

NATIONAL AEROSOL-CLIMATE INTERACTIONS PROGRAM

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# N A C I P

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A National Research Imperative

*WHITE PAPER*



# Authors

## Prepared by the NACIP Scientific Steering Committee

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# Executive Summary

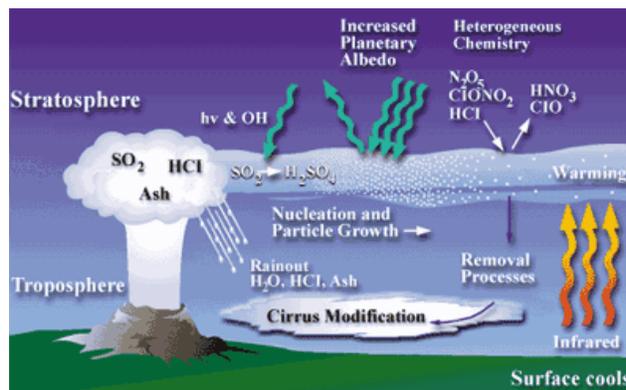
*A National Aerosol-Climate Interactions Program is needed to focus new research on aerosols and their interactions with the climate system. NACIP will provide breakthroughs in understanding of the roles of different types of aerosols in climate change that are unlikely to be achieved in the next decade without a focused inter-agency initiative. NACIP findings will help also to determine regional impacts of aerosols (e.g., on the hydrologic cycle, fresh-water availability, agriculture, and ecosystems) and to identify possible ties to climate mitigation strategies. In addition to coordination or redirection of existing U.S. research, substantial new research efforts are required: (i) to measure the sources, distribution and properties of aerosols (particularly soot) and their influence on cloud formation, rainfall and radiation budget globally on a region-by-region basis; (ii) to model the emissions, transport and transformation processes in the atmosphere that govern aerosol distributions and forcings, including realistic representations of aerosols in climate models based on observations; and (iii) to quantify the relative importance of aerosols and greenhouse gases in global warming, including regional climate impacts. The new program will include preparation of regular state-of-the-science reports with best values for and uncertainties of the aerosol forcing of climate on global and regional scales. Without this initiative national and international climate assessments planned for the coming decade will not be able to reliably quantify the role of aerosols in global warming to date or project climate change that would result from alternative emissions scenarios.*

## Aerosol Climate Effects: Summary and Recent Advances

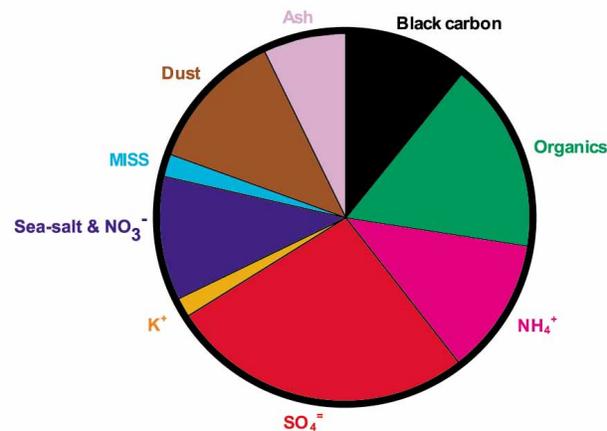
Aerosols, microscopic particles suspended in air, have increased significantly over the industrial period because of human activities. Their effects on climate are the largest source of uncertainty in the current IPCC estimates of the global climate forcing due to human activities. These tiny particles influence climate by scattering and absorbing solar radiation, by altering cloud properties such that they reflect more solar radiation and by inhibiting the ability of clouds to develop precipitation. Climate models that include the effects of increases in sulfate aerosols have shown that the resultant cooling of the Earth surface may have compensated for some or most of the greenhouse warming in many regions of the world. The global-scale cooling observed following large volcanic eruptions such as Pinatubo provides dramatic evidence for the influence of sulfate aerosols on climate. But sulfates are only one of many aerosol species added to the atmosphere by humans. Other species include black carbon (soot), organic compounds, and dust among others. Some types of aerosols, particularly black carbon, augment the global warming influence of greenhouse gases. This white paper is preceded by several reports (e.g. see the NACIP Reference Library, <http://www-NACIP.ucsd.edu/NACIPreferencelibrary.html>) that have made a compelling case for a national program on aerosols, in particular, the National Research Council's report chaired by Seinfeld et al. (1996), "A Plan for a Research Program on Aerosol Radiative Forcing and Climate Change".

