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Group Report: What Are the Observed and Anticipated Meteorological and Climatic Responses to Aerosol Forcing?

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INTRODUCTION

After considering the question posed to our group, we concluded that our response must consist of inquiries into two distinct areas:

1. modeling and verification of the *forcing*, and
2. modeling and verification of the climate *response*.

The first is a necessary condition for the success of the second, since the accuracy of forcing is crucial to the derivation of an accurate estimate of the response. The consideration of these issues prompts an important question concerning global climate change: to what extent and where geographically have the aerosols counteracted the greenhouse-gas forcing? As far as modeling is concerned, there have been investigations of aerosol forcing (e.g., Kiehl and Rodhe, this volume) and the simulation of its climatic effects (e.g., Roeckner et al., this volume). In the case of tropospheric aerosols, however, the verification of forcing and response is yet to be accomplished. In recognition of the central importance of verification in the question posed to our group, we highlight herein the gaps and inadequacies of present knowledge in regards to forcing and response, and discuss ways in which the uncertainties can be reduced.

Aerosol Forcing of Climate
Edited by R.J. Charlson and J. Heintzenberg

Some of the discussions here coincide with those from the other group reports, thus reinforcing the importance of the issues. For a broader perspective on the current status of the science, the reader is referred to other papers in this volume and to the state-of-the-art assessment by the IPCC (1994).

MODELING AND VERIFICATION OF FORCING

Tropospheric Aerosols (Direct Forcing)

Modeling aerosol forcing requires an understanding of many atmospheric physical and chemical processes, including those associated with precursor gas transformations, meteorology, cloud microphysics, and chemistry. Since these are dealt with elsewhere in this volume, they will not be discussed here.

Verification of the existence, magnitude, and trend of the direct climate forcing by the different types of aerosols (e.g., sulfate, biomass combustion products, organics, mineral dust, and soot) is a prerequisite in ascertaining the climate response. At present, there are large uncertainties (factor of two or more) in estimates of the radiative forcing by aerosols (IPCC 1994). Because of the potentially significant role of aerosols in the climate system (Coakley et al. 1983), there is an urgent need to improve the accuracy of current estimates. The main pathway towards improving our knowledge of aerosol-forcing estimates is through *in situ* process studies and monitoring that involve simultaneous and coincident microphysical, chemical, optical, radiative, and meteorological measurements—the so-called "closure" experiments. Ideally, closure experiments involve the acquisition of an overdetermined set of measurements that will ultimately permit a rigorous comparison of measured and calculated forcing. The degree of agreement or the magnitude of the discrepancy between measured and calculated quantities then becomes an objective basis for estimating the uncertainty of the forcing. Figure 20.1 presents examples of closure experiments that could be employed to quantify the aerosol forcing (Penner et al. 1994). To date, many of the parameters in Figure 20.1 have not been determined experimentally. To cite an example of closure: on a spatial scale, over which process studies are feasible (say, tens of kilometers), measurements of size distribution and chemical composition might be used to compute the single-scattering properties, which could then be compared with measured values through a given depth of atmosphere. Measurements of radiative quantities (radiances and irradiances) in the same area would allow verification of the computed values.

Over larger spatial scales (exceeding 100 km), such as in mesoscale and general circulation models (GCMs), such detailed comparisons between computations and measurements are going to be very difficult to execute. Nevertheless, because these are the spatial domains typically employed to estimate the meteorological and climate responses, it is highly desirable to verify the forcing on these scales as well. This is best accomplished from spaceborne platforms. Regardless of the scale of the studies,

