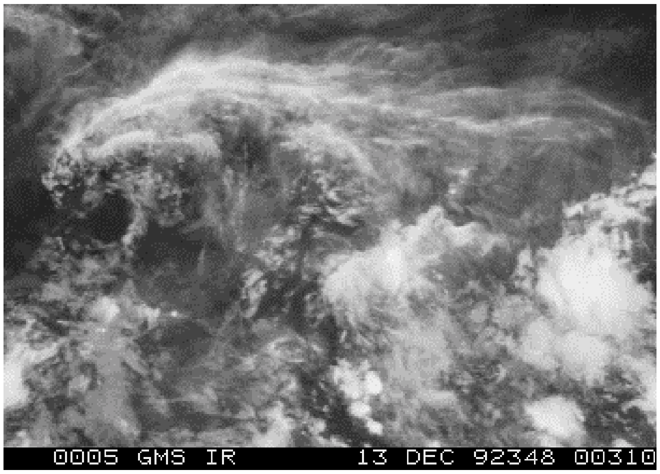

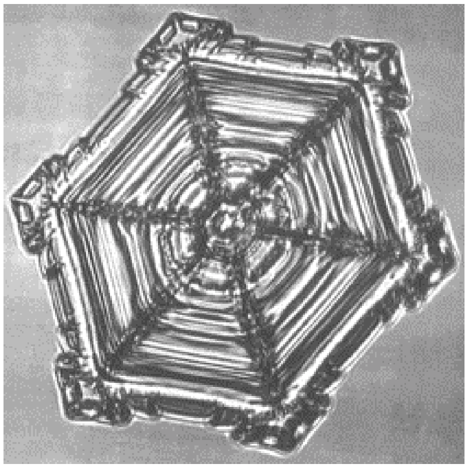

CRYSTAL Research Plan

January 2000

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CRYSTAL is a comprehensive scientific study consisting of modeling, observations and integrated analyses designed to address important questions surrounding tropical cirrus cloud systems and their role in both regional and global climates. The planned study includes participation by multiple agencies and international organizations. Leadership and coordination is provided by the NASA/Radiation Science Program.

Prepared by the FIRE-IV CRYSTAL Drafting Panel, with major contributions from Thomas Ackerman, Steven Ackerman, Stephen Cox, Anthony Del Genio, Gerald Mace, Patrick Minnis, David Starr and Bruce Wielicki.

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This document was prepared to provide a description of the scientific objectives for a comprehensive study of tropical cirrus clouds and their role in climate. The particular measurement approach described to accomplish the objectives is used for illustrative purposes only. It is anticipated that NASA will issue a research announcement for participation in this multi-agency and international study. Participants seeking NASA Radiation Science Program funding for participation will be asked to submit a proposal describing their participation. Proposals selected as a result of a peer review process, will define the actual measurement approach to be taken. Thus, the "candidate instruments" listed in this document are used only to describe potential measurement characteristics. Similarly, the instrument platforms (aircraft and ships) described are subject to their availability and the availability of adequate support for their use. Reference to a specific measurement instrument does not necessarily imply its endorsement or recommendation by NASA.

Cover Images

Images depicting the wide range of spatial scales to be measured in CRYSTAL.

Top Panel: A cumulonimbus cloud. The deep convective cell produces a heavy rain shower falling from the base of the cloud. Strong upper level winds produce a well defined cirrus anvil. Sunlight scattered by falling ice crystals produces the bright area beneath the anvil. Courtesy T. Ansel Toney

Bottom Left Panel: Global Meteorological Satellite (GMS) infrared image taken Dec. 13, 1992, over the Tropical Western Pacific (centered 10N, 155E) during TOGA/COARE showing old cirrus outflow and several convective storms with newer cirrus outflow. Many low and midlevel cumulus clouds underlie the cirrus. The image spans 1200 km north-south by about 1200 km east-west, an area roughly equivalent to Kansas-Nebraska-Colorado-Wyoming. Courtesy P. Minnis

Bottom Right Panel: A 2-millimeter hexagonal ice crystal observed in an upslope cloud in Colorado using the airborne Cloud Particle Imager (CPI). The concentric hexagons reflect a tendency towards "skeletal growth", i.e., the basal faces are depressed inward in a series of steps. Recent advances in technology allow high-quality imagery of crystals, even for very small ice crystals. CRYSTAL will measure cirrus ice crystals as small as 10 microns in size, a factor of 200 less than the ice crystal shown. Courtesy P. Lawson.

The three panels illustrate the wide range of spatial scales, ranging from 10 microns, to 10's of kilometers, to 1000's of kilometers (factor of 100 billion), involved with CRYSTAL's measurements of cloud and radiation properties. The temporal scale range is similar, from milliseconds to decades (climate).

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EXECUTIVE SUMMARY

CRYSTAL (Cirrus **R**egional **S**tudy of **T**ropical **A**nvils and Cirrus **L**ayers) is a comprehensive scientific program consisting of modeling and observational programs and integrated analyses designed to address the important questions surrounding tropical cirrus cloud systems and their roles in both regional and global climates.

The largest gaps in our understanding of global cirrus effects on climate involve tropical cirrus systems. High-level clouds dominate the cloud radiative forcing signal in the tropics and a variety of modeling and theoretical studies suggest that the response of these clouds to external forcing might have a controlling effect on global climate sensitivity. Tropical cirrus systems usually originate from water transports in deep convective cloud clusters, however a wide range of upper level cloud types may result. These include thick precipitating anvil clouds directly tied to the convective cells, moderately thick non-precipitating anvils, and the thinner cirrus that are a fairly ubiquitous feature of the tropics.

CRYSTAL will dramatically improve our knowledge of tropical cirrus cloud systems and the understanding of the roles of cirrus cloud systems in regional and global climate settings. As such, CRYSTAL will measurably reduce the present uncertainty about the internal workings of the present climate system, its natural variations, and projections of future climate.

Two overarching issues provide the context for CRYSTAL:

> 1) It is essential to gain improved knowledge of the global ice water and water vapor fields in the upper troposphere in relationship to the associated global radiative fields and on scales adequate to resolve the dominant physical processes (storm and cloud systems).
>
> 2) An improved knowledge and understanding of upper tropospheric cloud generation, re-generation and dissipation mechanisms are critical to formulation and verification of methods to realistically capture these processes in regional and large scale climate models.

CRYSTAL has been designed to address a series of very complex and challenging scientific issues:

I. How are the radiative, microphysical and spatial properties of tropical convective anvil cirrus clouds related to the convection that produces them? Assuming they are related, can these relationships be used in a practical manner in large-scale models to couple convection with tropical cirrus cloud systems and upper tropospheric moisture?

II. How do tropical cirrus cloud system radiative properties, microphysical properties and spatial properties evolve with time? What are the controlling factors in this evolution?

III. How can we best observe tropical cirrus cloud systems in a large-scale context for climate research?

IV. How do tropical cirrus cloud systems impact local, regional and global circulations?

To accomplish this challenging agenda, CRYSTAL will utilize both numerical modeling and observational approaches. Numerical models of atmospheric circulation, ranging from meso to global scales, including numerical weather prediction (NWP) models, will be employed. Observations from the ground, satellite and in-situ aircraft platforms will be used to initialize atmospheric circulation models, verify portions of their results, and develop new methods of parameterizing cirrus cloud production and evolution. The observations will include air motion, temperature and water vapor, cloud ice/water and microphysical properties as well as radiation and will be collected in modes supporting the investigation of time evolution of specific systems, compositing data from multiple events and developing local case studies.

The time frame from year 2000 to 2004 is especially fertile for advancing CRYSTAL's objectives. Beginning in 1999 with the EOS flagship mission Terra, followed by EOS Aqua in 2000 and EOS CHEM in 2002, unprecedented global information on the atmosphere and its cloud systems will be available. CRYSTAL will provide necessary documentation of the atmosphere and cloud systems to enable realization of the full potential of these capabilities and their application to understanding of tropical cloud systems. CloudSat and PICASSO-CENA, scheduled launch in 2004, are especially well suited to the study of tropical cirrus cloud systems. The critical linkages between these satellite measurements, surface baseline climate measurements provided by ARM, and modeling of climatically important cloud systems are described in detail in this plan. High resolution measurements of water vapor and other parameters will be available from the Geostationary Imaging Fourier Transform Spectrometer, or GIFTS, set for launch in 2004. There is a good chance that GIFTS can be moved over the CRYSTAL experiment area.

Acquisition of suitable observations is essential for progress in addressing the science issues of CRYSTAL. The present CRYSTAL Research Plan outlines a research strategy and an observational program that draws on past experience and present and anticipated capabilities. This strategy should enable us to achieve significant progress in describing and understanding tropical cirrus cloud systems and incorporating them into numerical models.

Simultaneous measurements of radiative fields and microphysical properties of tropical cirrus clouds with attendant environmental variables will support studies of microphysical evolution, cloud radiative properties and remote sensing of tropical cirrus clouds. These observations will be concentrated around conjunctions of aircraft, surface-based and satellite observations following a strategy to develop and validate satellite-based, large-scale observations of cirrus cloud systems.

The Tropical Western Pacific arena has been chosen as the preferred location for the CRYSTAL field phase. However, CRYSTAL has been designed as a two-phase field program, beginning with an experiment in the South Florida area, the Florida Area Cirrus Experiment or CRYSTAL-

FACE, in 2002, followed by an experiment in the Tropical Western Pacific, CRYSTAL-TWP, in 2004.

The rationale for the primary TWP campaign in 2004 includes: extensive background knowledge of (and specific interest in) cloud, ocean and meteorological phenomena in this region as manifest in TOGA and the associated and on-going modeling and analysis studies; uniqueness and climatic importance of cirrus cloud systems associated with Pacific warm pool convection; and linkage between tropical Pacific cirrus and subtropical jet stream cirrus systems observed over the south-central United States. The field program deployment will take place in the western Pacific Ocean region southeast of the island of Guam. Aircraft operations will be staged out of Guam and conducted over an area bounded by two research vessels and the island of Chuuk, Federation of Micronesia.

The CRYSTAL TWP campaign will not likely take place before 2004 because of the extensive logistics and pre planning for this complex, remote experiment. EOS satellite missions require field observation support for validation (EOS Terra 12/99 and EOS Aqua 12/00) and development (CloudSat and PICASSO-CENA 03/03), and implementation prior to 2004. Therefore an earlier field campaign, the Florida Anvil Cirrus Experiment, FACE, will be conducted in 2002. In addition to serving the validation, development and implementation needs of satellite missions focused on the observation of cloud systems, FACE will support critical studies of cirrus cloud systems in a distinctly different geographical and environmental setting than the TWP campaign.

Cirrus cloud systems in the South Florida and Tropical Western Pacific regions are different in several significant ways.

Lifetime: Florida anvil cirrus systems tend to be not so long-lived as their counterparts.

Height Regime: Florida anvil cirrus systems tend to be as much as 100 mb lower, and consequently warmer, than similar TWP systems.

Regional-scale Circulation: Florida anvil cirrus systems are often under the influence of a regional sea-land breeze circulation (tropical storms excepted). These regional influences are generally absent in TWP systems.

While systems in both regions are embedded in the large-scale Hadley and Walker circulations and are usually associated with tropical wave activity, the organizing influence of the sea-land breeze circulations imparts some continental characteristics, specifically stronger updrafts with the resultant likelihood of significant microphysical, and possibly radiative, differences. In addition, vertical wind shear is more likely to be a significant factor in Florida than in the TWP.

Ubiquitous Cirrus: The areally extensive, optically thin, subtropopause cirrus prevalent in the TWP is not as pervasive in the South Florida region. It is unknown to what extent differences in the above factors, or other factors, lead to this result.

In addition to essential and timely support of satellite missions and acquisition of tropical cirrus cloud data in a contrasting regime, there are three other compelling factors for the 2002 FACE campaign: Model development and advancement; Pre-TWP technique and instrumentation application and verification; and Florida area research assets.

The state of cirrus cloud system modeling is at a point where it will benefit greatly from new data sets specifically acquired to support cirrus cloud simulations. The FACE experiment in 2002 will provide these data in a timely fashion and better position the modeling community to support the TWP campaign in 2004.

Techniques and new instrumentation for measurement of physical and radiative properties of cirrus clouds will be tested in the Florida campaign before deployment in the more demanding TWP environment.

The south Florida area offers extensive assets in the form of rawinsondes, doppler radar and opportunities for surface based remote sensing observations that will not be available in the TWP. Data from these assets will be applied to documenting the relationships between dynamics and cirrus clouds observed by remote sensing systems and in-situ systems, thus linking the observational program to cirrus cloud model development.   These relationships are essential to coupling ice water production by convection to the upper tropospheric cirrus cloud layer – a key element in the successful modeling of the Earth’s climate.

CRYSTAL: Cirrus Regional Study of Tropical Anvils and Cirrus Layers

1.0 BACKGROUND

1.1 Rationale for the Study of Tropical Cirrus Cloud Systems

The largest gaps in our understanding of global cirrus effects on climate involve tropical cirrus systems. High-level clouds dominate the cloud radiative forcing signal in the tropics (1,2) and a variety of modeling and theoretical studies suggest that the response of these clouds to external forcings might have a controlling effect on global climate sensitivity (3,4,5,6). Tropical cirrus systems usually originate from water transports in deep convective cloud clusters, but a wide range of upper level cloud types may result, including thick precipitating anvil clouds directly tied to the convective cells, moderately thick non-precipitating anvils, and the thinner cirrus that are a fairly ubiquitous feature of the tropics. The latter two cloud types may be either directly associated with convection or detached and perpetuated by other large-scale forcing or internal regeneration processes. While deep convection is the dominant moisture source to the tropical upper troposphere, the nature and extent of synoptic or planetary scale forcing (uplift) in generating and/or maintaining the observed extensive areas of thin cirrus are unknown. The optically thicker anvil clouds dominate the shortwave radiative effect of clouds in the tropics, while thick anvils and thinner cirrus contribute about equally to tropical longwave effects (7), so the full range of tropical cirrus must be studied to gain the proper climatic perspective.

