

# RICO

## Rain In Cumulus over the Ocean Experiment

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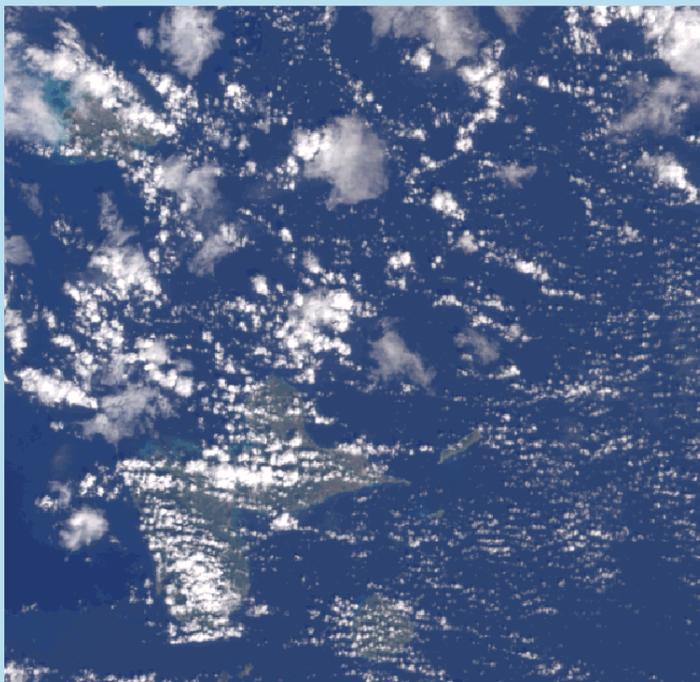
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Shallow Precipitating  
Caribbean Cumulus Cloud



MISR Image of Antigua  
and Guadeloupe

**Rain in Cumulus over the Ocean (RICO)**  
**Scientific Overview Document**  
*<http://rico.atmos.uiuc.edu/>*

**Executive Summary**

Shallow, maritime, cumulus convection is one of the most prevalent cloud types on the planet. Trade wind cumuli typically extend to no greater than 4 km altitude, the height of the tropical trade wind inversion, and are dominated by warm rain processes. They are ubiquitous over much of the tropical oceans, and characterizing their properties is important to understanding the global energy balance and climate. Because of the disparity in the range of scales from the microphysical/cloud scale (microns to a kilometer), to the cloud-interaction scale (kilometers to tens of kilometers), to the ensemble cloud field scale (tens of kilometers or more), past work has tended to focus on processes occurring on only one of these three scales – often neglecting the important interactions that occur across scales. The objective of RICO in the broadest sense is to characterize and understand the properties of trade wind cumulus at all scales, with particular emphasis on determining the importance of precipitation. At the smallest scale, the most fundamental problem – recognized for over a half century – is explaining the rapid onset of precipitation in shallow tropical clouds. At the intermediate scale, processes controlling the mesoscale structure and coverage of shallow tropical cloud systems are not well understood. At the largest scale, our inability to describe the statistical behavior of trade wind cloud fields confounds our attempts to properly represent the exchange of radiant energy, moist enthalpy, momentum and trace constituents between the atmosphere and ocean over vast expanses of the planet. These scales are inextricably linked and the nature of these linkages is an important aspect of RICO.

RICO will focus on the following interrelated scientific issues:

*a. The Microphysical/Cloud Scale*

*Research on spectral broadening and the initiation of precipitation in trade wind cumulus:* The microphysical mechanisms directly responsible for spectral broadening and the rapid onset of precipitation remain mired in controversy. A goal of RICO is to obtain the critical observations that, when analyzed in conjunction with numerical modeling experiments, will provide the key evidence required to confirm or refute hypotheses related to precipitation initiation. The RICO scientific objectives in this area focus on 1) the ultragravit nuclei hypothesis;

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Cover cloud photograph courtesy of Charles Knight and the National Center for Atmospheric Research.

Cover satellite image from the NASA EOS-Terra Multi-angle Imaging SpectroRadiometer (MISR) on January 26, 2003, over Antigua and Guadeloupe in the Lesser Antilles. Courtesy of Guangyu Zhao and Larry Di Girolamo, Department of Atmospheric Sciences, University of Illinois at Urbana-Champaign.

2) the effects of turbulence on spectral broadening and precipitation initiation; 3) the effects of entrainment on spectral broadening; 4) the effects of pre-existing clouds and cloud processing on precipitation initiation. The measurement of aerosol, particularly CCN, is essential to the evaluation of all hypotheses explaining the onset of precipitation.

*Research on the microphysics of the transition to a mature rainshaft:* It is unknown whether the processes responsible for the onset of precipitation are also important for the continued production of precipitation in trade wind cumulus. An objective of RICO is to understand the microphysical processes that are important as clouds undergo and complete the transition to a mature rainshaft.

*b. The cloud-interaction scale*

*Research on the mesoscale organization of trade wind clouds:* The mechanisms by which convection organizes in the trade wind environment are poorly understood. An objective of RICO is to understand the cloud and boundary layer processes that lead to the development and organization of convective structures in the trades. In particular, it is important to understand how dynamic and thermodynamic processes within and near precipitation-generated cold pools influence the organization and evolution of tropical cumulus.

*c. The ensemble cloud field scale*

*Research on the water budget of trade wind cumulus:* Although shallow cumulus cover vast expanses of the world's oceans, very little is known about how much they precipitate and how precipitation affects their statistical properties. One objective of RICO will be to estimate the water budget of trade wind cumulus using modern radar and satellite remote sensing, calibrated with in situ data. These estimates will be compared to inferences from thermodynamic budgets.

*Research on the large-scale trade wind cloud environment:* An objective of RICO will be to augment precipitation estimates with detailed characterizations of the large-scale environment, clouds, and their microphysical and aerosol properties. These data will be used to test hypotheses regarding scaling laws (e.g., for cloudiness, cloud base mass flux, entrainment and detrainment rates, cloud-environment differences, and momentum transport) for trade wind cumulus derived from recent large-eddy simulations (LES). They will also provide a basis for the next generation of LES studies that will strive to understand the dependence of trade-cumulus on microphysical and radiative processes, both affected by the properties of the environmental aerosol. The coupling of simulation/theoretical studies with field data across a range of scales will provide a basis for representing shallow convection in large-scale climate and weather forecast models.

*d. Related research studies*

RICO will involve a number of additional studies. These include research on 1) the age of cloud parcels, 2) the chemistry and origin of aerosols, 3) radar remote-sensing, 4) developing a satellite cloud climatology, and 5) studies of the effects of clouds on radiation.

RICO will integrate research and education through the creation of the “RICO Graduate Seminar Series” (RGSS), which will be offered during the last three weeks of the field campaign. The RGSS will include nine to fifteen lectures by RICO science team members and other field related activities. In this way, RICO will provide unique field research experiences to graduate students. RICO is scheduled for the winter of 2004-05 on an island in the Lesser Antilles. The specific site will be chosen to insure that opportunities to sample oceanic trade wind cumulus will occur on most days. Two islands currently under primary consideration are Antigua and Guadeloupe. Other possible islands include Martinique and Barbados. All of these islands appear to have suitable exposure to the easterly trades. A final decision on a site will be based on site surveys and operational considerations. Participants in this project include investigators from a large number of universities and agencies in the United States, the National Center for Atmospheric Research, and several international universities and agencies (Table 2). The field research will be tightly coupled with numerical modeling studies. Developments in instrumentation (see Table 3), analysis techniques and numerical models now provide new opportunities to advance our scientific understanding of trade wind cumulus.

## 1. INTRODUCTION

Trade wind cumuli in large eddy simulations (LES) and global climate models are normally assumed to be non-precipitating. However, radar observations of these clouds clearly show that they often precipitate. How could this conflict remain unresolved for so long? How soon do radar echoes form in shallow cumulus and what is their source? Why and how often do shallow cumulus precipitate? How critical is this to the dynamics of individual clouds on the one hand, and the cloud ensemble on the other? Through dynamic processes, precipitation clearly can be important to the organization and regeneration of cloud fields. For this reason, precipitation from trade wind cumulus can significantly impact radiation budgets and moisture and heat fluxes within the tropical atmosphere. The assessment of these impacts depends on our understanding of precipitation processes.

At the smallest scale, the most fundamental problem – recognized for over a half century – is explaining the rapid onset of precipitation in shallow tropical clouds. Several hypotheses have been proposed, including growth on ultragiant sea-salt particles, turbulent enhancement of microphysical growth mechanisms, and entrainment-induced spectral broadening. Although advances in our understanding have been made as the result of field studies such as the Small Cumulus Microphysics Experiment in 1995, none of these hypotheses have been convincingly verified. New technologies (including aircraft probes capable of measuring the full spectrum of particles and properties of turbulence, and remote sensors such as the dual wavelength-dual polarization SPOL radar, the Wyoming cloud radar, and the SABL lidar) provide an unprecedented opportunity to address these hypotheses and other important questions regarding trade wind cloud microphysics. These questions include: 1) What are the microphysical processes that are important as clouds undergo and complete the transition from the “onset stage” of precipitation to the development of a mature rainshaft? 2) How do cumulus modify their aerosol and thermodynamic environment and what impact do these modifications have on individual cloud’s microphysical processes? 3) What are the size distribution, spatial variability and composition of aerosol in the trade wind environment and how does the aerosol impact the microphysics of trade wind cumuli?

On the next larger scale, processes controlling the mesoscale structure and coverage of shallow tropical cloud systems are not well understood. Shallow precipitating cumulus clouds often occur in mesoscale rings, developing around an earlier convective cloud. There are at least three hypotheses to explain how these convective structures develop and evolve in tropical regions: one emphasizing thermodynamic processes within precipitation-generated cold pools, another highlighting the boundary layer dynamical processes at the outflow boundaries of these cold pools, and a third focusing on gravity wave processes within stable air above the convective boundary layer. These three processes would result in cumulus development in different locations relative to the outflow boundary. The resulting clouds would be organized in different mesoscale configurations, have updraft airmasses from different source regions, and may therefore have different microphysical characteristics. Key unresolved scientific questions include: 1) How is the boundary layer locally altered by evaporation of precipitation and by convective downdrafts? 2) What role does a cold pool from past convection play in triggering new convection in the trade wind cumulus regime? 3) What other factors may determine the triggering mechanism for convective cells?

