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Temporal and Spatial Variability of Clouds and Related Aerosols

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Hygroscopic Properties of Atmospheric Aerosols Appear to be Better Constrained than Other Key Parameters of Warm Cloud Formation

Aerosol–cloud interactions may have played an important role in the observed climate change of the 20th century, and, if so, this may have partly been caused by changes in cloud condensation nuclei (CCN) as a result of industrialization. Sea salt, sulphate, and organics are key components of CCN; the atmospheric sulphate load is known to have changed significantly because of industrialization. The relative change in CCN caused by industrialization depends critically on (a) preindustrial CCN levels, (b) anthropogenic emissions of particles and aerosol precursor gases, (c) atmospheric processing which generates, transforms, and removes aerosol particles, and (d) the ability of particles to act as CCN; that is, their hygroscopicity. Hygroscopicity, as a function of organic mass fraction, has attracted much attention in recent years (e.g., Bates et al. 2006). However, the first three aspects of the problem pose more important uncertainties.

Briefly, preindustrial CCN levels have been estimated almost exclusively using models that remove anthropogenic sources (e.g., Schulz et al. 2006). Andreae (2007), however, has argued that preindustrial CCN levels may have been fundamentally different. Transport models require detailed emission data (i.e., fluxes for all major particle constituents and precursor gases as a function of particle size, injection altitude, and with high temporal and geographical resolution), but such data are presently sparse and uncertain. Atmospheric transformations of aerosols are frequently dominated by in-cloud processing, which can generate particulate mass from precursor gases, remove particles via precipitation, and alter radically the particle size distribution. Currently, models represent all these processes, but observational constraints are again very sparse relative to the full range of atmospheric conditions. As a result, major uncertainties exist in terms of particle concentrations (number and mass), size distribution, and aerosol sources and sinks (primary emissions, secondary formation, dry and wet deposition). These continue to pose obstacles to our understanding of aerosol effects on warm cloud formation in the atmosphere.

Relative to the above issues, the warm-cloud hygroscopic properties of atmospheric aerosols (i.e., the effects of chemical composition on equilibrium water uptake) appear to be fairly well constrained. The effective hygroscopicity of aerosol particles can be efficiently approximated by a single hygroscopicity parameter (κ, Petters and Kreidenweis 2007). With simplifying assumptions, this parameter is easy to calculate from the chemical composition of the particles, and recent laboratory and field measurements suggest that on average it is constrained to fairly narrow value ranges for continental and marine boundary layer aerosols (0.3 ± 0.1 and 0.7 ± 0.2, respectively) (Andreae and Rosenfeld 2008; Kreidenweis et al., this volume; Kinne et al., this volume).

This result is significant because, at present, general circulation models (GCMs) employ a wide range of hygroscopic coefficients for organic particles, and simulations of the 20^{th}-century temperature record are sensitive to this parameter. Thus, it would appear that current understanding of CCN needs to be incorporated as a much tighter constraint (rather than a tuning parameter) in GCMs. At this point, the hygroscopic properties of aerosols do not appear to be a limiting factor for advances in large-scale atmospheric and climate modeling.

This is not to imply that aerosol hygroscopicity is fully understood. For detailed mechanistic studies, CCN closure experiments, and the like, more sophisticated approaches are essential to progress. Improved understanding of the hygroscopic properties of organic substances and organic–inorganic mixtures is needed as well as an improved understanding of kinetic limitations.

Ice Nuclei and Ice Microphysics Still Pose Many Open Questions

Our understanding of ice nucleation (the seemingly tiny fraction of aerosol particles that constitute ice nuclei; the roles of homogeneous and heterogeneous nucleation processes) is currently very poor, as is our knowledge of the "ice-multiplication" processes that generate observed concentrations of small ice crystals. These processes are critical not only for high-latitude precipitation but also for tropical and midlatitude rainfall. Heavy rainfall events generated by mesoscale convective systems, tropical cyclones, and extratropical storms all involve cold rain processes. If we wish to improve our ability to forecast extreme weather and to quantify the global climatology of precipitation, a better understanding of ice microphysics is imperative. Meteorologists have been stymied by these issues for many decades. There are severe limitations in current methods for measuring microphysics of mixed-phase and ice clouds, both in terms of *in-situ* approaches and remote sensing. Even the new satellite techniques (CloudSat and CALIPSO) provide only limited phase information, and only in the vicinity of cloud top.

GCMs are developing parameterization strategies that enable composition to be linked to droplet activation in clouds. In principle, the approach can also be used for ice activation. Unlike droplet activation, however, the links between atmospheric composition and ice formation (nucleation, multiplication) are not well known. Representing interactions between aerosols and ice or mixed-phase clouds in GCMs is problematic without adequate knowledge of ice particle formation.

Little to nothing is known about the collision efficiencies of ice particles, and thus most cloud-resolving bin microphysics models tend to assume that those efficiencies (ice–ice and ice–liquid) are the same as those between water drops, which is certainly a crude simplification that limits the reliability of simulations of mixed-phase and cold clouds with bin microphysics models.

