CloudSat Overview

CloudSat will provide, from space, the first global survey of cloud profiles and cloud physical properties, with seasonal and geographical variations, needed to evaluate the way clouds are parameterized in global models, thereby contributing to improved predictions of weather, climate and the cloud-climate feedback problem. CloudSat will measure the vertical structure of clouds and precipitation from space primarily through 94 GHz radar reflectivity measurements, but also by using a combination of observations from the EOS-PM Constellation of satellites (A-Train). CloudSat will fly in on-orbit formation with the Aqua and CALIPSO satellites, providing a unique, multi-satellite observing system particularly suited for studying the atmospheric processes of the hydrological cycle.

1. Science Objectives

- *Evaluate the representation of clouds in weather and climate prediction models.* CloudSat will provide a global survey of the vertical structure of cloud systems: This vertical structure is fundamentally important for understanding how clouds affect both their local and large-scale atmospheric and radiative environments.
- *Evaluate the relationship between cloud liquid water and ice content and the radiative properties of clouds*. CloudSat will estimate the profiles of cloud liquid water and ice water content. These are the quantities predicted by cloud-process and global-scale models alike and determine practically all important cloud properties, including precipitation and cloud optical properties. CloudSat will provide coincident profile information on the bulk cloud microphysical properties matched to cloud optical properties. Optical properties contrasted against cloud liquid water and ice contents provide a critical test of key parameterizations that enable calculation of flux profiles and radiative heating rates throughout the atmospheric column.
- *Evaluate cloud properties retrieved using existing satellite measurements and promote the development of new remote sensing methods for observing clouds*. CloudSat data provides a rich source of information for evaluating cloud properties derived from other satellite sensors, notably but not exclusively from other members

of the A-Train. Conversely, there are a number of ways CloudSat information will be improved when data from other sensors are combined with the radar.

- *Contribute to an improved understanding of the indirect effect of aerosols on clouds by investigating the effect of aerosols on cloud formation.* The potential of aerosol for changing cloud properties, including precipitation, and the subsequent influences of these changes on the radiative and water budgets of clouds are broadly referred to as indirect aerosol effects. The aerosol context provided by other constellation measurements (such as by the MODIS on Aqua, the lidar on CALIPSO and the polarimeter on PARASOL); the cloud water, ice and precipitation information of CloudSat and AMSR; the optical property information of MODIS and PARASOL; the environmental information from AIRS; and the CERES radiative fluxes combine to produce an unprecedented resource for advancing our understanding of these complex processes and their accumulated effects on the global scale.