Although the effect of aerosols on global temperature might itself justify a focused research program, recent observations raising the possibility that aerosols have substantive impact on regional climate in some parts of the world make the need for such a program even more imperative. Field experiments employing satellites, aircraft, ships and island stations have been conducted since the mid 1990s over the Amazon basin, southern Africa, East and South Asia, and downwind of the Eastern United States and Western Europe. Observations from these experiments together with recent studies using satellite data have

led to major breakthroughs in understanding of the mechanisms by which aerosols influence climate and of the magnitude and extent of these influences. The new observations have revealed aerosol effects, not represented in current climate models, which connect anthropogenic aerosols to alterations in rainfall and the hydrologic cycle, thus influencing regional climate.



The dispersal of volcanic aerosols has a drastic effect on the Earth's atmosphere. Following an eruption, large amounts of sulphur dioxide (SO<sub>2</sub>), hydrochloric acid (HCL) and ash are spewed into the Earth's stratosphere. Hydrochloric acid, in most cases, condenses with water vapor and is rained out of the volcanic cloud formation. Sulphur dioxide from the cloud is transformed into sulphuric acid (H<sub>2</sub>SO<sub>4</sub>). The sulphuric acid quickly condenses, producing aerosol particles which linger in the atmosphere for long periods of time and impact climate (<http://www-sage3.larc.nasa.gov/solar/learning-aerosol.html>).

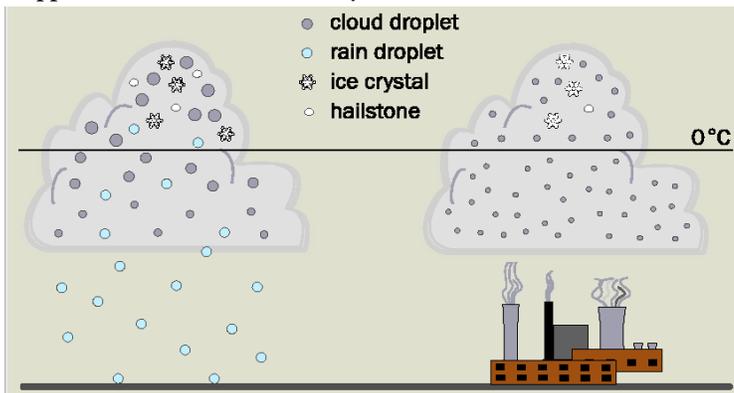


Composition of marine aerosols subject to pollution (location: tropical Indian Ocean).

These observations have revealed that absorption of solar radiation by aerosols can inhibit cloud formation by reducing atmospheric temperature and humidity gradients. The same aerosols reduce irradiation by as much as 10 to 15% at the surface thus reducing evaporation from the surface. These regional changes in solar radiative fluxes by anthropogenic aerosols are as much as a factor of ten greater than the global average changes in the radiative fluxes (referred to as climate forcing) by aerosols or greenhouse gases. Furthermore clouds formed on dense smoke or pollution aerosol have smaller droplets that do not develop readily into precipitation. Thus increasing aerosol concentrations have the potential to shift precipitation away from populated regions.

Furthermore, transport of both natural and anthropogenic aerosols from the boundary layer to the middle and upper troposphere through deep convective processes or large-scale lifting may have a significant effect on upper-level cirrus cloud microphysical and radiative properties. Once ingested into the base of a deep convective cloud, the CCN portion of an aerosol population first acts as sites for water droplets. When vertical velocities are sufficiently strong and the droplets are transported through the  $-40^{\circ}\text{C}$  temperature level, they will freeze by the “homogeneous ice nucleation process” to become small ice crystals. Droplet concentration and CCN concentration are related, and therefore, all else being equal in these situations, ice crystal and CCN concentrations will be related which can lead to enhanced cloud albedos. Upon reaching the middle and upper troposphere through deep convection of by synoptic-scale lifting, anthropogenically-produced aerosols are in a favorable location to influence cirrus cloud formation, evolution and radiative properties. We can speculate as to what effects may occur but data are needed to identify the magnitude of the effects.

Suppression of Rain and Snow by Urban and Industrial Air Pollution



Courtesy of D. Rosenfeld.