Remote-sensing Limitations

Ice water clouds are far more difficult to characterize from space than liquid water clouds. One level of complexity is added by the shape of ice crystals. In absence of that information, the lookup tables for visible/near-infrared retrievals are usually based on some mixture of crystal shapes. Since the composition of the actual cloud differs from the assumed shape, large errors in both effective radius and optical thickness may be introduced, which then propagate into the ice water path retrieval as well. There is currently no technique available to retrieve crystal shape from satellites. Less problematic is phase discrimination, though this is often merely qualitative and not always consistent between different techniques (e.g., MODIS and POLDER), especially for mixed-phase clouds. With the launch of CloudSat and CALIPSO, it has become possible to validate the cloud-top height products from infrared imagery, and first biases have been identified. However, algorithms for retrievals of liquid water path, crystal size, phase, and the vertical cloud structure remain to be validated with *in-situ* aircraft measurements.

In-situ Measurement Limitations

In-situ probes have persistent problems in ice clouds. This is reflected in the ongoing debate about the existence of small crystals, which have been detected through combinations of (bulk) measurements of ice water content, crystal number, and extinction (e.g., Garrett et al. 2003; Ström et al. 1994). Such small crystals change the warming/cooling properties of cirrus clouds substantially

(Heintzenberg et al. 1995). For crystal-size spectrometers such as the Cloud Aerosol and Precipitation Spectrometer (CAPS), it has been shown in wind tunnel tests that at least part of the small crystals may be attributed to particle breakup ("shattering") on the tips of the probe. A related problem is a major jump in the CAPS-size distributions, which occurs at the transition from the small-size range (forward scattering probe 2–50 μm diameter) to the medium-size range (cloud imaging probe, 50–1500 μm). This jump makes it impossible to derive meaningful properties, such as effective crystal radius from the size distributions, and can most likely be explained not only by shattering alone but through an association with multiple forward scattering peaks from multifaceted ice crystals, which are counted separately by the forward scattering probe but not by the imaging probe. A further practical problem is that there is no agreed upon standard on how to calibrate the probes and process the data and correct for various effects. Often, the probes are not calibrated at all during field experiments. Therefore, it is not unusual that wing-by-wing comparisons of size distributions differ by orders of magnitude in certain size ranges. Bulk probes (e.g., CVI and Nevzorov probes for ice water content and nephelometers and extinctiometers for extinction measurements) help constrain the size distribution obtained from size spectrometers and, when combined, provide an independent measurement for crystal effective radius. However, they may also suffer from shattering.

New techniques, such as Gayet's cloud nephelometer (Gayet et al. 1997) or polarized measurements, enable cloud phase discrimination and can therefore be used in mixed-phase clouds.

Verification of Remote Sensing Using *In-situ* Aircraft

It is essential to verify remote-sensing techniques, both ground- and satellite-based, with *in-situ* aircraft measurements and a clear specification of errors and limitations. For example, satellite retrievals of cloud phase, effective crystal radius, cloud ice water content, and precipitation must be validated taking into account horizontal and vertical inhomogeneities. In the absence of these comparisons, it is rarely possible to attach robust error bars to remotely sensed cloud parameters.

The Confounding Influence of Meteorology

Description of the Problem

Although it is crucial for our understanding of climate change to identify the influences of anthropogenic aerosol and global warming on cloudiness, this is a challenging problem since natural meteorological processes exert such a dominating control over cloud properties and precipitation. For example, in regions of persistent marine stratocumulus, over 80% of the seasonal/geographical variance in cloud cover can be explained by variability in lower tropospheric stability (LTS) (Klein and Hartmann 1993; Wood and Bretherton 2006). Despite the potentially strong susceptibility of marine stratocumulus clouds to aerosol perturbations that result from their low natural droplet concentration and intermediate optical thickness (Platnick and Twomey 1994), on scales larger than ship tracks, it is difficult to identify clearly aerosol effects amid the impacts of variations in LTS, temperature advection, and divergence. Moreover, because changes in aerosol concentration are associated with changes in the large-scale flow (i.e., the meteorology), even perfect observations of coincident clouds and aerosols are insufficient to determine the response of the clouds to aerosols alone (e.g., Mauger and Norris 2007). The extent of this covariance between meteorology and aerosols is poorly understood.

Another reason why large-scale aerosol effects on clouds have not been clearly discerned is that competing mechanisms, each of which is inadequately understood, may be involved. Straightforward physical theory and extensive observations indicate that increased particle number concentration will lead to a higher droplet number concentration at cloud base (e.g., Warner and Twomey 1967; Coakley et al. 1987; Breon et al. 2002), but beyond this, little is known with confidence. For example, hypotheses exist by which aerosols may increase cloud water through suppression of precipitation or decrease cloud water through enhancement of evaporation. These effects will, in turn, change the cloud dynamics (Feingold and Siebert, this volume). Currently, the important research questions are whether (and if so, how) aerosol-induced changes in droplet number affect cloud albedo, cloud cover, and precipitation. For a coupled system, it is both important and difficult to isolate the effects of a single variable.

