

CRYSTAL—the Cirrus Regional Study of Tropical Anvils and Layers

CRYSTAL— de Cirrus Regionale Studie van Tropische Aambeeldvormen en Lagen

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SAMENVATTING

CRYSTAL—de Cirrus Regionale Studie van Tropische Aambeeldvormen en Lagen—is een gedeelte van de voortdurende reeks van terrein proeven die worden ondernomen om wolken te bestuderen en hun uitwerking op het weer en het klimaat op aarde te onderzoeken. CRYSTAL zal trachten de toepassing van de effecten van wolken in globale klimaat modellen te verbeteren. CRYSTAL wordt voorbereid in twee gedeelten: een beperkte terrein expeditie in 2001 om hoog uitstekende wolken en aambeeld vorming te onderzoeken boven de Everglades in Florida, en de hoofdtocht in de zomer van 2003 in de tropische Westerse Stille Zuidzee. De hoofdtocht was vastgesteld op die tijd om te profiteren van verscheidene wolk metende satellieten die op dat moment in bedrijf zullen zijn. De huidige voordracht bespreekt enkele van de kwesties die in CRYSTAL ter sprake zullen komen, geeft een korte toelichting van het onderzoek plan en beschrijft de verwantschap met andere belangrijke terrein proeven.

SUMMARY

CRYSTAL—the Cirrus Regional Study of Tropical Anvils and Layers—is part of the ongoing series of field experiments to study clouds and their impact on world weather and climate, and will attempt to improve the application of cloud effects in global climate models. CRYSTAL is being planned as two parts: a limited CRYSTAL field campaign in 2001 to examine towering clouds and anvil genesis over the Everglades of Florida, and the main CRYSTAL field campaign in the summer of 2003 in the Tropical Western Pacific. The latter is timed to take advantage of several cloud measurement satellites that will be operational at that time. This paper discusses some of the issues to be addressed in CRYSTAL, gives a brief description of the research plan, and describes its relationship to other important field experiments.

INTRODUCTION AND SCOPE

As part of its ongoing series of field experiments focusing on cloud parameters and their role in global climate modeling, the NASA Radiation Science Program and its associated International Satellite Cloud Climatology Project (ISCCP) will conduct the CRYSTAL field campaign early in the next decade. Mission planning will be provided through the First ISCCP Regional Experiment (FIRE) Project Office.

CRYSTAL (Cirrus Regional Study of Tropical Anvils and Cirrus Layers) is a comprehensive scientific program consisting of modeling, observational programs, and integrated analyses designed to address the important questions surrounding tropical cirrus cloud systems and their role in both regional and

global climates. Two field campaigns are planned: a limited expedition in 2001 to investigate cloud systems over the Florida Everglades, and the full CRYSTAL mission in 2003 to study cirrus clouds in the Tropical Western Pacific. The timing of the full mission seeks to complement the science programs of three planned satellites which will be important to cloud investigations: PICASSO-CENA, CloudSat, and EOS/Chem.

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 depend heavily on both *in situ* and remote sensing measurements from aircraft, ground stations, sounding balloons, ships, and satellites. The data set will provide ample opportunity for the refinement of retrieval techniques and the validation of sampling schemes and geophysical algorithms.

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.

This paper will present the scientific objectives and the broad logistical considerations for CRYSTAL, and will describe its position in the context of other important field experiments.

The field phases of CRYSTAL will be managed from NASA's Langley Research Center, and will benefit from that Center's ongoing Clouds and the Earth's Radiant Energy System (CERES) Experiment and the Global Tropospheric Experiment (GTE).

BASIC QUESTIONS

These are the primary issues to be explored in CRYSTAL:

1. 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?
2. How do tropical cirrus cloud system radiative properties, microphysical properties and spatial properties evolve with time? What are the controlling factors in this evolution?
3. How can we best observe tropical cirrus cloud systems in a large-scale context for climate research?

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

Additional questions 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?
- > Why does "convective debris" cirrus appear to have such a long lifetime in the tropical upper troposphere?
- > 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? (a) Anvil cirrus (implying an attachment to a convective source), (b) Detached anvil cirrus (implying a substantial displacement in both time and space from its convective source), and (c) 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?

OTHER EXPERIMENTS

CRYSTAL seeks to extend the results of earlier experiments, and also to benefit from and also contribute to, several missions that are planned for the same time frame.

Atmospheric scientists have been interested in tropical cloud systems and tropical cirrus for many years, particularly since the advent of routine satellite observations. The first large field campaign directed at tropical convection was the Barbados Oceanographic and Meteorological Experiment (BOMEX), which took place in 1969 off the Windward Islands. This was followed by GARP (Global Atmospheric Research Program) Atlantic Tropical Experiment (GATE), which took place off the coast of Africa five years later to study the impact of anvil cirrus on the radiation budget of the atmosphere.

In 1987, the Stratosphere-Troposphere Exchange Program (STEP) deployed NASA's 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 there were other indications that most of the ice particles were smaller.

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 (and location) of the observations. The same can be said of the important data set collected on FIRE III (the Arctic Cloud Experiment, 1998), conducted in conjunction with SHEBA (the Surface Heat Budget of the Arctic), and which involved scientists from the Netherlands, Great Britain, Canada, and the United States.

