailed microphysics calculations now being used/developed by different modeling groups may well end up producing very different direct (and indirect) forcing values.

*Cloudy sky vs. clear sky:* The satellite or AERONET observations are all for clear sky only because aerosol cannot be measured in the remote sensing technique when clouds are present. However, almost all the model results are for all-sky because of difficulty in extracting cloud-free scenes from the GCMs. So the AOD comparisons discussed earlier are not completely consistent. Because AOD can be significantly amplified when relative humidity is high, such as near or inside clouds, all-sky AOD values are expected to be higher than clear sky AOD values. On the other hand, the aerosol RF at TOA is significantly lower for all-sky than for clear sky conditions; the IPCC AR4 and AeroCom RF study (Schulz et al., 2006) have shown that on average the aerosol RF value for all-sky is about 1/3 of that for clear sky although with large diversity (63%). These aspects illustrate the complexity of the system and the difficulty of representing aerosol radiative influences in climate models whose cloud and aerosol distributions are somewhat problematic. And of course aerosols in cloudy regions can affect the clouds themselves, as discussed in Section 3.4.



**Fig. 3.9.** Most probable aerosol altitude (in pressure, hPa) from the GISS model in January (top) and July (bottom). Figure from A. Lacis, GISS.

### 3.6. Impacts of Aerosols on Climate Model Simulations

#### 3.6.1. SURFACE TEMPERATURE CHANGE

It was noted in the introduction that aerosol cooling is essential in order for models to produce the observed global temperature rise over the last century, at least models with climate sensitivities in the range of  $3^{\circ}\text{C}$  for doubled  $\text{CO}_2$  (or  $\sim 0.75^{\circ}\text{C}/(\text{W m}^{-2})$ ). The implications of this are discussed here in somewhat more detail.

Hansen et al. (2007) show that in the GISS model, well-mixed greenhouse gases produce

**Table 3.7. Climate forcings (1880-2003) used to drive GISS climate simulations, along with the surface air temperature changes obtained for several periods. Instantaneous ( $F_i$ ), adjusted ( $F_a$ ), fixed SST ( $F_s$ ) and effective ( $F_e$ ) forcings are defined in Hansen et al., 2005. From Hansen et al., 2007.**

Forcing agent	Forcing $W\ m^{-2}$ (1880 – 2003)				$\Delta T$ surface $^{\circ}C$ (year to 2003)			
	$F_i$	$F_a$	$F_s$	$F_e$	1880	1900	1950	1979
Well-mixed GHGs	2.62	2.50	2.65	2.72	0.96	0.93	0.74	0.43
Stratospheric $H_2O$			0.06	0.05	0.03	0.01	0.05	0.00
Ozone	0.44	0.28	0.26	0.23	0.08	0.05	0.00	-0.01
Land Use			-0.09	-0.09	-0.05	-0.07	-0.04	-0.02
Snow albedo	0.05	0.05	0.14	0.14	0.03	0.00	0.02	-0.01
Solar Irradiance	0.23	0.24	0.23	0.22	0.07	0.07	0.01	0.02
Stratospheric aerosols	0.00	0.00	0.00	0.00	-0.08	-0.03	-0.06	0.04
Trop. aerosol direct forcing	-0.41	-0.38	-0.52	-0.60	-0.28	-0.23	-0.18	-0.10
Trop. aerosol indirect forcing			-0.87	-0.77	-0.27	-0.29	-0.14	-0.05
<b>Sum of above</b>			<b>1.86</b>	<b>1.90</b>	<b>0.49</b>	<b>0.44</b>	<b>0.40</b>	<b>0.30</b>
<b>All forcings at once</b>			<b>1.77</b>	<b>1.75</b>	<b>0.53</b>	<b>0.61</b>	<b>0.44</b>	<b>0.29</b>

a warming of close to  $1^{\circ}C$  between 1880 and the present (Table 3.7). The direct effect of tropospheric aerosols as calculated in that model produces cooling of close to  $-0.3^{\circ}C$  between those same years, while the indirect effect (represented in that study as cloud cover change) produces an additional cooling of similar magnitude (note that the general model result quoted in IPCC AR4 is that the indirect RF is twice that of the direct effect).