Strategies for Separating Aerosol and Meteorological Effects on Clouds

Inadequate Methods

Constant liquid water path (LWP). One common approach to "control" for meteorology in efforts to observe the effects of aerosols on cloud albedo in complex systems (i.e., those other than plume studies as typified by ship tracks) is through binning cloud observations by LWP. However, LWP is an emergent property that results from the interplay between meteorological conditions and cloud microphysics, on scales down to that of a cloud element (e.g., a stratocumulus cell). In fact, changing LWP may in some cases be the primary mechanism for aerosol-induced albedo changes. Thus, it is impossible to measure how clouds are being changed by an aerosol perturbation if one eliminates the most important response by design.

Common source region. Another way to distinguish meteorological and aerosol effects on clouds and precipitation in small regions is to segregate the data according to air mass back trajectories from different geographical regions. For example, in eastern Canada, when trajectories are from the south, the air masses come from heavily polluted areas, whereas with northerly trajectories, the air masses pass over areas with fewer aerosol and anthropogenic gas phase source regions. The limitation of this method is that air masses from different regions are usually associated with different meteorological conditions. For instance, air parcels over the ocean with higher aerosol concentration, which are the result of recent contact with a continental region, are likely to be drier and thus have fewer clouds on account of meteorology.

Useful Methods

Small-scale aerosol perturbations. For small-scale effluent plumes (e.g., ship tracks), the assumption of constant meteorology between impacted and unimpacted regions of the cloud appears to be robust in at least some cases (e.g., Radke et al. 1989). Extending the results of such studies to larger scales, however, is not straightforward because the diffusion of plumes and corresponding aerosol effects over larger areas occur at the same timescale as do changes in meteorology.

Meteorological proxies. In addition to identifying source regions by back trajectory, the large-scale meteorological conditions experienced by clouds prior to the time of observation can be obtained from reanalyses and measurements. It is essential to use the history of meteorological forcing rather than data obtained solely from the time of the cloud observation because cloudiness responds to changes in forcing with a time lag. The potential impact of aerosols on cloud properties can be estimated from a large sample of aerosol and cloud observations by comparing average cloud properties between subsets with similar meteorological history but differing aerosol amounts. For example, the study of Mauger and Norris (2007) found that satellite-reported large aerosol optical depth (AOD) was associated with both large low-level cloud fraction and large LTS during the previous three days. Moreover, the difference in cloud fraction between subsamples with large and small AOD, but equivalent LTS, was less than the difference in cloud fraction for subsamples with large and small AOD and unconstrained LTS, thus illustrating the confounding role of LTS in controlling cloud amount. Note that compositing on parameters like LTS only establishes a minimum value for the magnitude of meteorological influence (and an upper limit for aerosol influence), since other unidentified processes may also affect cloudiness. Failure to account adequately for all meteorological effects will lead to an overestimate of the influence of aerosols on cloudiness.

Cloud properties surveyed in diverse aerosol environments. The observation of similar cloud properties across many regions of the world, where diverse aerosol environments are expected, can be used to reject the hypothesis that aerosols are a major influence. For example, the statistics of cloud crystal number concentration were found to be similar in experiments over Canada, the United Kingdom, and the southern hemisphere. Specifically, Korolev et al. (2000), Gultepe et al. (2001), Field et al. (2005), and Gayet et al. (2006) all showed similar ice particle (effective diameter > 100 μm) concentrations around the world for clouds with temperatures warmer than about –35°C. Presumably, these experiments involve very different aerosol environments. Thus, one could infer that the concentration of large ice particles in clouds warmer than about –35°C is not sensitive to aerosol variations. The observation of different cloud properties across regions with diverse aerosol environments is not a sufficient condition for demonstrating an aerosol influence, however, since different regions have different meteorology.

Discussion

What is the appropriate null hypothesis? Many observational studies of aerosol–cloud relationships have mistakenly inferred causation from correlation; that is, if a change in aerosol amount is seen to occur with a change in cloudiness, then aerosols necessarily produced the cloud change. For example, Nakajima and Schulz (this volume) provide an extensive literature review of the apparent sensitivity of cloud properties to aerosols calculated via linear regression with aerosol loading as the sole independent variable. Considering the dominating impact of meteorology on cloudiness, a superior "null" hypothesis would be that aerosols and clouds do not interact, and that observed correlations only arise from their common origins and trajectories in the general circulation. This, however, is too strict a criterion since no predictors of clouds from either observation, forecast, or reanalysis are currently accurate enough to rule out such a "null" hypothesis. Nevertheless, the effects of meteorological factors known to control strongly cloudiness as well as satellite retrieval and other measurement biases must be eliminated before attributing cloud changes to aerosols.

Other confounding aspects of the problem exist. It is possible for clear-sky radiative effects of aerosols to alter directly the meteorology of a region by changing surface and atmospheric radiative absorption (Wendisch et al. 2008). This, in turn, could weaken or strengthen circulations on various scales and consequently change cloudiness. Observational analyses that controlled for meteorology would fail to reveal an indirect effect of this nature. To test such a hypothesis, examination of the sensitivity of atmospheric circulation to an imposed radiative forcing in a global or regional climate model seems to be the best option. One must be careful in interpreting the results, however, since inadequate boundary layer, convection, and cloud parameterizations or inappropriate boundary conditions (e.g., fixed sea surface temperature in long simulations) may cause the model to behave in an unrealistic manner.