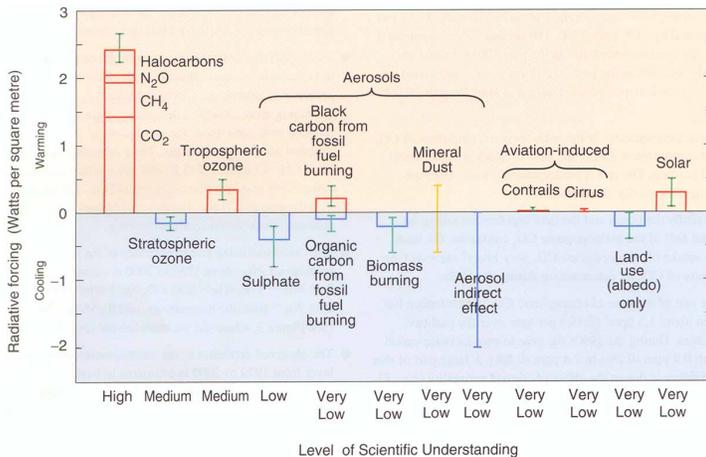
Greenhouse warming will increasingly dominate over radiative forcing effects of aerosols in the future as greenhouse gases continue to accumulate in the air. However, the aerosol effect will remain large enough for the next several decades (especially on the regional scales) that it must be known quantitatively in order to correctly interpret observed climate change and to develop optimum policies for dealing with climate change. Present understanding of aerosols and particularly of their interactions with clouds is insufficient to quantify their influence on global and regional climate change. A substantial concerted effort, with a new paradigm, is required to achieve the necessary understanding. This document presents the framework of such a research program.

## The Need for a National Program to Determine Aerosol Effects on Climate

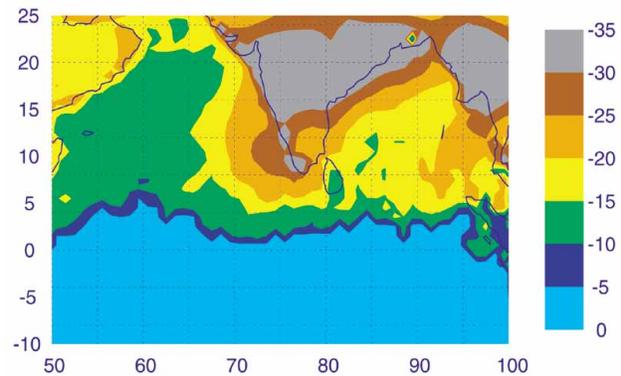
In January 2002 over 50 leading scientists together with representatives from several agencies met to assess the requirements for future research to determine the effects of atmospheric aerosols on global and regional climate change. The consensus of that workshop (<http://www-NACIP.ucsd.edu>) was that there is a critical need for a National Aerosol-Climate Interactions Program (NACIP) that will focus new research on aerosols and their interactions with the climate system.

The new paradigm of NACIP is to attack the aerosol-climate forcing problem from an observational basis. The observations will also constitute rigorous verification tests and constraints for models, thus leading to better quantification of the climate forcing and its linkage to the emissions. The global average climate forcing (radiative flux changes at the boundary between the troposphere and the stratosphere) due to greenhouse gases is about  $2.5 (\pm 0.5) \text{ Wm}^{-2}$  whereas current estimates of aerosol forcing range from  $0.5$  to  $-4 \text{ Wm}^{-2}$ . Regionally the aerosol induced radiative flux changes can be a factor of 2 to 4 times larger and the seasonal mean flux changes at the surface can be a factor of 10 larger.

The Global Mean Radiative Forcing of the Climate System for the Year 2000, Relative to 1750



