Aerosols, Clouds, Precipitation and Climate (ACPC)

Science Plan & Implementation Strategy

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I. Executive Summary

The goal of the Aerosols, Clouds, Precipitation, Climate (ACPC) research program is to obtain a quantitative understanding of the interactions between the aerosol, clouds and precipitation, and their role in the climate system. ACPC is a joint initiative of the International Geosphere–Biosphere Programme (IGBP) and the World Climate Research Programme (WCRP), which has been developed through the cooperation of the Integrated Land Ecosystem–Atmosphere Processes Study (iLEAPS) and International Global Atmospheric Chemistry (IGAC) core projects of IGBP; and the Global Energy and Water Cycle Experiment (GEWEX), a core project of the WCRP.

Interactions among the aerosol, clouds and precipitation are thought to shape the behavior of the climate system. The aerosol, in part through its interactions with clouds, has been widely identified as the leading source of uncertainty in the climate forcing of the anthropocene; clouds are the largest source of uncertainty in estimates of equilibrium climate sensitivity; precipitation is perhaps the most poorly quantified yet essential climate variable. The aerosol, clouds and precipitation are a strongly coupled system, but the nature of this coupling and its sensitivity to perturbations in one of the elements is poorly understood. Recent developments in process understanding, modeling, and observational capabilities make it now possible to address the long-standing and fundamental questions as to the nature of the interplay between the aerosol, clouds and precipitation. ACPC has been established to facilitate and enable international and interdisciplinary research directed toward answering this question.

In this context, the ACPC initiative has identified a set of questions as central:

- How do the amount and properties of the atmospheric aerosol affect cloud microstructure and precipitation-forming processes?
- In what way do aerosol particles influence the efficiency of precipitation?
- How do heating anomalies stemming from the radiative impact of the aerosol alone (light scattering and absorption) affect the distribution of clouds and precipitation?

- How do aerosol-driven changes in the vertical structure of latent heating affect the subsequent development of circulation systems on scales ranging from the cloud or cloud system to the regional and global?
- To what extent do changes in clouds, precipitation, and circulation systems regulate the distribution of the aerosol itself?

Because the nature of the coupling of the aerosol-cloud-precipitation system is regime dependent, ACPC has developed its strategy around the study of specific cloud regimes. These regimes were chosen because they represent climatologically important cloud formation and precipitation environments, for which there are strong indications of aerosol-cloud-precipitation interactions. They include some of the major convective and precipitating environments, such as the monsoon systems, organized deep convective systems over land, tropical cyclones, marine shallow and deep cumulus convection. Other regimes have been selected for their suitability to investigate key processes, *e.g.*, orographic clouds, diurnally variable convection over land, and mixed-phase clouds, including those that produce lightning and hail.

At present, aerosol-cloud-precipitation processes are represented in large-scale models only in a very crude and highly parameterized fashion. A central issue for the ACPC research program is thus to investigate how an improved process-level understanding of aerosol-cloud-precipitation interactions can be efficiently incorporated into large-scale models in order to constrain or improve estimates of the global effects of aerosol, clouds and precipitation on climate. Here again a regime-based approach is emphasized.

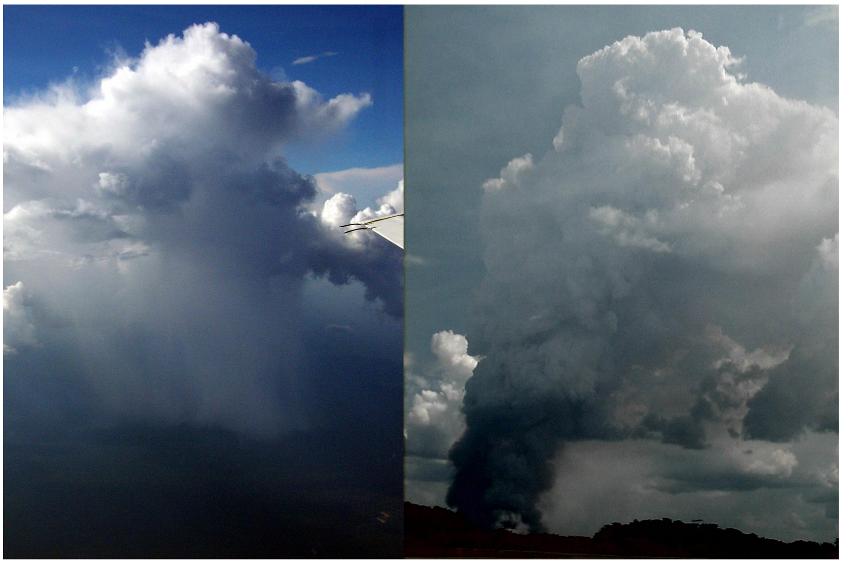
To implement ACPC as an international scientific program, we outline a coordinated effort encompassing a strategy that uses coordinated and ongoing field studies to integrate six strategic elements that we identify as follows: (i) a focus on regimes where there are strong indications of aerosol-cloud-precipitation interactions; (ii) an emphasis on statistical characterizations of aerosol-cloud-precipitation interactions; (iii) the development of approaches that leverage past and ongoing activities; (iv) thorough integration of modeling and observational activities; (v) a hierarchical approach to both modeling and data collection/analysis; (vi) continued development of measurement techniques. We present two examples of field centered studies as an embodiment of our proposed strategy. We envision that these examples will help stimulate further inputs from the broader scientific community to meet the objectives of ACPC.

II. Introduction

Environmental hazards in the form of air pollution, floods, and droughts affect a large part of the world's population. The atmospheric aerosol is an important contributor to air pollution, and is thought to play a role in determining important features of the hydrological cycle and other aspects of the climate system. The properties, amount and distribution of the atmospheric aerosol have changed greatly as a byproduct of industrialization and the accompanying explosion in human population. Recent studies suggest that increased aerosol loading, most evident at the regional scale, has changed the balance of radiant energy within the climate system and altered the hydrological cycle in ways that make the climate system more conducive to precipitation extremes.

Unfortunately, more definitive statements about the effects of changes in the atmospheric aerosol are limited by our incomplete understanding of the interplay between the aerosol, clouds and precipitation. This remains the principal barrier to advancing our ability to quantify the impact of the aerosol on precipitation and circulation systems from local to global scales. Hence, developing our understanding of this interplay is not just a major scientific challenge, but is also essential to the development of strategies for both adapting to, and mitigating, the deleterious effects of climate change.

These are not entirely new questions - in fact, many of the questions we pose date back to the middle of the 20^{th} century. But the intervening years have failed to produce a harmonized view of the interplay between the aerosol, clouds and precipitation for a variety or reasons. Foremost, in many situations we simply have not been attentive, which is to say that significant gaps in the observational record remain. But even when we have been paying attention, it has been difficult to extract a clear signal, with confounding factors being: the background roar of the ambient meteorology; a narrow focus on individual clouds for which the signal of circumstance is often loudest; consonance between the background aerosol and the meteorological conditions making it difficult, and often impossible, to isolate one from the other; and dissonance amongst myriad processes embodied by any categorical relationship.

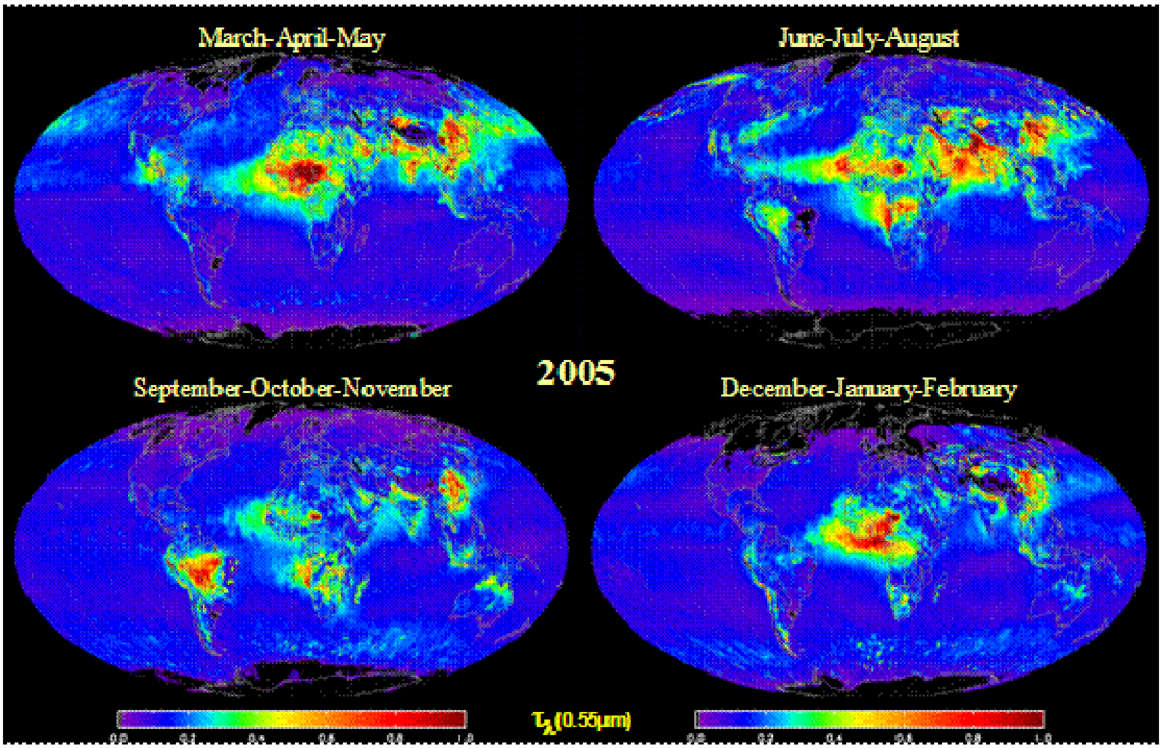


Two moderately sized cumulus clouds in the western Amazon separated by 100 km providing a striking example of aerosol effects on precipitation. Left: raining cloud in pristine air; Right: visible smoke entering cloud and suppressing rainfall.

As an example of this dissonance, we note that the relationship between cloud microstructure and rain appears to depend on many factors, ranging from micro scale processes such as the local intensity of turbulence in the cloud, to (at least in cold clouds) the non-equilibrium interactions among ice particles with differing habits, to larger scale processes, such as the efficacy of cold pool development, distribution of cloud top heights, or the relative humidity of the cloud environment. Trying to understand how perturbations to one aspect of the cloud environment (say the ambient aerosol) might work their way through the complex of cloud controlling processes and eventually change the underlying statistics of the cloud field is thus a task whose magnitude is only now becoming clear.

Our maturing understanding of the links among aerosol, clouds, precipitation and climate partly motivates this new initiative. This understanding is in large part the fruit of decades of weather modification research. Although this research was unsuccessful in demonstrating a robust relationship between environmental perturbations and changes in local precipitation, it greatly advanced our understanding of aerosol, cloud microphysical and precipitation processes. Additional motivation for this initiative on Aerosol, Clouds, Precipitation, and Climate (ACPC) is provided by the ongoing revolution in information technology. Both, observing systems and our capacity for simulation are qualitatively different from what they were just ten years ago. Indeed, the ease of making measurements and model simulations has helped spawn a generation of scientists whose interdisciplinary credentials far outstrips those of their predecessors. This in turn has fostered a discourse amongst diverse intellectual communities, from which ever more intriguing ideas and strategies have emerged to complement the emerging empiricism.