Previous FIRE (First ISCCP Regional Experiment) experiments have investigated the properties of midlatitude cirrus systems associated with baroclinic waves and the jet stream (8,9,10), but there are several reasons to believe that this knowledge cannot simply be extrapolated to understand the properties and behavior of tropical cirrus. Unlike midlatitude baroclinic cirrus situations in which cloud formation from the vapor phase occurs strictly within the upper troposphere, tropical cirrus anvils contain an additional source of condensate that forms in the lower troposphere in cumulus updrafts and detrains at upper levels to form, or enhance existing, cirrus anvil systems (11). The microphysics and radiative properties of such clouds are likely to be significantly different from their midlatitude counterparts. The tropical tropopause is one of the coldest parts of the atmosphere and is heavily populated with small-particle thin cirrus that exist in a microphysical regime found nowhere else on Earth (12,13,14). Tropical anvil systems are often many kilometers thick, and available evidence suggests that the cloud particle properties may change radically from their extremely cold tops to their bases near the freezing level (15). The strength and scale of dynamical forcing can be substantially different than that found in the middle latitudes, especially for young anvils. Midlatitude cirrus lifetimes are limited by the synoptic time scale governing development and decay of the baroclinic systems in which they are embedded. Tropical cirrus, on the other hand, often persist for long time intervals, well beyond the time during which they can be identified with particular convective systems; the dynamical, radiative, and microphysical forcing processes that maintain these cirrus and determine their evolution are not understood. The upper tropospheric water vapor associated with tropical cirrus formation is an important contributor to the greenhouse effect itself, and episodic transports of this water from tropical source locations to higher latitudes have been suggested to be an important source of subtropical and midlatitude upper-level moisture (16).

Because of the relatively weak advection and strong surface thermal forcing patterns in the tropics, cirrus systems there have a significant quasi-stationary component whose diabatic heating effects can influence tropical large-scale circulations (17,18).

The ice water content and radiative properties of tropical cirrus systems are so poorly understood that no useful constraints exist for their parameterization in general circulation models (GCMs). Current GCMs can produce similar top-of-the-atmosphere radiation budgets with ice water paths that differ globally by almost an order of magnitude (19), because existing uncertainties allow for a wide range of assumptions about tropical cirrus particle sizes, small-scale distributions of ice water content, and underlying low and mid-level cloud amounts (5). Addressing these observational issues in a way that charts a path toward improved GCM cloud parameterizations presents a unique set of challenges due to the wide range of time and space scales involved (20,21). These challenges demand a multi-faceted approach to the study of tropical cirrus systems that involves cloud-scale observations from aircraft, surface remote sensing to provide a longer temporal context, basic microphysics and radiative transfer studies, cloud-resolving models to characterize the three-dimensional context of point observations and to create an ensemble view of such systems, satellite observations to provide large-scale quantification of entire cirrus systems and provide a link to the other, smaller-scale models and data. Finally, GCMs will be used to integrate results from the previous studies into statistical descriptions upon which parameterizations can be based.

1.2 Previous Studies of Tropical Cirrus Cloud Systems

Atmospheric scientists have been interested in tropical cloud systems and tropical cirrus for many years, particularly since the advent of routine satellite observations. These images demonstrate the ubiquity of tropical clouds, their extreme height and cold radiative temperatures, as well as their dramatic impact on the planetary radiation budget. Because of this interest, there have been a number of smaller campaigns and large field programs aimed at tropical clouds and cirrus.

The earliest aircraft studies of tropical cirrus were carried out under the auspices of the Defense Department in the late 1960s and early 1970s in the tropical Pacific. This work targeted principally thin or subvisual cirrus at the margin of convectively active regions and consisted of studies of ice microphysics at low temperatures. The first large field campaign directed at tropical convection, the GARP (Global Atmospheric Research Program) Atlantic Tropical Experiment (GATE), took place off the coast of Africa in 1974. Data acquired from the National Center for Atmospheric Research (NCAR) Sabreliner aircraft during GATE (22,23,24) were used to study the impact of anvil cirrus on the radiation budget of the atmosphere. These early studies provided interesting insights into cirrus microphysics and radiative impacts, but were very limited in extent. The aircraft platforms were not able to sample both properties simultaneously, nor were the particle microphysics and water vapor instrumentation adequate for the conditions of high, cold cirrus. Also, the data were insufficient to connect convective activity to cirrus generation in a quantitative sense.

In 1987, the Stratosphere-Troposphere Exchange Program (STEP) deployed the National Aeronautics and Space Administration (NASA) ER-2 to Darwin, Australia, for a series of flights aimed at understanding the mechanisms responsible for injecting tropical tropospheric air into the stratosphere. On several occasions during these flights, the ER-2 penetrated briefly into cirrus just below the tropopause. While these STEP data provided useful information about crystal sizes at the top of cirrus outflows and their effect on the infrared radiation budget, the samples were too limited in number and lacked dynamical context. The particle microphysics instrumentation also lacked the ability to accurately measure particles smaller than about 50 microns in diameter, although rough measures using FSSP probes indicated that most of the ice particles were smaller than 50 micron. This experiment also demonstrated that the ER-2 was not well suited for microphysics measurements in cirrus because of its limited tolerance for turbulence.

Field experiments conducted as part of FIRE I (1986) and FIRE II (1991) collected small samples of cirrus clouds of subtropical origin. These data, while interesting on their own merit, do not address the tropical cirrus problem because their tropical identities may have been virtually lost by the time of the observation.

The Tropical Ocean and Atmosphere Ocean-Atmosphere Regional Experiment (TOGA COARE), which took place from November 1992 to February 1993 in the tropical western Pacific had a primary focus on the linkages between tropical ocean and atmosphere and their impacts on the initiation of tropical convection. The National Aeronautics and Space Administration (NASA) FIRE contribution to TOGA COARE included a series of coordinated flights with the ER-2 and DC-8. Identical radiometers were mounted on both aircraft and they were then flown on identical tracks above and below or in cirrus layers. In March 1993, a similar series of flights was carried out in the central tropical Pacific as part of the Central Equatorial Pacific Experiment (CEPEX) using the NASA ER-2 and a Learjet. These coordinated flights provided a detailed look at radiative flux convergence in tropical cirrus layers. Microphysical information was also obtained, but with limitations. The DC-8 ceiling (12 km) was too low to allow it to penetrate most of the cirrus in the western Pacific. Thus the microphysical information obtained from the DC-8 was infrequent and typically limited to the very bottom of extended cirrus. Unfortunately cirrus particle size is usually observed to be a strong function of height within the cloud layer, and cirrus layer tops can commonly extend to 15 km or more. During CEPEX, the Lear Jet, with its greater ceiling (13.5 km), obtained a more extensive set of microphysical measurements, but not in conjunction with simultaneous radiation measurements. Neither experiment provided a great deal of information on the linkage between convection and cirrus generation. In COARE, the DC-8 was flown in conjunction with airborne scanning radars on board the National Oceanic and Atmospheric Administration (NOAA) P3 or NCAR Electra. However, the primary focus was on precipitation from active convective cells and adjoining stratiform rain regions. The associated anvils were not characterized, especially in terms of their upper level ice content or later development. CEPEX did not have the capability to address this issue.

The Maritime Continent Thunderstorm Experiment (MCTEX), held off the coast of Darwin, Australia, in late 1994, provided a detailed look at the initiation and development of severe continental convection in the tropics using a variety of ground-based remote sensors and satellite imagery. While this data set is likely to provide qualitative linkage between convection and extended cirrus, it suffers from a lack of in-situ microphysical or radiation data.

The Indian Ocean Experiment (INDOEX) was held in Spring, 1999, in the equatorial Indian Ocean. This field program focuses on measurements of anthropogenic boundary layer aerosols and their role in tropical convection. INDOEX has only limited ability to address the linkage between convective fluxes and cirrus formation. Its ability to sample high altitude ice particle microphysics is uncertain at this time.

Previous and currently planned tropical field programs have addressed some aspects of the tropical cirrus problem but, unfortunately, not in a comprehensive manner. While tropical cirrus microphysical characteristics have been inferred from satellite data sets (25,26), very few in-situ observations of cirrus microphysics are available, particularly in and around active convective regions. Observations of radiative fluxes most often exist without any corresponding microphysical information. Ground-based remote sensing in the tropics has been infrequent at best and basically no in-situ data are available over the few ground-based observations. Thus, it is difficult to know whether remotely sensed cloud properties are realistic or not. Cloud programs in the tropics have tended to focus on convective initiation and cloud development during the first few hours of active convection. Little work has been done either observationally or theoretically on the relationship between anvil properties and convective activity, particularly on timescales greater than a few hours. But it is precisely the issues of (1) the relationship between tropical cirrus microphysics and radiation and (2) the formation and life-cycle of tropical cirrus, especially in relationship to deep convective activity, that we need to understand if we are to improve model representations of tropical cirrus and its radiative impact.

1.3: Current and Future Tropical Cirrus Cloud Studies

Past observational programs provide an historical context upon which future tropical cirrus missions can be based. What is evident upon review of the scope of the problem and the results from past work is that a single program working alone with access to realistic resources will not be able to reach the ultimate goal of improved cloud parameterizations in a reasonable time frame. The problem demands a multi-agency, multi-program synergy that effectively addresses the coupled temporal and spatial aspects of the problem outlined above.

A unique opportunity is emerging that will enable an improved understanding of tropical clouds through the synergism of several ongoing and planned efforts of the coming decade. This opportunity includes: 1) observational programs that examine the spatial aspects of upper tropospheric clouds over an extended time period (this is most effectively accomplished from earth orbit), 2) an observational component that examines in detail the vertical and temporal characteristics of tropical cirrus over multiple years (accomplished by long-term surface observing sites), 3) the observations necessary to provide ground truth of the retrieved data from the satellite and surface-based approaches and the means necessary to integrate the disparate observations into a consistent picture through numerical modeling at various scales (field programs), 4) the development and maturation of numerical and physical models capable of realistically simulating the evolution of cirrus cloud systems at different spatial and temporal resolutions .

CRYSTAL has been carefully crafted to fill the observational and modeling niches formed by the planned surface-based and satellite data collection efforts. This will ensure that the resulting description of tropical cirrus that emerges from the full suite of observations will be adequate to describe the roll of tropical cirrus in the climate system and provide the empirical information necessary to parameterize these clouds in climate models. The observational components of CRYSTAL have been phased to coincide with development, validation and application needs of several satellite systems coming on line beginning in 1999. The two CRYSTAL field campaigns FACE and TWP are tentatively scheduled for 2002 and 2004, respectively. These field campaigns are described in section 4.

An example of the space-based observational component of this programmatic synergy is composed of four separate satellite platforms; CloudSat, PICASSO-CENA, and EOS Terra (AM) and Aqua (PM). Three of these platforms will orbit in close formation beginning by mid-2004. Cloudsat (http://cloudsat.atmos.colostate.edu) will consist of a profiling, nadir- viewing 94 GHz radar and 02 A-band spectrometer (PABSI) and visible imager. The radar will provide profiles of radar reflectivity with a nominal 1.4 km footprint in 500m resolution volumes with a –29 dBZe minimum detectable signal. This information will provide unique information on the location and vertical structure of extended anvil systems and thicker cirrus. Cloudsat will be launched on the same vehicle as the first orbiting backscatter lidar system, PICASSO-CENA (http://www-arb.larc.nasa.gov/PICASSO- CENA/PICASSO.html). The PICASSO-CENA payload consists of a two-wavelength (532 and 1064 nm) polarization sensitive, nadir viewing lidar that will have horizontal and vertical resolutions of 250m and 30 m respectively. PICASSO-CENA will also include an 02 A-band spectrometer, a 10.5 and 12 micron infrared imager and wide field camera. Cloudsat will be maneuvered so that its footprint will always be very close to the lidar footprint in both space and time.

The combined Cloudsat and PICASSO-CENA data will provide vertical profile information from nearly all clouds in the vertical column ranging from the ubiquitous tropical cirrus to the precipitation regions of extended tropical anvils. The PICASSO-CENA and Cloudsat measurements augment observations collected by instruments on board the Aqua (PM) platform (MODIS, MISR, AIRS and CERES). The combination of orbiting passive and active remote sensors will provide a unique view of tropical cirrus.

The satellite platforms generate a detailed representation of the cloud systems in the tropics along their sun synchronous orbit. The satellite sensors will, however, provide little temporal information on clouds at a given location during the diurnal cycle. Furthermore, the satellite sensors have fairly coarse vertical and horizontal resolution and provide limited temporal data relative to a highly instrumented ground site. Therefore, an important component of the observational synergy being directed at the tropical cirrus problem is provided by the Department of Energy's Atmospheric Radiation Measurement (ARM) program (http://www.arm.gov). The ARM program has established two long-term ground sites in the tropical western Pacific on Manus (2.1oS, 147.4oE) and Nauru (0.5oS, 166.9oE) Islands. These sites are equipped with state of the art millimeter-wave Doppler radar (nominal resolution of 10s and 45 m), optical lidar and a full suite of radiometric instruments that generate continuous data streams. These sites have been operating since 1998 and are expected to continue operation through the CRYSTAL time frame.

These ongoing and future observational programs, when combined with CRYSTAL, form a coordinated holistic strategy that promises a significant advancement in our understanding of tropical cirrus cloud systems.

2.0 CRYSTAL BASIC OBJECTIVES

CRYSTAL seeks to expand our knowledge of cirrus cloud systems and our understanding of the roles of cirrus cloud systems in regional and global climate settings. As such, CRYSTAL will, working in concert with other projects, measurably reduce the current uncertainty about the internal workings of the present climate system, its natural variations, and projections of future climate.

1) It is essential to gain improved knowledge of the global ice water and water vapor fields in the upper troposphere in relationship to the associated global radiative fields and on scales adequate to resolve the dominant physical processes (storm and cloud systems).

If sufficiently accurate and certain, such information would provide a highly useful constraint against which to evaluate the credibility of GCM simulations and consequently lead to significant improvements in those models. In particular, the vertical distribution of ice and vapor is integrally tied to the structure of radiative heating/cooling within the troposphere, a fundamental driving mechanism for atmospheric circulations on large and small scales.