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 FIRE contribution to TOGA COARE included a series of coordinated flights with the ER-2 and DC-8. Identical radiometers were mounted on these two aircraft, which 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 ER-2 and a Learjet. These 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 relationship between convection and cirrus generation.

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.

The Indian Ocean Experiment (INDOEX) was conducted in the Spring of 1999 in the equatorial Indian Ocean. This field program focused on measurements of anthropogenic boundary layer aerosols and their role in tropical convection, but had only limited ability to address the linkage between convective fluxes and cirrus formation. The data are currently under analysis.

The U.S. Department of Energy Monterey Drizzle Experiment was conducted in the summer of 1999 to obtain *in situ* microphysical measurements in marine fog and stratus, using instruments which will be of interest in future experiments

These field programs addressed some aspects of the tropical cirrus problem but, unfortunately, not in a comprehensive manner, or were limited by resources or by the technology of the day. While tropical cirrus microphysical characteristics have been inferred from satellite datasets, 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 those few hours. But it is these issues that we need to understand if we are to improve model representations of tropical cirrus and its radiative impact.

CRYSTAL EXPERIMENT PLAN

A limited CRYSTAL field campaign will be mounted in the summer of 2001 to examine towering clouds and anvil genesis over the Everglades of Florida, and to gain field experience with certain new instruments and methods.

For each of the CRYSTAL missions, information will be gathered through a broad array of remote sensors and *in situ* instruments, carried aboard aircraft, satellites, and balloons, and at nearby ground stations. Additionally, ships and buoys are planned for the full mission.

The main CRYSTAL field campaign is planned for the summer of 2003 in the Tropical Western Pacific, and is timed to take advantage of certain cloud measurement satellites that will be operational at that time: CloudSat, to be launched in early 2003, will carry a near-nadir looking radar for cloud detection and classification and will produce detailed, three-dimensional images of vertical cloud structures. The simultaneously-launched PICASSO-CENA spacecraft will carry a spectrometer to measure solar energy reflected in the oxygen-A band. An additional satellite, EOS/Chem, will provide detailed aerosol measurements. There will also be a lidar; these instruments together will provide CRYSTAL with orbiting platforms for radar, lidar, and aerosol information, as well as 3-d cloud imagery.

The tropical western Pacific Ocean has been chosen as the preferred location for the main CRYSTAL field phase for several reasons: extensive background knowledge of (and specific interest in) cloud, ocean and meteorological phenomena in this region as

manifest in TOGA and on-going modeling and analysis studies; uniqueness and climatological 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 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 experiment is tentatively planned for July-August of the year 2003.

The proposed mode of observation will utilize a combination of at least three aircraft, two ships, an island surface site and a multitude of satellite sensors. A minimum experiment design is intended to address issues of remote sensing, radiation and microphysics, and cirrus lifetime. Two remote sensing aircraft are flown above and below a cirrus deck, with at least one additional aircraft directly sampling the microphysical characteristics of the cirrus layer. The research vessels and the surface site would be equipped with remote sensing instrumentation, possibly including radar, and rawinsonde capability. A more desirable, yet more complex, experiment design would better address issues of the relationship of cirrus generation to convection as well as cirrus lifetime. This configuration requires the same two remote sensing aircraft from the minimum configuration, one flown above the convection and associated clouds, with the other flown underneath the stratiform and cirriform regions. Two additional aircraft performing in-situ observations are required to sample the complex microphysical domain inside the stratiform and cirriform regions. An additional aircraft carrying a dual Doppler radar would be essential to define the associated circulation, precipitation and mass flux of the deep convective clouds. The surface site configurations (two research vessels and the island of Chuuk) would be the same as in the minimum design. Aircraft operations would be conducted in the region of one of the surface sites or within the triangular array defined by them.

The desired measurements, with inferred parameters will include: upward and downward solar irradiances (radiative flux divergences, heating and cooling rates), spectrally resolved solar irradiances (cloud parameters), multispectral radiance images (cloud top altitude, optical thickness, effective particle size, thermodynamic phase, reflectance, and ice water path), interferometric radiances (temperature profile, water vapor profile, sea surface temperature, cloud height, cloud emissivity, effective particle size, phase, and ice/liquid water content), aerosols, airborne and

shipborne doppler radar measurements (at 1-cm), vertical distributions, associated navigation and meteorology, and turbulence measurements. Detailed tables of desired parameters, arranged by proposed platform, are given in the Research Plan.

Although the research plan for the limited mission (Florida) is under development, that for the full mission (Tropical Western Pacific) is available in PDF format at this website:

<http://eosweb.larc.nasa.gov/ACEDOCS/index.html> .

PARTICIPATION

All interested organizations are invited to participate in CRYSTAL. NASA Headquarters expects to issue a National Research Announcement (NRA) by the end of 1999. Participation in this program is open to all categories of domestic and foreign organizations, including educational institutions, industry, non-profit

institutions, NASA centers, and other government agencies. Although participation by non-U.S. investigators must be on a non-U.S.-funded basis, such participation is mutually beneficial and is encouraged; the detailed instructions for such participation will be given in the NRA.

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