At the largest scale, the effect of precipitation in trade wind clouds is neglected in almost all large-eddy simulations and most simple theoretical models or parameterizations of shallow convection. It is imperative that these models be evaluated and verified using detailed measurements because they are the key link in our attempts to determine the exchange of radiant energy, moist enthalpy, momentum, and trace constituents between the atmosphere and ocean over vast expanses of the planet. By taking advantage of advances in active remote sensing and dropsonde technology, and the microphysical measurements which will be the focus of the small-scale part of this study, RICO will enable investigators to address key questions such as: 1) How important is precipitation in the water budget of the trade wind region? 2) What is the nature and variability of the ensemble statistics of fields of trade-wind cumuli? 3) How sensitive are the key attributes and processes of trade wind cumuli, such as cloud fraction, cloud-base mass flux, momentum mixing, etc. to the large-scale environment on the one hand, and to the representation of precipitation on the other? 4) How sensitive is the behavior of trade wind cumuli (through either radiative or microphysical processes) to changes in the aerosol environment? 5) What is the diurnal evolution of trade wind clouds and precipitation and what factors control it?

An island in the Lesser Antilles that has good exposure to the easterly trades and has no upstream islands is the prime candidate for the operation center for RICO. Two islands currently under primary consideration are Antigua and Guadeloupe. Other possible islands include Martinique and Barbados. All of these islands appear to have suitable exposure to the easterly trades. A final decision on a site will be based on site surveys and operational considerations. In preparation for RICO, the Principal Investigators have examined several years of GOES data and the wind climatology for the region. The December-January time frame is ideally suited because trade wind clouds are ubiquitous, present nearly every day, and heating and orographic lifting by the islands seldom triggers deep convection. Furthermore, deep convection is rarely present over the ocean during the early winter months.

RICO addresses a large number of scientific objectives that involve spatial and temporal scales ranging from the microscale to the cloud-ensemble scale. In this document, it is impossible to provide an in-depth review of each of the scientific issues to be addressed in RICO, and still maintain a reasonable length. This document therefore provides a scientific *overview* of RICO. Our approach here is to provide a succinct summarization of each of the key scientific issues and hypotheses that will be addressed in RICO. Detailed reviews of these issues and justifications of specific scientific objectives will be left to the individual scientific proposals from RICO participants.

## 2. SCIENTIFIC QUESTIONS AND HYPOTHESES

### A. The Production of Rain in Trade Wind Cumulus

#### 1. Spectral broadening and precipitation initiation

One of the major unresolved scientific issues in cloud physics is the explanation of the observed short time between initial cloud formation and the onset of precipitation in warm ( $> 0^{\circ}\text{C}$ ) clouds. The growth processes must account for growth from condensation nuclei to raindrops in about 15-20 minutes. Although diffusional growth theory can adequately explain the early stages of cloud droplet development with narrow size distributions, it cannot account for the observed broadening with time of the drop size distribution. Several hypotheses have been developed to explain this broadening, a requirement for the onset of significant collision-coalescence. One hypothesis is that large cloud droplets form on giant and ultragiant nuclei and then grow by accretion (Houghton 1938, Woodcock 1952, 1953, Johnson 1976, Ochs and Semonin 1979, Johnson 1982). Other hypotheses invoke turbulent effects to explain spectral broadening. These hypotheses involve a) stochastic condensation, the mixing of droplets that have different supersaturation histories (Cooper et al. 1986, Politovich and Cooper 1988, Cooper 1989, Srivastava 1989), b) fluctuations in supersaturation and droplet collision rates caused by droplet clustering induced by turbulence (Shaw et al. 1998; Vaillancourt and Yau 2000; Brenguier and Chaumat 2001, Shaw 2003), c) increases in the collision efficiency due to inertia of droplets moving within a turbulent flow (Khain and Pinsky 1995; 1997; Jonas 1996; Koziol and Leighton 1996; Pinsky and Khain 1996; Vohl et al. 1999, Pinsky et al 1999a; 2000), and d) in-cloud droplet nucleation caused by fluctuations of supersaturation in accelerating updrafts (e.g. Pinsky and Khain 2002). Entrainment and mixing of air parcels has also been invoked as a mechanism for spectral broadening (e.g. Ludlam and Saunders 1956, Latham and Reed 1977, Baker and Latham 1979, Telford et al. 1984). Finally, processing and recirculation of droplets by preexisting clouds may contribute to precipitation initiation (Rauber et al. 1991, Kogan 1993). *One goal of RICO is to obtain the critical observations that, when analyzed in conjunction with numerical modeling experiments, will provide the key evidence required to confirm or refute these hypotheses.*

#### a. Determining the importance of ultragiant nuclei in trade wind cumulus

The simplest mechanism to explain the onset of precipitation in warm clouds is that giant (dry radius  $r > 1 \mu\text{m}$ ) and ultragiant ( $r > 10 \mu\text{m}$ ) nuclei are the embryos for raindrops (Woodcock and Gifford 1949, Woodcock 1953, Ochs and Semonin 1979, Johnson 1982, 1993, French et al. 2000, Laird et al. 2000, Illingworth 1988, Knight et al. 2001, Tzivion et al. 1994, Reisin et al. 1996a,b,c, Yin et al. 2000a,b, Lasher-Trapp et al. 2001). Trajectory calculations suggest that ultragiant nuclei can lead to the development of large raindrops in 15-20 minutes (Johnson 1982, Szumowski et al. 1999, Lasher-Trapp et al. 2001). However, it is unknown whether there are enough of these nuclei to explain the initiation of actual rainfall in trade wind cumulus. Furthermore, several modeling studies have suggested that the importance of UGN for precipitation formation is diminished in clouds with very low CCN concentrations, as might be expected over the open ocean (Ochs and Semonin 1978, Johnson 1982, Tzivion et al. 1994, Feingold et al. 1999, Rosenfeld et al. 2002). These model calculations have not been verified. In

addition, there is considerable uncertainty about the range of CCN and UGN concentrations over the eastern Atlantic Ocean. This uncertainty exists because of the possible intermittent influence of Saharan dust on the aerosol concentrations (Haywood et al. 2001). Levin et al. (1996) have shown that mineral aerosol from the Sahara become coated with soluble material (e.g. sulfates and sea salt) during transit over the Mediterranean and become CCN of sizes that can significantly affect precipitation formation in clouds. One would expect the same to occur during the longer transit over the Atlantic. Although the concentration of Saharan aerosol arriving in the Lesser Antilles peaks in the early fall, episodes of Saharan aerosol occur throughout the year (Ellis and Merrill 1995, Husar et al. 1997). We therefore expect to encounter variations in the concentration of CCN.

Accurate measurements of UGN have remained illusive because 1) instrumental sample volumes were marginal for statistically significant concentration measurements; 2) few instruments can accurately measure particle size distributions in these size ranges; 3) there have been significant questions concerning the quality of measurements (Lasher-Trapp et al. 2002a); and 4) redundant measurements rarely if ever have been available from a single field experiment. It is critical to obtain these data, along with measurements of the hydrometer population in the clouds, to initialize and verify numerical cloud model simulations, which ultimately will be required to determine the importance of UGN in precipitation from trade wind cumulus.

Measurements of aerosol particle size distributions and concentrations outside of cloud as a function of relative humidity are required throughout the sub-cloud layer. To provide reliable statistics these measurements require long flight legs in clear air. Since these measurements are critical to this objective, RICO will use redundant measurements with instruments based on different measuring principles, e.g. 260X, 2DC, the SPEC 2D-S Stereo probe, the DRI cloud scope, the Tel Aviv University Big Particle Sampler, and the CSIRO Giant Aerosol Impactor system. Together, the deployed instruments provide redundancies across the size range of interest, which includes large, giant and ultragiant nuclei. In addition, CCN will be measured on the aircraft using as many as three separate instruments, the DRI continuous flow CCN spectrometer (Hudson, 1989), the Wyoming CCN counter (Delene and Deshler 2000) and the Roberts continuous flow CCN spectrometer.

Measurements of in-cloud particle size spectra are also necessary to determine the relationship between the small CCN, the large, giant and ultragiant nuclei, and the corresponding drop size distributions in clouds. Dual wavelength, dual polarization radar measurements (S-Pol with added K-Band) will also be used to record the early development of precipitation within the clouds. The evolution of  $Z$  and  $Z_{DR}$  within growing clouds, together with the particle measurements, will provide strong constraints that can be applied to the evaluation of model simulations of cloud growth and precipitation development on UGN.

The ultragiant nuclei mechanism for warm rain formation in trade wind cumulus is a very simple, deterministic mechanism, in that it posits a one-to-one correspondence between early raindrops and UGN. With new techniques to measure UGN in the cloud inflow air with aircraft instruments, measurements of the early raindrops in the clouds with both aircraft and radar, and modeling studies of the effects of UGN constrained by these observations, RICO should be able to reach a firm conclusion regarding the validity of this mechanism. Certainly if there are not

enough UGN to account for the rain, that conclusion might be very firm indeed; and if there are enough, within measurement uncertainty, then the measurements should be good enough that the verification can be almost as firm, since there is little uncertainty about calculating coalescence rates on UGN within a cloud. Therefore a rather strong result on this fundamental issue for trade wind cumulus is expected from RICO.

b. Determining effects of turbulence on spectral broadening and precipitation initiation

To what extent does turbulence affect the efficiency of the collection process (e.g., Shaw and Oncley 2001, Pinsky et al. 1999b), or the rate of condensation on favored droplets (e.g., Stepanov, 1976; Srivastava 1989; Cooper 1989), thereby broadening the droplet size spectra and accelerating the onset of precipitation? Both questions in essence depend on fine-scale inhomogeneity in the cloud microstructure, either induced locally during the activation process (i.e., through variations in cloud base vertical velocity or incipient inhomogeneity in the CCN spectra, c.f. Irons 2000) or through inertial clustering of drops in regions of fine-scale divergence. Most recent theoretical work has focused on the latter, primarily in terms of its effect on the collection process. Apart from our lingering inability to explain basic aspects of the observed cloud microstructure, a practical reason for renewed efforts to investigate the effects of turbulence is that this problem is becoming tractable for direct numerical simulation (DNS). Although DNS, and to a lesser extent laboratory measurements have shown indications that such processes could be very important (e.g., Shaw et al. 1998; Pinsky et al. 1999b; Vaillancourt et al. 2002, La Porta et al. 2002) these results remain controversial, primarily because the Reynolds numbers attainable by DNS are extraordinarily low by atmospheric standards.