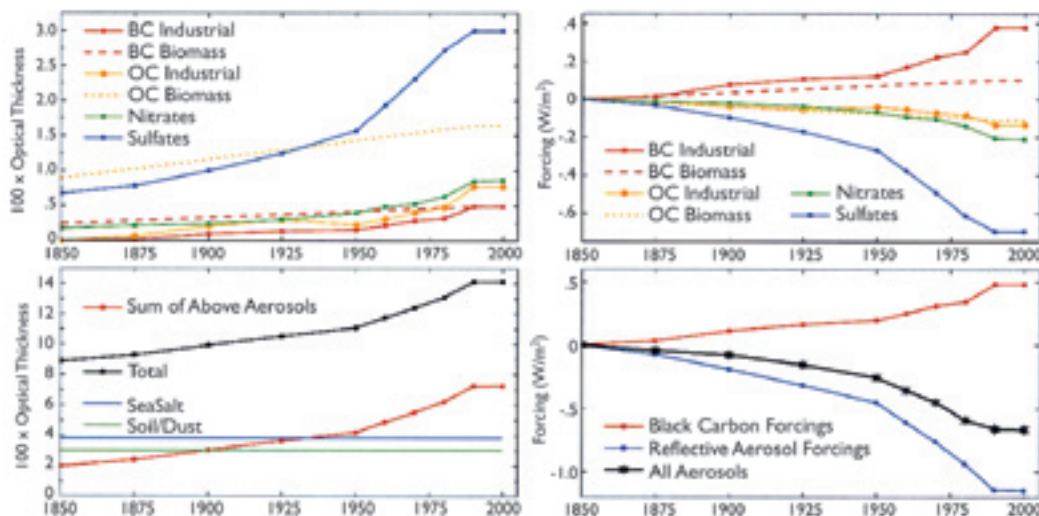
The time dependence of the total aerosol forcing used as well as the individual species components is shown in Figure 3.10. The resultant warming,  $0.53 (\pm 0.04)^{\circ}C$  including these and other forcings (Table 3.7), is less than the observed value of  $0.6-0.7^{\circ}C$  from 1880-2003. Hansen et al. (2007) further show that a reduction in sulfate optical thickness and the direct aerosol effect by 50%, which also reduced the aerosol indirect effect by 18%, produces a negative aerosol forcing from 1880 to 2003 of  $-0.91\ W\ m^{-2}$  (down from  $-1.37\ W\ m^{-2}$  with this revised forcing). The model now warms  $0.75^{\circ}C$  over that time. Hansen et al. (2007) defend this change by noting that sulfate aerosol removal over North America and western Europe during the 1990s led to a cleaner atmosphere. Note that

the comparisons shown in the previous section suggest that the GISS model already underestimates aerosol optical depths; it is thus trends that are the issue here.

The magnitude of the indirect effect used by Hansen et al. (2005) is roughly calibrated to reproduce the observed change in diurnal temperature cycle and is consistent with some satellite observations. However, as Anderson et al. (2003) note, the forward calculation of aerosol negative forcing covers a much larger range than is normally used in GCMs; the values chosen, as in this case, are consistent with the inverse reasoning estimates of what is needed to produce the observed warming, and hence generally consistent with current model climate sensitivities. The authors justify this approach by claiming that paleoclimate data indicate a climate sensitivity of close to  $0.75 (\pm 0.25)^{\circ}C/(W\ m^{-2})$ , and therefore something close to this magnitude of negative forcing is reasonable. Even this stated range leaves significant uncertainty in climate sensitivity and the magnitude of the aerosol negative forcing. Furthermore, IPCC (2007) concluded that paleoclimate data are not capable of narrowing the range of climate sensitivity, nominally 0.375 to 1.13



**Fig. 3.10.** Time dependence of aerosol optical thickness (left) and climate forcing (right). Note that as specified, the aerosol trends are all 'flat' from 1990 to 2000. From Hansen et al. (2007).



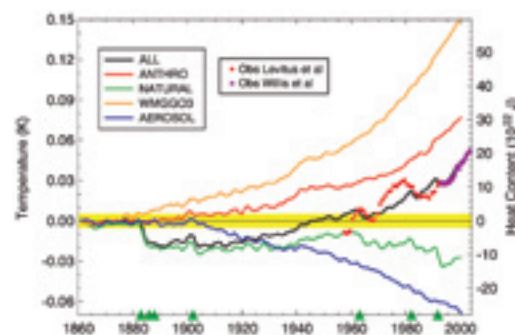
$^{\circ}\text{C}/(\text{W m}^{-2})$ , because of uncertainties in paleoclimate forcing and response; so from this perspective the total aerosol forcing is even less constrained than the GISS estimate. Hansen et al. (2007) acknowledge that “an equally good match to observations probably could be obtained from a model with larger sensitivity and smaller net forcing, or a model with smaller sensitivity and larger forcing”.