Reaching this central objective depends critically on improvements in global observations of cirrus clouds from satellites, both technological (instrumentation and the calibration thereof) and algorithmic. In turn, development of improved algorithms, and even new instrumentation, or the validation of existing algorithms, requires accurate knowledge of cirrus cloud radiative properties and especially their relationship to cloud microphysical properties. Reaching this central objective depends critically on observations provided by the planned Cloudsat/PICASSO-CENA and EOS AQUA (PM) trio of satellite platforms. Using algorithms that are still under active development the observations of radar reflectivity , lidar backscatter and spectral radiance will need to be converted into geophysical parameters such as cloud boundaries, ice water path, particle size and radiant flux convergence on a basin-wide scale over a period of months and years. However, before the satellite-derived constraints on the global water budget in the upper troposphere can be applied to climate models, extensive validation of the algorithm results are required. An effective strategy to obtain and validate the required cloud property information is to utilize highly-advanced active and passive surface-based remote sensing technology to provide observations that capture the full range of natural phenomena in a statistically meaningful way and on scales where comparison to satellite observations is facilitated, i.e., measurements over very extended time periods at a climatologically appropriate set of locations. This strategy relies on establishing the accuracy of such surface-based retrievals that can be accomplished through comparison with coordinated airborne in-situ observations as well as through consistency comparisons between a range of alternative approaches. The extended-time ground-based observations are also directly applicable to achievement of the second objective, as evident in the ARM strategy.

2) An improved knowledge and understanding of cirrus cloud generation, maintenance (including re-generation) and dissipation mechanisms is critical to formulation and verification of methods to realistically capture these processes in both regional and large scale climate.models.

Cloud parameterization can at best mimic what we know. In addition to the above requirements for accurate knowledge of cloud radiative and microphysical properties, this application also requires understanding of the role of dynamical processes, on large and small scales, and their relationship to radiative and thermodynamic processes to which they are strongly coupled, especially at the smaller scales.

While remote-sensing technology can provide some information on dynamical processes, balloon-borne sensors (rawinsondes) are still required to specify the large-scale environment. Characterization of important mesoscale and small-scale processes also require in-situ observations, such as from aircraft. Direct integration of much of this information into climate models may be beyond our capabilities. Even with the best observational information possible, many important processes remain only poorly resolved. Furthermore, given the diversity of naturally occurring upper tropospheric cloud systems, it is unlikely that we can achieve anything approaching a statistically robust sample with even a very optimistic assessment of expected resources. An alternative strategy is to utilize cloud resolving models (CRMs) to produce the requisite data sets to capture the full range of natural phenomena. Moreover, such models can produce parameters that are virtually impossible to observe directly given the present technology, but which are nevertheless important in governing the cloud system lifecycle. In this approach, the observations are utilized to validate the CRMs where the matches in temporal and spatial scale and resolution are fairly comparable.

2.1 Science Issues

Investigations of cirrus cloud systems conducted to date and outlined above have allowed us to identify key outstanding issues critical to our understanding of the roles of cirrus cloud systems in regional and global climates. These issues include:

> *Are the phenomenological classifications for tropical cirrus clouds: anvil cirrus clouds, detached anvil cirrus clouds, and ubiquitous upper tropospheric cirrus clouds (implying no identifiable linkage with a convective source and having extensive temporal and spatial extents), distinct in their radiative, microphysical, and physical structure properties?*
>
> *Is there a relatively straightforward quantitative relationship between tropical deep convection and cirrus anvil properties and the extensive cirrus cloudiness in the tropics? If so, what is it?*
>
> *What controls the maintenance/longevity of cirrus detrained from convective towers. Observations show that this longevity is highly variable.*
>
> *Are there reliable and consistent relationships between the lifetime and characteristics of high-thin cirrus and the upper tropospheric stability and relative humidity?*
>
> *What are the ice particle sizes, concentrations and shape characteristics for tropical cirrus higher than 11 km? What are the microphysical characteristics of ice particles smaller than 50 microns at all altitudes?*

How may satellite derived cloud properties and radiative fluxes be reliably compared with more direct observations from aircraft and ground based platforms?

What are the spatial and temporal extents of ice water and water vapor in the tropical upper troposphere?

What are the spatial and temporal extents of the following tropical cirrus cloud systems?

> *Anvil cirrus (implying an attachment to a convective source)*
>
> *Detached anvil cirrus (implying a substantial displacement in both* in *time and space from its convective source)*
>
> *Ubiquitous upper tropospheric cirrus (implying no identifiable linkage with a specific convective source and having extensive spatial and temporal extents)*

What are the accuracies of water vapor, cloud water, and cloud ice inferences from satellite platforms, relative to ground-based remote sensors, and likewise from ground-based sensors relative to in-situ observations?

Are in situ aircraft measurements of cloud properties able to reasonably constrain the parameters needed to validate 1) cloud resolving models, 2) cloud properties derived from surface-based remote sensors, or 3) cloud properties derived from satellite remote sensors? If so, what is the most efficient means of accomplishing this validation over a statistically meaningful set of cloud events?

Is there an identifiable, quantitative linkage between meteorological parameters resolved and predicted by general circulation models and the occurrence and properties of upper tropospheric clouds? If so, can these relationships be used to parameterize cirrus in global models?

3.0 STRATEGIES

An adequate understanding of the multiple roles played by cirrus cloud systems in the Earth's weather and climate systems will require a multi-faceted attack on this important and elusive phenomenon. The most ambitious component of the CRYSTAL program is a tropical western Pacific field campaign. Much of the time, personnel, infrastructure and fiscal resources of CRYSTAL will be required to successfully mount this campaign. However, there are other areas of activity that are just as essential as the field campaign to the investigation of cirrus cloud systems. Continued investigations in these areas are critical to the planning of the CRYSTAL campaign, are critical to the success of the campaign and will continue to be relevant throughout the analysis and application of the field campaign results. Chief among these cross-cutting areas of investigation are radiative properties and transfer, remote sensing, algorithm development, cirrus cloud modeling, and parameterization studies.

Remote sensing has been a central theme of CRYSTAL's scientific predecessors throughout FIRE investigations of cloud systems. This has been brought about by three facts: cirrus clouds have been relatively difficult to reach with many in-situ research platforms, it is difficult to make meaningful observations in this environment; and in recognition of cirrus cloud systems global importance, satellite studies of their spatial, temporal and radiative properties are highly desirable. Dramatic progress has been made in the inference of microphysical and radiative properties of cirrus clouds by remote sensing with both active and passive systems, however, much remains to be done to improve and evaluate these techniques. CRYSTAL will play a crucial role in providing validation opportunities for the Cloudsat/PICASSO-CENA/EOS Aqua (PM)/EOS CHEM suite of cloud property retrieval algorithms. Beyond validation of existing algorithms, however, the data set generated by the CRYSTAL field campaigns will likely lead to a suite of targeted retrieval schemes designed specifically for the retrieval of cirrus cloud properties and upper tropospheric water from remotely sensed data in the tropical atmosphere.

Remote sensing remains a central focus of the CRYSTAL strategy as described below.

3.1 How does CRYSTAL relate to the United States Global Change Climate Research Plan (USGCRP) strategy?

Studies to date (27) have shown that cloud feedbacks in the climate system represent the largest current uncertainty (a factor of 3) in attempting to predict the impact of increasing greenhouse gases over the next century. Cloud/climate feedbacks are in turn composed of three major elements:

a) Given an atmospheric state, predict cloud liquid and ice water distribution (both micro and macro physical).

b) Given the cloud liquid and ice water distribution, predict the solar and thermal infrared radiative fluxes from the top of atmosphere, through the atmosphere column, to the surface.

c) Incorporate items a) and b) into a global climate model that then allows the changes in radiative heating/cooling to modify the atmospheric state, thereby completing the feedback loop.

The major shortcomings in current global climate models are in accurately modeling items a) and b). Unfortunately, while cloud microphysics acts on spatial scales of microns, and atmospheric dynamical processes act on scales from meters through global, current climate models can at best explicitly handle scale variations of about 2.5 orders of magnitude (100 km to 40,000 km). As a result, first principle physical modeling of cloud dynamics and radiation in global climate models is unlikely in the foreseeable future, and indeed it remains an open question, if it will ever be attained.

Given this state of affairs, what can be done? Figure 1 (20) presents one plausible scenario to handle the wide range of space and timescales present in the cloud/climate problem. The diagram shows the major research areas involved as boxes with a division between research on long and short space/time scales, and a division between observations and modeling. Most of the relevant individual research projects tend to fall in one of these four boxes. The lines that connect the boxes are in a sense the key interdisciplinary research activities that must cross between and involve participants from two of the four discipline areas. A brief description of each task is given in the figure.

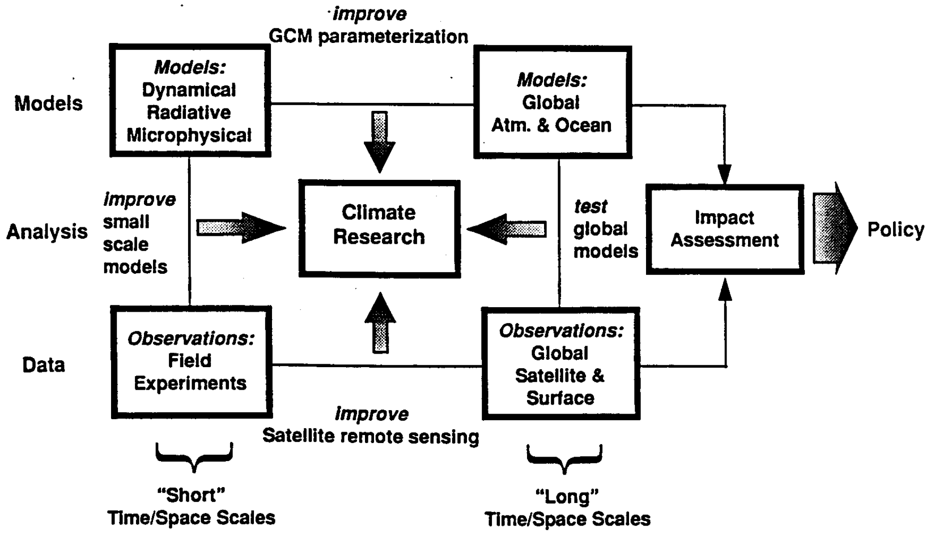

Figure 1. Observational strategy for the determination of the role of clouds and radiation in climate. Confidence in climate model predictions of global warming requires iterative improvements in global climate modeling, global satellite observations, field experiment and surface observations, and cloud/regional scale modeling of cloud dynamical and radiative processes (20).

At the longest time and space scales (global through the smallest scale resolved by a global climate model: currently 100km), GCMs are used to predict potential regional and global climate change (i.e. impact assessment). These models, however, are forced to use highly simplified (parameterized) versions of cloud dynamics and radiative transfer as discussed in items a and b above.

Verification of the GCM models' performance is most commonly made using global satellite observations of Top of Atmosphere Fluxes (e.g. Earth Radiation Budget Experiment (ERBE)) or physical cloud properties (e.g. ISCCP): this is represented by the vertical line at the right hand side of Figure 1 labeled "test global models". The satellite observations of clouds and radiative fluxes, however, are also difficult to derive, so that verification of the accuracy of these cloud/radiation properties must in turn be made using field experiment data (lower left box). This is particularly true now with the advent of a whole new generation of cloud products derived from algorithms using the most recent combined active and passive remote sensing observations. These surface and aircraft based field data by nature are taken at much smaller time and space scales. The process of validating the satellite global data using regional field experiment data is represented by the bottom horizontal line in Figure 1, and is the first cross-scale connection in the strategy. A key issue is: How to attain statistically robust tests of the global satellite data using only a few surface sites or field experiments? CRYSTAL proposes a mechanism in Section 3.2 to accomplish this goal for tropical ocean cloud systems.

The current state of affairs is that GCM results and satellite data do not agree, even to within the current satellite data accuracy. How do we fix the global models? Direct tuning of the models to the satellite observations must be avoided, as it invalidates the independence of the data and provides no new "physics" and therefore no new confidence in the model predictions (see the discussion in (28). Instead, the GCM cloud and radiation parameterizations look back to modeling studies at much higher time and space resolution (upper left box in Fig. 1) in much the same way that the global satellite data looked for verification against field experiment data. In this case Cloud Resolving Models (CRMs) can be run at much finer space and time scales to more accurately model cloud physics. An example is 2-D models of deep convective systems using 1 km grid mesh over a 1000 km domain (29). Other examples are detailed spectral radiative transfer models of the effects of clouds on radiative fluxes. In each case, there is a need to parameterize these detailed physical models in more computationally efficient ways to allow their use in the global climate models. The cloud parameterizations can then be tested both against the global satellite data (in GCMs) as well as against the cloud resolving models.

How do we verify the accuracy of the CRMs or radiative transfer models? These high resolution cloud models must be verified against field data. Field data must provide measurements of atmospheric state, cloud dynamics, and cloud radiation over the lifetime of cloud systems and cloud elements within those systems. The cloud models must be tested in a range of atmospheric states, for example varying states of boundary layer convection or deep convection, atmospheric stability, etc. The CRYSTAL strategy for cloud model verification is discussed in section 3.3.

At this point, the field experiments have closed the loop between the GCM cloud physics and the global satellite observations. While the field experiments for satellite verification and cloud model verification could in principle be separate experiments, efficiency in fact argues that these goals be merged, as they are in CRYSTAL, and as they have been in the past with many field experiments such as FIRE and Department of Energy's (DOE) Atmospheric Radiation Measurement (ARM) program. A summary of these strategies is presented in sections 3.2 (satellite validation) and 3.3 (cloud model validation). This process will result in the overall strategy presented in Fig. 1. The actual improvements in the GCMs will occur not in a single event, but in an iterative fashion, with continual improvements in both the accuracy and capability of each of the four major elements (boxes) in the figure. This process will result in a continuous narrowing of the uncertainties in the prediction of future global change until fundamental predictability limits are reached. These final limits remain to be discovered. The CRYSTAL experiment will narrow the uncertainties specifically in the observation and modeling of tropical ice clouds.

3.2 Validation of Satellite Observations and Cloud Property Retrievals

The radiance measurements from satellite must be validated to verify calibration procedures of the instrument. This is accomplished through theoretical simulations and aircraft observations. The radiative transfer calculations used in theoretical simulations require accurate specification of atmospheric conditions. This is accomplished through a coordination of observations from aircraft, ground-based, and balloon-borne instrumentation made at the time of the satellite observation. In addition, radiance observations from high-altitude aircraft are required to confirm the comparison between the satellite measurements and theoretical calculations. The aircraft radiance observations need to be well calibrated and at a higher spectral resolution than the satellite measurements to account for the spectral response function of the satellite instrument. This approach has been used to calibrate the NOAA geostationary and polar orbiting satellites and requires coordinated efforts of a field campaign.