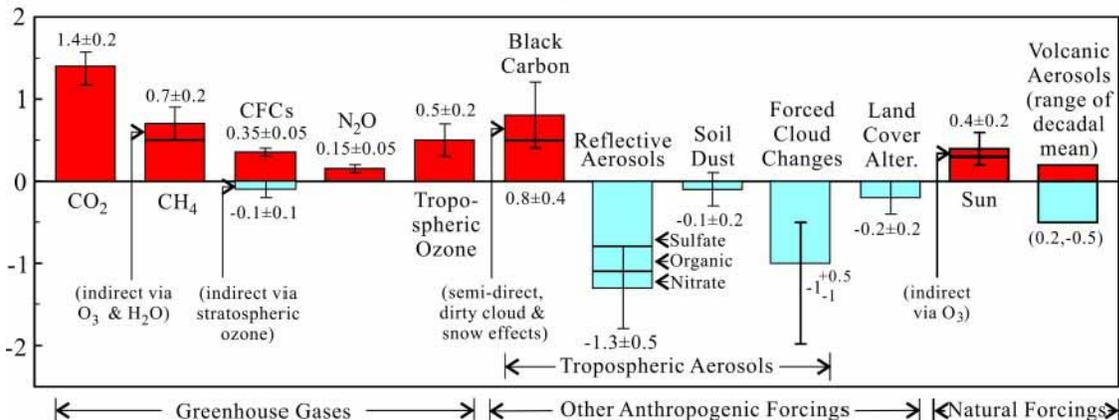
Regional Aerosol Forcing (W/m<sup>2</sup>)



Many external factors force climate change (IPCC, Climate Change 2001, The Scientific Basis, 2001).

The Indo-Asian haze effects on seasonal mean (January to April for 1996 to 1999) reduction in surface solar radiation (Ramanathan et al., *Science*, 2001).

Global Climate Forcings (W/m<sup>2</sup>): 1850-2000



Estimated climate forcings; error bars are partly subjective 1σ uncertainties (Hansen and Sato, *Proc. Natl. Acad. Science*, 2001).

The greenhouse forcing is known to within 25% because the forcing estimates are based on observed atmospheric concentrations of the gases and well known quantum mechanical calculations backed by laboratory infrared absorption spectra. The aerosol forcing on the other hand, is based on model simulations with too few observations to constrain the model input and its assumptions of various aerosol related chemical, microphysical, meteorological and radiative processes. In addition, the variations and trends in the global distributions and forcings, including the historical evolution of different aerosol species, is much poorly known than that for the well-mixed greenhouse gases.

Furthermore, climate effects are more complex and poorly known than those of greenhouse gases, in part because aerosols are heterogeneously distributed, quite variable in their properties, and not well measured, in part because aerosols play a more extensive role than greenhouse gases through their direct interaction with cloud formation and precipitation, and in part because the ability to simulate aerosols, their interactions, and their effects in climate models is still rudimentary.

### *The NACIP Objective*

The fundamental objective of NACIP is to determine the climate forcing of anthropogenic aerosols, including their effects on solar radiation at the surface, clouds, precipitation and the hydrologic cycle at regional to global scales. The forcing determined by NACIP will be constrained by observations. NACIP can be expected to derive, within ten years, a best estimate of the global climate forcing by anthropogenic aerosols with an uncertainty of  $\pm 25\%$  or less compared with the unconstrained (at least  $\pm 100\%$  or more) uncertainty in current IPCC estimates.

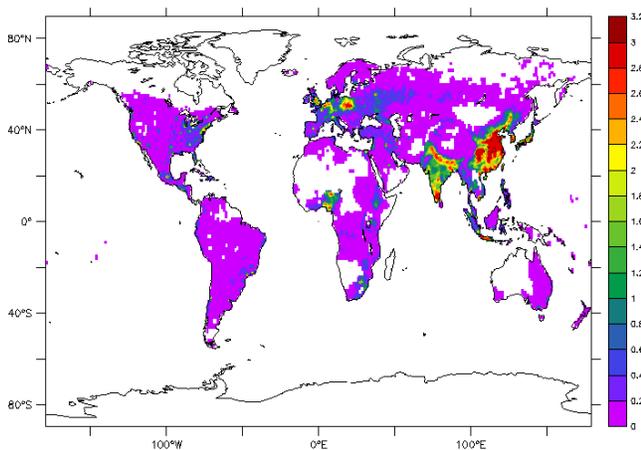
### *The NACIP Big-Five Issues*

To accomplish this ambitious objective, NACIP must first reduce the factor of two or more range in model estimates reported in IPCC in the following aerosol properties and effects:

- B1) The strength of aerosol emissions by fossil fuel combustion and biomass burning;*
- B2) The global distribution of black carbon and organics;*
- B3) The alteration of cloud properties and cloud albedo;*
- B4) The reduction in precipitation efficiency; and*
- B5) The increase in atmospheric solar heating, the reduction in solar radiation at the surface, and the impact on surface evaporation.*