The GFDL model results for global mean ocean temperature change (down to 3 km depth) for the time period 1860 to 2000 is shown in Figure 3.11, along with the different contributing factors (Delworth et al., 2005). This is the same GFDL model whose aerosol distribution was discussed previously. The aerosol forcing produces a cooling on the order of 50% that of greenhouse warming (generally similar to that calculated by the GISS model, Table 3.7). Note that this was achieved without any aerosol indirect effect.

The general model response noted by IPCC, as discussed in the introduction, was that the total aerosol forcing of  $-1.3 \text{ W m}^{-2}$  reduced the greenhouse forcing of near  $3 \text{ W m}^{-2}$  by about 45%, in the neighborhood of the GFDL and GISS forcings. Since the average model sensitivity was close to  $0.75 \text{ }^{\circ}\text{C}/(\text{W m}^{-2})$ , similar to the sensitivities of these models, the necessary negative forcing is therefore similar. The agreement cannot therefore be used to validate the actual aerosol effect until climate sensitivity itself is better known.

Is there some way to distinguish between greenhouse gas and aerosol forcing that would allow the observational record to indicate how much

of each was really occurring? This question of attribution has been the subject of numerous papers, and the full scope of the discussion is beyond the range of this report. It might be briefly noted that Zhang et al. (2006) using results from several climate models and including both spatial and temporal patterns, found that the climate responses to greenhouse gases and sulfate aerosols are correlated, and separation is possible only occasionally, especially at global scales. This conclusion appears to be both model and method-dependent: using time-space distinctions as opposed to trend detection may work differently in different models (Gillett et al., 2002a). Using multiple models helps primarily by providing larger-ensemble sizes for statistics (Gillett et al., 2002b). However, even separating between the effects of different aerosol types is difficult. Jones et al. (2005) concluded that currently the pattern of temperature change due to black carbon is indistinguishable



**Fig. 3.11.** Change in global mean ocean temperature (left axis) and ocean heat content (right axis) for the top 3000 m due to different forcings in the GFDL model. WMGG includes all greenhouse gases and ozone; NATURAL includes solar and volcanic aerosols (events shown as green triangles on the bottom axis). Observed ocean heat content changes are shown as well. From Delworth et al., 2005.

from the sulfate aerosol pattern. In contrast, Hansen et al. (2005) found that absorbing aerosols produce a different global response than other forcings, and so may be distinguishable. Overall, the similarity in response to all these very different forcings is undoubtedly due to the importance of climate feedbacks in amplifying the forcing, whatever its nature.

Distinctions in the climate response do appear to arise in the vertical, where absorbing aerosols produce warming that is exhibited throughout the troposphere and into the stratosphere, whereas reflective aerosols cool the troposphere but warm the stratosphere (Hansen et al., 2005; IPCC, 2007). Delworth et al. (2005) noted that in the ocean, the cooling effect of aerosols extended to greater depths, due to the thermal instability associated with cooling the ocean surface. Hence the temperature response at levels both above and below the surface may provide an additional constraint on the magnitudes of each of these forcings, as may the difference between Northern and Southern Hemisphere changes (IPCC, 2007 Chapter 9). The profile of atmospheric temperature response will be useful to the extent that the vertical profile of aerosol absorption, an important parameter to measure, is known.

### 3.6.2. IMPLICATIONS FOR CLIMATE MODEL SIMULATIONS

The comparisons in Sections 3.2 and 3.3 suggest that there are large differences in model calculated aerosol distributions, mainly because of the large uncertainties in modeling the aerosol atmospheric processes in addition to the uncertainties in emissions. The fact that the total optical depth is in better agreement between models than the individual components means that even with similar optical depths, the aerosol direct forcing effect can be quite different, as shown in the AeroCom studies. Because the diversity among models and discrepancy between models and observations are much larger at the regional level than in global average, the assessment of climate response (e.g. surface temperature change) to aerosol forcing would be more accurate for global average than for regional or hemispheric differentiation. However, since aerosol forcing is much more pronounced on regional than on global scales because of the highly variable aerosol distributions, it is insufficient or even misleading to just get the global average right.