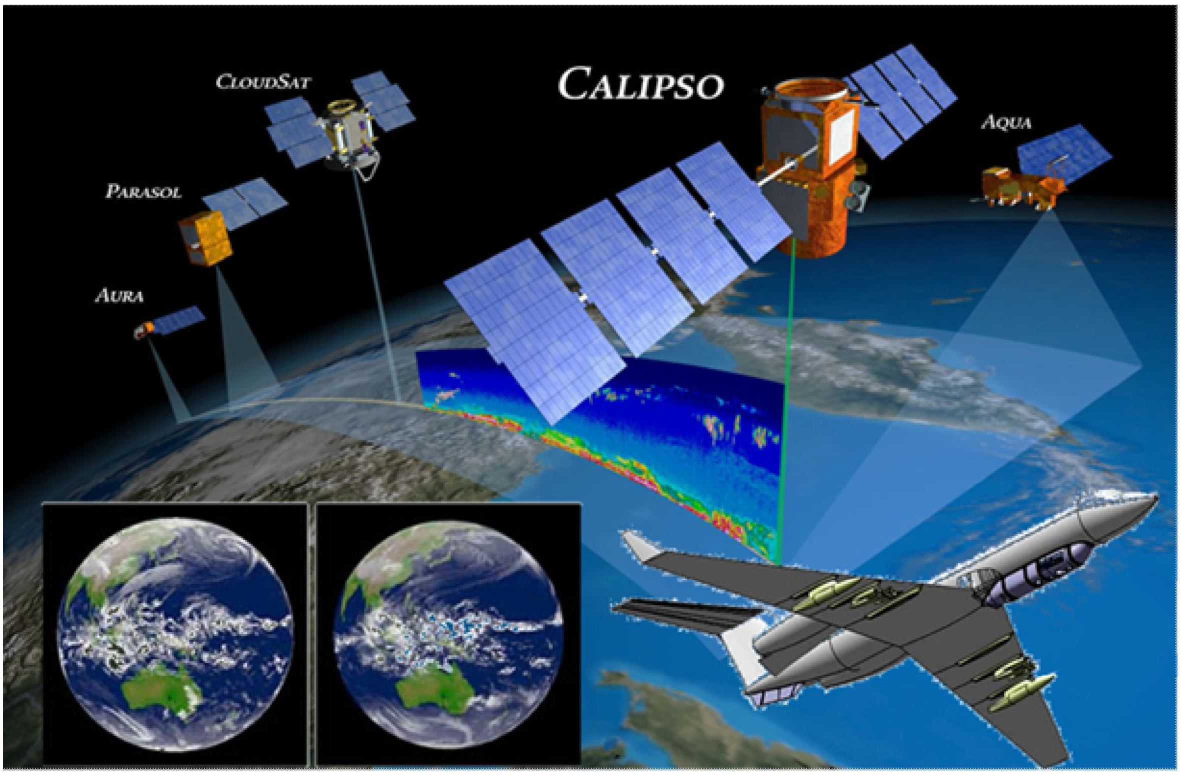
New measurements are documenting striking relationships among the aerosol, clouds and precipitation. Most evocative are the regions or pockets of open cellular convection embedded in regions of closed cellular (stratocumulus) convection. Here, simulations and some observations show that perturbations to the aerosol can dramatically reorganize the cloud field and greatly change the flux of ambient radiant energy to the surface.



MODIS-derived seasonal distribution of aerosol optical depth. Regions of high aerosol optical thickness are concentrated in tropical and subtropical land regions and adjacent oceans, and vary strongly with the seasons. These aerosols are mostly anthropogenic in origin, except for desert dust. Of equal interest are regions with very low aerosol optical depth on the subtropical eastern margins of the oceans where small aerosol perturbations can have a large influence on cloudiness. See further discussion in Section VII. (Lau et al., *WMO Bulletin*, 2009)

New ideas include the possibility that perturbations to the aerosol, which change the mixed-phase structure of clouds, can change the distribution and structure of convection, with attendant changes to regional scale circulations. Or that the regional aerosol loading can change the surface energy balance in ways that affect the development of precipitation on scales that range from the diurnal to the seasonal.

New strategies include the monitoring of vegetation fires in near-tropical regions, such as the South African savanna, the rain forests of the Amazon, or the sugar cane fields of Barbados. These provide opportunities for exploring the interplay between the aerosol, clouds and precipitation. To the extent that the burnings decorrelate with synoptic variations in the meteorology, they have the potential to serve as a natural laboratory in which one can hope, for the first time, to separate the effects of meteorology and the aerosol on large scales.



New measurement and modeling capabilities provide unprecedented opportunities for studying aerosol-cloud-precipitation interactions. Backdrop: the A-Train of satellites providing vertical profiles of aerosol, clouds and precipitation. Inset at lower right: Deutsches Zentrum für Luft- und Raumfahrt's new HALO aircraft for *in situ* and remote sensing of aerosol and cloud properties. Inset at lower left: Comparison of geostationary satellite (MTSAT, left) and detailed global model simulations (EarthSimulator, right) showing simultaneous hemispheric cloud fields.

But most striking is our growing capacity for measurement and simulation. In terms of measurement, notable is the tremendous advance in remote sensing (both space- and surface-based), which is providing an unprecedented view of cloud micro and macro structure, and surface rain rates across a range of space and time scales. When combined with surface networks of multi-parameter and multi-wavelength radars, lidars, and microwave radiometers, new classes of autonomous vehicles (unmanned aerial vehicles, UAVs), and a new fleet of modern aircraft capable of deploying large payloads with great endurance and at tremendous altitude, the opportunities are staggering. Meanwhile, simulations are providing qualitatively new insights. In the past five years we have begun to see a simulation capacity capable of resolving the structure of deep convective clouds across domains spanning the globe. Likewise, direct numerical simulation techniques are beginning to provide insight into the explicit interaction of drops and aerosol particles on scales much larger (and for flows considerably more complex) than what can be achieved in the laboratory.

These developments are the impetus for large observational, modeling, and theoretical efforts to understand the interplay amongst clouds, aerosol and precipitation. While past efforts have addressed pieces of this puzzle, especially in ice-free clouds, a comprehensive and integrated program is warranted. Such a program should accomplish four things:

i) act as a forum for bringing together the diverse expertise necessary to advance our understanding and help coordinate international efforts;
ii) ensure that experimental strategies encompass a sufficiently wide range of aerosol variability to properly characterize aerosol-cloud-precipitation interactions for the relevant regimes;
iii) coordinate and synthesize the findings of various components of the program;
iv) provide continuity and perspective for research initiatives.

Such a program has been initiated jointly by the International Geosphere-Biosphere Program (IGBP) and the World Climate Research Program (WCRP) under the guidance of their core projects iLEAPS, IGAC and GEWEX, as detailed further in the next section, which reviews the organizational background for ACPC. Its goal, specific scientific objectives, and implementation strategy are detailed thereafter. Throughout we avoid specific references, instead guiding interested readers to the technical literature by providing a short annotated bibliography outlining salient and recent review articles in Section IX. A list of acronyms is provided in an Appendix.

III. The Evolution of a Joint Initiative

Ideas for a broad program to study the linkages between aerosol particles, clouds, precipitation and climate had been circulating informally through the community for a few years, and in fact were part of the original iLEAPS Science Plan and Implementation Strategy. Also, better coordination with current and proposed IGAC/IGBP and GEWEX/WCRP aerosol-cloud-climate activities has long been warranted.

The plans and content for the initiative came into a clearer focus through the course of several meetings and workshops that have taken place over the last three years. These include: 3rd iLEAPS Scientific Steering Committee (SSC) meeting (20–21 January 2006, Boulder, Colorado, USA), 18th GEWEX Scientific Steering Group meeting (9–13 January 2006, Dakar, Senegal), joint IGBP and WCRP Steering Committee meeting in Pune, India, (2–7 March 2006), 4th iLEAPS SSC meeting (17–18 January 2007, Wageningen, Netherlands), ACPC Planning Group meeting (30 March 2007, Frankfurt, Germany), iLEAPS-IGAC-GEWEX ACPC Specialist Workshop (NCAR, Boulder, Colorado, 8–10 October 2007), and ACPC Planning Committee meetings (28–30 January 2008, 7–9 October 2008, 6–8 April 2009) at the International Space Science Institute (ISSI, Bern, Switzerland).

A first outline describing the initiative was presented at the joint IGBP and WCRP Steering Committee meeting in 2006 in Pune, India, where the special focus was to advance collaboration and discussion on common scientific questions and new initiatives between the two programs and also within the Earth System Science Partnership (ESSP). Following the joint IGBP/WCRP meeting in Pune, the scientific steering committees of iLEAPS, IGAC and GEWEX appointed ACPC representatives for each core project to produce separate white papers describing the scientific issues of relevance to the foci of the projects. A joint white paper was compiled by the planning group and was published in the iLEAPS Newsletter (iLEAPS Newsletter 4/2007). The Boulder meeting report along with several research articles based on the Boulder workshop presentations were also published in the iLEAPS Newsletter (iLEAPS Newsletter 5/2007). In addition, two review articles, one appearing in Science in 2008, another in Nature in 2009 evolved from the deliberations of the ACPC planning community and helped lay the foundation for elements of this document.

In early 2007, a small ACPC planning group consisting of representatives from iLEAPS, IGAC and GEWEX was established. The planning group representatives from iLEAPS were M. O. “Andi” Andreae, Markku Kulmala and Daniel Rosenfeld, from IGAC Sandro Fuzzi, Graciela Raga, Graham Feingold, and Colin O’Dowd (also representing SOLAS), and from GEWEX Tom Ackerman, Bill Lau, Ulrike Lohmann and Pier Siebesma. M.O. Andreae chaired the initial planning group. The group evolved into the ACPC Steering Committee with official representatives from the three international research organizations: 3 members from iLEAPS, 3 members from IGAC, and 4 members from GEWEX. Bjorn Stevens joined the team as co-chair in late 2008.

IV. Goal

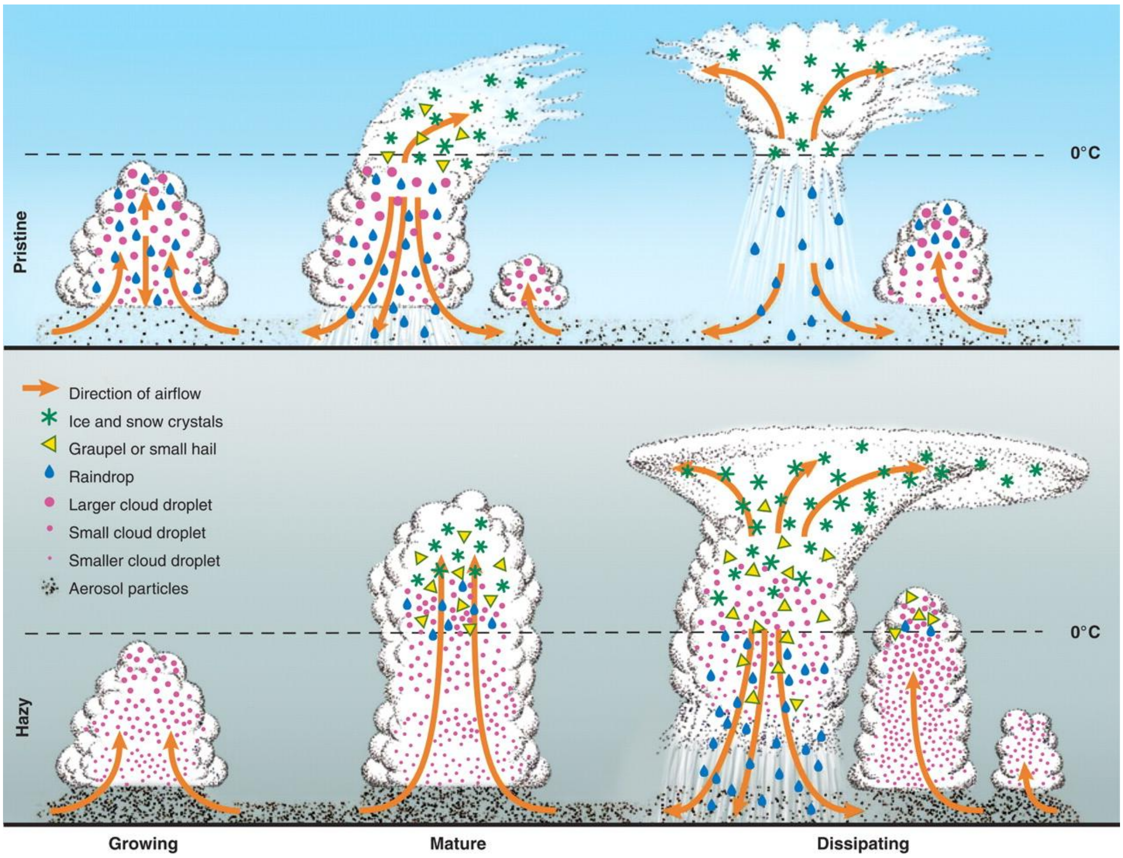
The goal of ACPC is to obtain a quantitative understanding of the interactions of the aerosol, clouds and precipitation, and their role in the climate system.