Because of their spatial and temporal variability, clouds are perhaps the most difficult component of the atmospheric system to observe. The spatial variability of clouds is best addressed by using satellite observing systems including the new instruments on Tropical Rainfall Measurement Mission (TRMM) (launched in December 1997), and on the Earth Observing System (EOS) Terra (AM) Platform (launched December 1999). Because of the close relationship between the upper tropospheric moisture budgte and cirrus clouds the EOS CHEM platform with its measurements of upper tropospheric water vapor and other constitutents becomes a potentially powerful contributor to CRYSTAL objectives. These new data sets, however, require validation, particularly in the retrieval of cloud microphysical properties, and require a temporal context. Initial attempts to provide validation of satellite cloud products focused on the use of aircraft to provide simultaneous in-situ observations. While such a strategy may be appealing, it has proven to be extraordinarily difficult to carry out with any regularity. In any given field program, the probability of finding appropriate clouds in the right place and time to be sampled simultaneously by satellite and aircraft was very small. A typical three or four week campaign might yield only a few acceptable cases. Moreover, the very real limitations of airborne in-situ sampling with respect to cirrus cloud systems, that are often fast moving especially in middle latitudes, and typically of substantial vertical depth with significant small-scale structure, introduce substantial uncertainties into any analysis no matter how "perfect" the aircraft-satellite coordination. With the advent of continuous ground-based remote sensing of cloud properties, however, a better strategy for satellite validation has evolved.

This new strategy involves a combination of continuous ground-based observations, field campaigns in which in-situ observations are made, and routine satellite observations. Elements of this strategy were first explored with great success during the 1990 FIRE Cirrus-II field experiment and later during the 1996 Subsonic Assessment: Contrail and Cloud Effects Special Study (SUCCESS) experiment in conjunction with the Oklahoma Cloud and Radiation Testbed (CART) site. The key element in this strategy is the relatively recent development of millimeter-wavelength radar (cloud radar) and low-energy lidar systems. Radar and lidar pairs, operating in conjunction with surface radiometry at solar, thermal infrared, and microwave frequencies, allow direct measurement of cloud occurrence and location at selected ground sites (30,31). Recent work has demonstrated the feasibility of retrieving microphysical information (32,9). Cloud location information is typically available at a vertical resolution of 30 to 90 meters, while microphysical information may be retrieved either at a similar resolution or for the layer as a whole.

This ground-based remote sensing of cloud properties is at the heart of the ARM program, which is being carried out under the auspices of the DOE. The ARM program currently has a fully operational site located near Lamont, Oklahoma, and an almost fully operational site at Barrow, Alaska. ARM has begun operations in the Tropical Western Pacific (TWP) at Manus Island, Papua New Guinea (PNG), in October, 1996, and a second facility located in Nauru in mid-1998. Both TWP sites include a cloud radar.

Because these ground sites operate continuously, data are available every time a satellite crosses over the facility. Consequently, if the ground-based cloud data can be taken as truth, it now becomes possible to acquire statistically meaningful samples of coincident ground-based and satellite measurements (33). While there are still some difficulties with correlating satellite observations having horizontal scales of a kilometer or so with the narrow-beam measurements of radar and lidar, this problem is actually less severe than trying to match up the very small volume typically sampled by aircraft microphysical instruments.

The obvious task then is to determine the accuracy of ground-based retrievals of cloud properties. This can be accomplished using in-situ observations above the ground-based sensors (33). Validation of the ground-based sensors requires deployment of aircraft (or other in-situ platforms) that can directly measure cloud location and cloud microphysics. Because the ground-based instruments operate continuously and (obviously) at a fixed location, it is much easier to coordinate aircraft flights to obtain the necessary coincident data than in the case of aircraft-satellite comparisons. This approach was begun during the FIRE campaigns and is now being carried out at the ARM Oklahoma site with good results. Unfortunately, the remote location of the ARM sites in the tropical western Pacific makes it much more difficult to carry out a similar program. The facilities at Manus Island and Nauru are inadequate for the support of sophisticated high-altitude research aircraft, which are necessary for sampling of tropical cirrus.

These considerations lead to the following strategy for tropical cirrus. A suite of instruments similar to those available at the TWP ARM locations are installed on two research ships. This has already been done in the tropics by a team of research scientists, principally from the NOAA Environmental Technology Laboratory, using a NOAA research vessel. These instruments are operating continuously from the ship platform, which may be located in reasonable proximity to a tropical airfield that can support the research aircraft. The research aircraft, equipped with similar remote sensing instruments, both radar and lidar, and in-situ instruments to sample cloud properties, overfly the ship(s). Analysis of the resulting data set will permit (1) comparison of ground-based and aircraft radar data to evaluate the extent of attenuation problems and (2) validation of ground-based retrievals of cloud properties with in-situ data.

Because the ground-based sensors deployed on the ships are nearly identical to those at the ARM locations and the environmental conditions for the proposed observations are similar, the transfer of the results to the ARM data set is straightforward. The ARM sites then become the principal mechanism for validation of the satellite retrievals. Each time the satellite passes over Nauru and Manus, data are acquired, thus providing a significant set of coincident data for research purposes.

3.3 Cirrus Cloud Modeling

The three major elements of research leading to increased confidence in cirrus cloud/climate feedback predictions were discussed in Section 3.1. To reach the CRYSTAL goals, three different types of cirrus cloud models are required:

- CRMs to simulate cloud formation, microphysical, and cloud-scale dynamical processes on local to regional scales;

- RT (Radiative Transfer) models to determine the effects of a given distribution of cloud ice and liquid water on radiative heating/cooling rates; and

- GCMs to portray the collective effects of an ensemble of such clouds on the large-scale energy balance and general circulation.

This section describes a strategy for the development, use, and validation of each type of model in the CRYSTAL context.

The starting point for any attempt to predict the effect of cirrus clouds on climate in large-scale models is a determination of where and when such clouds should form. This is a major uncertainty for all cloud types, since the atmosphere is generally not saturated on large scales and the factors that control small-scale variability of relative humidity are poorly constrained. It is even more uncertain for cirrus, because the reference for determining saturation (liquid vs. ice) may change with temperature, dynamical context, and availability of nucleating particles. The microphysical properties of the clouds introduce more questions: What determines the relative amount of ice vs. supercooled liquid water? What size and shape ice crystal should form in a given setting, and what are the relevant fall speeds for depleting cloud ice? How do the lifetimes of ice clouds compare to those of supercooled liquid clouds that form under similar atmospheric state conditions? How does the detrainment of cloud water into a cirrus anvil alter the microphysical properties of the cloud? What determines the extent of the condensate detrainment itself in an active cluster of convective cells and cirrus anvils? What cloud-scale dynamics are forced by the cirrus thermodynamic and radiative processes, and to what extent does this act to regenerate the cirrus and extend its lifetime? In essence, we need to know the progression and extent of forcing and input from deep convection, and the evolution of the deposited anvil cloud including its possible transition into a persistent detached regenerative cirrus state.

To answer these questions, a hierarchy of cloud-resolving models is required. These include one-dimensional explicit microphysics models, individual cloud-scale models, and cloud ensemble models with domains of hundreds of kilometers that crudely resolve individual updrafts and downdrafts and utilize bulk microphysics parameterizations. The first step in the CRYSTAL strategy for the use of CRMs is to validate them against CRYSTAL in-situ and surface remote sensing observations for a variety of case studies that include all phases of the tropical cirrus lifecycle: Actively growing cumulus anvils, mature cirrus anvils no longer being actively fed by the convection that generated them, and isolated cirrus that can no longer be identified with the process that originally produced it. This involves a series of case studies and is typical of the manner in which CRMs have been utilized in the past.

The next step, using CRMs to develop cirrus parameterizations for GCMs, is largely unrealized to date: a large ensemble of CRM simulations must be run, covering a variety of radiative and large-scale dynamical forcing conditions and a variety of sea surface temperature (SST) boundary conditions. Statistical relationships between cirrus properties and either domain-averaged state variables or domain-accumulated moments of these variables, derived from the ensemble of simulations, then form the basis for candidate GCM parameterizations. Long-term surface and satellite remote sensing observations may play a role here in the validation of such parameterizations.

The final step in the process is to see whether relationships based on the tropical western Pacific climate regime studied by CRYSTAL give reliable results when applied to other climate regimes, e.g., other tropical locations and the midlatitude cirrus studied in FIRE I and II. If not, an iterative process will be needed to isolate the differences that cause the results to diverge.

Equally important to the understanding of tropical cirrus are their effects on vertical profiles of radiative heating and cooling. This is important directly in calculating the climate feedback of changes in such clouds, and indirectly via the influence of cirrus on the small-scale dynamical processes that maintain them and the large-scale circulation that regulates the global distribution of all cloud types. Two fundamental uncertainties limit our ability to convert predicted ice water content distributions into radiative properties in large-scale models: (1) Small-scale inhomogeneities in ice water content and/or microphysical properties imply that the nonlinear relationship between ice content and albedo or emissivity cannot simply be mapped to the large scale; in addition, three-dimensional aspects of radiative transfer that are ignored in large-scale models may become significant. (2) The scattering properties of ice crystals of different shapes, and of different size distributions of ice particles, are not yet adequately understood.

CRYSTAL must therefore include fundamental radiative transfer studies aimed at the development of parameterizations of the radiative effects of ice clouds. This first requires communication between the CRM and radiative transfer communities. The former can determine the nature of typical small-scale distributions of cirrus ice, their dependence on cloud cover and dynamical state, etc. The latter can then explore the question of whether small-scale variability can be accounted for in large-scale model radiation codes via scaling, for example, using a limited number of "inhomogeneity parameter" corrections to grid-scale radiative properties. An important question here is whether such small-scale variability is universal or specific to different cloud types. Thus, collaboration between CRYSTAL researchers and their counterparts in previous field programs such as the FIRE-II Atlantic Stratocumulus Transition Experiment (ASTEX), FIRE-III Arctic Cloud Experiment, and ongoing programs such as ARM is crucial. Likewise, it must be determined whether a single, or a limited number of, ice phase functions can be applied in large-scale models to account for cirrus scattering effects. Obvious questions include the differences between the scattering properties of warm and cold cirrus, and of ice detrained into anvils from cumulus updrafts vs. ice formed in situ in isolated cirrus.

The last step in cirrus modeling is to implement cirrus parameterizations based on CRYSTAL investigations into GCMs and validate them using satellite data sets including, but not restricted to, those that have been developed and/or validated themselves using CRYSTAL field experiment and surface remote sensing observations. A successful CRYSTAL observational component will provide essential constraints for GCMs: A model will not be considered to be validated unless it can simultaneously match observed top-of-the-atmosphere radiative fluxes (e.g., from Clouds and the Earth’s Radiant Energy System (CERES) and the component cloud and atmospheric parameters that determine these fluxes (e.g., ice/liquid water content, cloud cover, physical thickness, particle size, optical thickness, humidity, and temperature). Furthermore, validation is not defined as simply matching monthly mean global distributions of such parameters. For global change applications, it will be necessary to show that observed variability on diurnal, seasonal, and interannual time scales, and observed relationships between cloud properties and atmospheric state variables, can be reproduced by the GCM. The latter type of comparison implies that the important modes of energy and moisture conversion and transport in GCM cloud-producing dynamical systems must resemble those in their real-world counterparts, if not on a case-by-case basis, then at least when composited over a sufficiently large number of events. The validated global satellite observations and the continuous observations at fixed locations obtained via ARM are essential for this evaluation.

Of course, cloud/radiation errors in free-standing GCM simulations can be caused either by cloud parameterization deficiencies or weaknesses in other parts of the model. Single column models (SCMs) forced by observed dynamical fluxes may help to isolate the sources of error in this case. GCMs with validated cirrus parameterizations can then be applied to simulate climate variability and change scenarios, ultimately leading to increased confidence in the predictions that result.

The process of parameterization development and validation is necessarily iterative, involving significant collaboration between the CRM and GCM communities. This is the strategy that has been adopted by the Global Energy and Water Experiment (GEWEX) Cloud System Study (GCSS), and it is expected that CRYSTAL cloud modelers will be active participants in one or more of the GCSS Working Groups, especially #2 (Cirrus) and #4 (Deep Convective Clouds). It is important to note that GCSS is an umbrella that merely serves to organize an array of individual modeling activities. CRYSTAL will make an important contribution to GCSS through its coordinated cirrus observation and modeling activities.

4.0 EXPERIMENTAL DESIGN

The proposed field program is designed to address three classes of issues:

1. Validation of remotely sensed cirrus cloud properties, both from the surface and from satellite.

2. Simultaneous measurements of cirrus microphysical properties and radiative effects over the cloud lifecycle.

3. Relate the properties of deep convective systems (such as core updraft speed and lifetime, and convective mass and water flux) to the generation of cirrus anvils and to horizontally extensive cirrus clouds which can persist for days.

The Tropical Western Pacific arena has been chosen as the preferred location for the CRYSTAL field phase. However, CRYSTAL has been designed as a two phase field program, beginning with an experiment in the South Florida area, the Florida Area Cirrus Experiment or CRYSTAL-FACE, in 2002, followed by an experiment in the Tropical Western Pacific, CRYSTAL-TWP, in 2004. The motivation for the TWP focus and the rationale for precedent FACE are described in this section.

Motivation for a Tropical Western Pacific Cirrus Experiment

The commitment to the Tropical Western Pacific (TWP) area as the preferred location is based on the following reasons: extensive background knowledge of (and specific interest in) cloud, ocean and meteorological phenomena in this region as manifest in TOGA and the associated and on-going modeling and analysis studies; uniqueness and climate importance of cirrus cloud systems associated with western Pacific convection; linkage between tropical Pacific cirrus and subtropical jet stream cirrus systems prevalent over south-central North America; collaborative opportunities with Pacific research partners including Australia and Japan.

TOGA-COARE and subsequent analysis and research studies have provided a wealth of information about the deep tropical environment in the Pacific basin. While TOGA-COARE concentrated upon the convective environment and convective processes, it provided only tantalizing hints at the relationships between the deep convection and radiative effects of the upper tropospheric clouds produced by that convection. Perhaps most important are the relationships among the convective ensembles that produce cirrus anvil outflows, the spatial extent and microphysical and radiative properties of these anvils, the subsequent evolution into extended cirrus systems, and the radiative effects of these systems on the convective environment. Important relationships also likely exist among many other phenonmena including the microphysical evolution of upper tropospheric cloud layers (34), stratiform cloud precipitation (35,36,37), the “anomalous” absorption of solar radiation (38), the thermostat hypothesis (4), and the strength of the Hadley cell (6). It is in this rich setting of recent scientific inquiry and activity that CRYSTAL can best continue the evolution of our understanding of tropical cirrus cloud systems in relationship to other key components of the global climate system. The complex and dynamic relationships between tropical convection and cirrus cloud systems require that we focus our inquiries in regions where we have the best information available. Thanks to COARE, significant strides have been made in understanding the TWP convective environment (21). Systematic efforts to simulate these convective systems have already been undertaken by the GCSS modeling community (39,40,41). One notable conclusion is the significant uncertainty associated with upper tropospheric aspects of these systems and models.