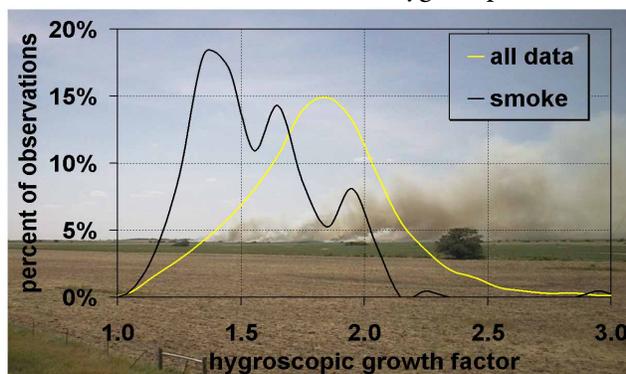
Particular emphasis will be given to organic aerosols and black carbon, as these aerosol components are currently the most poorly characterized, and there is an eightfold range in their emission estimates (see <http://www-NACIP.ucsd.edu> for working group reports).

An Estimate of Black Carbon Emissions  
(Gg/grid cell/year, 1996)



Estimate includes only fossil fuel and bio-fuel burning, and does not include open biomass burning. Courtesy of T. Bond and D.G. Streets, 2002.

Water Uptake by Aerosols:  
Smoke Particles Are Less Hygroscopic



Four years of continuous surface aerosol measurements by NOAA from the DOE ARM Southern Great Plains site (Sheridan et al., *J. Geophys. Res.*, 2001). These results show distinctive values of hygroscopic growth in the smoke aerosols from local field burning, allowing usage of realistic value of hygroscopic growth of biomass-burning aerosols in aerosol radiative forcing models.

## *The NACIP Paradigm*

The new paradigm of observationally constrained climate forcing requires focus, prioritization, an implementation plan that resonates with the NACIP objective and attacks head-on the Big-Five issues, and international collaboration. In addition to coordination and some redirection of existing U.S. research, NACIP requires substantial new research efforts.

With respect to focus, NACIP is designed to answer specific questions such as: What is the current climate forcing from anthropogenic aerosols? How has the aerosol forcing altered the global and regional precipitation? How has the aerosol forcing changed over the industrial period? The central issue is to link the forcing to the aerosol emissions (B1).

With respect to prioritization, high priority will initially be given to the following efforts:

*P1) Systematic measurements of sources, distributions and properties of aerosols, on a region-by-region basis (B1 and B2).*

*P2) In-situ and remote measurements of aerosol effects on clouds and precipitation (B3 and B4).*

*P3) Application of these measurements to develop realistic treatment of aerosols, including their chemical and microphysical evolution, and their interactions with radiation, clouds and precipitation in climate models (B1 to B4).*

*P4) Integration of the measurements and models to determine the aerosol effects on top-of-atmosphere and surface radiative forcing, precipitation efficiency and surface evaporation (B5).*

A detailed implementation plan based on the four priorities (P1 to P4) is being written in consultation with the national aerosol community, and we list here the six key ingredients of the plan, starting from observing platforms at the surface to space borne observations and models.

(i) *Deploy aerosol observatories at strategic regional locations to augment existing aerosol observing systems (P1).* These observatories are the only reliable way to determine the sources and emission inventories (B1),