Although data from past studies have been used to address these issues (e.g., Baker 1992, Chaumat and Brenguier 2001, Kostinski and Shaw 2001, Pinsky and Khain 2001, Gerber et al., 2001), new instrumentation, specifically designed with these questions in mind, presents an unprecedented opportunity to definitively address these issues during RICO (e.g., see description of recent workshop on measurements of fine scale turbulence in clouds, Shaw 2002). Particle-turbulence interactions are directly related to the turbulent kinetic energy dissipation rates, and therefore the measurement of this quantity will be an important aspect of the experiment. Standard velocity probes will allow for estimates of mean dissipation rates in a cloud; The proposed Phase Doppler Interferometer (PDI, see Table 3) will provide greater spatial resolution, allowing dissipation rates in entrainment zones to be differentiated from those in cloud cores. The PDI is currently under development and will be ready for deployment during RICO (Chuang and Shaw, personal communication 2002). The PDI allows one to simultaneously measure velocity fluctuations and fine-scale droplet clustering, both conditioned on droplet size. Combined with measurements using technologies such as the Fast FSSP, the new Meteo-France X-probe, the SPEC 2D-S probe, the Warsaw University Ultrafast Temperature Probe, and the OPHIR temperature probe, RICO should provide new insights into the extent of fine-scale structure in trade-cumulus, and its role in the initiation of precipitation. These simultaneous microphysical and turbulence measurements have great potential for evaluating the effect of turbulence on spectral broadening and rain initiation.

c. Studies of the effects of entrainment and mixing on spectral broadening

Entrainment also has been proposed to broaden drop size distributions and lead to the development of precipitation. For example, the studies of Latham and Reed (1977), Baker and Latham (1979), and Baker et al. (1980) have suggested that entrainment of subsaturated air into a cloud can cause some cloud droplets to grow faster than if no entrainment had occurred. This process, termed inhomogeneous mixing, depends critically on the time scales for mixing and the evaporation of droplets. Estimates by Baker and Latham (1979) based on inhomogeneous mixing in a simple parcel model indicated an appreciable broadening toward larger drop sizes relative to homogenous mixing or adiabatic growth. In contrast, Telford et al. (1984) proposed that special dynamical sequences of vertical mixing could achieve the same spectral broadening without invoking inhomogeneous mixing. Another hypothesis for explaining the rapid growth of a few cloud droplets was proposed by Korolev and Isaac (2000). They suggest that zones of high supersaturation result from isobaric mixing of saturated volumes with different temperatures, and that some proportion of cloud droplets may grow large enough over many supersaturation events to initiate collision-coalescence. Cooper (1989) described another effect of entrainment. He proposed that entrainment-induced variability in the supersaturation histories of individual drops all reaching the same point (in space and time) in a cloud could result in a large variation in drop sizes at that point. His theory does not appeal to specific dynamical sequences of the cloud or a specific model of mixing; instead it suggests that the in-cloud variability resulting from turbulent air motions and fluctuations in cloud structure, as produced by entrainment, is responsible for spectral broadening. Entrainment may not always be important. For example, Paluch and Knight (1986) found that the large drop peak in High Plains clouds increased with altitude in a manner more consistent with a closed parcel environment than a completely mixed one. They did not find evidence that mixing or cloud age increased the size or concentration of the largest drops. Paluch and Baumgardner (1989) found that the largest droplets occurred in regions with the highest droplet concentration and water contents, not in parcels having low concentrations from entrainment. At a more fundamental level, questions remain about how entrainment occurs in clouds. Blyth et al. (2002) maintain that there is substantial observational evidence that cumulus clouds are thermals, but it is not clear if the clouds become diluted as a result of the thermal circulation or if significant entrainment occurs through the edges of the updraft. It is also unclear what role edge eddies play in the entrainment process (Grabowski and Clark 1991). Controversy remains about entrainment and the role of mixing of subsaturated air into clouds.

In RICO, we plan to collect data necessary to initialize and evaluate models designed to simulate the effects of entrainment on spectral broadening in trade wind cumulus. For example, validation of the model approach outlined by Lasher-Trapp et al. (2002b), which exploits the theoretical description of the process in Cooper (1989), as well as the approach used by Su et al. (1998), which explicitly represents the mixing of entrained air on all relevant scales, require measurements of the CCN and UGN distribution at cloud base and in the cloud environment, the thermodynamic properties and turbulence structure of the updraft at cloud base, the thermodynamic properties of the air in the environment, and accurate measurements of temperature and drop size distributions in clouds. We also plan to employ fast-response trace gas instruments for quasi-conserved trace gases such as CO, Ozone, and DMS, which will provide an opportunity for much better resolution for a mixing analysis, and complement the techniques of Paluch (1979) and Betts (1982). These new measurement strategies to be employed in RICO will

provide an excellent opportunity to evaluate the many effects of entrainment on the development of precipitation in trade wind cumulus.

d. Effects of preexisting clouds on precipitation initiation

Early reports that rain forms within tropical cumulus in 15-20 minutes were considered problematic by the cloud physics community because there was no known mechanism to produce rain that quickly. A fundamental problem with the “15-20 minutes” is determining the “start time”. Both visual and radar observations suggest that a rather long-lasting stage of cloudiness often precedes the vigorous cumulus turrets in which the first precipitation forms. In these situations, the “15-20 minute time to rainfall” is highly questionable. Coalescence in warm clouds is a highly time-dependent process. This poses a difficulty when model calculated spectra are compared with observed drop spectra.

The early cloud fields need to be observed better with both radar and aircraft to discover what role they have in modifying the microphysical environment in which more vigorous cloud turrets grow and produce precipitation. Time-lapse video observations of trade wind clouds frequently show small convective cloud patches moving in the easterly trades. Visible satellite images show that these cloud patches are ubiquitous in the trades well outside the influence of the island. Cumulus towers often emerge from these cloud patches and produce rain showers. The material composing CCN is transported upward within drops in these towers, combined during coalescence, and falls to the surface or reappears as modified CCN upon evaporation. Aqueous-phase gas-to-particle conversion is rapid enough in some clouds to substantially increase the amount of soluble material in cloud droplets, thus enhancing the activity of CCN upon detrainment (e.g. Kramer et al., 2000, and references therein). In this way, recycling through clouds can also modify the aerosol and CCN characteristics of air with the trade wind cloud layer. CCN remaining in the atmosphere after detrainment and evaporation of a cloud serve as nuclei for subsequent clouds; however, the net effect of cloud processed CCN on subsequent cloud characteristics is poorly known. One focus of RICO will be to determine the importance of cloud recycling to precipitation processes. A unique combination of remote and in-situ sensors will be employed to study clouds and their detrainment regions. In-situ airborne measurements of the nuclei and droplet size distribution, temperature, high-resolution trace gases (CO, Ozone, SO<sub>2</sub>, DMS), and wind/turbulence will be made throughout the cloud lifetime. Simultaneous measurements of the cloud and its detrainment region will be made with an airborne lidar and the K and S band polarization radars. Because of its sensitivity to scattering by aerosol, the lidar will provide information on the distribution of aerosol within the detrainment region and the fine scale structure of the region. The S band radar, which is sensitive to Bragg scattering, will provide information about the near-cloud detrainment region in the cloud mantle (Knight and Miller 1998), while cloud boundaries will be defined by lidar and K-band radar. On select flights, multi-channel radiometer (MCR) data obtained during aircraft flights over cloud top will be used to characterize cloud optical depths and effective radii.

2. *Research on the microphysics of the transition to a mature rainshaft*

Even if giant and ultragiant nuclei are critical to the onset of precipitation, it is not clear that these particles contribute substantially to the bulk of precipitation from clouds. Other

precipitation embryo sources could dominate the production of the majority of the precipitation. These possible sources include large CCN, breakup fragments resulting from collisions between larger raindrops or other mechanisms such as turbulence that broaden the cloud drop spectrum. The microphysical processes dominant in warm rain showers that produce significant precipitation in the tropics have yet to be established. This question is distinct from that of precipitation onset. The causes and physical processes associated with the transition between precipitation onset and the mature rainshaft have yet to be investigated.

Modeling studies of maritime, warm cloud precipitation development have reached contradictory conclusions about the role of giant and ultragiant nuclei. For instance, Tzivion et al. (1994) concluded that these nuclei dominate precipitation formation, whereas Takahashi (1976), Takahashi and Lee (1978) and Takeda and Kuba (1982) concluded that they had no effect. The new capabilities of polarization radar (Illingworth et al. 1987, Illingworth and Caylor 1988, Illingworth 1988, Knight et al. 2001) will provide information about raindrop size distributions throughout clouds. These data will constitute strong constraints for the warm rain models that will be initialized with CCN and large, giant and ultragiant nuclei spectra measured during RICO.

Reflectivity and differential reflectivity data from past research experiments suggest that the initial precipitation in warm cumulus consists of large raindrops in very low concentrations, while the mature rainshaft contains a higher concentration of smaller raindrops. RICO will investigate the mechanism(s) responsible for this evolution. If drop breakup is important, then the mechanism of precipitation onset may be irrelevant to the total precipitation. It is clear that these questions must be answered through a combination of careful field observations, data analysis, and detailed microphysical cloud modeling. The observations alone are unlikely to resolve the relative importance of these processes, but comprehensive observations are necessary to provide the foundation for evaluation of the sensitivity of modeled precipitation to the inclusion of important microphysical processes.

## **B. Mesoscale Organization of Trade Wind Cumulus**

While tropical cloud systems are very important to the global heat, radiation, and moisture budgets (Moeng and LeMone 1995), the processes controlling their evolution and coverage are not well understood (Rickenbach and Rutledge 1998). This is particularly true of shallow tropical convection in the trade winds. Rickenbach and Rutledge (1998) showed that the most common precipitating cloud systems in portions of the western tropical Pacific Ocean were shallow. These shallow cloud systems, which accounted for a significant fraction of tropical rainfall, are often organized in mesoscale structures.

It is generally believed that alteration of the marine boundary layer through convective and precipitation processes plays an important role in subsequent development and organization of tropical convection. The role of downdrafts in deep convective systems has been studied extensively (e.g., Sherwood and Wahrlich 1999, Montmerle et al. 2000). However, differences in precipitation loading and evaporative cooling in trade wind cumulus may result in different thermodynamic structures of the resultant downdrafts and subsequent evolution of the cold pools. As a precipitation-generated downdraft moves below cloud base, it alters the boundary layer through bulk transport of air from aloft and evaporative cooling of boundary layer air.

While past observations of deep convection have generally suggested that new convection triggers along gust-fronts and feeds off undisturbed boundary layer air, recent modeling results suggest that convection may also be triggered within the cold pool via the wake recovery process (Tompkins 2001, Fovell and Tan 1998). Although these studies show a strong link between evolution of the convective wake/gust-front system and initiation of new convection, results differ as to the role of convective available potential energy (CAPE) recovery, convective inhibition (CIN) decay, and gust front updrafts. It is unclear whether any of these results can be applied to shallow trade wind convection.