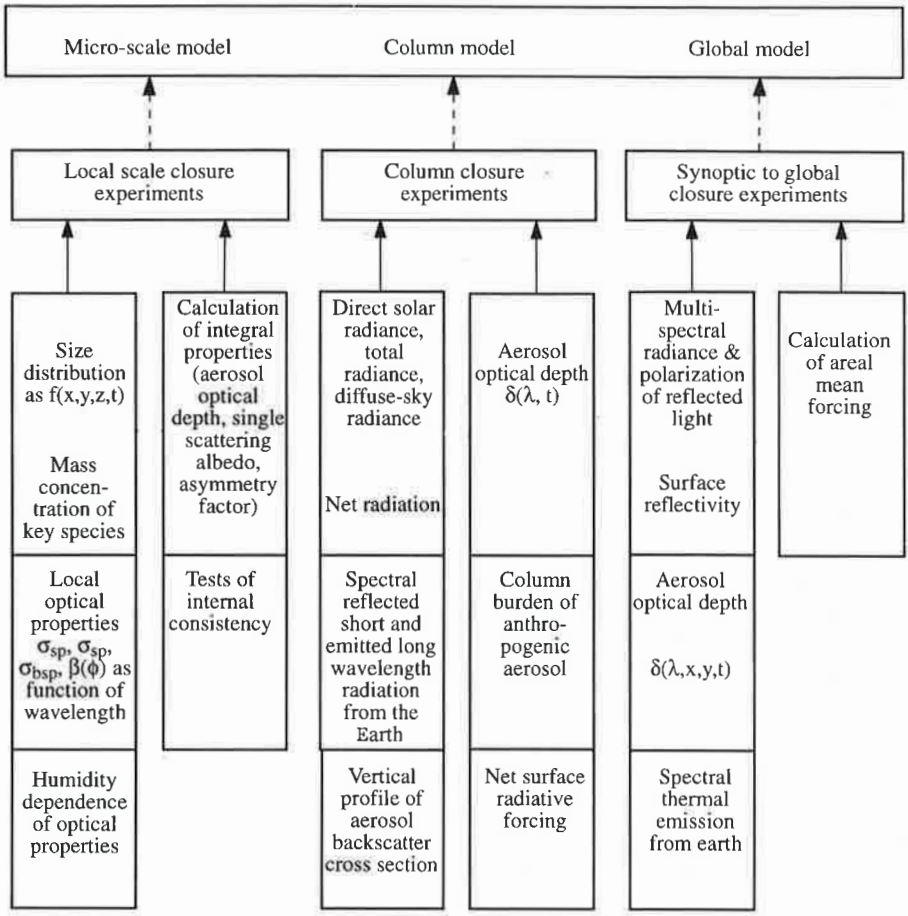

Figure 20.1 Examples of closure experiments used to quantify aerosol forcing. Adapted from Penner et al. (1994); used with permission from the American Meteorological Society.

aircraft- and surface-based radiation as well as chemical and physical composition measurements are also required. Spectrally resolved radiances (in both solar and infrared spectrum) should be measured since these afford a stringent verification of the radiative calculations.

A closure approach involving coordinated measurements of the relevant quantities would enable a quantitative assessment of the accuracy of the microphysical–chemical–transport–radiation models. Also, such exercises would permit a test of the applicability of extrapolating the aerosol forcing derived on smaller scales (wherein

the processes involved are better understood) to the coarser spatial domain typical of GCMs. It must be recognized that, while microphysical and chemical measurements are possible only on a local scale, it is the ensuing radiative effect operating over a larger spatial domain that results in the aerosol forcing of climate. One optical parameter that field campaigns should in particular attempt to determine accurately is the single-scattering albedo—a quantity that is of considerable significance in determining the radiative energy absorbed in the atmosphere.

Some observations of the effects of aerosols on radiative transfer have been reported and there have been limited campaigns that have sought to measure or infer aerosol optical and radiative characteristics. These include observations from satellites (e.g., Rao et al. 1988; Kaufmann and Sendra 1988; Kent et al. 1993) and from the surface (Ball and Robinson 1982; Husar and Wilson 1993). Some of the *in situ* observations have been conducted in polluted regions while the satellite observations have been near global in extent. These observational results suggest that the aerosol radiative forcing has a strong spatial and temporal dependence, in agreement with chemical models (see Kiehl and Rodhe, this volume). Closure approaches, however, with the possible exception of the investigation by Russell et al. (1979), have rarely been attempted. Recognizing this deficiency, we strongly recommend that future field campaigns include the closure strategy as an essential element of their plans. In the absence of such closure experiments, the uncertainties in the aerosol forcing are likely to remain large. Closure experiments could also provide an empirical basis for parameterizing physical and chemical processes that are not fully understood from a theoretical standpoint.

While process studies can reduce the uncertainties in estimates of climate forcing, it is also essential that monitoring strategies be given high priority. Continuous broadband and spectral measurements of the radiances and irradiances, using satellites and ground-based instruments, are crucial to monitoring the temporal evolution of the aerosol optical properties. These should be complemented by regionally representative *in situ* measurements of aerosol physical, chemical, and optical properties.

For satellite-, aircraft-, and ground-based instruments, instrument calibration and drift are major factors affecting data quality. In the case of the surface-based instruments, considerable improvements in the technology may become necessary. Surface instruments should be deployed at sites in a number of regions, ranging from highly polluted to "clean" conditions. We would like to point out that careful, precise measurements, sustained over long time scales (i.e.,"accurate monitoring"), demand, but have frequently lacked, adequate resources and have often not even received appropriate recognition. To rectify this situation, it is imperative that accurate monitoring of the key physical and chemical properties of atmospheric aerosol be recognized as a scientific venture of prime importance. Further, reliable long-term records of aerosol parameters, whether *in situ*, remotely sensed, or by proxy, are essential to the reconciliation of the observed and modeled radiative forcing. An additional need is to compile and archive aerosol data from past campaigns and measurement programs into a data set from which temporal changes over the past several decades can be

estimated. Such a compilation, however, demands a high level of care in assessing the quality of the contributing observations.