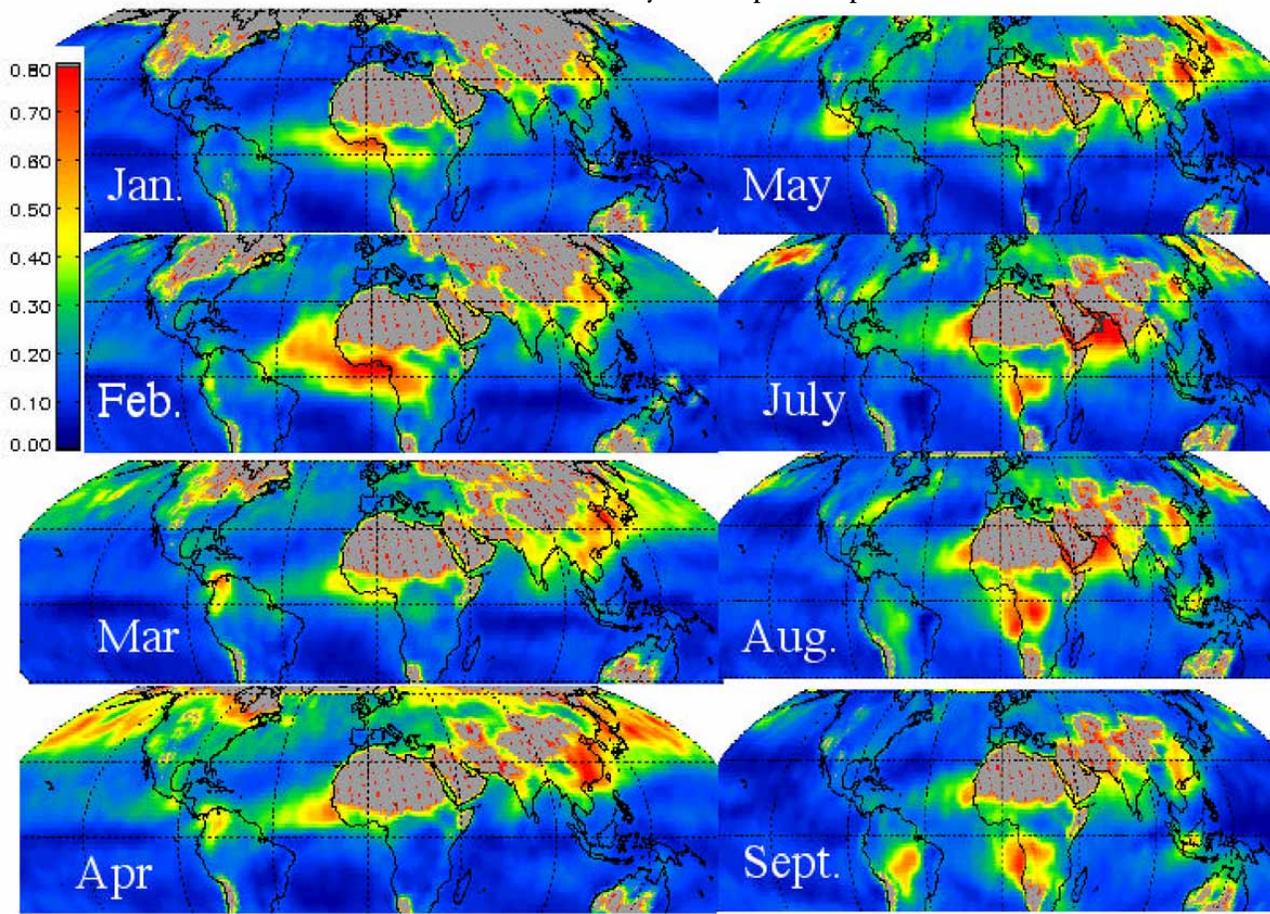
aerosol composition (including their vertical variation through systematic aircraft flights), the surface radiative forcing (B5), evaporation (B5), and the column integrated aerosol properties. The key issue is the quantification of black carbon emissions and this requires development of new measurement techniques. NACIP will use these observatories to link aerosol radiative forcing to aerosol composition and sources (natural and anthropogenic), a fundamental objective of NACIP; to validate satellite measurements; and to evaluate aerosol-chemical-microphysical-transport models. The number and location of these sites will be dictated by aerosol assimilation and transport models.

(ii) *Carry out exploratory flights using light and unmanned aircraft with aerosol and cloud physics instruments to determine the relationship between aerosols (composition and concentration), cloud properties and precipitation efficiency (P2).* This is the major unknown process in the aerosol-climate problem and it requires in-situ data. It is in this topic (B3 and B4) that NACIP is expected to provide major breakthroughs and contribute to a quantum jump in the treatment of aerosol-cloud interactions in climate models. Given the large variability of cloud properties on scales ranging from meters to several thousand kilometers, and from minutes (life time of a cumulus cloud) to several days of an entire cloud system (storm track, stratocumulus and cirrus), long duration and long range flights are required over different aerosol regimes to collect data on pristine to polluted cloud systems in the world.

(iii) *Design and develop satellite instrumentation to identify major types of natural and anthropogenic aerosols, including black carbon and other absorbing aerosols, and observe their global distribution and transport (P1, P3, P4).* Given the eightfold range in black carbon emissions and the fundamental importance of BC to climate change, observations of BC distribution around the world, would certainly go a long way toward solving the aerosol-climate problem (B2).