Evidence for Large-scale Aerosol Impacts on Cloud Albedo, Cloud Amount, and Precipitation Remain Ambiguous

Evidence for an aerosol influence on clouds at large scales has recently emerged from satellite studies (see Table 17.2 in Nakajima and Schulz, this volume), but these studies have significant limitations. First, there is inadequate consideration of meteorology as an alternative explanation for the reported aerosol–cloud correlation; another concerns the difficulty in distinguishing aerosols from clouds by remote sensing (Martins et al. 2002; Kaufman et al. 2005; Charlson et al. 2007), which could lead to artificial positive correlations between retrieved AOD and cloud fraction in satellite scenes. Studies of aerosol–precipitation relationships suffer from similar shortcomings, and Ayers and Levin (this volume) describe how meteorology is a more plausible explanation for precipitation changes than an aerosol microphysical mechanism is. Moreover, despite decades of research, there is no robust statistical evidence for the efficacy of intentional weather modification through aerosol impacts on cloud microphysics (i.e., "cloud seeding"; see Cotton, this volume). Recent evidence from satellites of cloud perturbations over the remote oceans downwind of fuming volcanoes (Gassó 2008) is suggestive of large-scale aerosol impacts on cloud albedo, yet the absence of data on aerosol concentration means that an aerosol mechanism cannot be conclusively established or quantified.

The potential influence of aerosols on cloud properties can also be assessed by looking for long-term trends in cloudiness in regions that have experienced long-term trends in aerosols. This type of analysis has the benefit of mostly (but not completely) averaging out the confounding effects of synoptic meteorological variability. If aerosols influence cloudiness significantly, and aerosols have strongly increased or decreased in a particular area over several decades, then one would expect to see a physically consistent change in cloudiness over the same time period. For example, the presence of absorbing aerosols in a cloud layer has been hypothesized to decrease cloud fraction because of the absorption of solar radiation and commensurate reduction of humidity (Ackerman et al. 2000). The observation that no long-term reduction of cloud cover has occurred over the Northern Indian Ocean, despite the large increase in absorbing aerosols, indicates that this aerosol mechanism has not actually had a measurable influence on cloud cover in this region (Norris 2001). As another example, an increase in the number concentration of hygroscopic aerosols has been hypothesized to enhance cloud fraction by reducing precipitation loss of cloud water (Albrecht 1989). The observation that cloud cover decreased over Europe during the time period of increasing sulfate emission and increased over Europe during the time period of decreasing sulfate emissions indicates that this aerosol mechanism has not had a measureable influence (Norris and Wild 2007). One observational study by Krüger and Graßl (2002) reported a decrease in cloud albedo over Europe during a time of decreasing sulfate aerosol, but they did not investigate whether this might have instead been the result of meteorology. The North Atlantic Oscillation exhibited a substantial trend during this time period, which could have affected cloudiness over Europe.

A Major Motivation to Study Aerosols and Climate Is to Understand 20th-century Temperature Change

Global mean climate forcing from anthropogenic aerosols is in the process of leveling off and, in strong contrast to forcing from greenhouse gases (GHGs), aerosol forcing is not expected to increase dramatically during the 21st century (Penner et al. 2001). If these projections are correct, then most of the aerosol perturbation to climate that humans will ever impose has already happened.

In global climate simulations of the 20th century, aerosol forcing appears to compensate for differences in climate sensitivity (Kiehl et al. 2007). Better understanding of aerosol forcing has the prospect of improving our knowledge of climate sensitivity and thus our forecasts of future climate change, where the anthropogenic forcing will be increasingly dominated by GHGs.

Anthropogenic aerosols exert regional perturbations with large temporal variations (both increases and decreases). Anthropogenic GHGs, in contrast, exert global-scale perturbations that continuously increase over time. Given these very distinct patterns, it should be possible to separate these two types of perturbation to the climate system. In particular, focusing on regional variations would seem to be a plausible approach for investigating aerosol effects. Although the aerosol is unlikely to exhibit substantial growth in the future, in terms of global mean loading, it will undoubtedly continue to exhibit strong regional signals in areas where it is either growing or diminishing. Nevertheless, the difficulty of separating aerosol from meteorological effects, as previously discussed, must not be overlooked.

Since Some Global Warming Signals Are Now Becoming Evident, We Should Search for Associated Cloud Changes