The indirect effect is strongly influenced by the aerosol concentrations, size, type, mixing state, microphysical processes, and vertical profile. As shown in previous sections, very large differences exist in those quantities even among the models having similar AOD. Moreover, modeling aerosol indirect forcing presents more challenges than direct forcing because there is so far no rigorous observational data, especially on a global scale, that one can use to test the model simulations. As seen in the comparisons of the GISS and GFDL model climate simulations for IPCC AR4, aerosol indirect forcing was so poorly constrained that it was completely ignored by one model (GFDL) but used by another (GISS) at a magnitude that is more than half of the direct forcing, in order to reproduce the observed surface temperature trends. A majority of the climate models used in IPCC AR4 do not consider indirect effects; the ones that did were mostly limited to highly simplified sulfate indirect effects (Table 3.6). Improvements must be made to at least the degree that the aerosol indirect forcing can no longer be used to mask the deficiencies in estimating the climate response to greenhouse gas and aerosol direct RF.

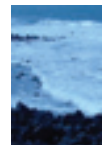
### 3.7. OUTSTANDING ISSUES

Clearly there are still large gaps in assessing the aerosol impacts on climate through modeling. Major outstanding issues and prospects of improving model simulations are discussed below.

**Aerosol composition:** Many global models are now able to simulate major aerosol types such as sulfate, black carbon, and POM, dust, and sea salt, but only a small fraction of these models simulate nitrate aerosols or consider anthropogenic secondary organic aerosols. And it is difficult to quantify the dust emission from human activities. As a result, the IPCC AR4 estimation of the nitrate and anthropogenic dust TOA forcing was left with very large uncertainty. The next generation of global models should therefore have a more comprehensive suite of aerosol compositions with better-constrained anthropogenic sources.

**Aerosol absorption:** One of the most critical parameters in aerosol direct RF and aerosol impact on hydrological cycles is the aerosol absorption. Most of the absorption is from BC despite its small contribution to total aerosol

The fact that the total optical depth is in better agreement between models than the individual components means that even with similar optical depths, the aerosol direct forcing effect can be quite different among models... Moreover, modeling aerosol indirect forcing presents more challenges.



load and AOD; dust too absorbs in both the short and long-wave spectral ranges, whereas POM absorbs in the UV to visible. The aerosol absorption or SSA, will have to be much better represented in the models through improving the estimates of carbonaceous and dust aerosol sources, their atmospheric distributions, and optical properties.

**Aerosol indirect effects:** The activation of aerosol particles into CCN depends not only on particle size but chemical composition, with the relative importance of size and composition unclear. In current aerosol-climate modeling, aerosol size distribution is generally prescribed and simulations of aerosol composition have large uncertainties. Therefore the model estimated “albedo effect” has large uncertainties. How aerosol would influence cloud lifetime/cover is still in debate. The influence of aerosols on other aspects of the climate system, such as precipitation, is even more uncertain, as are the physical processes involved. Processes that determine aerosol size distributions, hygroscopic growth, mixing state, as well as CCN concentrations, however, are inadequately represented in most of the global models. It will also be difficult to improve the estimate of indirect effects until the models can produce more realistic cloud characteristics.

**Aerosol impacts on surface radiation and atmospheric heating:** Although these effects are well acknowledged to play roles in modulating atmospheric circulation and water cycle, few coherent or comprehensive modeling studies have focused on them, as compared to the efforts that have gone to assessing aerosol RF at TOA. They have not yet been addressed in the previous IPCC reports. Here, of particular importance is to improve the accuracy of aerosol absorption.

**Long-term trends of aerosol:** To assess the aerosol effects on climate change the long-term variations of aerosol amount and composition and how they are related to the emission trends in different regions have to be specified. Simulations of historical aerosol trends can be problematic since historical emissions of aerosols have shown large uncertainties—as information is difficult to obtain on past source types, strengths, and even locations. The IPCC AR4 simulations used several alternative aero-

sol emission histories, especially for BC and POM aerosols.