(iv) *Develop satellite instrumentation tailored to simultaneously measure aerosols and their effects on clouds, precipitation and solar radiation (P4).* Satellite

### Global Aerosol Monthly Mean Optical Depth



MODIS monthly optical thickness 2001 (Courtesy of Y. Kaufman).

measurements provide the only mode for global observations of aerosols, their impact on radiation fluxes (at the top of the atmosphere), cloud microphysical and radiative properties, and precipitation (B3, B4, B5). Recently launched satellites have improved capabilities for these measurements, but still greater precision of aerosol properties is demanded by the climate application. Scheduled missions for this decade include new instruments of great interest to NACIP (e.g. CLOUDSAT, space-borne lidar, global precipitation mission), but support is required for analyses of multiple space-based datasets in synergistic ways, and still greater precision for detail of aerosol properties is demanded by the climate application. NACIP will promote development of satellite instrumentation tailored to precisely identify and measure natural and anthropogenic aerosols and their effects on clouds, precipitation and solar radiation.

(v) *Conduct integrated multi-platform (surface, ships, aircraft and satellites) field campaigns, relevant for climate studies.* The

last decade witnessed about 10 major field campaigns, lasting typically 4 to 6 weeks, conducted to understand specific aerosol related questions. Under NACIP, field campaigns will be designed to quantify the links between aerosols and the hydrologic cycle, to relate the aerosol forcing to aerosol types and their regional emission sources; and to the improvement of aerosol treatment in climate models.

(vi) *Develop models to represent the various aerosol species and their effects on radiative forcing, cloud formation and precipitation.* Ultimately, realistic models provide the only viable approach for determining aerosol forcing from the pre-industrial era to the present, and for assessing the impacts due to future emissions. Climate models are now capable of incorporating aerosols as well as greenhouse gases, but aerosol properties, especially their interactions with clouds, must be treated more realistically. The models should include not just sulfates, but also black carbon, organics and dust that constitute more than

International Global Atmospheric Chemistry Project  
**ACE - Asia**  
 Asian Pacific Regional Aerosol Characterization Experiment

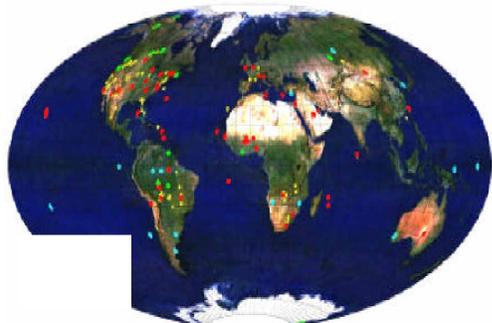


<http://saga.pmel.noaa.gov/aceasia/index.html>

50% of the anthropogenic aerosol loading. Observations will be used to conduct the research necessary to represent (in models) processes controlling aerosol chemistry, loading, distribution, properties and their impact on cloud properties and precipitation efficiency. Observations, together with model simulations, will enable identification of the factors that control the variations and trends in the distributions and the forcings.

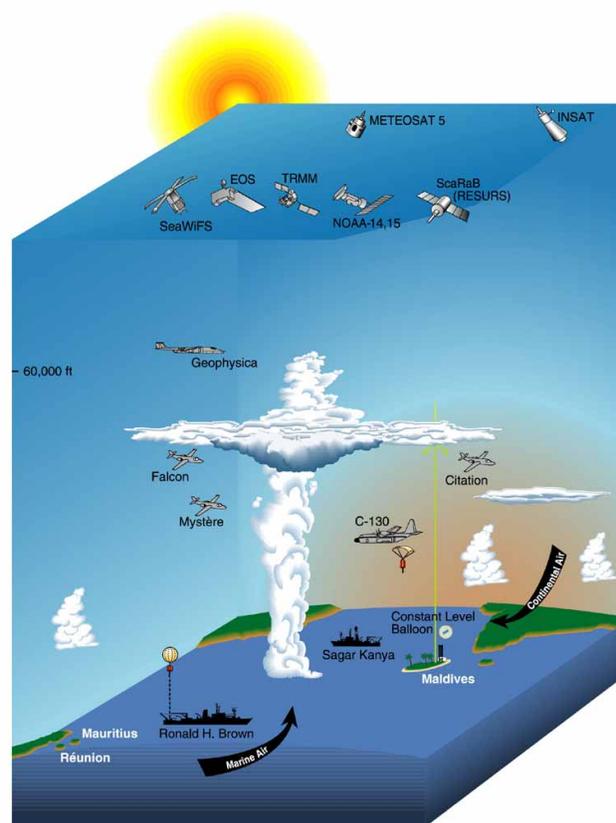
The list includes many ongoing activities that either satisfy NACIP criteria or can be made to address the Big-Five issues with NACIP support. For example, the AERONET network of sun-photometers and sky radiance radiometers includes 120 stations around the world (led by the US and France). NACIP needs to select a sub-set of these sites and augment them with instruments to meet NACIP priorities. Another major example is the 10 aerosol field campaigns conducted during the last decade. Nationally, NACIP will support