Analysis of ISCCP data (42) have recently shown that subtropical and tropical cirrus optical thickness show a complicated behavior that could be related to changes in the dynamical regime in which the clouds are formed. Among these unique properties of the tropical Pacific cirrus systems are the heights, temperatures and possibly ice water content and crystal size distributions of the convective anvil outflow. The tropical Pacific cirrus outflow regions are fully 100 mb higher and as much as 20°C colder than their tropical counterparts in other regions. Satellite imagery (43) suggests that these anvils are also more reflective, the possible result of an enhanced population of very small ice crystals. The unique placement, temperature and microphysical- thus radiative - character of these cirrus clouds over a basin as large as the TWP has strong potential ramifications on the effects that these cloud systems have on both regional scale circulations (6) and the climate (27). These unique properties may also play a role in the longevity of these cirrus systems as they stream from the tropics into the middle latitudes as well as the pervasiveness of optically thin ubiquitous cirrus clouds in the tropics.

A third reason for selecting the tropical Pacific is that this basin is the primary source region for much of the upper tropospheric moisture and cloud over the south and central United States. In the predecessor FIRE Cirrus-I and -II field campaigns, cirrus cloud systems associated with the subtropical jet stream were sampled and studied. One of the CRYSTAL objectives is to study the evolution of these persistent cirrus/moisture streams originating in the tropics and forming a teleconnection link with the higher latitudes. Geostationary water vapor imagery clearly links the Pacific source region with these systems. These same images also show curious evolution of these systems during their migration; this evolution is undoubtedly linked to internal dynamics, microphysical changes and temperature and height factors (43).

Two-Phase Field Experiment Approach

The observational component of CRYSTAL has been designed in two phases. The two separate, yet highly coupled, phases are separated in both time and space: one is set in southern Florida in 2002 (CRYSTAL-FACE) and the other in the Tropical Western Pacific region in 2004 (CRYSTAL-TWP).

Cirrus cloud systems in the South Florida and Tropical Western Pacific regions are different in several significant ways.

Lifetime: TWP systems tend to be longer lasting than their Florida counterparts.

Height Regime: TWP systems tend to be as much as 100 mb higher and consequently colder than in Florida

Regional-scale Circulation: Florida systems are often under the influence of a regional sea-land breeze circulations (tropical storms excepted). These regional influences are generally absent in TWP systems.

While systems in both regions are embedded in the large-scale Hadley and Walker circulations and are usually associated with tropical wave activity, the organizing influence of the sea-land breeze circulations imparts some continental characteristics, specifically stronger updrafts with the resultant likelihood of significant microphysical, and possibly radiative, differences. In addition, vertical wind shear is more likely to be a significant factor in Florida than in the TWP.

Ubiquitous Cirrus: The areally extensive, optically thin, subtropopause cirrus prevalent in the TWP is not commonly found in the South Florida region. It is unknown to what extent differences in the above factors, or other factors, lead to this result.

Similarly, it is not known with any certainty how the differences in height of the generating deep convection, or differences in regional or large-scale circulation, are related to the observed differences in cirrus cloud lifetime between Florida and the TWP.

Convective systems in Florida do contribute moisture to the subtropical jet stream circulation with subsequent transport to the European continent in a manner similar to the role that the TWP plays for the continental US.

Rationale for an Early South Florida Experiment

The compelling reasons for a two-phase observational program with a Phase 1 experiment to be conducted very soon are:

Preparing for TWP - Assembling and scheduling the resources to conduct CRYSTAL-TWP is a significant undertaking requiring substantial lead time and inter-agency and international coordination and cooperation. A major field experiment with the required resources is unlikely before 2004 at the earliest. Progress toward achieving CRYSTAL objectives would be significantly accelerated if at least some appropriate data sets were collected in the near future. Such data would enable very useful cloud system modeling studies to proceed, as well as various other radiative transfer and remote sensing studies. CRYSTAL-FACE would markedly speed progress in all areas and set the stage for CRYSTAL-TWP and subsequent EOS satellite missions.

Supporting Timely Satellite Algorithm Validation and Development - A major focus of CRYSTAL is the validation of upper tropospheric cloud data products derived from EOS satellite missions. By the summer of 2002, the two flagship EOS missions will have been launched, i.e., Terra (AM), successfully launched in December 1999, and Aqua (PM), planned for December 2000. The first year of the Terra (AM) validation program is strongly focused on mid-latitude cloud systems. Thus, CRYSTAL-FACE will be well timed to contribute strongly to the validation of tropical cloud products derived from these missions.

The following EOS CloudSat and PICASSO-CENA missions, scheduled for launch in April 2004, are highly focused on cirrus clouds. Both employ a mix of passive and new active remote sensing technology. CRYSTAL-FACE, in 2002, will provide an excellent and timely opportunity to collect quality data sets in support of algorithm development for these missions while CRYSTAL-TWP will serve as a key vehicle for validation of the actual data products derived from the satellite measurements.

The final EOS flagship mission, CHEM, is scheduled to be launched in December 2002 and will fly in close formation with Aqua (PM), CloudSat and PICASSO-CENA -- all in same sun-synchronous 1:30 am/pm orbit. The CHEM mission also has a focus on the tropical upper troposphere and could also potentially benefit from CRYSTAL-TWP in 2004.

Aqua (PM), CloudSat and PICASSO data will be essential to the execution of the Tropical Western Pacific Crystal campaign because of the remote, maritime location. Observations from Terra (AM) and CHEM will also be highly useful for this purpose, especially Terra (AM) because of the enhanced temporal coverage (9:30 am/pm).

Conversely, Aqua (PM), CloudSat and PICASSO (and Terra (AM) and CHEM) data will be essential to the application of knowledge gained in CRYSTAL to other geographic domains.

Testing Technology and Strategy - Techniques and new instrumentation for the measurement of physical and radiative properties of cirrus clouds are currently being designed and laboratory tested. Performance of these techniques and hardware, as well as observational strategies, will be evaluated in the CRYSTAL-FACE campaign to insure suitability and applicability in the more demanding tropical western Pacific campaign. In essence, CRYSTAL-TWP will benefit markedly by the lessons learned during CRYSTAL-FACE and subsequent analysis and modeling studies.

Taking Advantage of Unique Observational Strategies - CRYSTAL-FACE offers some observational assets that will not be available in the TWP region. These assets specifically include substantial rawinsonde support offered by the US NWS, opportunity for numerous surface site observations, multiple doppler radars to document convective system mass flux, and numerical model support in a data rich environment.

Because of the availability of multiple assets to document the atmospheric dynamics attending cirrus cloud formation and lifecycle; documentation of the relationship between dynamics and cirrus cloud systems will be an emphasis of the Florida campaign.

4.1 Conceptual Design

Prior radiation and microphysics studies of maritime tropical cloud systems have relied either primarily on aircraft, i.e., CEPEX, or on aircraft operating in conjunction with surface-based remote sensing instrumentation, i.e., TOGA COARE field experiment (see Figure 2). The latter approach is the preferred mode for CRYSTAL. However, obtaining the desired surface-based observations is difficult if the study is restricted to truly maritime systems.

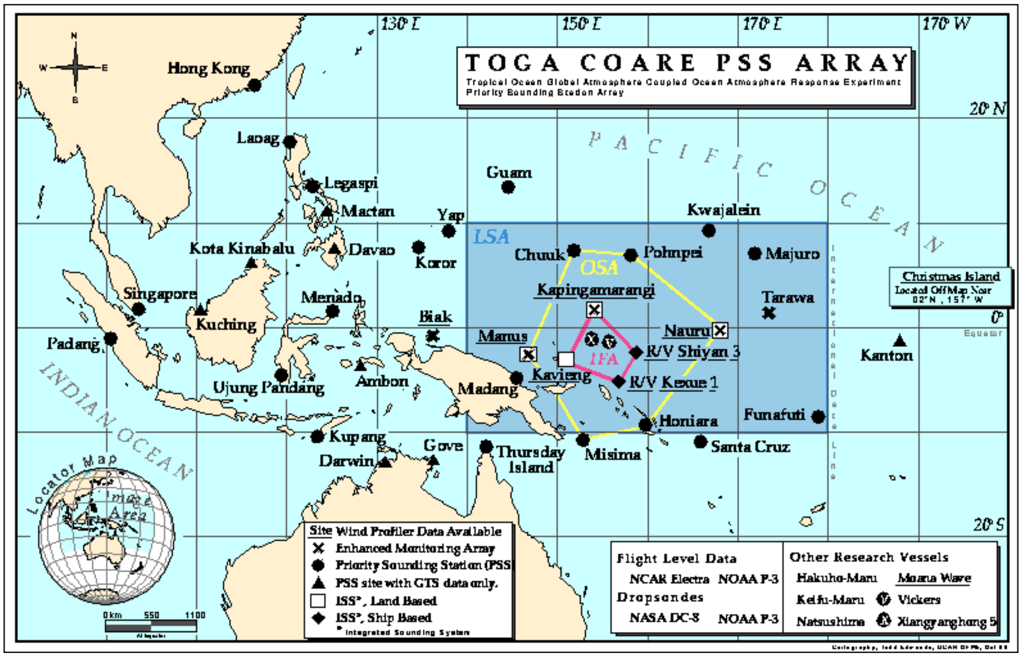

Figure 2. Map of the TWP region of TOGA COARE.

Because of the lack of suitable land facilities and the strong influence of any sizable land area on convective activity, obtaining active surface-based remote sensing observations is a particularly challenging endeavor in the Tropical Western Pacific. To avoid the undesired land influence, the DOE ARM Program has located ground facilities on the small islands of Manus (PNG) and Nauru. However, neither of these locations can support the deployment of sophisticated atmospheric research aircraft or large numbers of investigators. Locations such as the north of Australia or Guam have the infrastructure to support large research efforts, but the land effects are too large to provide data representative of oceanic convection. In order to circumvent these difficulties, a joint aircraft and research vessel experiment is proposed for the Tropical Western Pacific -- CRYSTAL-TWP. This will enable sampling of maritime convective systems and cirrus in the region of highest scientific interest without undue influence of land masses.

Land influence is unavoidable in the South Florida area. However, suitable sites for operation of sophisticated surface-based equipment are readily available as are convenient bases for operation of research aircraft. The potential to obtain critically needed data sets suitable for addressing CRYSTAL objectives in the near term, even if there is an undesirable land influence, is very valuable in and of itself, as well as in preparation for CRYSTAL-TWP. CRYSTAL-FACE will provide these necessary data at the earliest opportunity.

Remote sensing will constitute an important part of the field campaign measurement capability. Satellite data will provide the horizontal distributions of vertically integrated cloud properties at a variety of spatial and temporal scales. In addition to equivalent coverage by polar and inclined orbit satellites at each location, the location of CRYSTAL-FACE also allows utilization of near-continuous GOES satellite observations. GMS satellite observations will be used for CRYSTAL-TWP. Airborne and surface-based (land or ship) remote sensing systems will be heavily utilized to describe the spatial (especially vertical) and temporal structure of the cloud systems. Millimeter-wavelength cloud radar will characterize the spatial and temporal structure of cloud ice water content. Doppler rain (cm wavelength) radar will enable quantification of precipitation and the convective mass and water fluxes transported from the lower and middle troposphere into the cirrus layer. Wind profiler observations will provide a continuous measure of three dimensional motions throughout the troposphere. Lidar observations from the surface and aircraft will help characterize the spatial variability of cloud layers and their radiative properties. Because of their inherent differences in detectability and sensitivity, lidar and radar are quite complementary and together provide a much more complete and less ambiguous description of clouds than is possible with either system alone (44). The proposed mode of observation will utilize a combination of at least three aircraft, up to three surface sites, and a multitude of satellite sensors. For CRYSTAL-TWP, the surface sites will include two ships and an island site (Chuuk). Island sites may also be used for CRYSTAL-FACE, e.g., Andros Island, but the main surface site will be in the Florida Everglades. Measurements from a ship would be very useful for CRYSTAL-FACE, though this may be difficult to arrange in time for the experiment, i.e., 2-year lead times are usually necessary for research vessel deployments.

The **simpler experiment design**, Figure 3, is intended to address issues of remote sensing, radiation and microphysics, and cirrus lifetime. Two remote sensing aircraft are flown above (RS1) and below (RS2) a cirrus deck, with at least one additional aircraft (IS1) sampling in situ the microphysical characteristics of the cirrus layer. The surface sites would be equipped with remote sensing instrumentation, possibly including radar, and rawinsonde capability.