In RICO, we will investigate two mechanisms that have the potential to explain the organization of convection in the trade winds. The first mechanism considers thermodynamic processes within precipitation-generated cold pools, and the second considers boundary layer dynamical processes at the edges of these cold pools. Modeling studies of the first process (e.g. Tompkins 2001) have found that evaporative cooling, surface fluxes, and entrainment modify the cold pool thermodynamics, giving rise to rings of convection within the cold pool rather than at the boundaries. On the other hand, numerical modeling studies of the second process (e.g. Fovell and Tan 1998) suggest that dynamical processes near and just behind outflow boundaries can give rise to a succession of precipitating convective clouds. Evaluation of the importance of each of these cold pool processes requires in-situ data that can be used to understand the boundary layer evolution within, and at the boundaries of, convectively generated cold pools. *RICO will provide the opportunity to obtain detailed observations to evaluate the importance of these processes in the trade wind environment.*

Downdraft microphysical, thermodynamic, kinematic, and mass flux characteristics together determine the structure of the resulting cold pool. In this manner precipitation links convection to subsequent boundary processes. The interaction of the convection/cold-pool system with the background wind profile influences the organization of the cold pool structure and new convection. Although these processes have been studied for deep convection (e.g., Weisman et al. 1988, Rotunno et al. 1988), they are poorly understood for the more widespread shallow trade wind convection that covers much of the tropics. In the tropics, both surface fluxes and mixing may play important roles in the thermodynamic evolution of convectively generated cold pools. In RICO, we plan to measure the fluxes of boundary layer air into the cold pool from above and compare these fluxes to those resulting from air-sea interaction. If the surface moisture flux dominates over entrainment of dry air from aloft, the evolving cold pool may develop CAPE values in excess of those in the environment. Thus, as the cold pool recovers, it becomes thermodynamically more favorable for convection. This same recovery process reduces the gravity current forcing of the gust front updraft and so decreases the likelihood of dynamic initiation of convection at the cold pool edge. Because regenerative outflow-ring convection does not trigger new precipitating cells until the outflow ring has expanded to mesoscale diameter, it is hypothesized that the thermodynamic mechanism dominates. If true, we will observe the initiation of new convection within the cold pool rather than along or ahead of it. These processes are likely to be sensitive to the environmental profiles of wind, temperature, and humidity. In RICO, we will determine how the large-scale environment influences mechanisms for regenerative outflow-ring convection.

## C. Statistical Properties of Trade Wind Cumulus

Amidst the drive to understand basic questions such as how rain forms in shallow cumulus, one has to wonder how much precipitation matters to the large-scale energy budget? The idea that it could matter stems from a growing recognition that precipitation in trade-cumuli is commonplace, and the increasing recognition that shallow convection over the tropical oceans plays a fundamental role in a variety of large-scale circulations. Moreover, the susceptibility of the climate system to perturbations in the atmospheric aerosol depends in part on the importance of precipitation processes.

### 1. *How much do shallow cumulus rain?*

The evidence that precipitation is commonplace comes not only from in-situ studies, such as those designed by cloud physicists to study precipitation onset, but also from large-scale budgets. In the tropics the predominant balance is between radiative cooling on the one hand and latent heating by precipitating convection on the other. However, because the latent heating in regions of deep convection tends to be peaked in the upper troposphere, while the radiative cooling tends to be more uniformly distributed with height, or even bottom heavy as a result of enhanced cooling in shallow cloud layers, there is the implication of a missing heat source at low levels (cf., Bergman and Hendon 1998, Mapes 2000). The relatively small Bowen ratio over most of the tropical oceans makes it difficult to argue that this heating deficit is balanced by turbulent fluxes of sensible heat. The most likely scenario is that latent heating from precipitation by shallow clouds outside of the zones of deep convection balances this budget. This inference is supported by a survey of "storm tops" (i.e., the highest altitude of detectable radar echoes) using the downward looking precipitation radar on the Tropical Rainfall Measurement Mission (TRMM) which shows a distinct shallow mode peaked below 4 km (Short and Nakamura 2000). This shallow mode is associated with approximately 20% of the precipitation between 30 N and 30 S in the DJF and JJA seasons, an amount consistent with the inferences from large-scale thermodynamic budgets discussed above.

Further evidence for the prevalence of precipitation of shallow cloud systems is provided by a budget study of suppressed periods during TOGA-COARE (Johnson and Lin 1997). This study illustrates that during periods of shallow convection the moistening and cooling of the upper part of the cloud layer that would be expected for non-precipitating convection (e.g., Riehl et al. 1951) was largely absent. This can be explained if these cloud systems produce precipitation.

RICO provides a unique opportunity to quantify the amount and structure of precipitation falling from shallow cumulus in the North Atlantic Trades. In so doing, RICO will provide key information that can be used to make global estimates of precipitation using satellite remote sensors. To date, such efforts at relating information derived from satellite imagers to precipitation estimates have focused largely on deep convective clouds (Kidder and Vonder Haar 1995). There have been no attempts to conduct satellite studies over shallow trade wind cumulus for two main reasons: (1) lack of ground-based estimates of precipitation in these clouds, and (2) trade-cumulus are small shallow clouds that produce little in the way of useful thermal signatures because they are sub-pixel. However, RICO will bring together state-of-the-art instruments to collect in-situ, ground-based radar, and satellite data. Of particular interest is the higher spatial

resolution data from the EOS-Terra platform. For example, the Multi-angle Imaging SpectroRadiometer (MISR) on EOS-Terra allows for 275 m resolution radiometric data to be collected from nine directional cameras. This data provides accurate information on cloud cover, cloud-track winds, stereo-derived cloud-top altitude, and, in the case of trade cumulus, cloud geometrical thickness. These are all important parameters that are related to precipitation from trade cumulus.

RICO will overcome an important limitation of past field studies on trade cumulus, namely that they have tended to focus on either individual clouds or cloud clusters at the exclusion of the large scale, or on the large-scale budget at the exclusion of cloud microphysical structure. Modern remote sensing provides the opportunity to do both. The importance of doing both is motivated by the need to interpret reflectivity statistics from large-scale radar surveys of cloud fields. This is best done with in situ data obtained from studies of individual clouds whose characteristics are similar to those sampled in the survey. This interpretation is by no means trivial, but is critical to constraining attempts to reconcile reflectivity-derived estimates of net rain with those derived from large-scale thermodynamic budgets. Radar statistics from the NCAR S-Pol radar will be interpreted based on in situ measurements in the microphysical study regions. On select flights, the C-130 will be used to survey the larger-scale region. Retrievals of optical depth and effective radii from the MCR can be combined with estimates of precipitation from the radars to statistically investigate cloud properties associated with the occurrence of precipitation. Because the MODIS instrument on the TERRA platform has similar channels to those on the MCR, it is possible that these data will guide extensions of this analysis/cloud climatology to larger scales using satellite data. GPS dropsonde data will be used in conjunction with model analyses to estimate precipitation from large-scale thermodynamic budgets. A ship, such as the NOAA *Ronald H. Brown*, may also be used to collect radar data from the larger scale region, which can then be interpreted using the reflectivity relationships derived using S-POL for the inner microphysical study region. The consistency between these two estimates of area-averaged rain rates should help bound possible systematic errors in either. Moreover this multi-scale strategy can be taken to the next larger scale, as estimates from the large-scale study region can be used to bootstrap satellite derived global estimates of precipitation from shallow cloud systems. This becomes particularly valuable when it is realized that the small size of trade-cumulus present unique challenges to space based radars and imagers such as found on TRMM or planned for Cloud-Sat.

## 2. *Does precipitation in trade wind cumuli matter to the large-scale energy budget?*

Armed with estimates of the rain-rate from fields of cumuli, one can infer its importance by simply comparing the order of magnitude of the precipitation flux with fluxes of enthalpy in the lower troposphere. If latent heating from shallow cumulus over the entire tropical region does contribute at leading order to the overall heat balance in the tropics, the failure to represent this effect in almost all parameterizations of shallow convection forces the deep (precipitating) convection schemes to compensate. This would not be all bad if the aerial coverage of deep and shallow convection was similar; however, because deep convection is located in compact convection zones this would result in a distortion of the spatial distribution of low level heating. This may affect our ability to represent large-scale circulations with any fidelity.

A strategy for answering this question more definitively is to use data from RICO to help guide and calibrate theoretical studies using cloud-resolving models or large-eddy simulation. In this respect the multi-scale strategy of RICO is again critical and unique. By attempting to quantify the statistics of the cloud field and the large-scale environment, one creates a context in which detailed model evaluation can take place. To the extent the models represent well the statistical relationships found during RICO, causality questions can then be asked. This integration of theory and measurements presents the opportunity for truly advancing our understanding. Moreover the richness and complexity of microphysical data to be collected during RICO has the potential to significantly advance our representation of microphysical and precipitation processes in these models.

The importance of the RICO dataset in these respects cannot be over-emphasized. Although simulations of trade cumulus date to the early days of large-eddy simulation (Sommeria, 1976; Sommeria and LeMone 1978; Beniston and Sommeria 1981; Bougeault 1981; Nicholls et al., 1982), the use of this method has encountered something of a renaissance (e.g., Cuijpers and Duynkerke 1993, Siebesma and Cuijpers (1995), Brown 1999a,b; Stevens et al., 2001; Brown et al., 2002, Siebesma et al., 2002), with recent work focusing on increasingly sophisticated and precise theoretical questions. In so doing, the simulations have outstripped the ability of existing data-sets to constrain them.

Because past field observations of ensembles of trade-wind cumuli (e.g., BOMEX, ATEX) focused primarily on evaluating the structure and evolution of the mean state of the lower atmosphere, theoretical work and modeling studies were primarily evaluated on the basis of their ability to represent these budgets. For instance, the central strategy of the simulation studies of the Global Energy and Water Experiment (GEWEX) Cloud System Studies (GCSS) Working Group One was to determine if LES could maintain a realistic structure to the lower atmosphere with prescribed "large-scale" forcings (cf., Siebesma et al., 2002). Although one would like to have some confidence that the ensuing turbulent structure of the simulations was consistent with the observations, the lack of in situ data and quantitative cloud statistics largely prevented investigators from posing such questions.