In summary, without rational improvements in our knowledge of the chemical, physical, and optical properties of aerosols as well as their temporal and geographical distributions, it will be impossible to reduce the uncertainty in the radiative forcing due to aerosols, let alone how it might be evolving. The consequence of not reducing the uncertainty in the forcing will be an unacceptable continuation of the current inability to develop reliable predictive models of climate change.

Tropospheric Aerosols (Indirect Forcing)

Verification of indirect forcing by aerosols is not as well-posed a problem as it is for their direct effect. Fundamental gaps in understanding remain for certain key processes, such as the degree to which the size-dependent chemical composition is influenced by the full range of gaseous emissions and the role of in-cloud processing. The physical structure of clouds (e.g., finite size, internal inhomogeneities) and the thermodynamic characteristics of the cloud environment cause additional complexity. This area needs fundamental research and requires serious exploratory studies.

Satellite observations are expected to provide the best geographical and temporal monitoring of changes in cloud properties that might be linked to changes in the concentrations of aerosols. Satellites can provide indices of fractional cloud cover, frequency of occurrence, cloud top altitude, hydrometeor size, and liquid/ice water amounts. Shifts in hydrometeor size within a specific cloud system, such as opaque-layered clouds within a particular height range, are often used to identify polluted clouds (Durkee 1989). Reflectivities at nonabsorbing visible wavelengths for the same clouds are then used to obtain indices of liquid water path and absorption that might have been added to the cloud through the addition of an absorbing aerosol (Coakley et al. 1987; Kaufman and Nakajima 1993). Simultaneous observations of cloud liquid water using spaceborne microwave radiometers, for example, would allow changes in the visible reflectivity to be apportioned to changes in cloud liquid water and single-scattering albedo. Satellite-derived estimates of the effective drop sizes over Northern and Southern Hemisphere's oceans and continents (Han et al. 1994) indicate differences that are qualitatively consistent with the anticipated aerosol-induced microphysical changes and are also consistent with modeled estimates; this aspect, however, has to be pursued further before more definitive conclusions can be reached.

Confidence in indices, such as cloud liquid water and hydrometeor size, has grown through comparisons with *in situ* observations made during recent field campaigns (e.g., the Atlantic Stratocumulus Transition Experiment, ASTEX). These comparisons have demonstrated that the indices for hydrometeor size and cloud liquid water obtained from satellite observations bear a strong resemblance to their physical counterparts obtained *in situ* from aircraft observations, with uncertainties of 20%–40% in

such comparisons. It would appear that shifts in droplet size and liquid/ice water amount within similar cloud systems will be readily identifiable, while accurate estimates of droplet size and liquid/ice water amounts themselves remain elusive. One long-term data set that should be exploited, in an attempt to retrieve optical depth and effective radius over oceans, is the AVHRR data, which dates back to 1979.

The field campaigns mentioned thus far have been devoted to maritime clouds. Comparisons of satellite-derived cloud properties with *in situ* observations have yet to be performed on polluted continental clouds. Field programs that make such comparisons should ideally do so for single cloud types in both polluted and pristine conditions. Such studies should be localized to limit possible differences in cloud structure to the effects of the aerosol. These conditions might be met in an extensive cloud system, for example, that straddles the up- and downwind sides of a heavily populated urban region.

In addition to intensive field programs, long-term monitoring sites need to be equipped with simple, reliable tools that would allow confirmation of the inferences made by satellites. At issue are: monitoring the concentration of cloud condensation nuclei (CCN), ground-based and remotely sensed hydrometeor sizes, and ice/liquid water amounts. These observations are expected to be made on a long-term basis in addition to those such as surface irradiances, temperature, and moisture profiles, etc. Multispectral observations of directly transmitted and scattered radiation are suggested as one possible means for inferring indices of hydrometeor size and ice/liquid water amounts.

We recommend the development and validation of ground-based remote-sensing techniques for measurements of cloud properties. For example, monitoring the 11 μm downward radiance at the surface could help characterize cloud base height and the degree of spatial homogeneity within the cloud. Ground-based lidars, too, could be used to monitor the cloud base height accurately. As another example, it may be possible to retrieve radiative and microphysical properties from transmittance measurements at selected wavelengths in the visible and the near-infrared spectra. To carry out retrievals of microphysical properties, well-calibrated radiometers and temperature and humidity profiles throughout the atmosphere are also required. Such observations should be made with simultaneous measurements of aerosol and CCN concentrations. Problems with such techniques are that they may only work well for low-level clouds; also, they could suffer in accuracy if higher cloud layers are present. A problem with all ground-based CCN measurements is the relationship between concentrations at ground level and at cloud base. These may be closely coupled in a well-mixed boundary layer but not necessarily in a decoupled boundary layer. The effect of indirect forcing in the case of ice and mixed-phase clouds is even more complicated than for water clouds, and considerably more research is required in this area. The problem of anthropogenic perturbation of cirrus clouds poses a number of almost totally open questions.