V. Scientific Issues

In this section, we highlight some of the basic scientific issues involved. What is the aerosol, how does it matter for the formation of clouds and precipitation? How does precipitation in turn affect the aerosol? Throughout, we focus on the basic process level questions, which we later elaborate on in terms of specific cloud systems or regimes, whose essential characteristics the aerosol helps to determine.

1. Aerosol controls on cloud microstructure

Aerosol particles are ubiquitous in the Earth's atmosphere. Their diameters range from a few nm to a few μm, often with pronounced concentration modes around a few tens of nm ("Aitken mode"), in the range ~100–500 nm ("accumulation mode"), and at a few μm ("coarse mode"). Coarse-mode particles typically originate from the dispersion of solid or liquid matter in the atmosphere ("primary particles"), for example mineral dust and seaspray. Submicron particles are usually mixtures of primary particles (*e.g.*, biomass smoke and diesel soot) and secondary aerosols that have condensed out of the gas phase (*e.g.*, sulfuric acid from SO_2 oxidation and organics from oxidation of volatile organic compounds). The largest number of cloud-active aerosol particles is usually found in the size range around 100 μm, but coarse-mode particles, while being few in number, can also play important roles in cloud processes. Human activities, especially biomass burning and fossil fuel combustion, have dramatically increased the atmospheric aerosol burden, especially over populated and industrialized continental regions.



Some of the possible effects of anthropogenic aerosols on cloud structure and precipitation are illustrated in this conceptual cartoon. Cloud droplets coalesce into raindrops that rain out from pristine clouds. Anthropogenic aerosol perturbation causes formation of a larger number of smaller droplets which do not precipitate before reaching the freezing level, giving rise to deep and vigorous clouds that create thunderstorms and, possibly, hail. Secondary convection is promoted. (Rosenfeld et al., *Science*, 2008)

By definition, cloud condensation nuclei (CCN) are that subset of the atmospheric aerosol that can nucleate a cloud droplet at a given water supersaturation. The ability of particles to act as CCN depends mostly on their size and chemical composition. An essential issue is therefore to characterize the CCN population in terms of number/size distributions, size-dependent composition, hygroscopicity, surface tension, droplet activation spectrum, etc.

A key role in precipitation formation is also played by particles that can induce the nucleation of ice crystals at temperatures above that of homogeneous freezing of cloud droplets, the so-called ice nuclei (IN). While investigations in recent years have shown that mineral dust particles and some biological particles can and do act as ice nuclei, there is only very incomplete information about the actual sources and distributions of IN. To arrive at a predictive ability of aerosol influence in the climate system, we must relate the characteristic properties of IN and CCN to the sources and production mechanisms of the aerosol.

Cloud formation begins with the condensation of water vapor on aerosol particles when air becomes supersaturated with water vapor, typically as a result of upward movement of an air parcel accompanied by adiabatic cooling. Depending on the ambient temperature, a cloud droplet or ice particle forms, beginning a chain of events that eventually may lead to a drop or ice particle large enough to precipitate. Just how these events unfold, and their ultimate outcome – precipitation or re-evaporation of the cloud water – depends on the interplay of meteorological processes and the character (number and physico-chemical properties) of the aerosol.

In contrast to the measurements of CCN or IN spectra, which typically are conducted with unlimited supply of water vapor and in near-equilibrium conditions, the formation of droplets or ice in a real cloud occurs in a very dynamic environment. In real-world clouds, the thermodynamic state experienced by hydrometeors is often subject to rapid change, and there is dynamic competition between nuclei of different sizes and composition for water vapor. This can even result in a reduction of drop concentration from an apparent increase in CCN availability. The actual hydrometeor spectrum in a cloud is therefore the result of complex interactions between aerosol particles, hydrometeors, and the physical processes in the cloud, *e.g.*, the updraft velocity distribution, turbulence, shear, and mixing processes. In this context, one must not only consider the aerosol population in the air entering a convective cloud from below through the cloud base, but also that in the air that is mixed into the cloud by lateral entrainment processes. A critical issue to be addressed by this initiative will therefore be to relate the hydrometeor spectrum in different regions of the cloud to the characteristics of the aerosol population in the air entering the cloud.

2. Precipitation efficiency

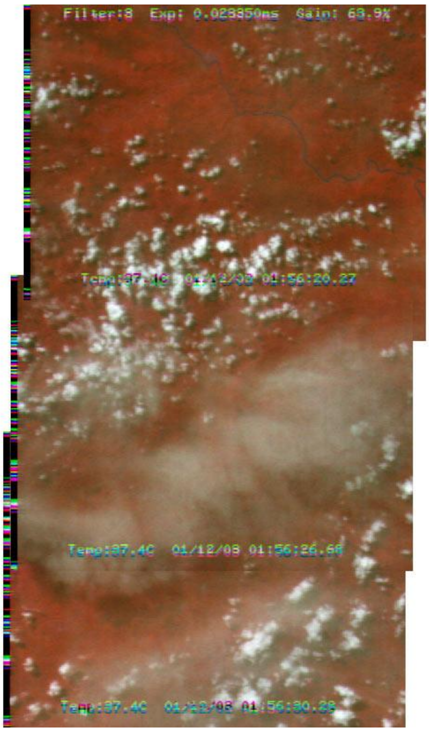
Precipitation efficiency (PE) is defined here as the fraction of water that reaches the surface from the total amount of condensed water within a cloud. This efficiency is a function of the ambient conditions that determine convection and that modulate cloud development (*e.g.*, relative humidity, potential instability, and wind shear). Once a cloud is formed, water can either evaporate or precipitate. An increase in PE would result in an atmosphere with locally lower relative humidity, since less evaporation would have occurred, thus affecting larger scale circulations. Precipitation efficiency is also a function of the details of the microphysical structure within the cloud, and the processes that determine the initiation and evolution of precipitation.

If atmospheric conditions are conducive for cloud development, rain drops can develop from the collision and coalescence of cloud droplets (autoconversion) in ice-free clouds. For a given cloud, the time-scale of this process depends critically on the cloud droplet spectrum and hence the character of the aerosol. Broad cloud droplet spectra with relatively few but large drops favor the rapid development of precipitation, as do the presence of giant CCN (*i.e.*, CCN with diameters larger than about 5 μm). In addition, the PE of a cloud may depend on where in a cloud (or within a cloud life-cycle) the coalescence process becomes active, as it has been argued that delaying the onset of precipitation (by forcing it to form higher, or later in the cloud lifecycle) may result in a reduced PE from warm clouds.

Efficiently precipitating trade wind cumulus cloud observed over Barbados in a clean environment. Photo credit Joseph Prospero.

In ice-bearing clouds, there exist more varied paths to precipitation, many of which remain poorly articulated. As a result, the role of the aerosol in regulating PE is even more uncertain in the presence of ice processes. Smaller drops can lead to less efficient contact freezing, ice multiplication and accretion onto ice particles, implying a reduction in PE. However, a decreased autoconversion process in the warm portions of the cloud results in more supercooled droplets available for freezing aloft. This enhanced release of latent heat of freezing has been shown in model studies to result in cloud invigoration. Under some circumstances, especially in deep, warm-base, convective clouds, the increased convective overturning can overcompensate the decreased PE and yield greater surface rainfall amounts. More vigorous overturning would lead to increased entrainment, so ambient conditions also play a role in the resulting PE.

3. Radiative effects



The reduction of cumulus cloud formation due to absorption of solar radiation by particles from biomass burning in Brazil. Absorbing particles warm the atmosphere and cool the surface resulting in stabilization of the boundary layer. In addition, surface fluxes are reduced. The result is a complete suppression of convection in the smoky region. Photograph taken from the ill-fated NASA Columbia shuttle STS-107 flight on January 12, 2003.

The aerosol interacts radiatively with the atmosphere through scattering and through absorption of light, with the balance between the two effects depending on the aerosol's physical and chemical characteristics (and the properties of the underlying surface). Scattering of visible light cools the surface, as some radiation is ultimately scattered back to space. Absorption of visible light by black and brown carbon also cools the surface, but in addition heats the atmosphere aloft. The cooling of the earth surface, and of near-surface air relative to the air above, tends to stabilize the atmosphere, thereby reducing convective instability. However, heating of the atmosphere by absorbing aerosol on a large scale can also be a source of baroclinicity, and can alter circulation systems on scales ranging from the sea-breeze to the monsoon. The circulation changes may feed back on the aerosol transport, and on heating and cooling processes in the atmosphere and at the earth surface. Black carbon and light-absorbing organic materials embedded in cloud droplets can result in localized warming and evaporation of cloud droplets.

Whether the aerosol, as a result of these processes, will eventually lead to an increase or decrease in rainfall at a specific location depends on complex processes, including the relative abundance of absorbing vs. non-absorbing aerosol. The characterization of the aerosol in the study region of an ACPC project must therefore also include those variables that define its interaction with radiation, such as spectral scattering and absorption coefficients, scattering phase function, and refractive indices. In order to scale up local and regional observations, it will be important to find statistical and physical relationships between optical and cloud-active properties of aerosol particles, and to enhance tools for their determination through remote sensing.

4. Dynamical response and feedbacks

If changes in the development of precipitation can be attributed to perturbations in the aerosol, how do changes in the vertical structure of latent heating affect the subsequent development of circulations systems? In the trade wind regions, the means by which the trade wind layer deepens into the descending branch of the Hadley cell is through the lofting and eventual evaporation of condensate. The combination of evaporative cooling above condensational heating is characteristic of non-precipitating convection, and is thought to play an important role in deepening the trade wind layer and preparing the atmosphere for deep convection. Changing the properties of the aerosol so as to inhibit precipitation development in shallow clouds should lead to a deeper, moister trade wind layer, which may change the phasing of the onset and the eventual intensity of deep convection, and hence the underlying circulation system itself. To the extent that the aerosol helps determine how clouds become glaciated (for instance as reviewed in the subsection on precipitation efficiency) it will also influence the profile of latent heating within the troposphere. This too will engender anomalous circulations whose magnitude, character and implications remain uncertain.