**Climate modeling:** Current aerosol simulation capabilities from CTMs have not been fully implemented in most models used in IPCC AR4 climate simulations. Instead, a majority employed simplified approaches to account for aerosol effects, to the extent that aerosol representations in the GCMs, and the resulting forcing estimates, are inadequate. The oversimplification occurs in part because the modeling complexity and computing resource would be significantly increased if the full suite of aerosols were fully coupled in the climate models.

**Observational constraints:** Model improvement has been hindered by a lack of comprehensive datasets that could provide multiple constraints for the key parameters simulated in the model. The extensive AOD coverage from satellite observations and AERONET measurements has helped a great deal in validating model-simulated AOD over the past decade, but further progress has been slow. Large model diversities in aerosol composition, size, vertical distribution, and mixing state are difficult to constrain, because of lack of reliable measurements with adequate spatial and temporal coverage (see Chapter 2).

**Aerosol radiative forcing:** Because of the large spatial and temporal differences in aerosol sources, types, emission trends, compositions, and atmospheric concentrations, anthropogenic aerosol RF has profound regional and seasonal variations. So it is an insufficient measure of aerosol RF scientific understanding, however useful, for models (or observation-derived products) to converge only on globally and annually averaged TOA RF values and accuracy. More emphasis should be placed on regional and seasonal comparisons, and on climate effects in addition to direct RF at TOA.

### 3.8 Conclusions

From forward modeling studies, as discussed in the IPCC (2007), the direct effect of aerosols since pre-industrial times has resulted in a negative RF of about  $-0.5 \pm 0.4 \text{ W m}^{-2}$ . The RF due to cloud albedo or brightness effect is estimated to be  $-0.7$  ( $-1.8$  to  $-0.3$ )  $\text{W m}^{-2}$ . Forcing of similar magnitude has been used in



some modeling studies for the effect associated with cloud lifetime, in lieu of the cloud brightness influence. The total negative RF due to aerosols according to IPCC (2007) estimates is therefore  $-1.3$  ( $-2.2$  to  $-0.5$ )  $\text{W m}^{-2}$ . With the inverse approach, in which aerosols provide forcing necessary to produce the observed temperature change, values range from  $-1.7$  to  $-0.4$   $\text{W m}^{-2}$  (IPCC, 2007). These results represent a substantial advance over previous assessments (e.g., IPCC TAR), as the forward model estimated and inverse approach required aerosol TOA forcing values are converging. However, large uncertainty ranges preclude using the forcing and temperature records to more accurately determine climate sensitivity.

There are now a few dozen models that simulate a comprehensive suite of aerosols. This is done primarily in the CTMs. Model inter-comparison studies have shown that models have merged at matching the global annual averaged AOD observed by satellite instruments, but they differ greatly in the relative amount of individual components, in vertical distributions, and in optical properties. Because of the great spatial and temporal variations of aerosol distributions, regional and seasonal diversities are much larger than that of the global annual mean. Different emissions and differences in atmospheric processes, such as transport, removal, chemistry, and aerosol microphysics, are chiefly responsible for the spread among the models. The varying component contributions then lead to differences in aerosol direct RF, as aerosol scattering and absorption properties depend on aerosol size and type. They also impact the calculated indirect RF, whose variations are further amplified by the wide range of cloud and convective parameterizations in models. Currently, the largest aerosol RF uncertainties are associated with the aerosol indirect effect. Most climate models used for the IPCC AR4 simulations employed simplified approaches, with aerosols specified from stand-alone CTM simulations. Despite the uncertainties in aerosol RF and widely varying model climate sensitivity, the IPCC AR4 models were generally able to reproduce the observed temperature record for the past century. This is because models with lower/higher climate sensitivity generally used less/more negative aerosol forcing to offset the greenhouse gas warming. An equally good

match to observed surface temperature change in the past could be obtained from a model with larger climate sensitivity and smaller net forcing, or a model with smaller sensitivity and larger forcing (Hansen et al., 2007). Obviously, both greenhouse gases and aerosol effects have to be much better quantified in future assessments.