As radiative forcing by anthropogenic GHGs becomes increasingly strong, we should expect to see specific changes in the Earth's climate system in addition to the rise in global mean temperature. Recent studies have accordingly reported a decline in the summertime Arctic sea ice area (Nghiem et al. 2007), a poleward shift of the Hadley circulation (Fu et al. 2006), a rise in tropopause height (Thomson et al. 2000), and trends toward more precipitation in wet places as well as less precipitation in dry places (Trenberth et al. 2007). Theoretical considerations and global climate models predict that all of these phenomena will occur with global warming, and they illustrate some of the changes we will experience over the coming decades. Considering the great importance of cloud feedbacks to climate sensitivity and our ignorance concerning them, it is essential to investigate the observational record for cloud changes that are likely to be associated with global warming. Although this has been previously difficult because of the large uncertainties in data and substantial natural variability, we expect that cloud signals will become more distinct as greenhouse radiative warming becomes increasingly globally dominant over aerosol radiative cooling. Moreover, distinct regional trend patterns will be more robust than the global average cloud changes. For example, one likely cloud change is a shift of frontal clouds accompanying the poleward retreat of the storm tracks. Cloud simulations in global climate models are unlikely to provide reliable guidance since current models represent cloud processes poorly and inconsistently. Nevertheless, global climate models can provide robust information on particular changes in atmospheric structure and circulation associated with global warming. Reasoning from theory, we can then hypothesize which cloud changes would be physically consistent with these. The identification of such cloud changes in the observed record would be useful for assessing which global climate models are likely to have the most realistic cloud parameterizations for global warming simulations. This, in turn, would help constrain the range of uncertainty in our estimates of cloud feedbacks and climate sensitivity. Although we know many meteorological factors that govern cloudiness (e.g., low-level cloud fraction and lower tropospheric static stability), it is not necessarily clear which factors will be the most influential under global warming. Thus, improved theories are needed.

Clouds interact strongly with mean thermodynamic properties and with organized circulations from the scale of individual convective cells, through mesoscale organization, to synoptic and large scales. These circulations are potentially sensitive to direct effects of GHG and aerosol changes as well as to the changes in temperature and humidity that are expected in association with global warming. Some circulations, such as the mesoscale circulations within convective cloud complexes in the tropics are strongly coupled to cloud microphysical processes (Houze 1982). Changes in the location or intensity of extratropical storms and associated storm tracks, which may occur in response to global warming, could have significant effects upon mean cloud properties and their effect upon climate.

One effect that is widely regarded to be important is the change in dry static stability that will accompany the decrease in temperature lapse rate in response to warming of the tropical sea surface (Knutson and Manabe 1995). The enhanced stability, coupled with radiative cooling rates which are not expected to change much, may decrease the rate of overturning associated with the Hadley and Walker circulations of the tropics. At the same time, the increase in surface saturation humidity associated with the warming will increase the amount of latent energy available in surface air. It is unclear how these two influences will change the structure, frequency, and intensity of tropical convective cloud systems. In addition, the changed large-scale circulation could influence the properties of trade cumulus and stratocumulus clouds, which are known to have a significant influence on the energy balance of Earth. None of these cloud effects are well understood, and it is likely that global climate models do not incorporate them accurately. It is unclear how these macroscale changes will interact with cloud changes associated with changes in aerosol loading, but they are likely to be as important and are not any better understood (cf. Bretherton and Hartmann, this volume).

What data and approaches are available to address cloud macroscale effects? The primary means to address these issues is to gain a complete understanding of the relevant processes, to develop models of these processes, and to test these models rigorously against data. Field programs to address these issues have been mounted in the recent and distant past (e.g., for tropical clouds GATE, TOGA-COARE, KWAJEX). Satellite data are providing a rich dataset which can be used to validate certain aspects of the cloud simulation. For example, MODIS cloud data provide a good representation of the optical properties of convective clouds that are important for the Earth's energy balance, such as the area covered by clouds with particular optical depths and cloud-top temperature pairings. These data can be provided on scales (~5 km) that can be used to test these properties, as they are simulated by a hierarchy of models, including models with high spatial resolution, often called cloud-resolving models. CloudSat and CALIPSO are producing information on the internal vertical structure of these clouds. AIRS is providing global analyses of water vapor and temperature profiles that are coincident with MODIS and CloudSat/CALIPSO data. Reanalysis datasets are providing estimates of global six-hourly analyses of large-scale vertical and horizontal winds that are much more accurate and reliable than previous estimates, even over remote ocean areas. Vigorous testing of emerging models with emerging datasets should lead to progress in understanding and simulating macroscale cloud processes that are critical to climate change.

Existing Cloud, Aerosol, and Radiation Records Need to be Reprocessed, and the Continuity of the Current Observing System Must be Guaranteed

It is very challenging to extract decadal trends from the current observational record for aerosols, clouds, and broadband radiative flux (energy balance). Prospects for improved understanding include (a) reanalysis of existing data, where the possibility exists of correcting known problems; (b) regional-scale analysis, where large secular changes in aerosol emissions and climate change signals are known; and (c) maintaining and expanding high-quality observations into the future.