5. Feedbacks of clouds and precipitation on the aerosol

Closing the loop, to what extent do changes in clouds, precipitation, and circulation systems regulate the distribution of the aerosol itself? Cloud processes and precipitation are a dominant sink for the atmospheric aerosol. By removing pre-existing aerosol, they make the atmosphere conducive to the nucleation of new particles from the gas phase. In fact, were it not for the fact that humanity is perturbing the balance of the aerosol, our central question would likely be: what is the role of cloud-processes in regulating the characteristics, amount and distribution of the atmospheric aerosol? In the context of the ACPC initiative, however, it still makes sense to ask how biases in the representation of clouds affect the distribution of the aerosol and how changes in clouds mediate aerosol effects. Intriguing in this regard are the regions of open cellular convection discussed in the Introduction. The development of such cells is thought to be associated with a proclivity of clouds to form precipitation, perhaps as a result of anomalously low aerosol concentrations, but the rain is in turn effective at depleting the aerosol. Hence low aerosol concentrations are associated with more rain and less cloud in such systems, but the causality can be difficult to establish.

VI. Scientific Approach: Regime Centered Studies

In this section we discuss some of the ways in which the scientific issues presented in the previous sections are manifest in terms of specific precipitating cloud regimes. Because they don't actively precipitate, some common regimes, such as cirrus, are left out. ACPC has adopted a regime based approach as the basis of its overall scientific strategy, because the interplay among the aerosol, clouds and precipitation is recognized to depend strongly on the type of cloud system (or regime) considered. Consequently, cloud regimes help define natural laboratories for exploring the ACPC scientific issues. In what follows, we review some of the more important regimes that have been identified through the course of the ACPC planning process. As the ACPC initiative evolves and our understanding develops, we expect this list to change and mature; hence what follows should be taken as a starting point.

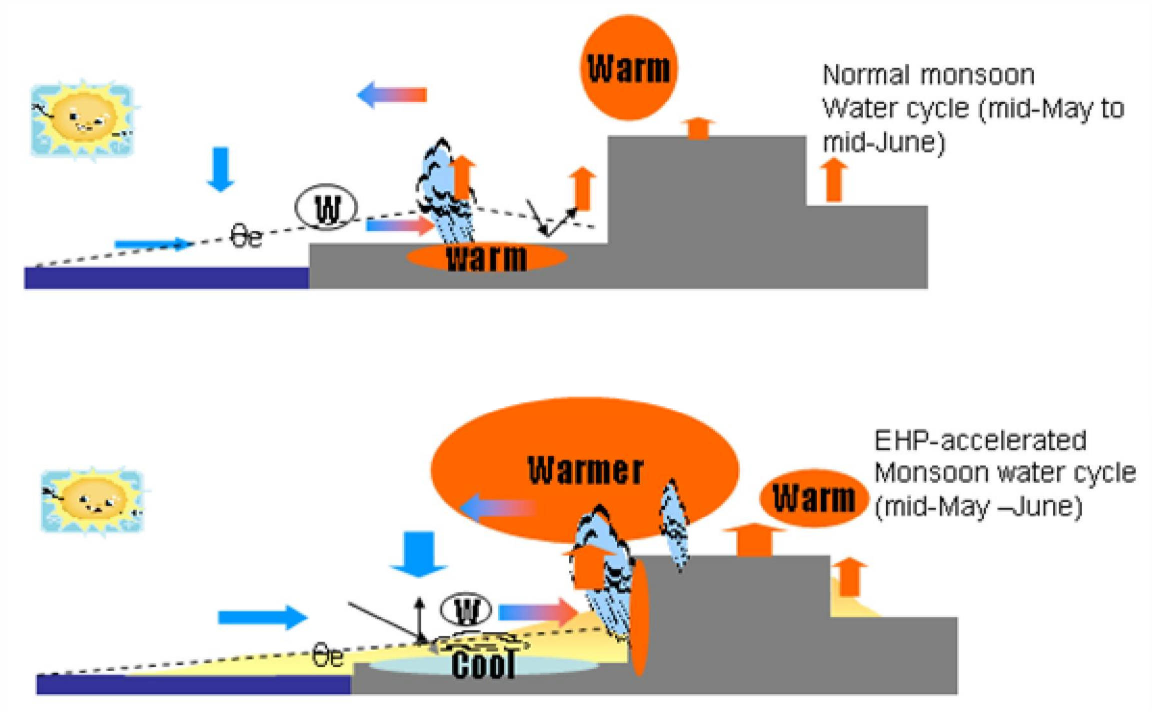
1. Diurnally varying convection over land

The diurnal cycle of convection over land is a prototypical system, involving a close interaction between surface and atmospheric processes. Important questions pertain to the time of onset of deep convection and its ensuing character. In the simplest regimes, where the organizing effects of topography, or shear in the large-scale winds, do not play a large role, the system evolves through a cycle that transitions from a shallow stable night-time boundary layer, from which a convective boundary layer emerges and deepens as the surface warms after sunrise. Shallow clouds initially develop atop the boundary layer, gradually deepen, and then transition, often explosively, to deep precipitation-producing convection. With nightfall the deep convection organizes and propagates if it can tap remote sources of moisture, or decays with the retreat of the sun. The rhythm of the system offers the possibility of frequent sampling, conducive to statistical analyses of the role aerosol perturbations may play in the development of this system; particularly when looked at through the filter of the weekly cycle.

The weekly cycle comes to mind because anthropogenic aerosols or aerosol precursor emissions show a pronounced weekly variation. This cycle varies in different parts of the world according to how economic activity is organized throughout the week, and is evident in measurements of both fine (less than 1 μm) and coarse particles. While it remains unclear whether this cycle translates into a weekly cycle in precipitation, such cycles offer an opportunity to separate aerosol effects from meteorological influences on clouds and precipitation. Moreover, even if the aerosol does not affect the net amount of precipitation, it may alter the phasing of the diurnal cycle, the pattern of convective heating, or the ambient humidity in the cloud-free environment.

2. Monsoon convective systems

Monsoon systems are driven in large part by land-sea temperature contrasts on large (semi-continental) scales. Hence they may be susceptible to aerosol induced heating anomalies, particularly if such anomalies are localized over land. Moreover, because aerosol perturbations can be very large and are often concentrated over regions affected by the monsoon, interest in the effects of the aerosol on monsoon systems has intensified. Examples include heating anomalies associated with sulfates and black carbon from industrial activity in Southeast Asia and the Indian subcontinent, as well as mineral dust over Africa, and biomass burning over the maritime continent and in the Amazon. General circulation model (GCM) studies are beginning to suggest specific and plausible scenarios through which perturbations to the aerosol may affect the monsoon water cycle. These include the north-south precipitation dipoles over East Asia, which some have attributed to increases in black carbon emission in India and China.



Schematic of the Elevated Heat Pump hypotheses explaining how aerosol may enhance the Indian summer monsoon circulation:
a) warming and moistening of the upper troposphere over the Tibetan Plateau;
b) an advance of the rainy season in northern India/Nepal region in May-June;
c) in June-July, the increased convection spreads from the foothills of the Himalayas to central India, resulting in an intensification of the Indian monsoon.
d) subsequent reduction of monsoon rain in central India in August.
(Lau et al., *Clim. Dyn.*, 2006. Lau and Kim, *Geophys. Res. Lett.*, 2006)

Radiative perturbations of the aerosol have been argued to reduce the thermal contrast between the Indian sub-continent and the surrounding ocean, thereby reducing rainfall over central and southern India. The absorbing aerosol has been shown to lead to an increase in rainfall and an advance of the monsoon rainy season in northern India. Furthermore, heating anomalies associated with the aerosol may be driving anomalous large-scale circulations, providing feedback on the aerosol forcing. Most of the aerosol-monsoon interactions have been hypothesized to be due to radiative effects of the aerosol, although attention is now turning toward microphysical effects associated with perturbations to the cloud-active aerosol, for instance the possibility that the aerosol may control the vertical distribution of latent heat release within the cloud systems.

3. Organized deep convective systems

As discussed in the context of the diurnal cycle, deep convection often organizes large mesoscale convective complexes whose character depends on ambient conditions. In particular, instability and vertical shear of the horizontal wind play large roles in determining the organization of convection. Organized multi-cell convection develops when very large available potential energy is present in the environment. The degree of organization increases with the ambient vertical wind shear, as this helps organize thermodynamic perturbations associated with precipitation so as to increase the longevity of the system. Typically, new cells tend to form in a certain quadrant of the existing convection, leading to systems that remain coherent for many hours. Squall lines evolve over a period of many hours and often appear to be in steady state, presenting a line of active convective cells and a large stratiform region, with a rear inflow jet that flows towards the front of the line and helps maintain the convection. Precipitation from the convective and stratiform regions in many cases can be comparable, but different mechanisms are responsible for its development.

Modeling studies have shown that increases in ambient CCN can lead to a decrease in precipitation when environmental instability and vertical wind shear are small. In contrast, an increase in precipitation is possible for large systems or for organized systems with more wind shear. However, such effects are sensitive to meteorological factors, including the distribution of ambient humidity, and may differ as a function of the system life cycle.

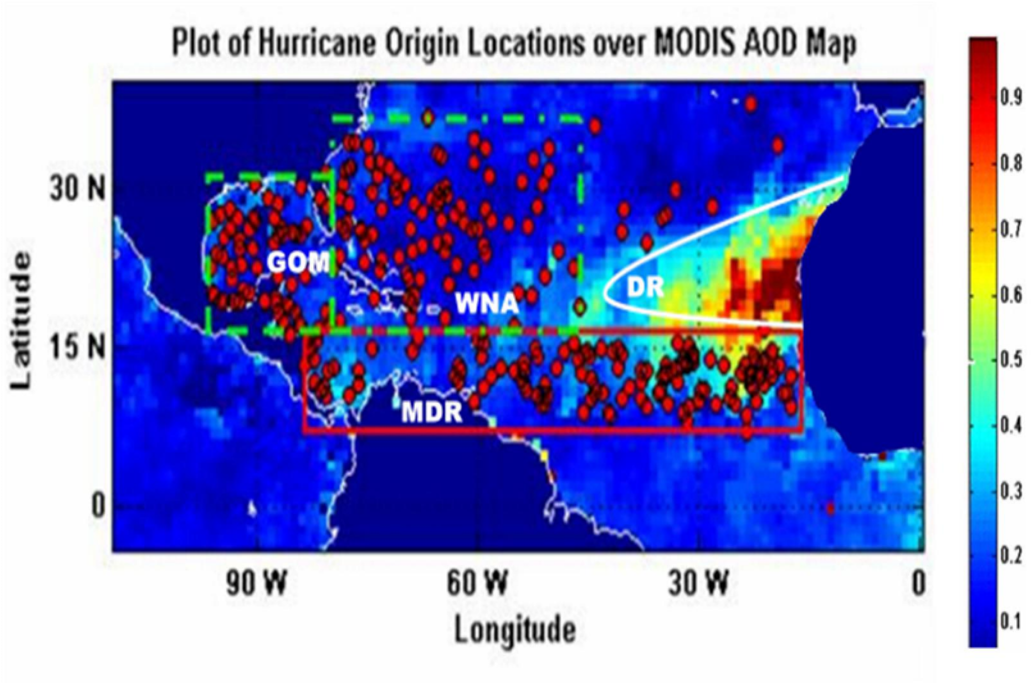
4. Deep convection – cloud electrification and hail production

Charge separation in clouds occurs typically when falling rimed ice hydrometeors (graupel) collide with ice crystals that ascend with the updraft within supercooled convective clouds. By suppressing early rainout, aerosol particles can lead to greater amount of supercooled water extending to a greater depth in the clouds. It has been suggested that the freezing of this additional supercooled water invigorates the storms, and hence increases their lightning activity. The smaller number concentrations of larger hydrometeors combined with smaller drops and stronger updrafts can also lead to the production of larger hail stones because there is less competition for the increased availability of supercooled water. Stronger updrafts and smaller cloud droplets can also be caused by greater instability and stronger sensible heat fluxes over drier land surfaces. Separating the aerosol influence from other meteorological effects remains a challenge.