RICO can rectify this problem. Using large-scale budgets derived from dropsondes, integrated with forecast model analyses, satellite data, cloud statistics from radar, possible ship-based measurements, and in situ turbulent statistics, one can address a number of nagging problems which LES has been unable to address (e.g. the relationship between cloud fraction and the environment, cf. Stevens et al., 2002a). These data can also be used to evaluate a number of hypotheses which have come from the past decade of simulation studies, e.g., the rate of mixing at cloud top (Grenier and Bretherton, 2000; Stevens et al., 2001; McCaa et al., 2002); the net entrainment and detrainment rates from cloud ensembles (Siebesma et al., 2002); the role of shear (Brown 1999a); the similarity structure of turbulence in the cloud layer and scaling laws for cloud base mass flux (Grant and Brown 1999).

To do this we envision flight tracks based on a strategy employed during DYCOMS-II (Stevens et al., 2002a, b). Here the aircraft flew 30-minute circular legs above the boundary layer at the beginning, middle of, and end of the measurement periods. During these circles remote sensors were used to survey the cloud field, and dropsondes were used to evaluate the mean

state. In between these periods, two circles each (totaling an hour of flight time) were flown at four levels: near cloud top, just above cloud base, near the surface and just below cloud base. In RICO it may be desirable to shorten some of these legs so as to also allow flight time nearer the middle of the cloud layer. In either case, this sampling strategy will be used to evaluate the turbulence statistics in the boundary layer for use in constraining theoretical predictions. When possible, these flights will be coordinated with overpasses by polar-orbiting cloud imaging satellites.

RICO will make extensive use of chemical tracers (e.g., DMS and to a lesser extent Ozone) with special properties to infer mixing rates. DMS has particularly useful properties as a tracer of boundary layer motions because its only known marine source is at the surface, it has a relatively short lifetime, and has good conservation properties (e.g., Lenschow et al. 1999). Past experience (e.g., Bandy et al. 2002) found significant quantities of DMS in the trade-wind boundary layer in the vicinity of Puerto Rico, suggesting that these methods can be used to similar effect during RICO. The compact nature of the turbulence in cumulus-cloud layers poses challenging sampling problems. By measuring the mean DMS, water vapor and ozone at different heights in the cloud layer one can evaluate the turbulence statistics and constrain simulations.

Although RICO will fill the data void that large-eddy simulation of trade-cumulus currently faces, perhaps its most important contribution will be its ability to integrate microphysical measurements with cloud statistics and large-scale environmental characteristics. This contribution becomes particularly valuable when it is realized that the small size of trade-cumulus present unique challenges to space-based radars, imagers, and microwave radiometers such as those found on the TRMM platform. This framework lays a foundation for significant advances in our understanding of one of the world's most prevalent cloud systems.

## **D. Additional Studies**

### *1. Research on the age of cloud parcels*

Identifying the age of cloud parcels using tracers provides a means of estimating the time over which the cloud droplet size spectrum has evolved. To determine the "age" of cloudy air parcels in RICO, a combination of conserved and time-varying tracers will be used. In non-precipitating cumulus, the thermodynamic analysis technique of Paluch (1979) may be used; she used the wet equivalent potential temperature ( $\theta_q$ ) and total water mixing ratio ( $Q$ ) as tracers. In precipitating clouds  $Q$ , in particular, is no longer conserved. Conservative tracers will be used to determine entrainment sources and amounts, and to model the oxidation of the non-conservative tracer  $SO_2$ , thus matching predicted and observed  $SO_2$  concentrations. Fast (sample rates of more than 1 Hz) and accurate measurements of tracers such as ozone ( $O_3$ ), carbon-monoxide (CO) and dimethyl-sulfide (DMS) are now available, and these are relatively unaffected by chemical changes in clouds. In many clouds, these conservative tracers may be used to determine the fractions of cloud-base and entrained air. In contrast to the conservative tracers, sulfur-dioxide changes rapidly in clouds as a result of aqueous oxidation to sulphate. The rate of conversion of  $SO_2$  depends on the ambient concentrations of oxidants hydrogen peroxide and ozone, as well as the pH in cloud drops, which in turn depends on the ambient aerosol and cloud liquid water content. The fraction of  $SO_2$  removed is directly related to the age of the cloud for a given

concentration of these trace gases and aerosols, thus facilitating a meaningful comparison between observed and predicted drop spectra. If successful, these tracer studies will provide valuable new techniques that can be applied to a wide range of RICO microphysical objectives such as entrainment and mixing studies, and model validations.

## 2. *Aerosol Chemistry, CCN, and Clouds*

Clouds characteristics are determined by their thermodynamic and dynamic environment. It is being increasingly recognized that they are also products of their chemical environment. Indeed, the idea that perturbations to cloud properties (especially trade cumulus, e.g., Albrecht 1989, Ackerman 2001) via perturbations to the atmospheric aerosol might significantly impact the earth's climate is a centerpiece of the new multi-agency initiative being organized under the auspices of the National Aerosol-Climate Interactions Program (Ramanathan et al., 2002). In this respect several important issues can readily be addressed in the context of RICO. These include the role of organics in determining the properties of aerosol that may act as CCN (e.g., NRC 1996, Facchini et al., 1999, Novakov and Penner, 1993, Hegg et al., 2002); the extent to which variability in the concentration of CCN is evident in the macroscopic properties of the cloud field (e.g., Rosenfeld 2000, Baumgardner et al., 2002); and our ability to relate measured properties of the aerosol distribution to contemporaneous CCN measurements, to predict which aerosol particles actually form cloud droplets, and to relate all of these measurements to cloud base droplet spectrum measurements (cf., Stevens et al., 2002a, Twohy and Hudson 1995, Twohy et al. 2001, Snider et al. 2003).

RICO provides an opportunity to address all of these issues in the context of a large-scale environment whose properties are well characterized, and whose cloud fields are particularly relevant to the underlying motivation for studying the aerosol. Aerosol particles can be sampled from aircraft using a high-volume dichotomous sampler. The possibility arises of also using impactors such as the Micro-orifice Uniform Deposit Impactor (MOUDI) and the Dekati Low-Pressure Impactor (DLPI) on an island site to collect aerosol samples over different size categories (10  $\mu\text{m}$  down to 7 nm). The collection of such samples and its subsequent analysis using ion chromatography for the water-soluble ions, evolved gas analysis and thermo-optical analysis for the carbonaceous aerosol, and total organic carbon analysis for the water-soluble organic component of the aerosol will greatly complement aircraft based estimates of aerosol properties. To the extent that island induced dynamic and thermodynamic perturbations are small, such measurements may even provide a basis for comparing the characteristics of clouds downwind of the island, with those upwind of the island. To the extent such a strategy is successful one could help bound aerosol effects on clouds.

## 3. *Radar remote-sensing studies*

There are opportunities to investigate additional uses of the S and K wavelength combination with polarization diversity and matched, 1° beams and scans. One example is exploring the possibility of improving remote rainfall estimation using attenuation at K-band. Since the radar will be dual-wavelength and precipitation strongly attenuates K but hardly attenuates S at all, this wavelength combination may be useful in rainfall measurement. Another example is exploring the "mystery echo" first discovered in SCMS (as found in small clouds; Knight and Miller,

1998). There often exists a period in the evolution of early cumulus in Florida when the cloud's radar echo at X-band is dominated by Rayleigh scattering from hydrometeors but the S-band echo is transitioning from domination by Bragg scattering to Rayleigh scattering. During this time, there is a rather strong preference for the difference in reflectivity factor at the two wavelengths to be about 10 dBZ. This observation may involve Bragg scattering from an uneven distribution of hydrometeors (Knight and Miller, 1998; Erkelens et al., 2001) though no reason for a 10 dBZ preference is obvious. At present, we call this the "mystery echo," and simply do not understand it. We will determine whether the mystery echo exists for the K and S Band combination in trade wind clouds, and if so, what the offset of the radar reflectivity factor is with this new wavelength pair. These constitute fundamental problems in interpreting radar data, and as such will be important to the microphysical objectives of RICO.

#### 4. *Satellite cloud climatology studies*

The World Climate Research Program has stressed the importance of accurate cloud climatologies. In July 1983, they launched the International Satellite Cloud Climatology Project (ISCCP), which has been collecting satellite measurements since that time (Schiffer and Rossow 1983). Cloud climatologies are required for both the monitoring and modeling of climate. Monitoring cloud cover along with other climate variables can lead to a better understanding of the sign and magnitude of cloud feedback. Indeed, cloud cover is recognized as a critical variable required to accurately assess cloud feedback effects in climate (e.g., Harshvardan 1982; Arking 1991). It also is important in the parameterization of cloud field albedo (e.g., Kobayashi 1988; Welch and Wielicki 1989) and in the derivation of surface radiation budgets (e.g., Frouin *et al.* 1988). Accurate cloud climatologies are also essential for the successful simulation of clouds in weather and climate models (e.g., Hansen *et al.* 1983; Cess 1987); however, as pointed out by Arakawa (1975), knowing cloud cover alone is insufficient to model the impact of clouds on climate. Global cloud climatologies also need to include the seasonal and geographic distribution of cloud type. These are needed to verify and tune the climate model.

Unfortunately, the derivation of cloud climatologies is affected by such factors as measurement resolution (Di Girolamo and Davies 1997), the amount of contrast between cloud and background (Rossow 1989), the logic used to determine the threshold of an observed quantity that separates clear from cloudy (Rossow *et al.* 1985), cloud type (Wielicki and Parker 1992), the view angle (Minnis 1989) and the viewing perspective (Henderson-Sellers and McGuffie 1990). These factors tend to have the largest impact for cirrus clouds, owing to their low optical thickness and emissivity, and for shallow cumulus, such as the trade-cumulus being studied by RICO, owing to their small size and low cloud tops. Thus, shallow cumuli tend to be poorly represented in existing cloud climatologies. Moreover, trade-cumulus is not a distinct cloud type in any existing cloud climatology.

One of the objectives of RICO is to provide in-situ data to help establish a global cloud climatology of trade-cumulus to facilitate climate studies of the trade wind regime. The climatology will be constructed using data from instruments on satellite platforms like EOS-Terra and EOS-Aqua. The data record for these satellites at the end of 2004 (the time of RICO) will be 5 years for EOS-Terra and 3 years from EOS-Aqua. These provide reasonable time periods to produce a climatology for trade-cumulus. However, it is important to note that these

platforms are in sun-synchronous orbits, with Terra having an equator crossing time of 10:30 AM (descending node), and Aqua 1:30 PM (ascending node). It would be desirable to include data from geostationary satellites as well, but their poor spatial resolution will limit the accuracy of a trade-cumulus climatology. RICO will provide the framework for examining ways to extend the results from EOS measurements to geostationary data.