As in direct forcing, we cannot overemphasize the need for a closure-type approach. Also, as for the direct effect, it is absolutely necessary to conduct long-term monitoring,

including surface-based measurements, at a few selected sites, in order to discern the geographical and climatological variations in the forcing. It is important to know, for example, if the CCN actually varies with time (at present, Cape Grim, which has a 12–year CCN record, is the only site on the globe where such a record exists for more than a few years [Gras 1990]).

Stratospheric Aerosols

As shown by recent examples, it is far less complicated to estimate the radiative forcing due to stratospheric sulfur-containing aerosols produced by large volcanic eruptions than that due to tropospheric aerosols. For example, the global distribution and optical depths of aerosols due to the 1991 volcanic eruption of Mt. Pinatubo have been well determined by space, airborne, and ground-based measurements (see GRL 1992; McCormick et al. 1995). Computations of radiative forcing due to the aerosols resulting from this eruption yield estimates (Hansen et al. 1992) that are in reasonable agreement with flux measurements at the top of the atmosphere (TOA) (Minnis et al. 1993). We recommend that the Pinatubo study be further pursued by employing more realistic values of optical properties, as a function of latitude and time (on the basis of an entire suite of measurements rather than those used to date), and by evaluating the accuracy of the computed spatially and temporally dependent forcing through comparisons with flux measurements. In contrast to the situation for tropospheric aerosols, it has been possible to establish a quantitative consistency between satellite and aircraft- and ground-based retrievals of stratospheric aerosol properties (Russell and McCormick 1989).

Stratospheric aerosols also have indirect climate effects. Heterogenous chemical reactions occurring on the surfaces of the particles can lead to ozone destruction which, in turn, perturbs the radiative balance of the atmosphere and climate (WMO 1992). Ozone loss in the stratosphere allows more UV radiation to penetrate the tropopause and affect the chemistry in the troposphere, in particular affecting tropospheric ozone concentrations (IPCC 1994). Further, stratospheric particles may nucleate clouds in the vicinity of the tropopause, although the magnitude and spatial extent of this effect are not known and further fundamental studies are required.

In the event of future major volcanic eruptions, quick response airborne operations, complemented by balloon- and surface-based measurements, should be an essential element of stratospheric aerosol research plans. The extensive measurement campaigns following the Pinatubo eruption are a good example. In addition, continuous satellite coverage of the global stratosphere is required to monitor the temporal evolution of the stratospheric aerosol globally, complemented by long-term ground-based lidar measurements at selected sites. It is worth noting that accurate spaceborne estimates of the tropospheric aerosol can only be made when the contribution to reflected sunlight by the stratospheric aerosol layer is known. Thus, continuous satellite observation of the stratospheric aerosol layer is also essential to the monitoring of the tropospheric aerosol.

MODELING AND VERIFICATION OF RESPONSE

Tropospheric Aerosols

GCM Simulations

Thus far, climate modeling efforts have involved the study of the effect of anthropogenic sulfate effect using coupled atmosphere–ocean (static mixed-layer ocean) GCMs. The sulfate concentrations used to determine radiative forcing currently are being computed off-line using a microphysics–chemistry–transport model. Forcing due to anthropogenic sulfate aerosols is negative and occurs in a spatially inhomogeneous manner over the mid-latitude continental regions of the Northern Hemisphere. The surface temperature response of a GCM (Roeckner et al., this volume) to this kind of forcing is spatially nonuniform, with the modeled impact being a marked cooling in the mid- to high-latitude regions of the Northern Hemisphere, including a large cooling in the vicinity of the aerosol-forcing regions.

There are a number of reasons why a strict comparison of the model simulations by Roeckner et al. with observed data (e.g., Karl et al., this volume) is not possible:

- The model runs are equilibrium simulations while the observations are not necessarily representative of equilibrium responses.
- The model considered only the forcing due to a computed anthropogenic sulfate component of the aerosol, and not the influences due to all other species that exist in the actual atmosphere.
- The natural variability of the model and that in the real world on decadal-to-century scales is not known, so that the assessment of signal-to-noise ratio is problematic.

It should also be noted that aerosol forcing is not known as well as that due to the greenhouse-gas increases (IPCC 1994). Notwithstanding these limitations, some useful insights can be obtained with regard to the climate sensitivity exhibited by modeling efforts to date. First, the negative aerosol forcing leads to a surface cooling effect in contrast to the warming due to the greenhouse gases. Second, an important outcome of the Roeckner et al. study is the recognition of a spatially confined nature of the response to the regional forcing imposed by anthropogenic sulfate aerosols. Compared with the response to greenhouse-gas forcing, there is a dependence on the sign and structure (globally uniform or regionally confined) of the forcing applied in the model. For greenhouse-gas forcing, the equilibrium simulations exhibit a spatial temperature response that is superficially similar to that from the transient experiments. It remains to be seen whether this similarity applies to the anthropogenic sulfate aerosol forcing as well, particularly for the areas exhibiting a strong cooling in the mid- to high-latitude regions of the Northern Hemisphere.