In addition, lightning is an important source of nitrogen oxides NO_x ($NO+NO_2$) which is of particular importance for upper tropospheric NO_x concentrations, especially in the tropics, because of the comparatively long lifetime of NO_x in this region. Lightning NO_x plays an important role in atmospheric chemistry, driving ozone formation and influencing OH concentration and the oxidizing capacity of the atmosphere, with implications for aerosol particle formation and composition.

5. Tropical cyclones and their interactions with mineral dust

Every year, of the order of a billion tons of dust are swept up from the Saharan desert and transported over large distances across the entire span of the tropical Atlantic, as well as to Europe, the Middle East and South Asia. Saharan dust transported over the Atlantic, and the very dry layers they are often associated with, may interact with maritime deep convection. During boreal spring and summer, the hot dry interior of the desert promotes dry convection, which carries dust particles and dry air to high elevations. The elevated dust is transported by the easterly trades and by African easterly waves that originate over West Africa and propagate along the Atlantic inter-tropical convergence zone (ITCZ) to the mid-Atlantic. Some of these easterly waves will intensify into tropical



Climatological distribution of aerosol optical depth (AOD) from MODIS for June-July-August, 2001-2007, and location of hurricane genesis. Hurricanes tend to form in the ITCZ south of the Saharan dust layer, and to the west, away from the dust layer. Many recent studies have shown possible suppression of tropical cyclogenesis through interaction of dynamics with the dry and dusty Saharan air layer, compounded by the reduction in sea surface temperature due to radiative forcing of the dust.

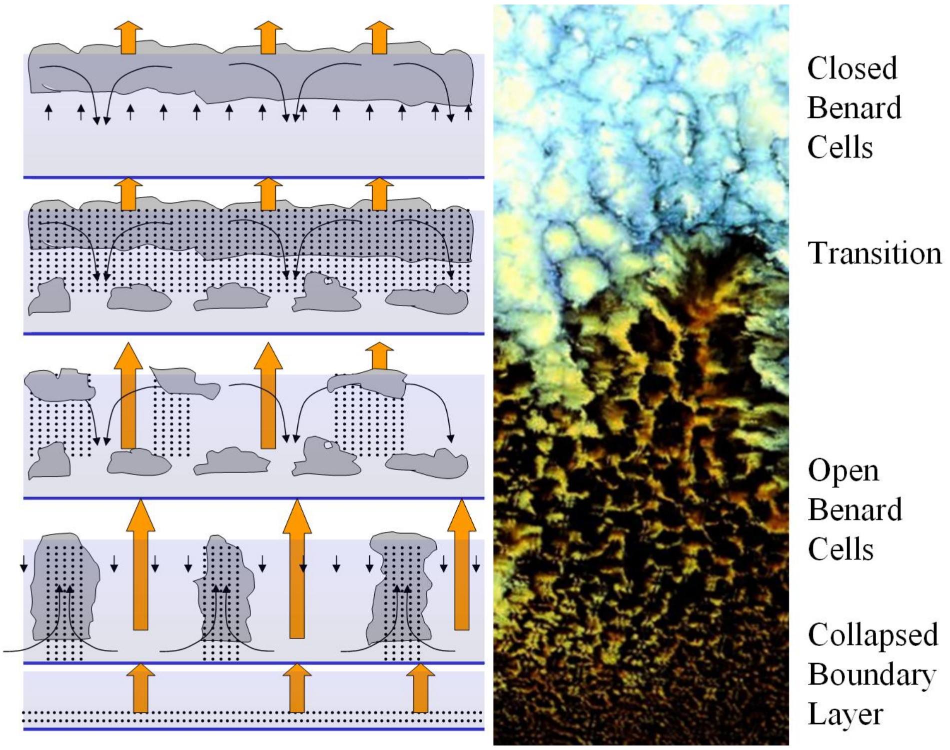
cyclones, through the cumulative effect of deep cumulus convection, and thus act as hurricane embryos. The perturbation of such incipient storm systems, for instance by mineral dust intrusions, may affect their ability to develop into more mature and devastating storms such as tropical cyclones.

When a developing easterly wave occurs simultaneously with a dust outbreak, the hot, dry air associated with the outbreak may be entrained into the core of the developing cyclone, suppressing the cyclone development by stabilizing the atmosphere and depriving it of the moisture that fuels it. The radiative effect of dust may further suppress cyclogenesis and hurricane formation. Over the Atlantic, the elevated dust absorbs solar radiation and heats the atmosphere around the dust layer, at the same time blocking solar radiation, which results in a cooling of the layer between the bottom of the dust layer and the ocean surface. During the African Monsoon Multidisciplinary Analyses (AMMA) field experiments this characteristic dipole heating structure (warm above, cold below) has been observed in a number of easterly waves that did not develop into tropical storms. Modeling studies indicate that dust might also weaken tropical cyclones by suppressing warm rain. Further studies have shown that Saharan dust loading over the Atlantic is inversely related to hurricane activity, although it remains unclear as to what drives this relationship, as weather conditions that favor more dust may disfavor cyclogenesis.

6. Marine stratocumulus clouds

Stratocumulus clouds modify the net radiative balance at the top of the atmosphere more than any other cloud regime. They also offer the most evocative example of possible aerosol effects. Here, regions of enhanced aerosol concentrations associated with ship plumes or coastal effluents often markedly enhance the albedo of thin stratocumulus layers. In regions favoring thicker stratocumulus layers, observations and simulations suggest that the development of precipitation engenders structural changes in the boundary layer circulation and concomitant changes in cloud structure.

Regions of open cellular convection, sometimes embedded as pockets of open cells within broader regions of closed-cellular convection, tend to have a greatly reduced albedo, and greatly reduced aerosol concentrations. What role, if any, does the aerosol play in modulating such cloud transitions? Or do other processes determine the development of precipitation, which then in turn (through wet deposition) depletes the aerosol? The idea that the aerosol might play a role is supported by observations (and some modeling studies) that suggest that massive infusions of aerosol (from passing ships) can increase the albedo and cloud fraction of open cellular patterns and may aid in closing them.



Right: Satellite image showing the transition from closed to open cellular structures in a marine stratocumulus cloud sheet associated with increases in drop size (reddish colors) and the development of precipitation. The schematic at left describes the sequence of events leading to the transition to an open-cellular structure and the eventual collapse of the boundary layer. (After Rosenfeld et al., *Atmos. Chem. Phys.*, 2006)

7. Trade wind regime

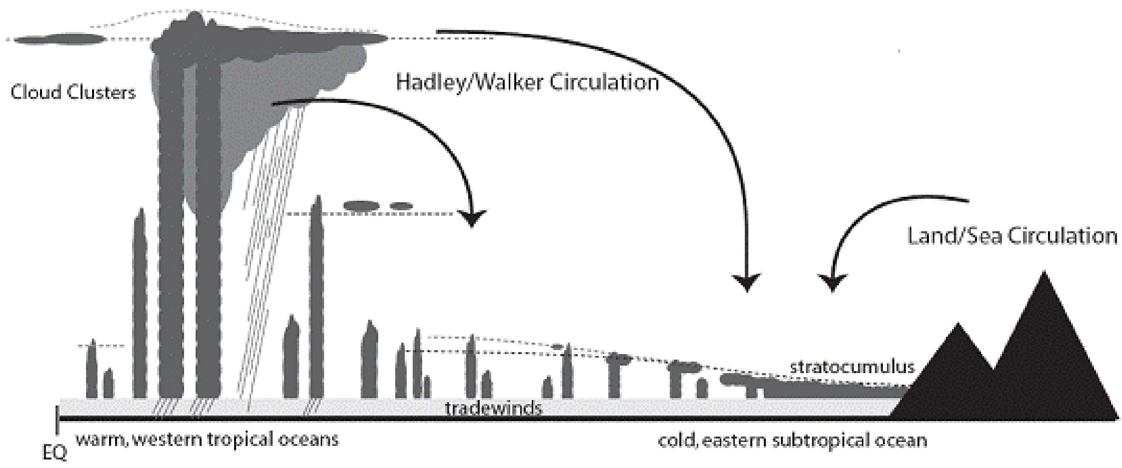
In regions of cumulus convection it has long been hypothesized that enhanced precipitation efficiencies, say associated with reductions in the aerosol, may deplete the lower troposphere of moisture, thereby reducing cloud cover. However, subsequent work has engendered a number of competing hypotheses, for instance that smaller drops not only precipitate less, but also evaporate more efficiently, and more effectively drive circulations that dilute clouds and reduce cloud cover. A corollary being the idea that moderately sized drops, *i.e.*, ones that are not removed rapidly by precipitation to the surface, will take longer to evaporate and may prolong the lifetime of the cloud. These complications are compounded by the fact that non-raining clouds destabilize their environment, thereby preconditioning the layer for deeper convection, which then may result in more rain.

As discussed in the review of the scientific issues in Section V, the characteristics of the aerosol (both the number and its physico-chemical properties) are thought to affect the initial development of precipitation. On balance, it appears that aerosol number concentration and size play significantly more important roles in determining drop concentration than does composition, especially in high updraft conditions. In addition, details of the distribution, such as the number of large and giant nuclei, *e.g.*, inorganic salt or mineral dust particles with dry diameters greater than a few microns, can have an inordinate influence on drop activation, growth, and the formation of precipitation, thereby complicating attempts to relate the character of the cloud to low-order parameters of the aerosol distribution.

Hence the relationship of cloud fraction to precipitation efficiency remains ambiguous, and the strength of the coupling between the concentration of cloud condensation nuclei and the precipitation efficiency remains uncertain. However, given the global coverage of regions of trade wind or fair-weather cumulus convection, even small effects can have profound influences.

8. Transition to maritime deep convection

The question of which processes regulate the position of the ITCZ is of crucial importance for our understanding of the hydrological cycle, regional circulations, and coupled atmosphere-ocean interactions, such as the El Niño - Southern Oscillation. The delicacy of the position of these tropical rain bands is manifest in how difficult it is to represent their position with fidelity in models of the current climate. Modern coupled models have long-standing problems in representing hemispheric asymmetries between the northern and southern convergence zones; likewise theoretical ideas as to the position of the ITCZ remain unconsolidated and have limited explanatory power.



Schematic of the transition from marine stratocumulus under the subtropical high to the trade-wind cumulus regime that in turn transitions to deep convection in the ITCZ. Aerosol-precipitation interactions may affect the transition from solid to broken clouds. (Stevens, *Annu. Rev. Earth Planet. Sci.*, 2005)

Because, to a first approximation, the ITCZ is a maritime manifestation of the transition to deep convection, many of the questions pertaining to the role of the aerosol in modulating precipitation efficiency, and hence processes such as the diurnal cycle of convection over land, naturally translate to questions relating to the control and position of the tropical convergence zones. By inhibiting precipitation in the trades, convection can more effectively charge the atmosphere with moisture, thus accelerating the onset of deep convection. Similarly, just as it has been hypothesized that the aerosol may play a role in determining the transition to the ice-phase (and hence the lapse rate of the middle troposphere) in regions of deep continental convection, such processes may also play a role in maritime circulations, thereby affecting the myriad processes determining the position and character of the tropical rain bands.

9. Orographic clouds

Orographic clouds form as a result of moist air masses impinging on mountain ranges, thereby potentially forming orographic precipitation, which is a key component of the hydrology, agriculture, and the local climate in many regions of the world. Orographic precipitation is hypothesized to be susceptible to the aerosol because the time available for precipitation to develop is constrained by the flow over the mountain. By suppressing the onset of the collision/coalescence process, changes to the aerosol may considerably alter the amount and distribution of precipitation over terrain, thus affecting the distribution of precipitation.