##### *5. Studies of cloud effects on radiation*

During an exploratory trip to the Caribbean in December 2001, significant and quick changes in the brightness of cumulus clouds were noted. In time periods as quick as 1 minute, the brilliant white color of actively growing cumulus clouds could change to duller white or grey. Further, when viewing fields of cumulus clouds, a few brilliant actively growing white clouds were interspersed among several dull white, grayish clouds. The change in radiative properties that occurs during the transition of an actively growing cloud to a mature cloud or rainshaft must be associated with a rapid change in the drop sizes or concentrations of cloud particles.

During RICO, flight paths will be chosen so that cloud-radiative interactions can be explored and relationships between radiances and microphysical properties quantified. The RICO in-situ observations of the sizes and concentrations of cloud and aerosol particles will be combined with Mie theory to derive cloud mean single-scattering properties and multi-spectral three-dimensional radiative transfer models will be used to predict radiative fluxes. These fluxes can be compared against those measured by a multi-channel radiometer (MCR) that can be installed on the NCAR C-130. The relevant data can be collected using either one aircraft or two aircraft flying in tandem. When one aircraft is available, it will fly 2 to 4 km above a line of trade cumulus chosen to include at least one actively growing bright cloud. The multi-spectral fluxes will be measured, and then the aircraft will descend to approximately 100 to 200 m below cloud top, measuring the microphysical characteristics of the same cloud bank. If two aircraft are available, they could fly in tandem with one measuring the microphysical properties at various levels within the clouds and the other measuring radiative fluxes above clouds. Multi-spectral retrieval algorithms applied to MCR data can also be used to estimate cloud liquid water path and typical drop sizes, which when compared against radiances, will allow a determination of microphysical properties associated with changes in radiative characteristics. Further, the retrievals of cloud microphysical properties will be available for parameterization development at a wide variety of scales: the optical depths, effective radii, cloud top temperatures, and cloud sizes most susceptible to precipitation initiation can be deduced. These studies can be extended to larger scales using the MODIS instrument on the TERRA platform, which has similar channels as the MCR.

### 3. LOCATION OF PROJECT AND OPERATIONS

RICO is proposed for the early winter of 2004-05. The project will be based on an island in the Lesser Antilles, a site chosen because of the common occurrence of trade wind cumulus, and the weak tropical inversion that limits the depth of many clouds. The clouds approaching the eastern islands of the Lesser Antilles have a long fetch over the open ocean and should have microphysical characteristics of shallow trade wind clouds over the broad expanse of the Atlantic Ocean. The time of year was chosen to avoid tropical storms, mid-latitude fronts and deep convection driven by island forcing. Early winter was also selected based on a study of NEXRAD radar from Puerto Rico and satellite data covering the Atlantic and Caribbean that showed that trade wind cumulus are ubiquitous and often produce precipitation.

We are proposing that RICO occur from November 15, 2004 through January 24, 2005. The initial period, from November 15 through November 30 (excluding the Thanksgiving Holiday period), will be devoted to a radar only study. The purpose of this period will be to fine-tune flight strategies based on the observed spatial and temporal distribution and evolution of the trade wind cloud and precipitation fields. This strategy worked extremely well during the Small Cumulus Microphysics Study in 1995. Flights will begin on December 1 and continue through December 21. A break in operations is planned over the Holidays from December 22 through January 3. Flights will resume January 4 and continue through January 24. This schedule will allow sufficient time and flight hours to accomplish all of the scientific objectives described in Section 2.

RICO plans to have all aircraft deploy from a single airport. This will simplify project coordination and maximize scientific coordination and collaboration during the field phase. An operations center at this location will facilitate cost effective in-field forecasting, planning and operations support. The UCAR Joint Office for Science Support (JOSS) would be requested provide scientific, technical and administrative support services to RICO for planning organizing and implementing the field campaign.

While finalization of flight plans and radar scanning strategies will only occur after meetings with all participants and the projected two-week initial period of radar-only operation, our present plans are to operate using two distinct strategies, statistical sampling studies and cloud process studies. The first strategy, statistical sampling of microphysical properties, will consist of a series of constant altitude legs that intersect as many clouds and rainshafts as possible, within a fairly wide sector. The radar will scan in PPI mode, covering about 120°, rapidly enough to provide adequate cloud histories in the whole sector. The aircraft legs will be at different levels (below cloud base, just above, mid-cloud, near cloud top), but during the statistical studies, there will be no attempt to fly multiple levels in a single cloud, or coordinate aircraft at different levels to target the same cloud. Rather, the S and K band radar data will be used in post-analysis to determine the stage of the lifecycle of individual clouds at the time of aircraft penetration. Aircraft penetrations of clouds will be guided in real time by visual cues and sometimes by the aircraft's forward-looking hazard avoidance radar. This approach is designed to obtain a large data set that can be applied to the scientific objectives related to microphysical studies.

The second approach is to conduct process studies within individual clouds. In the past the strategy has been to target individual clouds and to perform repeated aircraft penetrations (coordinated with a radar scanning in a fairly narrow sector) to get good time and space resolution. This strategy has worked poorly primarily because of the difficulty of selecting clouds early in their lifecycle. RICO presents an opportunity to address this problem. Our video surveillance of trade wind cumulus has suggested a way to improve on past process studies. On many days, the videos show a series of turrets emerging from relatively small, low-level, long-lived cloud patches within the trades. Turrets develop regularly from the same cloud patch. The low-level cloud patches most likely are associated with mesoscale forcing from past precipitation events (see Section 2B). In RICO, we will identify a target low level cloud patch, and then fly through and over it, penetrating immediately any emerging turrets. If a single aircraft is airborne, the strategy will be to sample one or two levels during the lifecycle of any single turret, and as many levels as possible during the evolution of several turrets from the same cloud patch. When more than one aircraft is airborne, these aircraft will coordinate to sample the same turrets at different levels. The characteristics of the low-level cloud patch will also be sampled.

For budget studies of the large-scale cloud field, long legs at two different levels within the sub-cloud layer and three different levels within the cloud layer will be flown. The legs will be primarily composed of long circular patterns that drift with the mean wind (similar to what was flown during DYCOMS-II). The budget studies will include remote-sensing/dropsonde legs. A novel aspect of RICO will be its additional emphasis on the statistics of cloud elements, clouds, and cloud fields, as deduced by radar. The aircraft data will be used to interpret the radar statistics from the broader cloud field and help constrain the energy budget. Low-level flight legs can provide surface flux estimates to calibrate flux estimates from satellites and forecast model analyses. Ship data, which would further constrain these estimates by measuring radiative and turbulent surface fluxes and cloud liquid water path using microwave radiometers, could help bridge scales across the various platforms.

Many of the microphysical flights, especially penetrations through rainshafts and flights near cloud top, will complement the budget studies. Similarly, many of the budget study flights will complement the microphysical studies. For instance, the enhanced cloud statistics conducted during the precipitation studies will also be useful for constraining theoretical relationships derived from large-eddy simulation, while long sub-cloud legs in the budget studies are well suited to evaluating the spatial and temporal statistics of ultra-giant nuclei. Moreover, by interleaving flights of the two types, information from one can be used to help interpret the other. For instance, the ability of the precipitation study flights to provide calibration points for surface based radar statistics will augment interpretations of budget study flights. Likewise, the context provided by budget study flights should augment the data collected in preceding, or subsequent, precipitation study flights.

Processes controlling the mesoscale structure and coverage of shallow tropical cloud systems will be investigated primarily using the University of Wyoming King Air. This aspect of RICO requires a different approach than the microphysical and budget aspects discussed above. Because the mesoscale structure results from a sequence of causally related events, this problem is best addressed using multiple case studies. To study this chain of causality, each case study requires detailed observations from the time the convection initially develops precipitation and a

cold pool to when subsequent convection develops within or ahead of the evolving cold pool. Each flight will start with a transit to the open ocean and a short period at above-cloud altitude selecting the initial cloud based on its likelihood of developing precipitation. Stacks of short flight legs near and below cloud base will be used to examine the initial development of the convective downdraft, modification of the sub-cloud boundary layer, and initial development of the cold pool. Subsequent evolution of the cold pool will be determined using flight legs radiating out from the initial cloud to beyond the gust front edge. These cold pool flight legs will be conducted at two heights within the outflow boundary layer. At least one of these flight legs will be below the base of new clouds, to determine characteristics of the air entering the new clouds. When possible, these flights will be timed to coincide with overpasses of polar orbiting satellite imagers. These flights will give unprecedented, critical information on the evolution of the cold pool and processes controlling development of new convection.

The number of flight hours that will be requested for NSF facility pool aircraft, for the SPOL radar, and for an Integrated Sounding System (ISS). The hours are grouped by broad scientific objective. We will request four C-130 flights of duration 8.5 hrs per week for six weeks in the field. Each C-130 flight will include approximately 5 hours devoted to ensemble cloud field scale studies, 3 hours devoted to microphysical/cloud scale studies, and 0.5 hours ferry time. The number of flight hours requested for the Wyoming King Air includes 12 flights of 5 hours duration for cloud interaction scale studies, and 12 flights of 5 hours duration for microphysical/cloud scale studies. We will request that the SPOL radar, with the K-Band addition, be operated continuously (24 hour) between November 15, 2004 through December 21, 2004, and again from January 4, 2005 through January 24, 2005. We are also requesting one ISS system to be co-located with the radar. Two soundings will be launched daily to document the diurnal cycle. On flight days, we plan to launch two additional soundings, one near takeoff time and one near landing to document the environmental conditions during the flight. Table 1 summarizes these requests.

**Table 1. Facility Pool Requests**

<b>Facility</b>	<b>Request</b>
C-130	204 hrs + Ferry from NCAR and return
Wyoming King Air	120 hrs + Ferry from Laramie, WY and return
Integrated Sounding System	164 soundings

The table above lists only NSF facility pool equipment that is required for RICO. A number of scientists plan to propose to NSF or other domestic and foreign agencies to bring additional facilities to RICO. The participation of these facilities in RICO will enhance and expand the observing capabilities of RICO. Table 3 lists all of the instrumentation platforms and instruments that have been proposed for RICO.

#### **4. RICO AND EDUCATION**

In addition to providing unique field research experiences to graduate students, RICO will integrate research and education through the creation of the “RICO Graduate Seminar Series” (RGSS), which will be offered during the last three weeks of the field campaign (i.e., in early January). This time period will allow the greatest student participation because it coordinates well with the academic calendar. The RGSS is motivated by two facts: (i) the realization that modern field programs have such a degree of automation that students are often left with little to do beyond routine monitoring tasks; (ii) the assemblage of scientific instrumentation and expertise provides unique educational opportunities for students. The goals of the RGSS will be to educate students about theoretical issues underlying the field campaign, the techniques and instrumentation used to address these issues, and the process of designing and executing a field campaign such as RICO. We anticipate that students from numerous U.S. universities and foreign countries will participate.