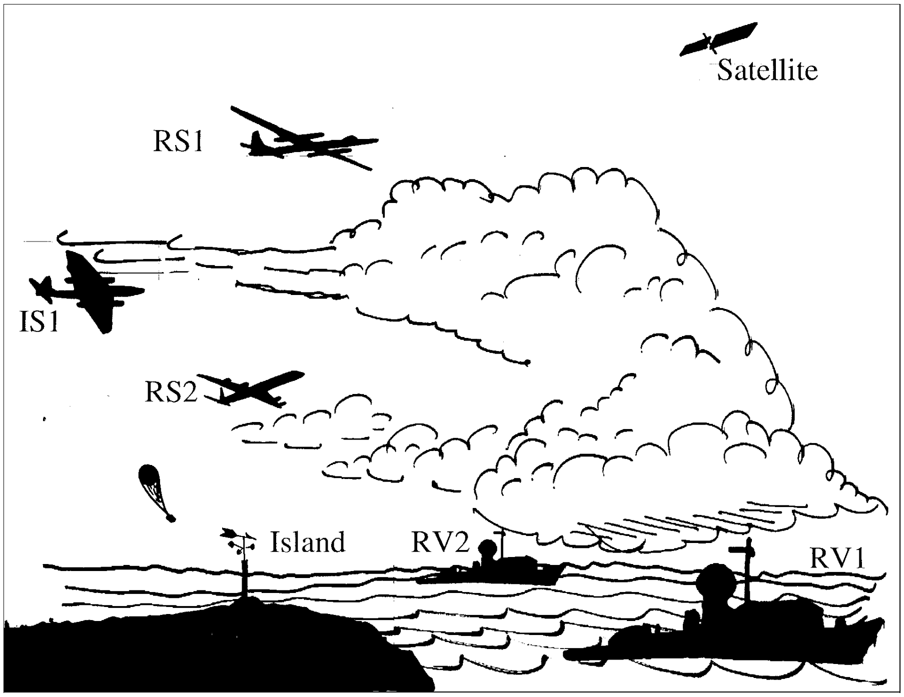

Figure 3 - Schematic of **simpler experiment design**

The more desirable, yet more **complex, experiment design** would dramatically enhance the capability to address issues of the relationship of cirrus generation to deep convection as well as cirrus lifetime. This configuration, illustrated in Figure 4, requires the same two remote sensing aircraft (RS1 and RS2), one flown above the convection and associated clouds, with the other flown underneath the stratiform and cirriform regions. Two additional planes performing in-situ observations (IS1 and IS2) are required to sample the complex microphysical domain inside the stratiform and cirriform regions. An additional aircraft carrying a dual Doppler radar (such as Electra Doppler Radar, ELDORA) would be essential to define the associated circulation, precipitation and mass flux of the deep convective clouds. The surface site configurations would be the same as in the first mode. Aircraft operations would be conducted in the region of one of the surface sites or within the triangular array defined by them.

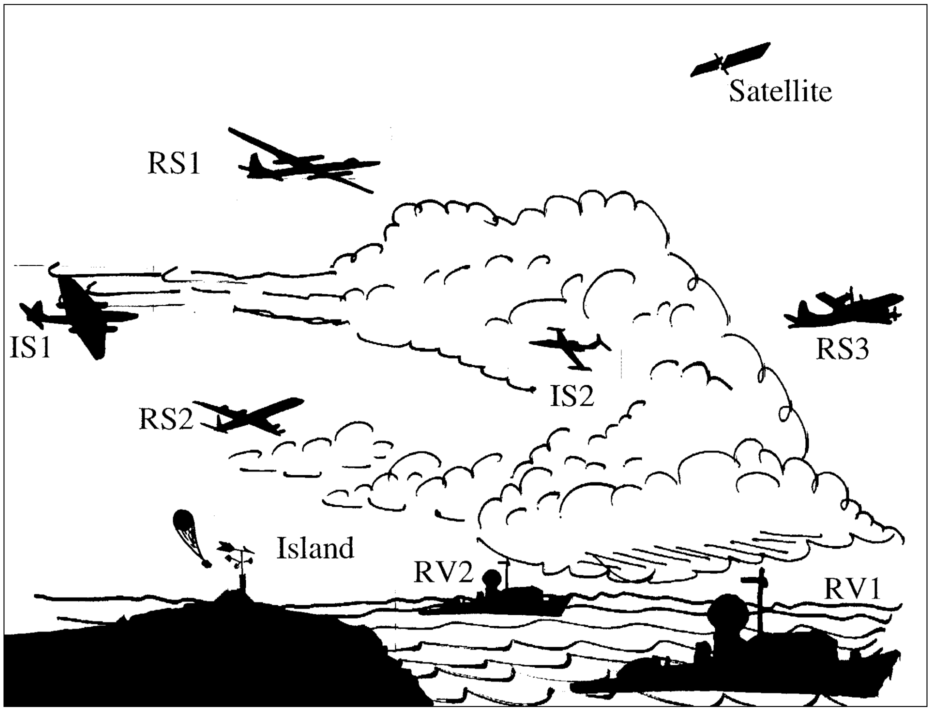

Figure 4 - Schematic of **complex experiment design**

This latter experiment design explicitly addresses the quantitative relationship between deep convection (mass flux) and cirrus generation in terms of parameters carried in GCMs. This is a key aspect in developing realistic linkage between these important components of the climate system and is not addressed under the simpler experiment design.

4.2 Time and Location

CRYSTAL-FACE

For the Florida Area Cirrus Experiment component of CRYSTAL, the intended site of airborne observations are the waters off the tip of southern Florida, including the Florida Keys. The anticipated base of airborne operations is Patrick Air Force Base which is located on the central Atlantic coast of Florida, about 300 km from the Florida keys (see Fig 5). This base has been previously used for ER-2 and DC-8 operations during CAMEX-3 and other deployments in this region. It is far enough from the intended site of observations to limit the impact of the observed weather systems on airborne operations, e.g., ER-2 and WB-57 take-off and landing constraints, yet close enough to minimize transit time. Ground-based remote sensing equipment will be located at a site in the Florida Everglades that is operated by the University of Miami. Other locations could also be used include the Florida Keys and Andros Island (located about 250 km east of the Florida Keys). Andros Island was recently used by NASA for similar installations during CAMEX-3. The Everglades site is particularly attractive because of the tendency for cirrus outflow from offshore (to the southwest) convective disturbances to advect over this site in a generally southwesterly flow aloft. The preferred time for this experiment is July-August 2002.

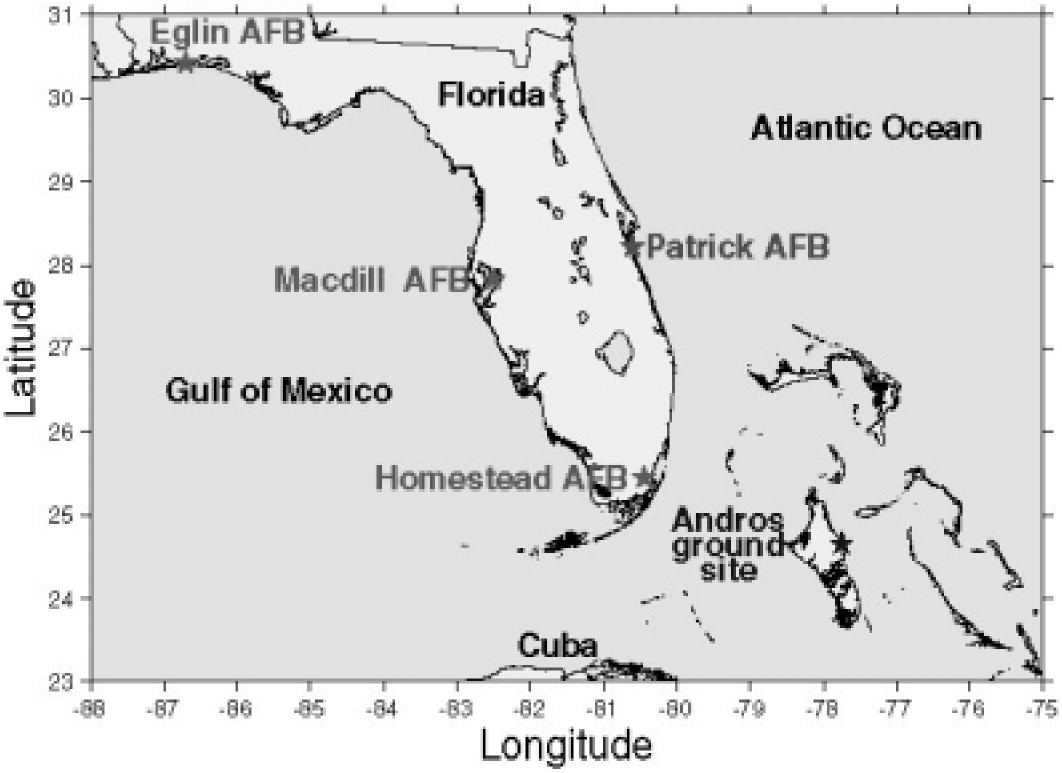

Figure 5. South Florida Operations area -- CRYSTAL - FACE

CRYSTAL-TWP

The anticipated base of operations for the Tropical Western Pacific Experiment component of CRYSTAL is Guam, Northern Mariana Islands. There are adequate facilities for all aircraft and personnel on the island. Research vessels would be located south or southeast of Guam between 5° and 10°N. Latitude (see Figure 6). An island surface site on the island of Chuuk, Federation of Micronesia, will be developed with basic remote sensing, rawinsonde and radiation instrumentation. The preferred time for the aircraft/ship component of the experiment is June-July, 2004.

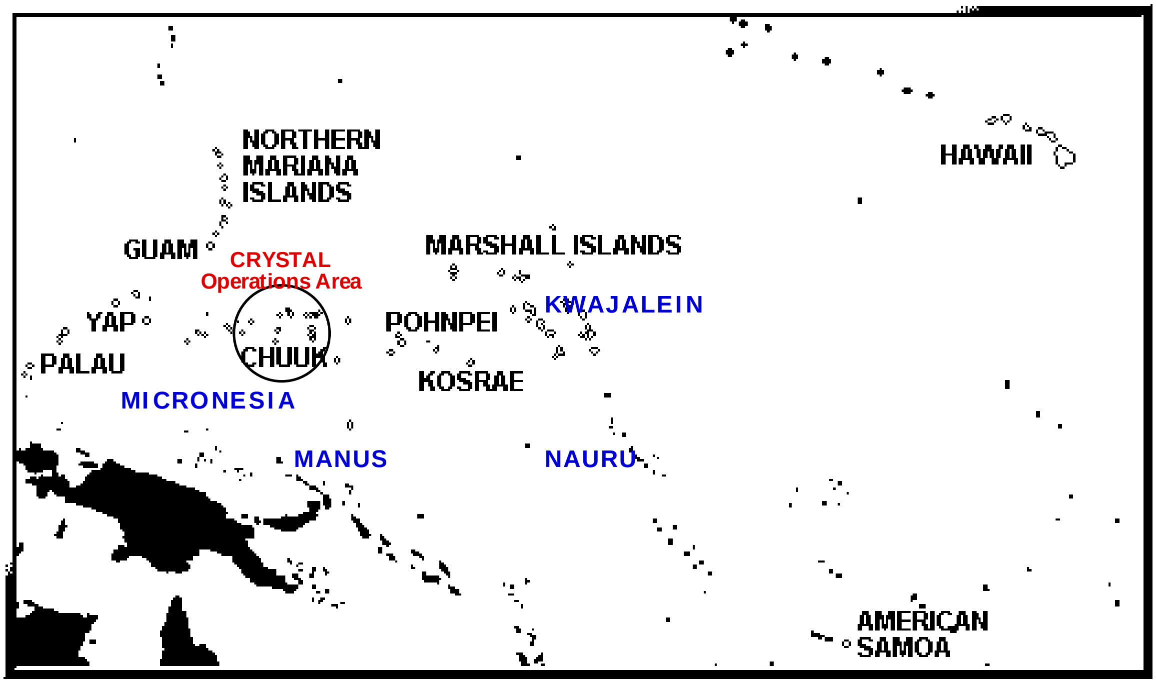

Figure 6 - Map of proposed CRYSTAL operations area.

4.3 Platforms

The following references to specific platforms and instruments are not meant to be exclusive. They are intended to represent a class of observational capabilities known to the drafting panel at the time of preparation of this document. Other platforms/instruments of equal or superior capability would certainly be considered.

4.3.1 Aircraft Platforms

Candidate airborne platforms are the NASA ER-2, NASA WB-57, NCAR Electra (ELDORA) , NASA DC-8 and an additional small jet capable of in-situ measurements in the upper troposphere.

The NASA ER-2 provides an indispensable payload of state-of-the-art active and passive airborne remote sensing instruments. This platform serves as satellite simulator with the invaluable capability of loitering over an area for extended time to enable repeated sampling of a specific scene at greater spatial resolution than possible from satellite altitude. There is presently no alternative for this platform.

The NASA WB-57 provides the unique capability to obtain a broad range of *in-situ* measurements in the tropical upper troposphere, including microphysical, aerosol, chemical and state variables. It is only with the availability of this capability that direct observations of the upper portions of tropical cirrus systems can be made. For CRYSTAL-FACE, a small to medium size jet, such as Lear or Citation, might be able to meet most of the present requirements, as was done for TEFLUN-A and TEFLUN-B. However, the unique altitude capability of the WB-57 is absolutely essential for CRYSTAL-TWP. Gaining the necessary experience with using this platform in the challenging operational environment considered by CRYSTAL-TWP argues strongly for a WB-57 deployment in CRYSTAL-FACE as well.

Both the ER-2 and WB-57 are capable of deploying dropsondes for characterization of the overall state of the atmosphere within the sample region, i.e., temperature and wind profiles. This is especially important for operations over data-sparse regions, such as the Tropical Western Pacific.

The ELDORA Doppler rain radar provides a unique mobile airborne capability to measure the convective mass and water flux associated with deep convection. The capability to adjust the sample volume to the geometry of a specific convective system is a tremendous advantage over fixed surface-based systems, e.g., the capability to fly box patterns around a convective line as done in TOGA-COARE. The ELDORA may be moved to another aircraft platform within the next couple of years. While alternative systems exist (NOAA P-3), the scan pattern, sensitivity and wavelength of the ELDORA system make it the preferred system for CRYSTAL.

The NASA DC-8 provides a platform for up-looking active remote sensing instruments focused on cirrus cloud and water vapor measurements, specifically a Differential Absorption Lidar (DIAL) and millimeter-wavelength cloud radar as well as passive radiometers. While such instruments could potentially be integrated on the aircraft carrying the ELDORA, they have already been integrated on the DC-8. Moreover, the emphasis of the DC-8 measurements would be on the cirrus outflow while ELDORA would necessarily focus on measurements of the deep convective system itself. Thus, two platforms are optimal. Alternatively, mm-wavelength cloud radar has also been integrated on a small prop plane. This could be used as a cost containment measure for CRYSTAL-FACE but may not be feasible for CRYSTAL-TWP due to range limitations. It is unknown if a DIAL system could be integrated on such a platform.

A second *in-situ* aircraft platform, e.g., Lear or Citation, is highly desirable, especially for CRYSTAL-TWP. Tropical cirrus systems, even more than their mid-latitude counterparts, tend to rapidly develop large vertical depth through the ice crystal fall process. Systems with depths of 4-5 km are typical and larger values occur. Thus, to generate a microphysical profile at a vertical resolution of 0.5 km requires 8-10 flight legs. While spiral decent patterns can also be used to generate such profiles, data obtained during longer level flight legs are very valuable in characterizing the dynamical structure of the cloud system and also help establish the statistical integrity of the microphysical measurements. Experience has shown that two *in-situ* aircraft provide an essential enhancement in data coverage such that the whole is much greater than the sum of the parts, i.e., the applicability of the data is markedly improved by increased sample volume in this highly variable microphysical environment.