**Aerosol Robotic NETWORK (AERONET)  
 of Ground-based Sun/Sky Radiometers**



Courtesy of B. Holben, NASA GSFC.

**INDOEX**  
 INDIAN OCEAN EXPERIMENT



<http://www-indoex.ucsd.edu>

coordination of multi-agency efforts to help focus the research to attain 10-year goals. Basically, NACIP in addition to requiring some redirection of available resources urgently needs new research support to attack key problems, especially, the global sources and distribution of carbonaceous aerosols (B2), the quantitative link between aerosols and clouds (B3) and improvement of aerosol effects in climate models.

International collaboration with developed and developing nations is the key for the success of the observatories, aircraft flights and field campaigns because many of them will be located outside USA. In addition, European nations, Brazil, Japan, China and India also maintain ground based aerosol observations. These nations also have satellites that monitor aerosol distribution and some have active aircraft programs. Aerosol loading is especially heavy in (in addition to the eastern United States in summer) Eastern Europe, Africa, the Amazon basin, and especially in India and China. Asia, by itself, contributes about 50% of the global black carbon

and organic carbon emissions (<http://www-NACIP.ucsd.edu>). These continental and the adjacent Atlantic, Pacific and Indian Ocean regions provide good test beds for studying aerosol climate effects. International collaboration will minimize the cost for setting up the observatories and field campaigns, for personnel to run these observatories, and for data analysis. For example, for the \$25M US-led Indian Ocean Experiment aerosol campaign, about 40% was borne by European nations, India and Maldives and the rest was supported through US funds. NACIP will work closely with international programs such as LBA, IGAC, GEWEX and GAW to seek cooperation across national boundaries.



### Major Deliverables of NACIP

*NACIP will produce i) an observationally constrained global estimate of the aerosol climate forcing and the anthropogenic contribution to this forcing, including robust evaluation of its uncertainty; and ii) a triennial evaluation of the state of the science and the progress of NACIP.*

### Links with Air Pollution

In addition to their climate influence, aerosols are tied to other areas of public concern. The same aerosols that impact climate are key contributors to air pollution on local and regional scales. In regions of heavy pollution, aerosols are linked to health impairment and increased mortality, visibility reduction, and decreased agricultural productivity. Aerosols and their precursors also contribute to acid deposition. Recognition of these environmental impacts of aerosols has led to establishment of air quality standards for aerosols — fine particle or PM-2.5 standards. Devising effective and efficient strategies to meet these standards requires much of the same knowledge of processes affecting aerosol loading and distribution as is required for evaluating the climate influence of aerosols. Although the requirements for aerosol research for air quality studies are rather different from the requirements for climate research, much of the information on aerosol sources and aerosol chemistry generated by NACIP would also be of direct benefit to EPA and other agencies responsible for developing implementation strategies to meet fine particle standards, and likewise NACIP will benefit from research directed to this problem by the air quality research community.

### Community Readiness

The complexity of atmospheric aerosols, their cross-boundary and trans-continental distribution, their regional and global climate effects, and their impacts on agriculture and health make quantifying these aerosol influences a challenging scientific problem. The atmospheric and climate science community has over the past two decades built considerable expertise in the modeling, observational and technological aspects of the problem. Equally important, the recent international field campaigns and joint development of surface observatories have afforded unprecedented experience in international collaboration with developed and developing nations. Given the infusion of adequate new funds, the atmospheric aerosol research community is ready to tackle this most important environmental problem that connects air pollution, global warming, and the fresh-water budget of the planet.