Since several decades may be needed for human-induced trends in cloudiness and radiation flux to rise above natural variability, it is essential that we improve the satellite record as well as sustain and develop further our present observing system. Currently, the available satellite cloud and radiation datasets with lengthy records, sometimes back to around 1980, are generally not useful in analyzing long-term changes that result from the presence of many inhomogeneities and artifacts. These arise from changes in satellite instrumentation, degradation of sensors, drifts of satellite orbits, and shifts in satellite view angle. Most data originated from weather satellites, which were never intended to be an accurate and stable observing system. Careful processing must therefore be applied to produce a homogeneous record (as is the case for nearly all other climate measurements). Although the amount of resources needed for this task is very small compared to the cost of a satellite, the provision thus far has been inadequate. Most previous corrections and adjustments to satellite records have had an empirical and statistical origin, whereas it would be preferable to develop better physical models for the algorithms. New information gained from recent satellites (e.g., CERES, MODIS, CloudSat, and CALIPSO) will be useful for interpreting the more limited measurements of the older record, and multiple satellite datasets can be brought together to provide a "best guess" of trends and variability. Even if global trends in the reconstructed satellite record suffer from large uncertainties and unknown systematic biases, regional trends are likely to be more robust. The importance of clouds and aerosols in our understanding of the climate provides a strong motivation to overcome the difficulties in getting the best use out of the satellite radiance record.

It is clearly important to make the best use of the existing archive of satellite data on clouds. Reprocessing this data with new or improved algorithms is one approach. Another idea with great potential is to assimilate the satellite radiances into numerical weather prediction (NWP) models to produce reanalyses that include clouds. The existing reanalyses from NWP centers, such as the European Centre for Medium-Range Weather Forecasts (ECMWF) and National Centers for Environmental Protection (NCEP), have created consistent long-term datasets for dynamic and thermodynamic variables. Until recently, NWP centers have avoided the assimilation of cloudy radiances, and the representation of the hydrological cycle has been only partially successful. However, methods for addressing cloud parameters (e.g., radiances) are now being introduced, and this suggests the possibility of using the reanalysis methodology to add clouds to the list of variables and to perform a complete reanalysis of the hydrological cycle. Among other things, this would require knowledge of the error characteristics of the data and a reasonably good simulation of clouds in the model. Although challenging, this objective could deliver datasets with a consistent representation of both clouds and the meteorology, which has thus far been lacking. Currently, data assimilation systems are also being used to provide analyses of the global distribution of aerosols (work in progress at ECMWF). Adding clouds would enable the relationships between the meteorology, clouds, and aerosols to be studied within a consistent framework—a necessary step toward understanding the global impact of aerosols on clouds and climate.

Top-of-atmosphere (TOA) radiation budget for detection of cloud feedback requires the ability to detect global trends on the order of 0.3 W m^{-2} per decade (Loeb et al. 2007). This is extremely challenging and yet critical if we are to improve our knowledge of climate sensitivity. In addition to continuing the satellite programs dedicated to this objective (ERBE/CERES), it makes sense to pursue independent approaches:

1. Monitoring ocean heat content provides a similar capability to detect interannual variations in global energy budget through an entirely independent method.
2. The Earthshine method appears promising, even though initial implementation at a single site may have been flawed. This is a low-cost method such that maintenance of a consistent record over the next three decades (or longer) would not be difficult. Expansion to additional sites (to provide more nearly global coverage) and analysis by other groups would have potentially high value.
3. Whole-earth monitoring from Lagrange point L1 (DSCOVR mission) would provide a continuous, well-calibrated albedo proxy with potential diagnostic value.

Surface sites provide direct measurements of many variables relevant to the aerosol–cloud problem. Variables currently measured include the surface radiation budget (e.g., BSRN, GEBA) and remote sensing of AOD and Ångström coefficient (e.g., AERONET). There are a few sites with a comprehensive range of instruments (e.g., ARM, Cloudnet) that extend the list of variables to include active sensing of the vertical structure of clouds and aerosol layers. Although the distribution of these sites is extremely heterogeneous and is limited to land, they provide a wealth of direct measurements that are used in process studies to detect trends in surface radiation, to support field studies that evaluate the simulation of clouds and aerosols in operational and climate models, and as "ground truth" for satellite retrievals. Compared with new satellites, these sites are relatively inexpensive to establish and maintain. Continuation and indeed expansion of these sites for the coming decades should therefore be a high priority in planning a well-balanced observation system for monitoring aerosols and clouds.

New Strategies Are Required to Observe Key Variables More Accurately for Understanding Perturbed Clouds in the Climate System

Because of the complex and coupled nature of the Earth system, scientific progress requires tight integration of modeling and observational efforts. Both models and observations exist across an extremely wide range of scales, and integration across these different scales is probably the most challenging aspect of developing a coherent scientific strategy in climate research. In addition, there are the usual challenges of developing effective collaborations across various subdisciplinary divides (e.g., *in-situ*/remote sensing, aerosol/cloud, or laboratory/field).

A general strategy for fostering a fully integrated approach would involve (a) modelers framing specific (but realistic) data needs, (b) designing measurement and data archiving protocols that are tailored to modeling needs, (c) getting experimentalists from different groups and communities to combine and synthesize their results intelligently, and (d) getting modelers to actually use the data products. These goals can be facilitated by focusing research efforts on broadly defined domains in a way that attracts the involvement of experimentalists and modelers from many subdisciplines.

In terms of detecting aerosol effects on the global cloud system, some strategic principles include (a) looking for regional/temporal signatures where large aerosol variations are known to exist, (b) developing testable hypotheses, (c) including model validation in experimental design, and (d) combining chemical/physical approaches into one integrated strategy. Aerosols are very variable in time, so it is inherently challenging to compute their integrated effect on clouds and climate. This challenge constitutes a wonderful opportunity for integrating modeling and observational approaches at many scales.