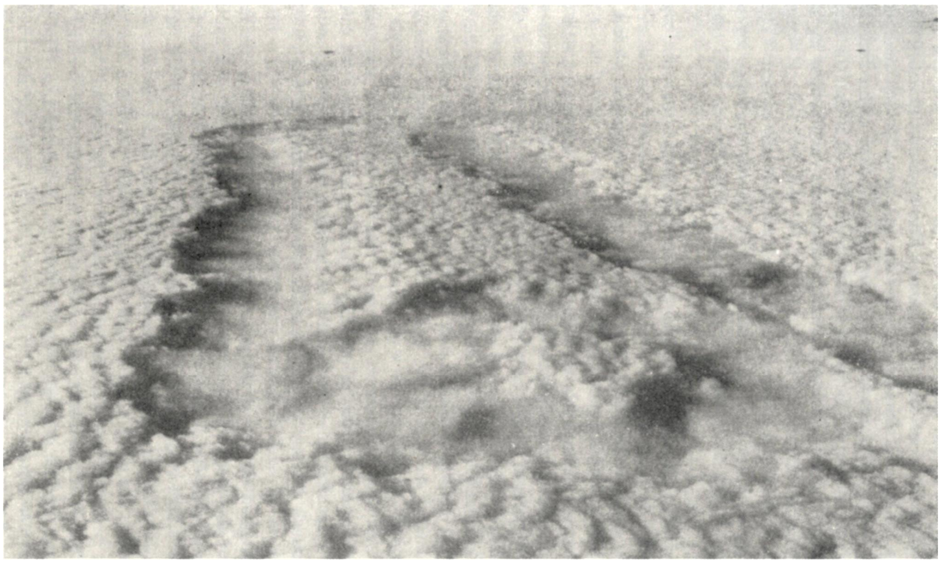
The ability of the aerosol to initiate freezing in orographic clouds, the complexity of mixed-phase microphysics, and the variety of small-scale dynamical processes pose challenging problems for both observing and modeling aerosol effects on orographic precipitation, and introduce large uncertainties. *In situ* microphysical observations in orographic clouds indicate a decrease in riming rates with increasing number concentrations of anthropogenic aerosol, but the implications for orographic precipitation remain unclear. Statistical quantifications of aerosol particles affecting orographic precipitation inferred from time series of paired rain gauge data suggest strong sensitivities of decreasing orographic precipitation to increasing air pollution for several mountain ranges in Israel, China, and the United States (*e.g.*, Sierra Nevada, Colorado Rocky Mountains), but results from these inferences are controversial and partially contradictory. Modeling studies find both decreasing and increasing orographic precipitation, depending on the heterogeneous freezing properties of the aerosol (composition and mixing state), dynamical conditions of the flow, and geometrical aspects of the mountain range.

10. Fair weather clouds over the boreal forests

Boreal forests cover a large fraction of Earth's land surface. They are known to be a significant source of cloud-active primary aerosol (IN and CCN), as well as biogenic volatile organic compounds (isoprene, monoterpenes, sesquiterpenes) that may condense onto existing particles, nucleate new ones, or influence the oxidizing capacity of the atmosphere, which in turn may determine the character of the atmospheric aerosol. How susceptible are such emissions to temperature, available sunlight, water, and nutrients? To the extent that emissions and wildfires can be related to variations in clouds and precipitation, it may be possible for such interactions to amplify or dampen external changes. However, our understanding of such issues remains in its infancy. And, while many of these questions are also pertinent to cloud regimes over other biota (*e.g.*, phytoplankton over the ocean), the extent of the boreal regions and their role in determining the surface albedo merits singling them out for special focus, initially through the development of enhanced long-term measurement activities.

11. Mixed phase processes in shallow cloud regimes

A cloud consisting of cloud droplets at temperatures below 0ºC is called a supercooled cloud. For a given temperature, it can glaciate once ice nuclei are available that initiate freezing at that temperature. Ice nuclei (IN) are a tiny subset of all atmospheric aerosol particles that meet one or more of the following criteria: They need to be solid particles and they should be of sizes larger than the critical size of an ice germ ($> \sim 0.1\ \mu m$). Good ice nuclei might also have a lattice structure that is close to that of ice and/or have active sites, which are surface imperfections where the water vapor can more easily deposit. The last criterion is more readily fulfilled, the larger the size of the IN is. Known types of IN in the atmosphere are mineral dust particles, bacteria, and other biological particles.



The general view of a dry ice-seeded racetrack pattern in a supercooled cloud layer 37 minutes after the start of the seeding and 24 minutes after the end of the seeding. The cloud layer extended between 4500 and 6800 feet over Utica, New York, with a cloud- top temperature of -5.6 C. The picture was taken at 15:21 on 24 November 1948, from an altitude of 17,630 feet. (From Langmuir, 1961)

The rate and nature of the partitioning of the water vapor between ice particles and liquid droplets depends on the availability of IN and the vertical velocity. If the vertical velocity is strong enough so that supersaturation with respect to water is exceeded, then new cloud droplets will form continuously, and both cloud droplets and the already existing ice crystals will grow. If, on the other hand, the vapor pressure falls below water saturation but remains above ice saturation, then the cloud droplets will evaporate and the ice crystals can grow at the expense of evaporating cloud droplets. This process is also known as the Wegener-Bergeron-Findeisen process. Because of the scarcity of IN, some clouds in the atmosphere can remain liquid at temperatures as low as -35ºC, whereas others are completely consisting of ice crystals at temperatures as warm as -5ºC.

VII. Strategies

To meet the challenge of understanding physical relationships among aerosol, clouds and precipitation and to capitalize on the opportunities afforded by new experimental techniques and the ever-growing prowess of observations and simulations, we propose a coordinated international effort encompassing a strategy that embodies the following elements: (i) isolation of, and focus on systems where there are strong indications of aerosol-cloud-precipitation interactions; (ii) an emphasis on statistical characterizations of aerosol-cloud-precipitation interactions; (iii) the development of approaches that leverage past and ongoing activities; (iv) thorough integration of modeling and observational activities; (v) a hierarchical approach to both modeling and data collection/analysis; (vi) continued development of measurement techniques. We further propose that these elements be brought together through a small number of field studies, perhaps one for each of the eleven regimes identified in the previous section. The field measurements, whose characteristics likely would differ based on the questions being asked, would localize initiatives, both geographically and scientifically. This will provide the necessary cohesion to ensure the successful implementation of the six elements of our strategy listed above.

In what follows we briefly elaborate on the different elements of our strategy, and outline two very different types of field studies as examples of possible experimental focal points for the study of aerosol interactions in regions of deep tropical convection on the one hand, and in regions of shallow trade-cumulus convection on the other.

1. Strategic elements

a. Cloud-precipitation regimes as an organizing principle

As should have become clear in the discussion in Section VI, clouds are not one thing, but many. And as a result, there is unlikely to be one answer as to how the aerosol affects cloud processes. The varied ways in which clouds couple to larger-scale circulations, radiative, and surface processes, and their efficacy in converting vapor to liquid or solid are the physical basis for the varied cloud types. Because cloud types tend not to commingle, one often thinks of cloud regimes, wherein one type of cloud, or cloud system, dominates the sky. For this reason, any study of the interplay among the aerosol, clouds and precipitation must be centered about these cloud regimes. This regime-based strategy has been successfully adopted by the GEWEX Cloud System Study (GCSS) with its emphasis on five broad regimes: deep convection, extra-tropical storm systems, cirrus, polar, and boundary-layer cloud regimes. Within these, one identifies more specific regimes, such as fields of cumulus congestus or squall lines as a form of deep convection, or stratocumulus and fair-weather cumulus as boundary layer cloud systems. Hence the strategy of ACPC will be to focus its effort on those specific regimes that are both thought to be sensitive to aerosol perturbation and whose climatic importance can be established. Two candidate regimes include deep convective systems over land, and fair-weather or trade wind clouds over the ocean. Both present opportunities for deeper interactions with GCSS and are discussed further in Section VI.

b. Statistical characterizations of aerosol-cloud-precipitation interactions

The second element of the strategy emphasizes the development of robust statistical relationships. The challenge of the coming phase of research on the aerosol-cloud-precipitation system is to move beyond anecdotes and isolated examples. To do so, studies must consider extended ranges in space and/or time, such as remote sensing studies at basin scales and long-term measurements at potentially sensitive locations worldwide. Statistical relationships are most likely to arise from large samples in homogeneous conditions, thus favoring observational regions that maximize the observational area while minimizing the heterogeneity in both the underlying surface and the expected composition of the aerosol.

Among monsoon and tropical regions, the Amazon Basin and Equatorial Africa satisfy this constraint best, both because of more homogeneous land-surface features, but also because of the perception that they are more locally forced, *i.e.*, large-scale factors associated with the reorganization of monsoonal circulations are still poorly understood.

Also, past experience suggests that it is important to first evaluate the likelihood of observations being able to test a particular statistical hypothesis. Such an evaluation is critical to both the framing of the hypotheses and the design of the observational network intended to test them. Hence initial work incorporating simulation studies of cases from past and ongoing field work should focus on such an evaluation. Preparatory work of this type may usefully be performed in the context of the GCSS working group activities.

c. Development of approaches that leverage past and ongoing activities

The importance of leveraging past and ongoing work is essential to both the observational and the simulation components of the ACPC program. In terms of simulations, GCSS has a rich history of using observations to evaluate models and, in cases where existing observations have been insufficient, designing entire field campaigns (for instance the phase two of the Dynamics and Chemistry of Marine Stratocumulus, DYCOMS-II, and Rain in Cumulus over the Ocean, RICO) centered on specific questions that emerged from modeling.

In terms of ongoing and past field work, AMMA2006 provides an exemplary opportunity to explore how enhancements to the observational network better constrain the understanding of tropical clouds. Likewise, AMY2008-2012 provides new chances to test components of an emerging experimental strategy, and perhaps, through modest augmentation of the already planned resource deployment, begin developing the basis for better exploring the effects of the aerosol on deep convection in the context of the Asian Monsoon. Apart from the deployment of additional instruments during the Asian Monsoon Year (AMY) AMY2008-2012, one idea that addresses many aspects of the above is to use GCSS to develop case studies from the AMMA2006 or AMY2008-2012 field data, with an eye toward better framing the issues for a possible future Amazon field study.

d. Thorough integration of modeling and observational activities

The integration of models and measurements also places growing demands on the models. The physics of current models, particularly general circulation models (GCM), inadequately (if at all) represents relevant processes for aerosol effects on clouds and precipitation. Traditionally, cloud microphysical processes are only included in GCM parameterizations of stratiform clouds but not convective clouds. Also, most GCMs only allow one convective cloud type per grid cell instead of the whole spectrum of convective clouds.

Options to be exploited include the development and implementation of different (more physically based) representations of parameterized convective clouds, for which the multi-scale model framework, and global (or very large-scale) cloud resolving models are examples. This approach of increasingly moving towards resolved representation of convection to explore the potential effects of the aerosol offers synergy with operational weather forecast centers, which are increasingly turning to high-resolution cloud-resolving weather prediction systems. The emphasis on AMMA2006 by the Cascade project provides an exciting example of how numerical weather prediction tools may be used to explore issues pertaining to aerosol, clouds, and precipitation in the context of very large-scale cloud resolving modeling studies. Alternatively one hopes that, as our understanding develops, simple regime based rules may be developed in ways that are appropriate for yet larger-scale studies in which cloud effects must be parameterized, as only these provide a basis for evaluating how local changes are mediated by yet larger-scale circulations.

e. Hierarchical approach to both modeling and data collection/analysis

Finally, the development of a systematically multi-tiered, or hierarchical approach is of paramount importance. In terms of the modeling, this involves the careful design of test cases that link the full range of relevant models: (1) detailed physico-chemical models of aerosol-cloud processes; (2) microphysical models of the precipitation formation process; (3) fine-scale models that explore cloud and boundary layer-scale interactions associated with the effects of a changing aerosol on cloud radiative or microphysical properties; (4) cloud-system resolving models that can explore the effects of aerosol mediated changes on the radiative forcings and/or precipitation on the scale of cloud systems; and (5) regional or global scale models capable of both feeling the global constraints that may restrict the effects of perturbations seen on smaller scales, and extending the effects of such perturbations remotely (through teleconnections).