In the case of two *in-situ* aircraft platforms, the WB-57 will be used for cloud sampling in the region from 13 to 18 kilometers while the second jet will be used for cloud sampling at altitudes below 13 kilometers and in regions closer to the more active regions of the convection. The maneuverability and hardiness of small research jets is superior to that of the WB-57.

Additionally, the use of unmanned aerospace vehicles (UAV) would be a desirable addition to the airborne resources identified above. While this technology is still in the formative stage, recent efforts show that UAVs could be especially useful to CRYSTAL investigations. A UAVs maximum altitude (50-60K') and on-station flight duration (4-6 hrs) make it a very attractive tropical cirrus research platform.

4.3.2 Ship Platforms and Land-based Sites

For CRYSTAL-FACE, ground-based measurements will be obtained from a site in the Florida Everglades that is operated by the University of Miami. Measurements will include a millimeter-wavelength cloud radar, a sophisticated cloud lidar system, and a variety of passive remote sensing instruments. Also of extreme value, both to operations as well as to characterization of the convective systems, are observations from the NOAA NEXRAD system in South Florida. Deployment of an additional Doppler rain radar, such as the mobile NCAR system, to the Everglades site would be a significant enhancement. It would be particularly valuable if an MMCR-class radar were deployed at this location because of the inherent sensitivity and water attenuation differences, ~ 10 db greater sensitivity than over any research grade 94 GHz radar (45). Ground-based measurements from other sites are also possible, such as Andros Island, as are observations from ships. Finally, CRYSTAL-FACE will benefit tremendously from the availability of routine operational rawinsonde soundings over the region - mainland and island sites -- and the consequent improved quality and resolution of the NCEP operational analysis in this region. Enhancements to the operational sounding schedule should be strongly considered as 3-hourly soundings provide a markedly superior description in convective situations.

For CRYSTAL-TWP, ship-based measurements are key. Participating ships are expected to carry instrumentation similar to that available at the DOE ARM sites in the tropical western Pacific, including millimeter cloud radar, precipitation radar, and cloud lidar as well as a suite of passive radiometric instruments. NOAA is currently evaluating the possibility of permanent deployment of this instrumentation on the research vessel Ron H. Brown; other ships provided by international participants would be encouraged to support similar instrumentation. It is also essential that research vessels provide frequent rawinsonde soundings to enable characterization of the thermodynamic and dynamical state of the convective environment which is essential for modeling studies. An island site (Chuuk) will provide a substantial subset of the proposed ship-borne observations, including soundings. The present ARM sites are too distant for coordination with aircraft operations out of Guam but would nonetheless provide additional information on tropical cloud systems in the larger region.

The proposed platforms for deployment data collection in CRYSTAL are listed in Table 1.

Table 1 - Mission/Candidate Platforms Table

MISSION	**CANDIDATE PLATFORMS**
Remote sensing observations for $h > 13$ km	NASA ER-2
In-situ microphysics observations	
$13 < h < 18$ km	NASA WB-57
$h < 13$ km	Learjet/Citation
Remote air motion/precipitation	NCAR Electra or NOAA P3
Remote sensing cloud and water vapor observations, meteorological observations	NASA DC-8
Surface-based observations Remote sensing	*CRYSTAL-FACE* U.Miami Everglades site Possible other sites (e.g., Andros Island) *CRYSTAL-TWP* Research Vessel: NOAA Ron Brown Research Vessel: International Collaborators Supplementary Surface Site (Chuuk) Permanent ARM sites (Manus and Nauru)
Rawinsonde	Enhanced routine upper air soundings Special rawinsonde observations ER-2 - dropsonde WB-57 - dropsonde Research Vessels (CRYSTAL-TWP) Chuuk (CRYSTAL-TWP) Other sites (TBD)
Satellite remote sensing	EOS Terra (AM) and Aqua (PM) TRMM (CRYSTAL-FACE) EOS CloudSat, PICASSO-CENA and CHEM (CRYSTAL-TWP only) NOAA Polar Orbiters GMS and FY-2 DMSP LANDSAT ERS-1 and -2

4.4 Measurements

To achieve the objectives of CRYSTAL, a relatively comprehensive suite of radiative, microphysical, and remote sensing measurements are required. In essence, CRYSTAL seeks to characterize and quantitatively relate cirrus cloud microphysical and radiative properties and to quantitatively understand the coupled system of cirrus generation via deep convection and the subsequent cloud evolution in an environment subject to mesoscale and large-scale dynamical controls, as well as radiative forcing.

The basic radiative measurements are the upwelling and downwelling solar and infrared irradiance both above and below cirrus cloud decks from aircraft and from surface-based systems. These measurements should be of sufficient accuracy that the radiative flux divergence and associated heating rates can be reliably derived. In order to better understand the transmission of solar radiation and issues related to cloud absorption, spectrally-resolved measurements of the solar irradiance are highly desirable. Solar and infrared imagers, particularly those that simulate satellite observations, are also an important component of the aircraft payload.

Measurements of cloud macrophysical and microphysical properties are essential to the success of the proposed experiment. Remote sensor determinations of cloud boundaries from above and below cloud are required (e.g. cloud lidar). Measurements from below include both aircraft and surface-based systems. Ice water path and profiles of ice water content are critical measurements (e.g. mm radar). A wide variety of *in-situ* cloud microphysical measurements are needed including, but not limited to, measurements of ice crystal size distribution, ice crystal shape (habit), and aerosol size distribution. Because small ice crystals are likely to be an important component of tropical cirrus, measurements of crystals as small as 5 microns are critical, while measurements to 1 micron are desirable. The focus of the aerosol measurements is expected to be on those aerosols that serve as ice crystal nuclei. Thus, measurements of aerosol composition are highly desired, especially for the larger size particles. Aircraft altitude will be a prime consideration. It is expected that two microphysical aircraft will typically be required: one for altitudes below 13 km and another for altitudes above 13 km. Use of two in-situ microphysical aircraft is optimal even in the "simple experiment" design because of the substantial depth (3-5 km or more) of many tropical cirrus systems, the consequent time required to obtain microphysical profiles using an aircraft, and the central importance of microphysical profile information to the science objectives.

Critical to the success of efforts to quantitatively understand the linkage of deep convection to anvil production are measurements of the size and intensity of the convective systems, and particularly of cumulus mass and water flux. Such measurements will be made by airborne and surface-based Doppler radar. The NCAR airborne ELDORA system is particularly well suited to this task. In addition, down-looking Doppler precipitation radar measurements from above cloud top are highly desirable for completing the characterization of the convective core region and surrounding dense outflow. Such measurements would complement the millimeter wavelength radar observations of cirrus cloud properties in the anvil and extended cirrus outflow.

Measurements of environmental variables are also essential to the success of this experiment. Airborne high-frequency *in-situ* measurements of temperature, relative humidity, turbulence, and vertical velocity are required within the cirrus clouds. To enable diagnostic studies and modeling of the coupled deep-convection and cirrus-cloud system, measurements (soundings) of environmental temperature, relative humidity and horizontal velocity are required over a larger domain surrounding the convective system. This enables characterization of the larger-scale forcing and response and provides an independent measure of convective intensity and mass flux. Sounding will be made from surface-based systems (land sites and ships) as well as via dropsondes from high-altitude aircraft.

Table 2 identifies the table numbers for each of the platforms. Tables 3-10 summarize the proposed measurements for CRYSTAL for each platform. Each entry also contains a priority as assigned by the drafting panel as follows.

Priority 1 = Absolutely essential
Priority 2 = Highly desired; if absent, may have to modify scientific objectives
Priority 3 = Desirable; if absent, minor impact on objectives
Priority 4 = Neutral, may participate on non-interference basis

Table 2 - Table Number Locations of Platforms

Platform	**Table Number**
NASA ER-2	3
NASA WB-57	4
Learjet/Citation	5
NCAR Electra or NOAA P3	6
NASA DC-8	7
Research Vessels/Chuuk	8
Satellites	9
Other Activities	10

Table 3 - NASA ER-2

Platform/Activity	Desired Measurements	Observed/Derived/ Inferred Parameters	Candidate Instruments	Priority
NASA ER-2 (down looking remote)				1
	solar and IR irradiances - up and down	calculated radiative flux divergences heating/cooling rates	Flux radiometers	1
	spectrally-resolved solar irradiances	cloud parameters	SSFR	2
	multispectral radiance images	cloud parameters: top altitude optical thickness effective particle size thermodynamic phase reflectance ice water path	VIS/IR imagers (satellite sensor simulators): MAS AirMISR	1
	interferometric radiances	temperature profile water vapor profile sea surface temp cloud height cloud emissivity, effective particle size, phase, and ice/liquid water content	SHIS	2
	profiles of: differential lidar backscatter lidar backscatter and depolarization	vertical structure of cloud height water vapor cloud height cloud particle habit	*****Cloud Lidar: LASE CLS	1
	cm doppler radar	Characterization of convective cores	EDOP x band	2
	mm-radar reflectivity profile	IWC vertical structure effective particle size	cloud mm-radar TBD	1
	spectral sub-mm radiances	ice water path effective particle size	FIRSC	2
	microwave brightness temperatures	ice water path	Microwave Radiometer: MIR	2
	in-situ meteorology	T, p	T, p	3
	meteorological profiles	profiles: p(z), T(z), T_d(z), u(z), v(z)	Dropsondes	1
		real time transmission of selected parameters	STARLINK	4
	navigation	location, time		1

*****LASE or CLS is essential

Table 4 - NASA WB-57

Platform/Activity	Desired Measurements	Observed/Derived/ Inferred Parameters	Candidate Instruments	Priority
NASA WB-57 (in-situ top):				1
	cloud microphysical parameters	cloud particle: concentration size phase habit	FSSP 2D probes Replicator CPI g meter	1
	aerosol parmeters	aerosol size concentration	CCN counter and/or	2
			IFN counter and/or CN	2
			counter	2
	aerosol/ice crystal chemistry	aerosol chemistry ice surface chemistry	TBD	3
	meteorology	T, p, RH, u, v	T, p, RH, u, v	1
	water vapor	water vapor	spectroscopic, Lyman alpha, cryogenic hygrometers	1
	turbulence	parameter fluxes	TBD	2
	meteorological profiles	profiles: p(z), T(z), T_d(z), u(z), v(z)	dropsondes	1
	mm-radar reflectivity profile	ice/water path ice/water profiles	mm-cloud radar: TBD	3
		real time transmission of selected parameters	STARLINK	4
	navigation	location, time	TBD	1

Table 5 - Learjet or Citation

Platform/Activity	**Desired Measurements**	**Observed/Derived/ Inferred Parameters**	**Candidate Instruments**	**Priority**
Learjet or Citation (in-situ bottom):				1
	cloud miicrophysical parameters	cloud particle: concentration size phase habit	FSSP 2D probes Replicator CPI g meter	1
	aerosol parameters	aerosol size concentration	CCN counter and/or IFN counter and/or CN counter	2 2 2
	aerosol/ice crystal chemistry	aerosol chemistry ice surface chemistry	TBD	3
	meteorology	T, p, RH, u, v	T, p, RH, u, v	1
	water vapor	water vapor mixing ratio, relative humidity, frost point temperature	hygrometers: spectroscopic Lyman alpha cryogenic	1
	turbulence	parameter fluxes	TBD	2
	meteorological profiles	profiles: p(z), T(z), T_d(z), u(z), v(z)	dropsondes	2
	navigation	location, time	TBD	1

Table 6 - NCAR Electra or NOAA P3

Platform/Activity	Desired Measurements	Observed/Derived/ Inferred Parameters	Candidate Instruments	Priority
NCAR Electra or NOAA P3 (side looking remote):				2
	Doppler cm-radar reflectivity	convective mass and water flux, cell size u, v, w components updraft velocity horizontal convergence	scanning cm Doppler radar: ELDORA	1
	solar irradiances - up and down	radiative flux divergences heating/cooling rates	flux radiometers	2
	IR irradiances - up and down	radiative flux divergences heating/cooling rates	flux radiometers	2
	backscatter profile - up looking	vertical structure of cloud height	cloud lidar: TBD	3
	meteorology	T, p, RH, u, v	T, p, RH, u, v	1
	water vapor	water vapor	TBD	2
	turbulence	flux parameters	TBD	2
	navigation	location, time	TBD	1

Table 7 – NASA DC-8

Platform/Activity	**Desired Measurements**	**Observed/Derived/ Inferred Parameters**	**Candidate Instruments**	**Priority**
NASA DC-8 (Uplooking remote):				2
	solar and IR irradiances - up and down	calculated radiative flux divergences heating/cooling rates	Flux radiometers:	1
	spectrally-resolved solar irradiances	cloud parameters	SSFR	2
	profiles of differential backscatter profile - up and down	vertical structure of cloud height water vapor	Lidar: DIAL	1
	backscatter and depolarization	cloud height cloud habit	CLS/VIRLS	3
	mm-radar reflectivity - up and down	ice/water profiles effective particle size	cloud mm-radar TBD	1
	cm-radar reflectivity	ice/water hydrometeor profiles	Precipitation radar: TBD	2
	interferometric radiances - up and down	radiances	8-14 micron radiometer	2
	spectral sub-mm IR radiance	ice water path effective particle size	FIRSC	2
	meteorology	T, RH, p, u, v	T, RH, p, u, v	2
	microwave T_B's - up and dn	liquid and water vapor paths	AMMS AMMR	2
	microwave brightness temps	Temperature profile	MTP	2
	chemistry	various species	TBD	4
	navigation	location, time	TBD	1

Table 8 - Research Vessels/Chuuk

Platform/Activity	**Desired Measurements**	**Observed/Derived/ Inferred Parameters**	**Candidate Instruments**	**Priority**
- NOAA Ron Brown **- International collaborators** **- Chuuk**			ARM-like instruments	1 2 2
	surface SW/LW fluxes	radiative flux divergences heating/cooling rates	BSRN-type instruments	1
	direct beam solar irradiances	spectral aerosol optical depth	MFRSR or CIMEL	1
	microwave brightness temp	integrated water vapor/liquid water	microwave radiometer	1
	spectral radiances - up and down	IR radiances surface skin T	M-AERI IR spectrometer - up - down	1
	solar flux	solar flux	solar flux spectrometer (0.4 - 2.5 μm)	1
	backscatter and depolarization profiles	scattering ratio cloud base height depolarization ratio extinction coefficients particle phase particle orientation relative optical depth	cloud/aerosol lidar (to 20 km)	1
	Doppler mm-radar reflectivity	ice/water profiles effective particle size	Doppler cloud mm-radar	1
	Doppler cm-radar reflectivity	convective mass flux water flux, cell size updraft velocity	scanning Doppler precip. cm-radar	1
	meteorology	p, T, RH, u, v	p, T, RH, u, v	1
	T, RH, u, v, p, time profiles	profiles: p(z), T(z), T_d(z), u(z), v(z)	rawinsondes (4/day)	1
	navigation	location, time	TBD	1