Progress in better quantifying aerosol impacts on climate will only be made when the capabilities of both aerosol observations and representation of aerosol processes in models are improved. The primary concerns and issues discussed in this chapter include:

- Better representation of aerosol composition and absorption in the global models
- Improved theoretical understanding of subgrid-scale processes crucial to aerosol-cloud interactions and lifetime
- Improved aerosol microphysics and cloud parameterizations
- Better understanding of aerosol effects on surface radiation and hydrological cycles
- More focused analysis on regional and seasonal variations of aerosols
- More reliable simulations of aerosol historic long-term trends
- More sophisticated climate model simulations with coupled aerosol and cloud processes
- Enhanced satellite observations of aerosol type, SSA, vertical distributions, and aerosol radiative effect at TOA; more coordinated field experiments to provide constraints on aerosol chemical, physical, and optical properties.

A discussion of the “way forward” toward better constraints on aerosol radiative forcing, and hence climate sensitivity, is provided in the next chapter.

Progress in better quantifying aerosol impacts on climate will only be made when the capabilities of both aerosol observations and representation of aerosol processes in models are improved.





Aerosols scatter incident sunlight in all directions, reducing the visibility of distant objects, and also decreasing the amount of solar energy reaching the surface, which exerts a cooling influence on the climate. Figure taken in Korea. Credit: Stephen E. Schwartz, DOE.



## 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  $\text{m}^2 \text{g}^{-1}$ .

**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.

#### **Ångström exponent ( $A$ )**

exponent that expresses the spectral dependence of *aerosol optical depth* ( $\tau$ ) (or *scattering coefficient*, *absorption coefficient*, etc.) with the wavelength of light ( $\lambda$ ) as inverse power law:  $\tau \propto \lambda^{-A}$ . 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  $\mu\text{m}$ , 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 azimuthally 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 scattering. 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  $\mu\text{m}$  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*, 2<sup>nd</sup> edition, American Meteorological Society.