Another strategic challenge is to achieve "critical mass" in field experiments. For example, if we do not get good observations of vertical profile of cloud microphysics, we really have nothing with which to build or constrain a model; that is, there is no way to understand the controlling processes. Putting this in context of large-scale observables and bringing in detailed modeling capability requires a major, coordinated effort.

Strategies for Integrating Modeling/Measurement Activities

One successful strategy is to have modelers in the field during field campaigns. This builds relationships, gives modelers a chance to learn what types of data are realistic, and gives measurement people a chance to become familiar with modeling capabilities and needs. This strategy works well for detailed process models, but a more challenging problem consists of engaging the global climate modeling community. As fully coupled models, GCMs are difficult to run for case studies. Recent projects like VOCALS and AMMA are attempting to integrate modelers working across a full range of temporal and spatial scales. For example, large-scale climate links associated with low clouds affecting ENSO.

Improving GCMs Is Not Straightforward

It is very easy to identify deficiencies in GCMs and yet very hard to correct them. One of the sad aspects of GCMs is that an improved parameterization based on successful field measurements may result in a worse simulation. Why? Implementing any change in a GCM will effect multiple aspects of the model, often degrading model performance in unexpected ways. Every GCM group has wonderful counterintuitive examples of such effects. Thus, implementing a significant change requires that the model be re-tuned to ensure that it continues to simulate successfully known aspects of the climate system. Tuning a GCM, in turn, is a complex, multidimensional optimization problem. Given the importance of GCMs to climate science (not to mention society), it is rather shocking how few people are working on developing and implementing model improvements.

Need for Consistent Global Data

Measurement protocols must be globally consistent to be able to identify geographical differences, trends over time, and to allow valid interpretation of satellite data. Such consistency is facilitated by coordinated monitoring networks (Kinne et al., this volume) that include uniform and rigorously enforced quality control and data analysis procedures. The cost and effort required to establish and maintain such programs is not trivial, although they generally amount to a small fraction of the cost of launching a satellite. There is thus a need for improved financial support for ground-based networks and integrated data analysis.

A major gap in current scientific strategies involves extrapolating from detailed local measurements to consistent global datasets. Effective new strategies will need to include satellites, models spanning the entire range of scales, and mathematical methods to account for varying measurement/retrieval uncertainties as well as spatiotemporal variability. One example is the need for consistent, global aerosol datasets. "The complexity of the aerosol–climate problem implies that no single type of observation or model is sufficient to characterize the current system or to provide the means to predict aerosol impacts in the future with high confidence. Consequently, information must be drawn from multiple observational and theoretical techniques, platforms, and vantage points, and strategies that explicitly plan for the integration and interpretation of the various components need to be designed" (Diner et. al. 2004, p. 1492).

Scaling up the Results of Field Studies to Large Models

Using measurements to impose constraints on models that exist at the same scale is difficult enough. For example, constraining large eddy simulation (LES) models with *in-situ* measurements runs into the difficulty that data are needed simultaneously throughout the domain. It is even more challenging to devise ways of using measurements obtained at one scale to constrain a model at a larger scale. However, this is essential in the development of regional- and global-scale models. At present, there is some effective collaboration between the global climate modeling and measurement communities, a leading example being the GEWEX Cloud System Study (GCSS). However, for the perturbed-cloud problem, there is no framework at present. An obvious suggestion, therefore, would be to establish a GCSS working group on perturbed clouds.

Specific Examples and Proposals

Weekly cycle of aerosols. Look for cloud changes associated with the weekly cycle of industrial aerosol emissions (the "weekend" effect). A weekly cycle of diurnal temperature range has been observed in many of the world's industrialized regions, suggestive of aerosol effects and possibly involving aerosol–cloud interactions (Forster and Solomon 2003; Gong et al. 2006). Research aimed at better elucidating the physical mechanisms would be useful. Advantages of this technique are that it involves short timescales (no need to observe long-term trends) and that it can make use of current observational capabilities.

Regional aerosol studies. Detection of aerosol effects becomes less daunting if we go to the regional scale, where the perturbation is large. Coherent regional patterns should be easier to detect and attribute to causes.

Amazon smoke investigation. The aerosol perturbation associated with dry-season biomass burning over Amazonia is massive, yet highly localized in some cases. The forest provides a uniform environmental context such that there should be minimal meteorological differences between impacted and unimpacted locations. In addition, there are year-to-year variations, since the amount of burning varies with socio-economic factors like the price of soybeans. A problem that must be confronted (in this and other regions) is sorting out the direct thermal effect of aerosol from microphysical effect on clouds.