In terms of observations, a multi-tiered approach means that the observational strategy must be refined through the exploration of existing data sets, particularly from a whole range of satellite sensors and consolidated meteorological data sets (*e.g.*, AMMA2006), strategic partnerships in ongoing or planned experiments (*e.g.*, the Joint Aerosol Monsoon Experiment (JAMEX)/AMY, also the Year of Tropical Convection), and the development of sustained baseline measurements in an area targeted for more intensive study. Additionally, periods of more intensive study should be repeated in two or more seasons and in ways that afford the best opportunity to extrapolate local findings to regional and even global scales, using the current generation of earth observing satellites.

In this context, advanced data assimilation techniques are essential; one possibility in this regard would be to initiate closer links with the European Center for Medium Range Weather Forecasting (ECMWF), whose state-of-the-art data assimilation system is essential to integrated assessment activities spanning a wide range of scales. Climate groups are also increasingly moving toward the development of data assimilation systems for use in climate studies, for instance by constraining initial forecast errors.

f. Development of measurement and modeling capacity

Many key quantities remain inadequately measured, and key processes remain inadequately modeled, particularly for questions pertaining to clouds. For example, in-cloud thermodynamic properties (such as temperature and absolute humidity) prove difficult to measure with sufficient accuracy and sampling density to constrain the cloud buoyancy. The droplet spectrum is in many respects poorly quantified, particularly on small spatial scales, and at drop sizes near the coalescence threshold (between 20 and 40 microns in diameter). Vertical velocities, particularly on scales and of amplitudes necessary to characterize the ambient environment (*i.e.*, on meso and larger scales), are also not measurable using available instrumentation. For most of these quantities, however, instruments have been proposed, or are being developed, which could address deficiencies in existing instrumentation. Similar advances are needed for aerosol physical and chemical characterization. Thus it is critical that a program such as ACPC supports efforts aimed at advancing our capacity to make measurements. Similarly, efforts to develop models that reflect our process understanding with numerical and physical fidelity should be emphasized, especially those types of models capable of bridging gaps between processes.

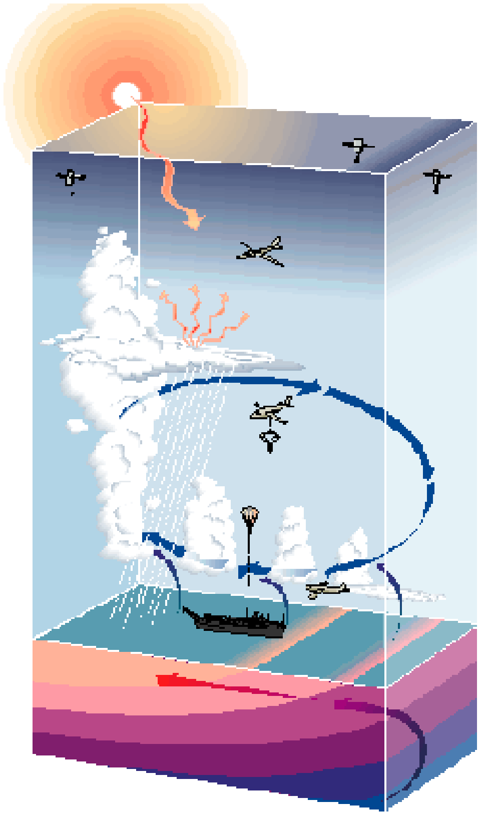
2. Examples of (contrasting) measurement strategies for focused field studies

a. Local closure studies

Global circulation models explicitly represent the balance between sources within, and fluxes of mass, matter, momentum and energy across control volumes (or grid cells). Aerosol radiative and microphysical processes emerge as source terms in these balance equations; for instance, by modifying the precipitation efficiency, the aerosol acts as a source or sink of rainwater; likewise the aerosol can act as a source of energy by absorbing photons. Therefore, a powerful way to validate our physical understanding as expressed by models is with a closure experiment that is localized in both time and space, and in which all fluxes are measured to an accuracy that is better than the hypothesized impacts of the aerosol source term on these budgets of matter and energy. These types of studies are commonplace and have been used for the last half century to study clouds and convective processes. What we propose is to fully incorporate aerosol processes in such studies.

Hence, in addition to the constraints that normally govern such studies (*i.e.*, relative homogeneity, and preferentially a reasonable scale separation between adiabatic and diabatic processes) the area for such a study should be one in which large variation of the aerosol occurs for the same externally forced meteorological conditions. The Amazon, with and without smoke from vegetation fires, in the same region and season, is a good example of such a region. It would provide a natural laboratory for studies of aerosol effects on deep convection, corresponding to the first regime discussed in Section VI.

Critically important to the success of local closure studies is the ability to detect the trace of the aerosol signal amidst the noise of the background meteorology. Hence, the measurement requirements must be specified through exploratory modeling studies that can help frame the questions. For example, non-hydrostatic weather forecast models run at cloud resolving scales, such as are routinely used by a number of weather services, could be used to explore the interplay between boundary forcings, aerosol loading, and the convective response. How well do boundary forcings need to be determined to constrain the convective response for different levels of aerosol loading? How many realizations are necessary to reduce sampling uncertainty? What flight strategies are optimal for sampling the simulated fields? How should instruments be best deployed to attain closure? What is the trade off between dense, but noisy measurements versus highly accurate but sparse data?



An illustration of a measurement network for a budget closure experiment. Components of the system include satellites, airplanes, radiosondes, radars, lidars, and surface measurements.

The various components of the budget (balance) equations for matter, momentum and energy require a diversity of measurements. Measurements of the air motions and its properties can be performed with balloons, lidar and profiler soundings, satellite profiles and motion vectors, scanning radars, and networks of surface stations. The latter can also measure the surface energy fluxes. Radiative fluxes to space are best measured by satellites. Precipitation is a major component of the water and energy budget, and is best measured with a polarimetric radar network supported by rain gauges. Aerosol particles and their precursors can be measured with surface and airborne aerosol spectrometers and chemical analyzers. The CCN supersaturation activation spectra and IN activity are essential properties of the aerosol that have to be measured. This has to be done with CCN and

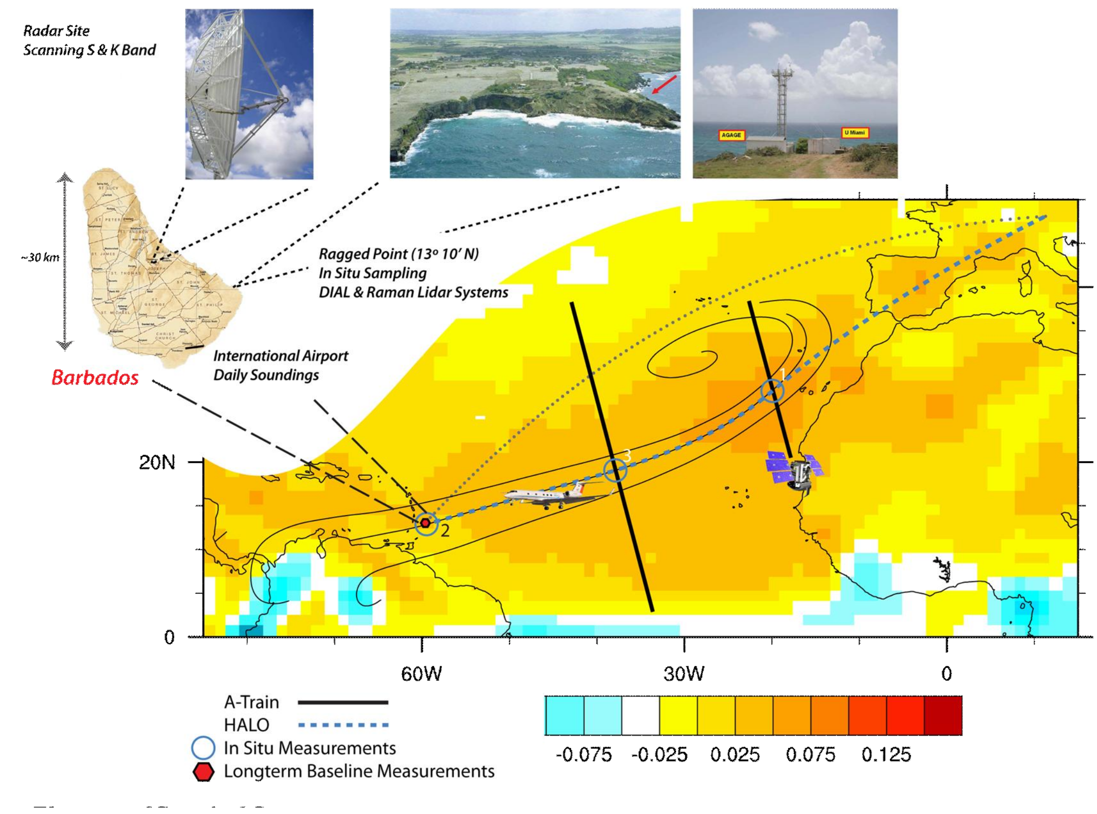
IN counters both on the ground and on aircraft measuring vertical profiles. The aerosol optical properties such as spectral extinction and absorption also need to be determined, perhaps through a combination of *in situ* and remote sensing techniques.

Finally, a clear documentation of the relationship between the large-scale, or adiabatic, forcings (as given by the large-scale flow and the ambient state of the aerosol) and the diabatic response of the system (*i.e.*, how convection behaves) will not be sufficient to constrain our ideas. It will also be necessary to establish that the processes that contribute to the net diabatic response of the system are well encapsulated by our theory and models. Hence such studies define a framework, but must be complemented by measurements that constrain specific processes. For example vertical profiles of cloud microstructure in growing convective clouds under different aerosol and thermodynamic conditions are required as a basis for assessing the balance of cloud microphysical processes.

b. Statistical closure studies

A complementary approach to the intensive local closure studies would be the use of extensive (in time) statistical closure studies. Here long-term measurements would in effect trade comprehensiveness and intensity for more realizations, with the implicit idea that closure can be obtained by averaging over independent samples. Such a strategy may be most effective in situations where aerosol perturbations are more subtle, and difficult to separate from the meteorology. Such approaches are also likely to be most practical for cloud regimes that do not embody very large scales, for instance marine stratocumulus and trade cumulus cloud regimes. The US Department of Energy has long maintained a network of sites, under the auspices of their Atmospheric Radiation Measurement (ARM) program, that attempt to implement a variant of this strategy to explore the interaction of clouds and radiation. In essence our suggestion would be to augment this successful strategy with measurements designed to better identify the possible role of the aerosol on radiation, clouds and precipitation, and to make such measurements in cloud regimes where one expects to find a signal.

Hence, for the questions ACPC is interested in, suites of measurements attempting to provide statistical closure must include vertically resolved measurements of clouds and cloud properties, the aerosol, and relevant meteorological parameters, such as the relative humidity. For instance, measurements from scanning cloud and precipitation radars, complemented by near surface measurements of CCN and remotely sensed aerosol properties throughout the vertical column, would in combination with standard measurements of radiative fluxes, temperature and humidity profiles, and vertical profiles of cloud properties, provide an excellent basis for exploring the statistical relationship between cloud amount and ambient large-scale conditions. Given sufficient data of this type one should be able to statistically separate the effects of the aerosol on clouds and precipitation from those of meteorology. Again, modeling studies can be useful to help evaluate how many samples should be sufficient, given that the aerosol loading may prove difficult to completely separate from the meteorological forcing.