Transient simulations with a coupled atmosphere–full-ocean GCM would be a step higher in complexity relative to the study by Roeckner et al. For example, given the

estimated changes in the rate of global sulfur emissions over the past several decades, it would be possible to model the transient response and examine the evolution of temperature change during this period.

Other Models

It is conceivable that other types of models, such as mesoscale and the limited area nonhydrostatic models, and "nested" GCMs can also be used to ascertain the response on different spatial scales. Although such models may be particularly useful in learning more about localized land responses due to strong aerosol forcings, all categories of models have fundamental weaknesses in simulating the salient features of the hydrologic cycle. Therefore, these models may also be deficient in simulating surface temperature responses. However, limited area models can provide valuable inputs on transport and hydrological processes that could directly benefit the larger-scale microphysics–chemistry simulation of aerosol concentrations. Mesoscale models might prove useful to the observational community in choosing sites to conduct field experiments.

We expect that off-line transport models will continue to be the determinants of aerosol spatial and temporal distributions in GCMs, although satellite techniques could also become available in the future. Diagnostic as well as semi-prognostic modeling efforts should be extended to aerosols other than sulfate and biomass products, e.g., dust and organics. This process would open the way for GCM studies to simulate the climate effects due to these additional aerosols.

Observations of Surface Temperature Changes and Model-Data Comparisons

The observed global and hemispheric mean-temperature increases are smaller than those simulated by GCMs using greenhouse-gas emissions alone (IPCC 1992). Further, these simulations predict an amplification of the warming in the northern polar region that is also not apparent in the observations. These discrepancies constitute unresolved but important puzzles in climate change. The GCM study of Roeckner et al. indicates that the direct forcing by the anthropogenic sulfate component has the potential to reduce the mean surface temperature, particularly over the Northern Hemisphere continents. This suggests a possible aerosol role in counteracting the radiative forcing due to greenhouse-gas increases. HOWEVER, this does not imply, and it would in fact be misleading and dangerous to entertain the notion, that any degree of compensation in any specific meteorological or climatological parameter should necessarily be expected. There are several factors for this:

- The forcings due to greenhouse gases and aerosols have fundamentally different characteristics (e.g., in the partitioning of the radiative forcing between surface and troposphere).

- The forcings due to greenhouse gases and aerosols have different spatial and temporal patterns.
- The diurnal nature of the two forcings is different.
- The two entities have vastly different geochemical time constants (e.g., atmospheric residence times).

Karl et al. (this volume) indicate that, over the North American region, there has been a decrease in the clear-sky diurnal temperature range until about 1970 and an increase thereafter. These changes appear to coincide with the increase and decrease in sulfur emissions before and after ~1970, respectively. The change in the indicated diurnal temperature range is largely due to a change in the temperature maximum, while the minimum hardly exhibits any change. For overcast sky conditions over the same region, the observations suggest that changes in cloud optical properties could have coincided with those in sulfur emissions. While such apparent coincidences are useful in stimulating a closer scrutiny, it is premature to conclude a direct causal relationship between sulfur emissions, sulfate aerosol concentrations, and diurnal temperature variations. This is because we have a very limited knowledge of the variability in the climate system. Indeed, the observed "signal" may simply be a feature of the "natural" long-term climate variability.

The observational data presented by Karl et al. (this volume) are for the 1946–1993 or 1946–1986 time periods. These are different time periods than the one used in the model study by Roeckner et al. Sulfur emissions have changed with time to varying degrees over the various continents. Thus, comparisons between simulated and observed effects are made difficult because one has to factor in a temporal evolution in aerosol forcing, which has not been consistent over all continents. This situation is expected to continue into the future as North America and Europe decrease their sulfur emissions, but as emissions from Asia on a whole grow. It would appear that a stringent comparison of the modeled effects with observations would be afforded by providing the temporal trends in anthropogenic sulfur emissions and its associated radiative effects as inputs for a transient GCM simulation.

While there are difficulties in making strict comparisons between present GCM simulations and the observed temperature records, a technique that can be brought to bear upon the problem is the analysis of the presence or lack of spatial coherence between the anticipated or calculated and the observed patterns of surface temperature change (Engardt and Rodhe 1993; Hunter et al. 1993; Karl et al., this volume). Studies are underway to analyze the results from GCM simulations with greenhouse-gas increase only and with greenhouse gases plus aerosol (anthropogenic sulfate component) increases, respectively, and to compare them with the spatial pattern of the observed temperature changes (B.D. Santer, pers. comm.).