Table 9 - Satellites

Platform/Activity	**Desired Measurements**	**Observed/Derived/ Inferred Parameters**	**Candidate Instruments**	**Priority**
NOAA Polar Orbiters (9:30 am, 1:30 pm) Combined NOAA and Metop satellites beginning in 2004	lambertian reflectance at 0.58 - 0.68 and 0.725 - 1.10 µm brightness temperature at 3.55 - 3.93, 10.3 - 11.3, and 11.5 - 12.5 µm TOA VIS image TOA IR image TOA VIS radiance TOA IR radiance	cloud fraction cloud optical thickness cloud particle size cloud top temperature cloud IR emissivity cloud albedo cloud reflectivity clear sky albedo clear sky temperature cloud liquid water temperature profile water vapor profile cloud height cloud amount	AVHRR: GAC HRPT AMSU TOVS: HIRS	 1 1 1 1
GMS	TOA 0.55 - 0.75 µm radiance 3.9, 11 & 12 micron brightness temperatures TOA IR image	cloud fraction cloud optical thickness particle size cloud top temperature cloud liquid water cloud IR emissivity cloud albedo cloud reflectivity number of cloud layers clear sky albedo clear sky temperature temperature profile water vapor profile cloud height, cloud amount	VISSR	1
CloudSat (1:30 pm)	Aerosol and cloud vertical distributions	Radar reflectivity Visible/near IR Radiances Cloud base/top heights Cloud water/ice content Cloud particle size, Cirrus asymmetry parameter	Cloud profiling radar, A-band spectrometer, imaging radiometer	1
PICASSO-CENA (1:30 pm)	Aerosol and cloud vertical distributions	Backscatter profile Extinction profile Optical depth Cloud height/thickness Cloud ice/water phase Effective particle size Cirrus asymmetry parameter	Lidar, A-band spectrometer, infrared imaging radiometer, visible imager	1
EOS AQUA (PM) (1:30 pm)	Atmospheric state, aerosol, and cloud properties	Same as AVHRR, except with directly measured broadband radiances $T(p)$, $q(p)$ LWP, Sea sfc wind column water vapor	MODIS CERES AIRS/AMSU/ HSB AMSR-E	1 1 1 1 1

Table 9 - Satellites - (continued)

EOS TERRA (AM) (9:30 am)	Aerosol and cloud properties, surface properties, chemical distributions	Same as AVHRR, except with directly measured broadband radiances Surface properties CO/CH4	MODIS MISR CERES ASTER MOPITT	1 1 1
EOS ICESAT	Aerosol and cloud vertical distributions	Backscatter profiles Extinction profiles Optical depth	GLAS	1
EOS CHEM (1:45 pm)		Chemistry and water vapor Chemistry, water vapor, aerosols Chemistry Ozone, chemistry, clouds	MSU HIRDLS TES OMI	2 3 3 3
EO-3		Water vapor	GIFTS	3
ADEOS II (10:30 am)		T(p), q(p), SST Aerosol/cloud polarization Sea surface winds	AMSR-E POLDER	2 2
DMSP	TOA VIS radiance TOA IR radiance	cloud structure	Imager:	
(Sun-Synchronous)	TOA microwave radiance	total cloud liquid water estimate water vapor precipitation rate surface wind SST	SSM/I	2
	TOA microwave radiance	temperature profile	SSM/T1 SSM/T2	2 2
ERS-1 and -2	along track scan of TOA radiance	SST cloud liquid water surface wind stress		2
TRMM	TBD	Same as AVHRR, except with directly measured broadband radiances liquid water path rainfall lightning	CERES VIRS TMI LIS PR	3 2 2 2 3

Table 10 - Modeling in Support of Field Experiment

Platform/Activity	**Desired Measurements**	**Observed/Derived/ Inferred Parameters**	**Candidate GCMs**	**Priority**
Large-scale model support	initialization data sets	forecasts	ECMWF	1
		trajectories	NCEP	1
		reanalyzed data sets	DAO	1

5.0 PROGRAMMATIC CONNECTIONS

In addition to the past and continuing basic Research and Development (R&D) programs funded by a variety of agencies including the Department of Defense, the National Science Foundation, the NOAA, the DOE, and NASA, there are three national programs and one international program that are of particular relevance to CRYSTAL and achievement of its objectives.

5.1 Earth Observing System

Implementation of the centerpiece of NASA's Earth Science Enterprise, EOS, began in earnest in 1999 with the launch of Landsat 7 and the Terra platforms. The Terra satellite carries an advanced instrument suite for sensing the Earth in the visible and infrared wavelengths with the following instruments: Advanced Spaceborne Thermal Emission and Reflection radiometer (ASTER), CERES, Multi-angle Imaging Spectro-Radiometer (MISR), Moderate-resolution Imaging Spectrometer (MODIS), and Measurements of Pollution in the Atmosphere (MOPITT). This mission will be complemented with the launch of Aqua in December 2000. Aqua will carry MODIS and CERES, the Advanced Microwave Scanning Radiometer (AMSR/E) and the Atmospheric Infrared Sounder (AIRS)/ Advanced Microwave Sounding Unit (AMSU)/ Humidity Sounder for Brazil (HSB) instrument suite. Observations from these two platforms will enable advances in the detection and characterization of tropospheric cloudiness with global coverage from a polar orbit.

Additional insight on cloud properties and their vertical distribution will be provided through spaceborne lidar observations on ICESat (launch in 2001) and PICASSO-CENA (2004), and with spaceborne radar measurements from CloudSat (2004). The PICASSO-CENA and CloudSat missions will offer a distinct measurement advantage in that they are designed to fly in formation with EOS Aqua. This will permit near-simultaneous measurements of clouds by both active and passive sensors. The EOS CHEM mission (launch in December 2002) is also scheduled to fly in close proximity to EOS Aqua, and will provide additional measurements of water vapor in the upper troposphere needed to understand cirrus distributions. The Stratospheric Aerosol and Gas Experiment III (SAGE III) instrument will be launched on board the Russian Meteor 3M spacecraft in 2000 and also placed on the International Space Station in 2004. These instruments will provide additional data to characterize water vapor, clouds and aerosols in the upper troposphere. Data on tropical precipitation and other observations may still be available from the Tropical Rainfall Measurement Mission (TRMM), launched in 1998.

Validation of the satellite radiance and data products produced from these missions is a high priority for EOS, and will involve field measurements similar to those required by CRYSTAL. Validation activity also supports the continued development and refinement of the retrieval algorithms. CRYSTAL offers a very appropriate vehicle for conduct of these activities with respect to tropical cirrus within the context of a broader effort in which the data collected will be more fully utilized for a wide range of scientific objectives. The mutual benefits in terms of synergy, cost containment, and scientific output resulting from a more complete characterization of the physical environment are substantial.

High resolution measurements of temperature, water vapor, wind and chemical composition will be available from the Geostationary Imaging Fourier Transform Spectrometer, or GIFTS, set for launch in 2004, as part of the Earth Observing-3 initiative.

5.2 ARM

The ARM program of DOE is currently developing a series of instrumented ground-based remote sensing sites in the Tropical Western Pacific area.   The first site was installed at Manus Island, PNG, in October, 1996. The second site was installed in 1998 on the island republic of Nauru. These sites measure all the components of the surface radiation budget, surface meteorology and cloud properties. The latter are measured using a combination of active sensors (radar and lidar) and passive sensors (solar, infrared, and microwave radiometers, and whole sky imager). A highly beneficial partnership is emerging between the EOS Validation Program and ARM, and between ARM and NASA’s Radiation Sciences Program. Joint experiments have already been carried out at the ARM Oklahoma site between DOE and NASA and at the SHEBA ice station and Barrow, Alaska, as part of the collaborative FIRE-III Arctic Cloud Experiment. Similar activities will no doubt occur in the tropics. The ship-based instruments being planned for CRYSTAL are duplicates of the instrumentation at the ARM TWP sites. The scientific insights developed from CRYSTAL will be directly transferable to the ARM TWP effort, particularly in the area of validation of ground-based retrieval algorithms. The two programs are intrinsically linked and close coordination will enhance efforts in both programs.

The ARM program has also been active in the development of research capability using unmanned aerospace vehicles (UAVs). The UAV program has developed and flown radiometers, a small lidar, and an imager on several UAV platforms. These platforms have the ability to stay aloft for long period of times and there are plans to install this instrumentation on a plane with a ceiling that would place it in the tropical lower stratosphere. It is possible that such a platform could be deployed in support of the CRYSTAL campaign.

5.3 NOAA R.V. Ron Brown

NOAA has conducted a long-term program of instrument development. This program has been of great benefit to ARM. In cooperation with the ARM Program, a sophisticated array of passive and active sensors was placed on the research ship, the R.V. Ron Brown for an extended research cruise in 1999, including participation in INDOEX, NAURU99 near the ARM TWP site, and KWAJEX. The latter was a validation experiment for TRMM focused on precipitating tropical cloud systems near Kwajalein Atoll and included significant *in-situ* microphysical observations in the upper ttroposphere. A similar deployment of the R.V. Brown during CRYSTAL would greatly enhance the observational capability. Ongoing analysis of data collected during the NAURU99 and KWAJEX deployments may prove very useful in developing plans and strategies for CRYSTAL.

5.4 GEWEX GCSS

Use of CRMs to bridge the gap between observations and large-scale models is the cornerstone strategy of the Global Energy and Water Cycle Experiment (GEWEX) Cloud System Study (GCSS), an international coordinated effort to enhance progress toward improved treatment of cloud processes in GCMs used for both numerical weather prediction and climate studies. CRYSTAL would provide significant support to, and gain substantial benefit from, GCSS activities focused on cirrus cloud systems (GCSS Working Group 2). In addition, there will be opportunities for synergy between CRYSTAL and other GCSS Working Groups, e.g., GCSS Working Group 4 is concerned with deep convective systems and has a strong tropical focus.

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7.0 ACRONYMS

AirMISR	Airborne MISR Simulator
AMMR	Airborne Multichannel Microwave Radiometer
AMMS	Advanced Microwave Moisture Sounder
ARM	Atmospheric Radiation Measurement
ASTER	Advanced Spaceborne Thermal Emission and Reflection radiometer
ASTEX	Atlantic Stratocumulus Transition Experiment
AVHRR	Advanced Very High Resolution Radiometer
BSRN	Baseline Solar Radiation Network
CART	Cloud and Radiation Testbed
CCN	cloud condensation nuclei
CEPEX	Central Equatorial Pacific Experiment
CERES	Clouds and the Earth’s Radiant Energy System
CLS	Cloud Lidar System
CN	cloud nuclei
COARE	Coupled Ocean-Atmosphere Regional Experiment
CPI	Cloud Particle Imager
CRMs	cloud resolving models
CRYSTAL	Cirrus Regional Study of Tropical Anvils and Layers
DIAL	Differential Absorption Lidar
DMSP	Defense Meteorological Satellite Program
DOE	Department of Energy
ECMWF	European Center for Medium-Range Weather Forecasts
ELDORA	Electra Doppler Radar
ERBE	Earth Radiation Budget Experiment
EOS	Earth Observing System
ERS	European Remote Sensing Satellite
FIRE	First ISCCP Regional Experiment
FIRSC	Far Infrared Sensor for Cirrus
GAC	global area coverage
GARP	Global Atmospheric Research Program
GATE	GARP Atlantic Tropical Experiment
GCMs	general circulation models
GCSS	GEWEX Cloud System Study
GEOS	(check with T. DelGenio)
GEWEX	Global Energy and Water Experiment
GIFTS	Geostationary Imaging Fourier Transform Spectrometer
GMS	Global Meteorological Satellite
HIRS	High Resolution Infrared Radiation Sounder
HRPT	high resolution picture transmission
IFN	ice freezing nuclei
INDOEX	Indian Ocean Experiment
IR	infrared
ISCCP	International Satellite Cloud Climatology Experiment

IWP	ice water path
LASE	Lidar Atmospheric Sensing Experiment
LIS	Lightning Imaging Sensor
LW	longwave
LWP	liquid water path
MAERI	Marine Atmospheric Emitted Radiance Interferometer
MAS	MODIS Airborne Simulator
MCTEX	Maritime Continent Thunderstorm Experiment
MFOV	Multi-field of View
MFRSR	Multifilter Rotating Shadowband Radiometer
MIR	Microwave Imaging Radiometer
MISR	Multi-angle Imaging Spectro-Radiometer
MODIS	Moderate-resolution Imaging Spectrometer
MOPITT	Measurements of Pollution in the Atmosphere
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction
NOAA	National Oceanic and Atmospheric Administration
PR	Precipitation radar
PNG	Papua New Guinea
PVM	Particulate Volume Monitor
R&D	Research and Development
SAGE	Stratospheric Aerosol and Gas Experiment
SGP	southern Great Plains
SHEBA	Surface Heat Budget of the Arctic
SHIS	Scanning High-resolution Interferometric Sounder
SSFR	Solar Spectral Flux Radiometer
SSM/I	Special Sensor Microwave/Imager
SSM/T	Special Sensor Microwave/Temperature sounder
SST	sea surface temperature
STEP	Stratosphere-Troposphere Exchange Program
SUCCESS	Subsonic Assessment: Contrails and Cloud Effects Special Study
SW	shortwave
TIROS	Television Infrared Observation Satellite
TMI	TRMM Microwave Imager
TOA	top of atmosphere
TOGA	Tropical Ocean and Global Atmosphere
TOVS	TIROS Operational Vertical Sounder
TRMM	Tropical Rainfall Measurement Mission
TWP	Tropical western Pacific
VIRLS	Visible and Near IR Lidar System
VIRS	Visible Infrared Scanner
VIS	visible
VISSR	Visible/Infrared Spin-Scan Radiometer