The RGSS will include a series of nine to fifteen lectures by RICO science team members. No more than one lecture will be given per day, with each lecture lasting from 50 to 75 minutes. The RGSS will include hands-on practical experience with instrumentation and data analysis. A special aspect of RGSS will be a dedicated flight of six hours that will be designed by participating students. The students will coordinate this flight with radar operations, and design the flight to be consistent with the goals of RICO. The flight will take place at the end of the project, which will give students the opportunity to meaningfully apply what they learn during the RGSS. After the field program, RICO scientists will help students coordinate and analyze data from this flight and will encourage them to publish their results in the *Bulletin of American Meteorological Society*.

A second thrust of the RICO plan for education and outreach will be to hold a media and outreach day. This will be coordinated with local schools and media to provide access to the instruments and scientists participating in RICO. In this manner, the scientific objectives of RICO will be communicated to the public.

## **5. DATA MANAGEMENT**

Because of the scope of RICO, the number of research platforms, and the large number of participants, data management and field project coordination is a serious concern. For this reason, we will request that the UCAR Joint Office for Science Support (JOSS) provide scientific, technical, and administrative support services to RICO for the purpose of planning, organizing, and implementing the field campaign. JOSS will be asked to coordinate in-field collection and cataloging of supporting datasets (e.g. satellite, surface, SST) as well as develop a RICO Field Catalog. This catalog will document project operations, be a source for special data products and allow exchange of in-field data products. JOSS will also be requested to archive and distribute RICO generated datasets to be used for subsequent analyses. We also plan to organize a post-project data workshop, to be held 6-12 months after the field program, to assess data issues and preliminary research.

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**Table 3.**

**Facilities and New/Special instrumentation to be requested for RICO**

The following is a table listing instruments and facilities that will be requested for RICO. Some of these instruments have new and unique capabilities that will be important for achieving the objectives of RICO.

**Aircraft**

*EC-130Q Hercules aircraft:* This four-engine, medium-size utility turboprop has been modified from a U.S. military tactical aircraft to a versatile and capable research platform that will deliver the scientific instrumentation to the target area. The Hercules has a 10-hour flight endurance, covers a 2,900 nautical mile range at 20,000 ft, and carries a payload of up to 23,000 lb. In addition to the standard sensors that measure atmospheric state parameters, cloud physics, and radiation, the C-130 will be equipped with specialized instrumentation for measuring the state of the atmosphere away from the aircraft. These latter instruments include the Staring (Scanning) Aerosol Backscatter Lidar (SABL), the ATD Dropwindsonde System, and the Wyoming cloud radar.

*Wyoming King Air:* The University of Wyoming King Air has a wide range of sensors to measure a large array of atmospheric parameters. These include standard Instrumentation for measurement of atmospheric state parameters (temperature, pressure, humidity) air motion (wind), Cloud properties and video photography. Special instrumentation potentially available includes turbulent flux measurements of momentum, moisture, and carbon dioxide, radiometers (shortwave, longwave, and ultraviolet), instrumentation for atmospheric trace gas sampling, and a cloud condensation nucleus CCN counter.

*BAE aircraft:* The United Kingdom Natural Environment Research Council BAE 146 aircraft will be requested by UK scientists for participation in RICO. This aircraft has the capability of measuring the size distribution, concentration and type of aerosols, including CCN. The BAE aircraft will be equipped with a full range of optical particle counters covering particle sizes from approximately 0.1 to ~ 300  $\mu\text{m}$ . In addition, a suite of condensation particle counters will extend the measurements to 3 nm, with some estimates of the size distribution at nanometer sizes being derived from comparison of CPCs with differing lower cut-off thresholds. In addition, a volatility system based around a PMS ASASP-X will be available to measure the composition of the sub-micron aerosol particles. This system employs a rapid-response, micro-processor controlled heater and has been used very successfully on the MRF C-130 for several field campaigns. Although the volatility technique lacks the chemical precision of filter techniques or newer aerosol mass spectrometers, it offers an excellent near real-time analysis of inorganic aerosol species such as ammonium sulfate and sea salt. It will be especially beneficial to this project in being able to clearly define the sea-salt contribution (volatile ~ 650°C) to the aerosol spectra observed near cloud base. With a suitable counter-flow inlet system, it can also be utilized to examine the non-activated interstitial aerosol particles so that the role of sea-salt particles as CCN is clearly defined.

*SPEC aircraft:* Stratton Park Engineering Company (SPEC) Inc. operates an instrumented Learjet 25 aircraft for cloud physics research. Scientists working with SPEC INC will request this aircraft for participation in RICO. The aircraft has state-of-the-art optical instruments for measuring properties of cloud and precipitation particles, liquid water content, thermodynamic properties and extinction. The Lear is capable of making repeated, rapid penetrations of the same cloud. It can sustain twice-standard rate turns (i.e., 6 degrees per second turn rate), so that a 270 degree turn back to cloud can be accomplished in 1 minute.

## **Ship**

*Ron Brown:* The NOAA Ship Ronald H. Brown is a state-of-the-art oceanographic and atmospheric research platform that is the largest vessel in the NOAA fleet. The Ron Brown will be requested by RICO scientists to observe the statistical properties of trade wind clouds over the open ocean upwind of the island. The ship has a C-Band scanning Doppler radar, a wind profiler, the capability of launching radiosondes, standard surface meteorological instrumentation, and instruments to measure properties of the ocean.

## **Remote sensors**

*S-Pol Radar with polarization diversity K-Band:* The system consists of a sensitive Ka-band transmitter-receiver attached to the S-Pol radar. The beams of the two radars are carefully matched to insure the radars are sampling the same volumes. Both radars have polarization and scanning capability. We have requested that the Ka-Band radar have the capability to measure  $Z_{DR}$  and understand that this capability will be available for RICO.

*Wyoming Cloud Radar:* The Wyoming Cloud Radar is an observational system for the study of cloud structure and composition. It is intended for airborne use; principally on the Wyoming King Air. Operating at 95 GHz (3 mm wavelength), the radar provides high-resolution measurements of reflectivity, velocity and polarization fields in vertical or horizontal sections. Coupled with the in situ observations of hydrometeors and air motions from the same aircraft these data yield unique information for analyses of cloud and precipitation processes. During RICO it is proposed that the radar be mounted on the C130.

*Miami Millimeter Cloud Radar:* The Miami Millimeter Cloud Radar is an excellent tool for the observation and study of the vertical structure of clouds and especially "weak" meteorological targets which are normally undetectable by a conventional weather radar. The radar is portable and primarily operates in the vertical mode. It has a space resolution of 30 m, can detect small particles in non-precipitating clouds, and has a velocity resolution of  $0.031 \text{ ms}^{-1}$ .

*SABL Lidar:* The SABL lidar is a compact and reliable instrument that detects backscatter from air molecules, aerosols, and hydrometeors (water and ice) and is used to measure and map distributions of relative aerosol concentrations. The instrument operates at two wavelengths 532 (green) and 1064 nm (infrared). On the C130 aircraft, it operates from zenith to nadir out to distances from 10 to 15 km with range resolutions down to 7.5 meters and along-track resolution to 4 meters.

## Airborne Probes

*GPS Dropsondes:* These third-generation dropsondes use a new sensor module and a GPS receiver from Vaisala Inc. A unique square-cone parachute is used to reduce the initial shock load and slow and stabilize the sonde. The parachute is immediately deployed on exit from the launch chute and streamers for about five seconds until filled by ram-air. The stability of the square cone parachute is very good during the sonde's descent and reduces or eliminates any pendulum motion of the sonde. The fall speeds of the sondes in the trade wind boundary layer are estimated to be between 10 and 15 m/s, yielding profiles with a resolution of less than 10m. Four sondes can be tracked from the aircraft simultaneously.

*Counter-flow virtual impactor (CVI):* The CVI measures the liquid water content of cloud droplets larger than about 8  $\mu\text{m}$  diameter. The instrument can also be used to measure the residual particles from evaporated cloud droplets and analyze their size, composition, critical supersaturation, and electric charge.

*Desert Research Institute CCN spectrometer:* The DRI CCN spectrometer has been modified to measure nuclei that activate at critical supersaturations down to 0.002%. This instrument continuously provides more than 100 channels of CCN and large nuclei resolution with less than a few seconds time resolution. It also accepts CVI residual aerosol as input so that cloud droplet size distributions can be more directly related to CCN distributions outside of clouds.

*Roberts CCN counter:* A light-weight continuous-flow thermal gradient diffusion chamber developed by Roberts (2002, personal communication) for autonomous operation in airborne studies was used in IDEAS 2002 and CRYSTAL-FACE and will be employed in RICO. The instrument employs a novel technique of generating a supersaturation along the longitudinal axis of the instrument. Model simulations suggest that direct measurements in the climatically important range of supersaturations of less than 0.1% are possible. This instrument will provide needed redundancy for CCN observations.

*Wyoming CCN counter:* The Wyoming CCN counter (Delene and Deschler 2000) is a static thermal-gradient diffusion chamber, taking a grab sample every 30s. Both, the top plate and the bottom plate of the chamber are covered with water-saturated blotter paper. A temperature controller regulates the differential temperature between the plates, thus creating a supersaturation in the center of the chamber. Particles with critical supersaturation less than the controlled supersaturation activate and grow to the size of cloud droplets. A laser illuminates these droplets and the scattered light intensity is recorded. For redundancy two identical instruments are generally deployed and are generally configured to measure the CCN number concentration at supersaturations of 0.2%, 0.4%, 0.8%, and 1.6%.

*Commonwealth Scientific & Industrial Research Organisation (CSIRO) Giant Aerosol Impactor:* The CSIRO giant aerosol impactor system will be used to measure the size of aerosols with dry radius from 4 micron to tens of micron, i.e. the size range suspected of initiating the majority of warm raindrops. This system consists of a  $7 \times 21$  mm glass slide impaction rod, used to collect giant aerosol particles in the air well off the skin of the aircraft. Analysis of the slides is done in the laboratory using an automated microscope system. The slide sample volume is 17

liters per second, or equivalently, 1 cubic-meter per minute, assuming a flight speed of 120 m/s. Slides may be exposed for periods of a few seconds to minutes. Given that the main precipitation flux for normal rain is carried in the 100 largest drops in a cubic meter, this sensor will allow for statistically significant sampling of the most significant giant aerosol particles in a short time period. Analysis of the impactor slides is done using an automated microscope system. The slides are mounted up-side down in a humidity controlled box under the microscope objective. The microscope stage is a scanning 3-d stage, and images can be acquired using a digital camera. The camera system does focus analysis, and particle sizing is done automatically. The humidity in the chamber can be adjusted to allow for the examination of the particles at different humidities. At relative humidities of 80% and more, the sea-salt particles are spherical cap solution drops. Image analysis, using Fourier technique, allows for discrimination between irregular (dust) and round (sea-salt) particles. From the measured relative humidity in the chamber, and assuming that the particles are in equilibrium with the ambient humidity, the salt size can be calculated using the Kohler equation. This instrument provides vital redundancy with other measurements of giant and ultragiant nuclei.