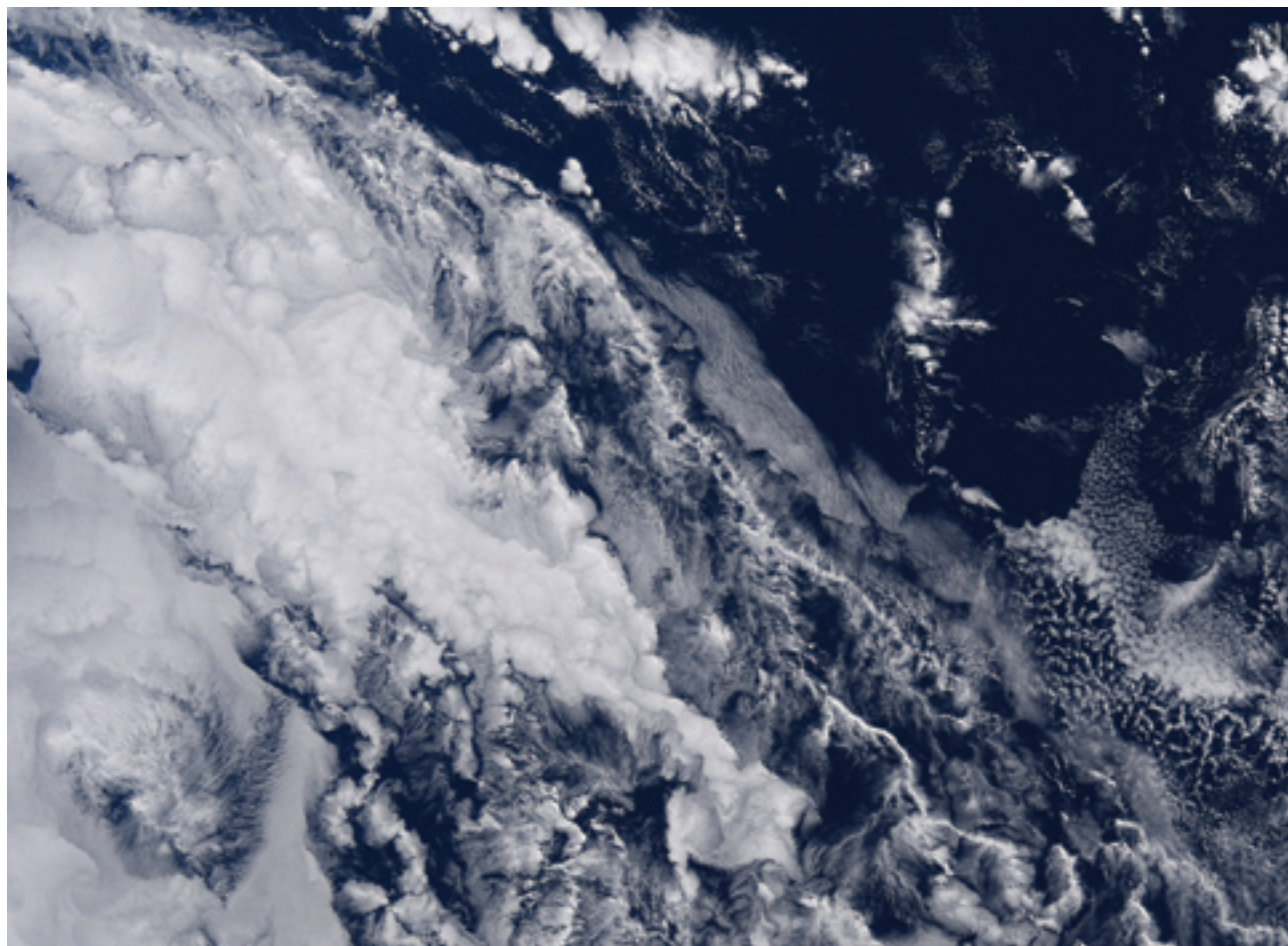
**ACRONYMS**

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

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



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



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.



- 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. Neustub, 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<sub>2</sub> 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. Thornton 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 short-wave 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. Podgorny, 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. Liou, H. Cachier, and J. Feichter, 1999: Construction of a  $1^\circ \times 1^\circ$  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. Geroso, 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 Spectroradiometer (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 (September-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<sub>2</sub> 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. Liou, 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. Spinhrne, 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. Yamamoto, 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.
- Lelieveld, 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:10.1029/2007JD008853.
- 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.



- Lioussé, 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:** Multi-year 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**, 411-415.
- 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 Addressing 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 short-wave 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:10.1029/2005GL024322.
- 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 2<sup>nd</sup> 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. Kaufman, 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. Johnsdud, 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. Anan, 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 AERO-COM. *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, doi: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. Jenenak, 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.

## Photography and Image Credits

### Cover/Title Page/Table of Contents:

**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.

For other images in this report, please see the captions/credits located with each image.

## Contact Information

Global Change Research Information Office  
c/o Climate Change Science Program Office  
1717 Pennsylvania Avenue, NW  
Suite 250  
Washington, DC 20006  
202-223-6262 (voice)  
202-223-3065 (fax)

The Climate Change Science Program incorporates the U.S. Global Change Research Program and the Climate Change Research Initiative.

To obtain a copy of this document, place an order at the Global Change Research Information Office (GCRIO) web site:  
<http://www.gcrio.org/orders>.

---

## Climate Change Science Program and the Subcommittee on Global Change Research

**William Brennan**, Chair  
Department of Commerce  
National Oceanic and Atmospheric Administration  
Director, Climate Change Science Program

**Jack Kaye**, Vice Chair  
National Aeronautics and Space Administration

**Allen Dearry**  
Department of Health and Human Services

**Anna Palmisano**  
Department of Energy

**Mary Glackin**  
National Oceanic and Atmospheric Administration

**Patricia Gruber**  
Department of Defense

**William Hohenstein**  
Department of Agriculture

**Linda Lawson**  
Department of Transportation

**Mark Myers**  
U.S. Geological Survey

**Tim Killeen**  
National Science Foundation

**Patrick Neale**  
Smithsonian Institution

**Jacqueline Schafer**  
U.S. Agency for International Development

**Joel Scheraga**  
Environmental Protection Agency

**Harlan Watson**  
Department of State

### EXECUTIVE OFFICE AND OTHER LIAISONS

**Robert Marlay**  
Climate Change Technology Program

**Katharine Gebbie**  
National Institute of Standards & Technology

**Stuart Levenbach**  
Office of Management and Budget

**Margaret McCalla**  
Office of the Federal Coordinator for Meteorology

**Robert Rainey**  
Council on Environmental Quality

**Daniel Walker**  
Office of Science and Technology Policy



U.S. Climate Change Science Program  
1717 Pennsylvania Avenue, NW • Suite 250 • Washington, D.C. 20006 USA  
1-202-223-6262 (voice) • 1-202-223-3065 (fax)  
<http://www.climatechange.gov>