There are some suggestions from surface-based cloud cover observations of changes in the tropical and mid-latitude middle- and low-level cloud cover. However, it is difficult to confirm whether these observations from ordinary merchant or military ships represent a statistically significant result. Even if the results were significant, it

is extremely difficult to identify this as an aerosol-induced change, a response to climate forcing due to trace gases, or simply a geophysical variation in the hydrologic cycle or circulation.

Stratospheric Aerosols

The problems associated with the verification of tropospheric aerosol forcing and climate response are not as severe in the case of stratospheric aerosol loadings following volcanic eruptions. As noted earlier, the estimated global forcing in the case of the aerosols following the Pinatubo eruption is in good agreement with satellite flux observations at the TOA. It is interesting to note that the current anthropogenic sulfate-forcing estimates over the past century (IPCC 1994) are comparable to those computed for the duration of the Pinatubo aerosols. A GCM simulation (Hansen et al. 1993) of the response to the forcing by the Pinatubo aerosols indicates a transient warming of the lower stratosphere where the aerosols are located and a cooling of the surface, both borne out by observations in a general sense (Labitzke and McCormick 1992; J. Angell, pers. comm.). Precise comparisons for the troposphere, however, are hampered by the fact that a moderate El Niño event occurred at the same time. Nevertheless, the modeled global cooling is seen to be statistically significant in both the observations and the model.

While the agreement between the computed and observed flux changes provides a measure of confidence in using the forcing to evaluate the climate response in GCMs, the broad confirmation of the modeled global temperature changes due to volcanic aerosol is an even more encouraging development. This demonstrates that the fundamentals of climate modeling, as applicable to the impacts due to a moderately large and global aerosol forcing of limited duration (order of 2–3 years), are well posed. Although the details of the climate response depend upon modeling the temporal evolution of the aerosol characteristics accurately, we concluded that the Pinatubo aerosols have provided a test of the ability to model climate change due to a transient, aerosol-induced radiative perturbation, and that the present GCM simulations have proved adequate to the challenge. It is equally important to realize, however, that this test does not necessarily provide an appropriate analog for the accurate simulation of the climate response due to a tropospheric aerosol forcing having a secular trend over the past several decades. In particular, the Pinatubo experiment does not offer a complete test of the role of oceans in climate change, nor does it involve the land–sea contrast of the forcing characteristic of tropospheric aerosols.

In addition to temperatures, model simulations of the changes in the circulation pattern due to stratospheric aerosols exhibit reasonable agreement with other climatological information, e.g., lofting of the lower stratospheric layer in the tropical regions owing to local warming caused by the aerosols (Kinne et al. 1992), and changes in the wintertime features of the mid- to high-latitude regions (A. Robock, pers. comm.).

A problem with the Pinatubo modeling experiment is the absence of a return of the simulated lower stratosphere to the somewhat colder temperatures observed. This discrepancy could be due to the ozone reduction recorded by satellite-, balloon-, and ground-based platforms, and that has not been accounted for in the models. A test of models that account for both aerosol and ozone changes is if their stratospheric temperatures recover when the ozone recovers, as is indicated by observations (D.J. Hofmann, pers. comm.). Future studies should simulate and verify the modeled transport of stratospheric aerosols, including their distribution with latitude and time. Comprehensive verification of the modeled spatial and temporal radiative forcing as well as the temperature response should be continued.

Monitoring of Climate Parameters

The climate parameter that has been most extensively studied is the surface temperature, followed next by temperatures at selected altitudes in the atmosphere. While these observations have been examined for confirmation of the modeled responses to greenhouse-gas forcings, such studies must now be extended to include considerations of the aerosol forcing as well.

Spectral radiances and irradiances at the TOA and at the surface can and should be measured. Long-term monitoring at even a few chosen sites would be an asset in ascertaining the temporal evolution of forcing and climate change. Global monitoring of the broadband and spectrally resolved radiative parameters (covering the entire solar and infrared spectrum) from space should be accorded a high priority, along with the capability for validating them through proper *in situ* measurements periodically.

Humidity, total precipitable water, and cloud ice/water content measurements should be carried out with great precision since they are essential parameters affecting radiative and climate processes. Other elements of the hydrologic cycle that demand attention are cloud cover and cloud microphysical properties, sea ice, and snow cover.

Other meteorological parameters that are potentially useful in analyzing climate change are precipitation (this is essential for accurate microphysical–chemical–transport modeling as well), soil moisture, and appropriate chemical and photochemical properties of the atmosphere.

Besides the above, conventional general circulation features should also be analyzed. In particular, the presence of a Northern Hemisphere aerosol radiative forcing would change the equator-to-pole gradient of radiative heating compared to the case with greenhouse gases only, with potential dynamical consequences.