*Tel Aviv University Big Particle Sampler (BPS):* The BPS is a new instrument for collecting giant particles with aircraft. This instrument has been flown on a number of experiments including the Mediterranean Israeli Dust Experiment in January 2003. The instrument is mounted outside the plane and collects particles  $> 2 \mu\text{m}$  diameter on different substrates (e.g. Electron Microscope grids). Up to 6 substrates can be exposed sequentially during the flight, allowing sampling at different heights. Since RICO will mostly be carried out over the ocean, the role of organics together with NaCl and dust can be studied.

*DRI Cloud Scope:* Measurement of giant nuclei will be undertaken using a Hallett Cloudscope. The Cloudscope measures dry particle diameters in the range of  $0.9 \mu\text{m}$  to  $> 50 \mu\text{m}$ . The Cloudscope sample volume can be varied between  $0.05$  and  $>10 \text{ L s}^{-1}$ . The Cloudscope provides videos that must be subsequently analyzed for size and hygroscopicity.

*SPEC 2DS-Stereo Probe:* A new probe, called a 2D-S (stereo) probe, has been designed to minimize the sizing and counting errors associated with the 2D-C and 2D-P probes. The 2D-S will record simultaneous stereo images of particles. The 2DS will also measure particle spacing. The new electro-optics will minimize the uncertainties associated with particles passing outside the optical DOF, and will also will have sufficient time response to detect particles from  $10 \mu\text{m}$  to  $1.28 \text{ mm}$  at airspeeds up to  $183 \text{ m s}^{-1}$ , or  $5 \mu\text{m}$  to  $640 \mu\text{m}$  particles at airspeeds up to  $92 \text{ m s}^{-1}$ .

*Meteo-France X-Probe:* The new Fast-FSSP, called the “X-Probe”, will be used to measure droplet spacing. The new instrument is designed to mitigate the main limitations of FSSP and Fast-FSSP probes. The improvements include (i) an extended range of particle diameters to as small as  $0.2 \mu\text{m}$ , in order to examine the CCN activation process in detail and precisely measure the separation between activated and unactivated particles; (ii) side scattering in the range from  $0.8$  to  $50 \mu\text{m}$  to avoid Mie ambiguities of the forward scattering measurements and thus reduce instrumental spectral broadening in the measurement of small droplets; and (iii) synchronous measurements in two converging beams to reduce significantly the impact of droplet coincidence. These modifications will allow a new look at interstitial unactivated nuclei, better measurements of spectral broadening inside adiabatic cores, more accurate evaluation of droplet

spectra just above the cloud base, and permit the discrimination of big droplets (precipitation embryos) from coincidence artifacts.

*SPEC High Volume Particle Sampler (HVPS):* The HVPS is a 2-D optical array probe that measures the size, shape, and concentration of precipitation-sized particles with a resolution of 200  $\mu\text{m}$  and a size range extending to about 5 cm.

*Gerber PVM:* The Gerber Particle Volume Monitor measures liquid water content at sampling frequencies of 1 and 2 kHz.

*Nephelometer:* The nephelometer is a commercial instrument (Radiance Research Inc.) that measures the light scattering extinction coefficient of air (molecules + aerosol particles) at a wavelength of 530 nm.

*Particle/ Soot Photometer:* The particle/soot aerosol photometer (PSAP, Radiance Research, Inc.) measures the coefficient of absorption at a wavelength of 565 nm.

*Radial differential mobility analyzer:* The radial differential mobility analyzer measures aerosols in the range from 0.008 to 0.123  $\mu\text{m}$  utilizing the technique of particle separation as a function of inertia and electrical mobility. This is a device constructed at Universidad Nacional Autonoma de Mexico from a design of Lynn Russell (Russell et al., 1996) and differs from the standard DMA design primarily in the residence time of particles and minimum detectable size.

*Phase-Doppler Interferometer:* A new instrument is being developed to measure droplet spacing along the flight path (with uncertainty between 50 and 100  $\mu\text{m}$ ), 2-D droplet velocity (with uncertainty to 1 cm/s), droplet size (with uncertainty of  $< 2 \mu\text{m}$  and a range of 2-200  $\mu\text{m}$ ), and concentration (with uncertainty of  $\sim 5\%$  in each 2  $\mu\text{m}$  width size bin). This instrument will be used to study fine-scale turbulence.

*High-Volume Dichotomous sampler:* The high-volume dichotomous sampler (Solomon et al., 1983) allows the collection of particles in fine ( $D_p < \text{ca. } 2.5 \mu\text{m}$ ) and coarse ( $D_p > \text{ca. } 2.5 \mu\text{m}$ ) modes. The face velocity is around 86  $\text{cm sec}^{-1}$  for a total average flow of about 330  $\text{L min}^{-1}$ . In the sampler, two quartz filters are placed directly on top of each other (tandem arrangement) in each filter holder (fine and coarse). After sampling, portions of these filters will be used for chemical analysis. This sampler was used in the NCAR C130 during INDOEX.

*Condensation Particle Counter:* The condensation particle counter (CPC 3022A, TSI) measures the total aerosol particle number concentration from particles from 7 nm to 3  $\mu\text{m}$  in diameter. (May be used on the ground or in the air).

*Aethalometer:* The aethalometer (AE-31, Magee Scientific) is an instrument that measures light absorption of aerosols at 7 different wavelengths (from 370 to 950 nm).

*Warsaw University Ultrafast Temperature Probe:* Thermometric probe able to measure temperature fluctuations in cloud with centimeter resolution (Haman et al. 2001).

*NCAR OPHIR Temperature Probe:* The Ophir radiometer employs passive radiant gas thermometry. The 15  $\mu\text{m}$  Air Temperature Radiometer is capable of measuring the air temperature in clouds where wetting of other probes is a significant problem. NCAR has recently improved the operation of this instrument on the C-130.

*Multi-channel radiometer (MCR):* The MCR is a seven-channel radiometer (Curran et al. 1981) that scans between plus or minus 45 degrees of nadir. The visible (0.630, 0.761, 0.763  $\mu\text{m}$ ), near-infrared (1.06, 1.64, and 2.16  $\mu\text{m}$ ) and infrared (10.8  $\mu\text{m}$ ) channels are ideally suited for the retrieval of optical depths, liquid water paths and effective particle sizes (e.g., Nakajima and King 1990; Nakajima et al. 1991), cloud top altitude (e.g., Fischer and Grassl 1991; Fischer et al. 1991), and other cloud and aerosol properties. The MCR has a field of view of 0.007 radians, and the mirror scans at a rate of 3.47 revolutions per second.

*Drexel University fast DMS and SO<sub>2</sub>:* Atmospheric pressure ionization mass spectrometry (APIMS) is used to measure DMS. The reagent ion  $\text{H}_3\text{O}^+$  is formed from primary ions from ionization of nitrogen and water vapor ( $\text{H}_2\text{O}$ ) by a nickel-63 beta emission. The monitored ion is  $\text{DMSH}^+$ , which is formed from the reactions of DMS with  $\text{H}_3\text{O}^+$ . The use of APIMS includes the continuous addition of high isotopic purity d3-DMS as an internal standard. This results in high precision of the measurements and also allows unambiguous determination of the sensitivity of the technique as atmospheric conditions vary. DMS measurements are made by sampling for ambient DMS for 20 milliseconds followed by 20 milliseconds of the DMS standard to yield a net sampling rate of 25 Hz (samples/sec). The detection limit is estimated to be 1 pptv for a 1 second integration. The instrument can also be used to measure  $\text{SO}_2$  at high rate, interleaved with the DMS measurements.

*University of Rhode Island H<sub>2</sub>O<sub>2</sub> and CH<sub>3</sub>OOH:* This sensor works by wet collection of gas-phase hydrogen peroxide and methylhydroperoxide ( $\text{H}_2\text{O}_2$  and  $\text{CH}_3\text{OOH}$ , respectively), followed by liquid-chromatographic separation of the  $\text{H}_2\text{O}_2$  and  $\text{CH}_3\text{OOH}$  from other organic peroxides, and fluorescence analysis. The current sensor is a slow-rate sensor, one sample every 2.5 minutes. For  $\text{H}_2\text{O}_2$  the detection limit is better than 15 pptv, and for  $\text{CH}_3\text{OOH}$  the detection limit is better than 25 pptv. Accuracy for both is estimated as the sum of the detection limit and 15% of the reported value. A proposal for instrument improvement has been submitted to NASA for support. The improvements include a reduction in sample processing to time to between 30-60 sec, and a reduction in detection limits to better than 5 pptv for  $\text{H}_2\text{O}_2$  and 15 pptv for  $\text{CH}_3\text{OOH}$ .

*NCAR fast ozone:* This chemiluminescent sensor uses a reaction with NO to quantify ozone. The instrument has a 3 Hz frequency response and a 0.2 ppbv detection limit.

## **Ground Based Instruments**

*Integrated Sounding System:* The ISS consists of four separate subsystems: a balloon borne radiosonde navaid (GPS, Loran) sounding system, an enhanced surface observing station, a 915 MHz Doppler clear-air wind profiling radar, and a Radio Acoustic Sounding System (RASS).

*Scanning Mobility Particle Sizer:* The scanning mobility particle sizer (3936L10, TSI) measures high-resolution size distributions for particles from 10 nm to 1  $\mu\text{m}$ .

*Sunphotometer:* The sunphotometer (CE318-1, CIMEL) measures aerosol column burden and properties (e.g., aerosol optical thickness, size distributions) (from AERONET).

*Dekati-Low Pressure Impactor:* This low-pressure impactor (DLPI, Dekati) works at a pressure of ca. 100 mbar and a flow of ca. 30 LPM and size classifies particles according to their aerodynamic diameter ( $D_p$ ) from 10  $\mu\text{m}$  down to 30 nm with 13 evenly distributed impaction stages. The filter stage, after the lowest impaction stage, extends the measurement range down to 7 nm. After sampling, portions of filters/substrates used will be used for chemical analysis.