An illustration of a measurement network for a statistical closure experiment. The system is based around limited, but long-term, measurements at one or more points at some location, which well samples an important cloud regime. In addition to the choice of site and suite of instruments, important features include the ability to integrate the chosen measurements into the larger-scale context, here shown by aircraft measurements that are coordinated with satellite overpasses in the upstream flow.

Such a strategy would also be usefully complemented by process studies that explore the extent to which the *in situ* structure of clouds is consistent with what is being interpreted based on less comprehensive measurements. These studies could be conducted in bursts through the lifetime of the measurement site, as has been done successfully in the ARM program. Additionally, sampling should be designed to facilitate the integration of local point measurements with the satellite record. Periods of more intensive study should be used to explore the extent to which relationships developed for a small number of points are more broadly representative of the cloud regime being studied. A critical component of such a study is its endurance, as meaningful relationships are likely to emerge only after long periods of sampling, as even in relative homogeneous weather regimes clouds can respond profoundly to subtle meteorological changes.

VIII. IMPLEMENTATION PLAN

The scientific issues and impetus for the Implementation Strategy for the Aerosol, Cloud, Precipitation, Climate Program are outlined and discussed in detail in the previous sections. More programmatic issues are discussed below.

1. Objectives

The ACPC program aims to bring together a variety of communities for large observational, modeling, and theoretical efforts to understand the interplay amongst clouds, aerosol, and precipitation within a comprehensive and integrated research program. In particular, this program aims to:

- act as a forum for bringing together the diverse expertise necessary to advance our understanding;
- ensure that experimental strategies address regimes where the meteorology is sufficiently constant, and aerosol variability occurs over a sufficiently wide range, so as to assist in the separation of meteorological from aerosol drivers;
- coordinate and synthesize the findings of various components of the program;
- help coordinate international efforts;
- provide continuity and perspective for research initiatives.

2. Research guidelines

The strategy to make progress in understanding physical relationships among aerosol, clouds and precipitation centers on a coordinated international effort encompassing a strategy that embodies the following elements:

- ***isolation*** of, and focus on systems where there are strong indications of aerosol-cloud-precipitation interactions;
- emphasis on ***statistical*** characterizations of aerosol-cloud-precipitation interactions;
- development of approaches that ***leverage*** past and ongoing activities;
- thorough ***integration*** of modeling and observational activities;
- ***hierarchical*** approach to both modeling and data collection/analysis;
- continued development of measurement techniques and modeling ***capacity***.

The scientific issues are addressed in terms of regimes: monsoon convective systems, tropical cyclones, deep convection over land, maritime deep convection, marine stratocumulus clouds, trade wind shallow (warm) cumulus clouds, orographic clouds, and shallow mixed phase clouds, etc.

3. Project management

The ACPC Steering Committee (SC) comprises representatives from three international research organizations: 3 members from iLEAPS, 3 members from IGAC, and 4 members from GEWEX. The SC is lead by one chair or two co-chairs. The respective organizations' scientific steering committees each nominate their representatives for the ACPC SC, and are also responsible for the rotation of members. Members serve for three years with an option for a second three-year term. The chairs are selected by the ACPC SC in collaboration with the steering committees of the three parent organizations, iLEAPS, IGAC and GEWEX. The co-chairs should represent different organizations. The major tasks of the SC are to: (i) provide scientific guidance and oversee project development, planning and implementation; (ii) promote ACPC within the various scientific communities, including by appropriate acknowledgement of ACPC and the organizations, iLEAPS, IGAC and GEWEX in publications; (iii) demonstrate progress and achievements by defining and monitoring milestones and results; (iv) expose ACPC goals to national, regional and international funding agencies and encourage them to support ACPC research.

The coordination of ACPC activities is done by Coordinator/s responsible for: (i) assisting in planning and implementation of research, database management, data synthesis, and training activities (training courses, summer and winter schools); (ii) actively promoting communication within the ACPC community and between ACPC and other communities; (iii) assisting the SC in assembling and synthesizing ACPC research.

4. Activities

ACPC will initiate and promote ACPC research activities including long-term, integrated field studies, field campaigns, model development, synthesis studies, conferences and workshops. The parent organizations (iLEAPS, IGAC and GEWEX) will provide leadership, political, and financial support (to the extent possible) for workshops and conferences.

ACPC initiates projects with clearly defined goals and (when appropriate) a limited lifetime, including: (i) encouragement of process studies to elucidate specific scientific questions; (ii) field campaigns; (iii) modeling (tool development, validations and intercomparisons); (iv) long-term integrated field studies; (v) large international interdisciplinary campaigns; (vi) synthesis studies; (vii) databases; and (viii) conferences addressing specific scientific questions; and (ix) synthesis meetings. To the extent possible, ACPC will encourage field studies as a basis for integrating other elements of the strategy, with the idea of defining initiatives for field studies that target specific regimes (for instance those that we outline in Section VI) in an enduring and coordinated way. Initially this will be accomplished through the organization of topical meetings that leverage existing proposals with the aim of exploring how these proposals can be refined so as to better address the scientific goals, and incorporate the strategic elements, of the ACPC initiative.

5. Capacity building and knowledge transfer

Capacity building and knowledge transfer are essential components of IGBP, iLEAPS, IGAC and GEWEX, and therefore also of ACPC. Both interdisciplinary training and capacity building via student outreach are important to ACPC. The research projects within ACPC are essentially interdisciplinary, and integrate both measurements and modeling. The training activities will take the form of summer and winter schools and intensive training courses. Scientists involved in ACPC are encouraged to contribute to, and lecture in, such training activities. Additionally, ACPC recognizes the profound social importance of many of the issues it addresses. Through the organization of expert workshops and other forums, ACPC would help to organize linkages between the broader policy community and the disciplinary experts on this important subject.

All IGBP/WCRP research is essentially capacity building, and this is particularly important in regional integrated studies and long-term observation and research projects. Previously, the majority of research has been conducted in developed countries where amenities are easily accessible. There is however, a growing need for regional studies in developing countries, where many ACPC initiatives are expected to be concentrated (*e.g.*, Brazil, India, Barbados), and particularly where land-use changes are extensive. In order to continue long-term studies in these regions it is crucial to build local capacity. This can be achieved through post-graduate students, student exchange, in-region or on-site courses and training.

IX. Background Reading

Andreae, M. O. and D. Rosenfeld, 2008. Aerosol-cloud-precipitation interactions. Part 1. The nature and sources of cloud-active aerosols. *Earth Science Reviews,* 89, 13-41. This review article provides a comprehensive review of the nature and sources of cloud condensation and ice nuclei. It presents “fundamentals of the cloud droplet and ice nucleation process and the role chemical composition and particle size plays in this process.” It provides a contemporary starting point for scholars interested in the basics of cloud aerosol interactions.

Denman, K. L., G. Brasseur, A. Chidthaisong, P. Ciais, P. M. Cox, R. E. Dickinson, D. Hauglustaine, C. Heinze, E. Holland, D. Jacob, U. Lohmann, S. Ramachandran, P. L. da Silva Dias, S. C. Wofsy and X. Zhang, 2007. Couplings Between Changes in the Climate System and Biogeochemistry. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. This chapter of the Fourth Assessment Report of the IPCC provides a summary of the current state of our understanding of aerosol, cloud (and to a lesser extent precipitation) interactions and their importance for climate. This, along with the review by Lohmann and Feichter (see below) provides a good starting point into the literature on global assessments of aerosol effects on clouds and climate.

Heintzenberg, J. and R. J. Charlson (Eds), 2007. *Clouds in the Perturbed Climate System: Their Relationship to Energy Balance, Atmospheric Dynamics, and Precipitation*, MIT Press, 576p. This edited volume contains 24 chapters of contributions from over fifty world-renowned experts on aerosols, clouds, precipitation and climate. It provides an excellent overview of many of the issues involved; the different strategies used to address them; the history of efforts to understand cloud-aerosol interactions, from the early days of weather modification to the present. The cloud regime based study of the issues advocated in the present study is also adopted within the structure of this book, with different chapters focusing on different cloud regimes, among other issues.

Levin, Z. and W. R. Cotton (Eds), 2008. *Aerosol Pollution Impacts on Precipitation*, Springer, 386p. This edited volume contains ten chapters that "review our knowledge of the relationship between aerosols and precipitation reaching the Earth's surface and it includes a list of recommendations that could help advance our knowledge in this area." Originally commissioned by the World Meteorological Organization and the International Union on Geodesy and Geophysics, the chapters are compiled by 27 world experts, and the book is particularly oriented toward a key question being posed by ACPC, namely the effects of aerosol on precipitation.

Lohmann, U. and J. Feichter, 2005. Global Indirect Aerosol Effects: A Review, *Atmos. Chem. Phys.*, 5, 715-737. This comprehensive survey of global modeling and observational efforts to assess the net effects of the aerosol on clouds and radiation gives an up to date view of the status of attempts to understand the effects of the aerosol on clouds in the global energy budget. Many of the difficulties, deficiencies and uncertainties inherent in large-scale model studies are well encapsulated by this paper.

Rosenfeld, D., U. Lohmann, G. B. Raga, C. D. O'Dowd, M. Kulmala, S. Fuzzi, A. Reissell and M.O. Andreae, 2008. Flood or Drought: How do Aerosols Affect Precipitation? *Science*, 321, 1309-1313. This review article by many members of the ACPC team emphasizes recent work arguing the important role that the aerosol may play in regulating precipitation, as well as the regime dependent response of precipitation to the changing aerosol.

Stevens, B., 2005. Atmospheric Moist Convection, *Ann. Rev. of Earth Planet. Sci*. 32, 605-643. This review article provides an introduction into some of the basic ideas associated with moist atmospheric convection; it focuses on tropical maritime convection and provides an introduction to much of the broader literature on the topic.

Stevens, B. and G. Feingold, 2009. Untangling aerosol effects on clouds and precipitation in a buffered system. *Nature*, 461 (7264) 607-613. doi:10.1038/nature08281. This review article proposes that past difficulties in untangling relationships between the aerosol, clouds and precipitation reflect in part a failure to take into account the many processes that act to buffer cloud and precipitation responses to aerosol perturbations. In particular, the article identifies that research needs to focus on understanding specific regimes of aerosol, cloud and precipitation.

Aerosol, Clouds Precipitation and Climate, 2008. iLEAPS Newsletter Issue No 5, available at http://www.ileaps.org/. This document was a starting point for many elements of this plan. The

newsletter includes articles from a number of experts who participated in the initial Boulder planning meeting of the ACPC initiative and helped set the structure of the present document.

Appendix

Acronyms (that appear more than once in the text)

ACPC	Aerosols, Clouds, Precipitation, Climate program
AEW	African easterly waves
AMMA	African Monsoon Multidisciplinary Analyses
AMY	Asian Monsoon Year
AOD	Aerosol optical depth
ARM	Atmospheric Radiation Measurement program
CCN	Cloud condensation nuclei
GCM	General circulation model
GCSS	GEWEX Cloud System Study
GEWEX	Global Energy and Water Cycle Experiment
IGAC	International Global Atmospheric Chemistry project
IGBP	International Geosphere–Biosphere Programme
iLEAPS	Integrated Land Ecosystem–Atmosphere Processes Study
IN	Ice nuclei
ITCZ	Inter-Tropical Convergence Zone
MODIS	Moderate Resolution Imaging Spectroradiometer
NASA	National Aeronautics and Space Administration (USA)
PE	Precipitation efficiency
SOLAS	Surface Ocean–Lower Atmosphere Study
WCRP	World Climate Research Programme