Finally, there are two general comments that we would like to make regarding response detection strategies. One is the need to gather regionally representative data. The other, and this cannot be overemphasized, is the need for long-term dedicated and accurate measurements in order to detect any climate change "signal" clearly and unambiguously.

SUMMARY AND CONCLUDING REMARKS

The direct radiative forcing of the tropospheric aerosols is estimated to have a negative sign and differs significantly in character from the positive forcing due to greenhouse gases. The direct forcing due to the anthropogenic component of the sulfate aerosol is estimated to have a magnitude that is a significant fraction of the greenhouse-gas forcing on a global scale. On continental scales, the aerosol forcing magnitude can become comparable to or even exceed the greenhouse-gas forcing. The indirect aerosol-forcing problem is not as well-posed as that for direct forcing.

To reduce the uncertainty in the tropospheric aerosol radiative-forcing estimates, experiments that determine how well we can calculate aerosol optical effects at a point and how well these can be extrapolated to columns and areas, that is *CLOSURE* experiments, are absolutely essential. A strong emphasis should be placed on long-term, continuous, accurate monitoring of the broadband and spectral radiative quantities (radiances, irradiances) at the TOA and at the surface, complemented by *in situ* monitoring of aerosol physical and chemical properties. Without field campaigns that can be used to verify model estimates of aerosol forcing, and without the benefit of long-term monitoring strategies, it is impossible to assess the uncertainties in the aerosol climate forcing. Not reducing this uncertainty will lead to an incomplete understanding of the radiative perturbations driving climate change. For indirect-forcing assessments, exploratory campaigns are recommended.

The equilibrated model surface temperature response to the anthropogenic sulfate aerosol forcing consists of a nonuniformly distributed cooling in the mid- to high-latitude regions of the Northern Hemisphere, with a strong response near the aerosol regions. Thus, the anthropogenic aerosols, which occur in a spatially inhomogeneous manner mainly over the continents of the Northern Hemisphere, tend to cause a continental-scale surface cooling. The characteristics of the aerosol-induced responses differs from the simulation of the global warming due to greenhouse-gas increases only. Further GCM studies should continue to identify the climate sensitivity on regional scales to different types of aerosol forcing. Transient GCM experiments that simulate the evolution of the climate response to temporal trends in sulfur emissions would further extend our understanding of the aerosol climate effects.

The estimated forcings and the GCM results with tropospheric sulfate aerosols suggest that aerosols have the potential to mask regionally the greenhouse-gas forcing over the past century, especially in the Northern Hemisphere. Data on diurnal temperature variations indicate that the temperature trends are to some extent those anticipated for the sulfur emission trends in North America, but there are doubts whether the observed trends rise above the "noise" level for long-term climatic trends. Studies performed thus far should be regarded as exploratory since there are fundamental differences between the character of the observational data sets and the model used for the comparisons. Long-term, accurate monitoring of radiative and meteorological parameters are critical to evaluate the modeled climate response.

Estimates of the forcing and the temperature response in the case of the stratospheric aerosols following the 1991 eruption of Mt. Pinatubo are in good agreement with observations. In many respects, the climate problem involving stratospheric aerosols from volcanic eruptions is much better understood than for tropospheric aerosols. The reasonable agreement between the simulated and the observed global mean-temperature response following the Pinatubo eruption has provided a partial verification of some of our basic theories on the functioning of the climate system. Model studies, involving more detailed comparisons of the spatial and temporal evolution of the aerosol optical depth, forcing, and temperature response, should be continued.

The reasonable success of the climate model simulations in the case of the stratospheric aerosols does not necessarily offer a ready means to assess the fidelity of the model responses to tropospheric aerosol forcings. Nevertheless, it is instructive to compare and contrast the forcings and responses due to tropospheric aerosols derived from anthropogenic activities over the past several decades with those due to stratospheric aerosols following volcanic eruptions, since the optical depths in both cases are roughly comparable.

REFERENCES

Ball, R.J., and G.D. Robinson. 1982. The origin of haze in the central United States and its effect on solar irradiation. *J. Appl. Meteorol.* **21:**171–188.

Coakley, J.A., R.L. Bernstein, and P.A. Durkee. 1987. Effect of ship-track effluents on cloud reflectivity. *Science* **237:**1020–1022.

Coakley, J.A., R.D. Cess, and F.B. Yurevich. 1983. The effect of tropospheric aerosol on the Earth's radiation budget: A parameterization for climate models. *J. Atmos. Sci.* **40:**116–138.

Durkee, P.A. 1989. Observations of aerosol–cloud interactions in satellite-derived visible and near-infrared radiance. Preprints, AMS symposium on the role of clouds in atmospheric chemistry and global climate, pp. 157–160.