Recent intensification of industrial emissions in China. Currently, industrial emissions over China constitute a massive aerosol perturbation that has been growing over the past several decades. Several datasets exist for assessing changes in surface radiation and cloudiness in conjunction with the aerosol increases. One suggestion is that aerosol particles are so absorbing that they change deep convection. Investigating this poses an interesting methodological problem. One would want to compare model simulations of the convection with and without the observed aerosol (or with the varying aerosol concentrations observed in the different cases). However, mixed-phase convection is so poorly understood that it is questionable whether model sensitivities to even large aerosol perturbations could be trusted. Investigating aerosol effects on cloud cover would have to take care that cloud cover observations were not directly affected by high aerosol concentrations (Charlson et al. 2007). A more general problem is that the direct thermal effects of the aerosol could alter the meteorological context (e.g., affect the strength of the monsoon circulation or alter convective instability by changing the height of latent heat release). This could lead to cloudiness changes, which need to be separated from aerosol-induced microphysical changes.

Ice formation problem. A sustained laboratory program is needed to identify precisely which particles act as ice nuclei and by which mechanisms. Thereafter it should be possible to design a new generation of *in-situ* airborne devices to identify them. Extensive field programs with airborne *in-situ* sensors for ice nuclei and ice particle size spectra, coupled with ground-based or airborne multi-parameter Doppler cloud radars and lidars sensing the same parameters, should provide a more complete description of the development of frozen precipitation.

Ice formation problem. It is known from field experiments and cloud modeling studies that secondary ice multiplication (e.g., splintering of existing ice crystals or the so-called Hallett–Mossop effect) are important factors in cloud development and for the initiation and intensity distribution of precipitation. Only a few laboratory investigations exist on secondary ice formation. More laboratory experiments are needed to investigate and quantify secondary ice formation, if possible for relevant ice crystal shapes and sizes, under conditions (temperatures, saturations, and turbulence) resembling those encountered in real clouds. Such experiments may be conducted with single droplets and ice crystals or in cloud simulation chambers.

Precipitation. Integrate observed changes in precipitation (Takayabu and Masunaga, this volume) with observed changes in aerosol and other potentially controlling factors.

LES validation for convective clouds. Cumulus updrafts play a central role in the vertical transport of water, momentum, trace chemicals, and heat. Still, there are inadequate observations of the statistical distribution of buoyancy, vertical velocity, and condensate in cumulus updrafts, as a function of cloud depth and aerosol profiles, and surface forcing environment. Such measurements are key constraints on LES and cumulus parameterizations. They are challenging to make from aircraft because of the associated sampling challenges and wetting issues, but shortwave-length radar-based remote-sensing techniques may provide a new opportunity to gather such statistics.

Cloud overlap representation in GCMs. Currently, GCMs predict cloud fraction in each vertical level. Uncertainty as to how to distribute this fractional cloud, both as a function of horizontal resolution and as a function of the distribution of clouds in the other layers of the model, gives model developers considerable freedom in distributing the modeled cloud amount so as to satisfy the radiative constraints at the top of the atmosphere. Experience with different GCMs shows that although they may have large layer-by-layer differences in cloud fraction and cloud amount, suitable choices for the cloud overlap assumption enables each to match the top of the atmosphere radiative constraints. Therefore, providing measurements of cloud overlap would provide further and valuable constraints on the model.

Observational study of cloud lifetime. Satellite measurements with high spatial resolution typically lack temporal resolution. Being able to measure the temporal evolution of clouds as well would provide a valuable constraint on process models of clouds and their environmental interactions. In this regard, for instance, a geostationary observatory that focused a large telescope on particular cloud scenes (to complement field measurements or *in-situ* studies) would be invaluable.

Spectrally resolved radiation budget measurements from space. Stable and accurate observations of changes in the Earth's radiation field over several decades are needed to quantify the forcing and radiative response of the climate system. For the purpose of quantifying trends in the Earth's radiation field, spectrally resolved measurements are especially useful for separation and attribution of the radiative effects from climate forcing and climate response (Goody et al. 1998). The small magnitude of the effects and long integration times required for detection together imply that very stable, absolutely calibrated satellite instruments are required. Several groups are now exploring satellite radiometers designed to detect the radiative forcing, thermal response, and radiative feedbacks in the Earth's climate system. Spectral radiometers can be developed with absolute calibration against traceable standards to insure that trends in the observations are as free as possible of instrumental artifacts (Keith et al 2001; Anderson et al. 2004). Potentially both the infrared and ultraviolet/visible/near-infrared radiation fields could be measured with such instruments. Although the feasibility for detection of infrared GHG forcing has been amply illustrated in modeling and satellite studies (e.g., Haskins et al. 1997), it is important to recognize that the utility of the infrared measurements or detection of longwave cloud feedbacks remains unproven (Leroy et al. 2008). The advantages of the ultraviolet/visible/near-infrared radiation data for detection and estimation of shortwave forcings and feedbacks have not been demonstrated in detail.

Earth observations from Lagrange point L1. Satellites deployed at Lagrange point L1, which are designed to measure the radiation emitted by the sunlight side of the Earth (e.g., the Deep Space Climate Observatory, DSCOVR; Valero et al. 1999), could provide valuable long-term measurements. DSCOVR would include several single-pixel NISTARs with a ground-based calibration chain tied directly to primary national standards. These instruments would measure the total solar, near-infrared, and infrared radiance field emitted by the Earth in the direction of Lagrange point L1. The inherent stability and traceable calibration of these instruments are ideally suited for the detection of secular trends in the Earth's short- and longwave radiation.

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