Engardt, M., and H. Rodhe. 1993. A comparison between patterns of temperature trends and sulfate aerosol pollution. *Geophys. Res. Lett.* **20:**117–120.

Gras, J.L. 1990. Cloud condensation nuclei over the Southern ocean. *Geophys. Res. Lett.* **17:**1565–1567.

GRL. 1992. The stratospheric and climatic effects of the 1991 Mt. Pinatubo eruption: An initial assessment. *Geophys. Res. Lett.* **19(2):**149–218.

Han, Q., W.B. Rossow, and A.A. Lacis. 1994. Near-global survey of effective droplet radii in liquid water clouds using ISCCP data. *J. Clim.* **7:**465–497.

Hansen, J., A. Lacis, R. Ruedy, and M. Sato. 1992. Potential climate impact of Mount Pinatubo eruption. *Geophys. Res. Lett.* **19:**215–218.

Hansen, J., A.A. Lacis, R. Ruedy, M. Sato, and H. Wilson. 1993. How sensitive is the World's climate? *Natl. Geogr. Res. Explor.* **9(2):**142–158.

Hunter, D.E., S.E. Schwartz, R. Wagener, and C.M. Benkovitz. 1993. Seasonal, latitudinal, and secular variations in temperature trend: Evidence for influence of anthropogenic sulfate. *Geophys. Res. Lett.* **20:**2455–2458.

Husar, R.B., and W.E. Wilson. 1993. Haze and sulfur emission trends in eastern U.S. *Environ. Sci. Tech.* **27:**12–16.

IPCC (Intergovernmental Panel on Climate Change). 1992. Climate Change 1992: The Supplementary Report to the IPCC Scientific Assessment, ed. J.T. Houghton, B.A. Callander, and S. K. Varney. Cambridge: Cambridge Univ. Press, 200 pp.

IPCC. 1994. Climate Change 1994: Radiative Forcing of Climate Change and an Evaluation of the IPCC 1992 Emission Scenarios, ed. J.T. Houghton, L.G.M. Filho, J.P. Bruce, H. Lee, B.T. Callander, E.F. Hailes, N. Harris, and K. Maskell. Cambridge: Cambridge Univ. Press, 352 pp.

Kaufman, Y.J., and T. Nakajima. 1993. Effect of Amazon smoke oncloud microphysics and albedo—Analysis from satellite imagery. *J. Appl. Meteorol.* **32:**729–744.

Kaufmann, Y.J., and C. Sendra. 1988. Satellite mapping of aerosol loading over vegetated areas. In: Aerosols and Climate, ed. P.V. Hobbs and M.P. McCormick, pp. 51–67. Hampton, VA: A. Deepak Publ.

Kent, G.S., D.M. Winker, M.T. Osborn, and K.M. Skeens. 1993. A model for separation of cloud and aerosol in SAGE II occultation data. *J. Geophys. Res.* **98:**20,725–20,735.

Kinne, S., O.B. Toon, and M. Prather. 1992. Buffering of stratospheric circulations by changing amounts of tropical ozone: A Pinatubo case study. *Geophys. Res. Lett.* **19:**1927–1930.

Labitzke, K., and M.P. McCormick. 1992. Stratospheric temperature increases due to Pinatubo aerosols. *Geophys. Res. Lett.* **19:**207–210.

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

Minnis, P., E.F. Harrison, and G.G. Gibson. 1993. Radiative climate forcing by the eruption of Mt. Pinatubo deduced from NASA's Earth radiation budget experiment data. *Science* **259:**1411–1415.

Penner, J.E., R.J. Charlson, J.M. Hales, N. Laulainen, R. Leifer, T. Novakov, J. Ogren, L.F. Radke, S.E. Schwartz, and L. Travis. 1994. Quantifying and minimizing uncertainty of climate forcing by anthropogenic aerosols. *Bull. Am. Meteorol. Soc.* **75:**375–400.

Rao, C.R.N., L.L Stowe, E.P. McClain, and J. Sapper. 1988. Development and application of aerosol remote sensing with AVHRR data from the NOAA satellites. In: Aerosols and Climate, ed. P.V. Hobbs and M.P. McCormick, pp. 69–79. Hampton, VA: A. Deepak Publ.

Russell, P.B., J.M. Livingston, and E.E. Uthe. 1979. Aerosol-induced albedo change: Measurement and modeling of an incident. *J. Atmos. Sci.* **36:**1587–1608.

Russell, P.B., and M.P. McCormick. 1989. SAGE II aerosol data validation and initial data use—An introduction and overview. *J. Geophys. Res.* **94:**8353–8366.

WMO (World Meterological Organization). 1992. Scientific Assessment of Ozone Depletion. WMO Global Ozone Research and Monitoring Project, Report No. 25. Geneva: WMO/UNEP.