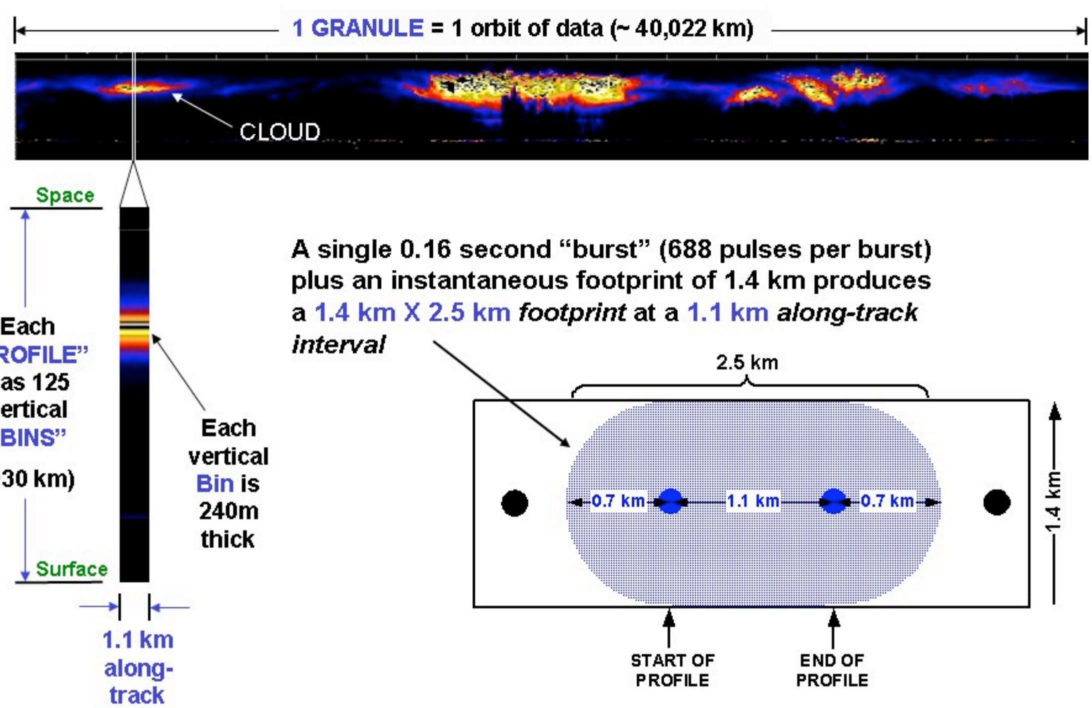
2. Mission Description

CloudSat is planned for launch in June 2005. CloudSat will maintain an on-orbit formation with respect to two spacecraft, namely Aqua and CALIPSO. The formation with CALIPSO is such that the lidar footprint trails the radar footprint by approximately 15 seconds, and the radar and lidar footprints are offset from each other in the cross-track direction by no more than 2 km (overlay is expected at least 50% of the time). CloudSat and CALIPSO in turn fly in formation with Aqua, such that the CloudSat radar trails Aqua by an average of about 60 seconds. This means that CloudSat, CALIPSO and Aqua provide observations of the atmosphere that are nearly coincident in time. The CloudSat mission is planned for a nominal 22-month mission lifetime but could operate longer.

3. CloudSat Data products

The CloudSat Data Processing Center is located at the Cooperative Institute for Research in the Atmosphere (CIRA) on the Foothills Campus of Colorado State University in Fort Collins, Colorado. The CloudSat DPC will produce two types of products for distribution to the science community. The first is a set of Standard Data Products (Table 1) and the second is a set of auxiliary data products that are mapped to the CloudSat CPR profile locations (Table 2).

CloudSat Standard Data Products are produced at each CloudSat profile location. Profiles consist of 125 vertical bins, each approximately 240 meters deep. Each CloudSat profile is generated over a 160 millisecond interval which corresponds to a 1.1 km along-track distance. With orbital motion, this produces a footprint which is approximately 1.4 km (across-track) by 2.5 km (along track) as shown below.



A granule of CloudSat data is defined as one orbit, consisting of approximately 39,400 profiles. A granule begins at the descending node and includes approximately 125 profiles of "overlap" at the beginning and ending of each profile to facilitate along-track averaging.

Auxiliary data products are produced from Ancillary data that are mapped in the horizontal to the CloudSat profile location and, where appropriate, in the vertical to the center of each CloudSat profile bin.

Detailed specifications for each of these products can be found at the CloudSat DPC website: http://cloudsat.cira.colostate.edu. Users can go to the Data Products section of the website where data formats and sizing information can be found for each standard and auxiliary data product.

In addition to these standard and auxiliary products, the CloudSat project encourages the development of a class of experimental data products providing supplementary information enhancing the science of the mission. These products are expected to be less mature than the standard products but potentially of high value. Examples of experimental products under development by the current CloudSat team are precipitation estimates including snow. The newly formed science team will consider the transition of selected experimental products to standard products at the time of data reprocessing planned after year 1 of operations.

4. Data Access

During the operations phase, CloudSat data will be stored and distributed by CIRA. CIRA will provide an on-line data access system that will allow users to view browse images and order data by date/time interval and geographic location. Ordered data will be placed on an ftp server for retrieval by the requestor.

Data will not routinely be provided to users via magnetic or optical media. Larger data volumes (for example a user who places an order toward the end of the mission for every orbit of a group of products for the entire mission) will be provided on media at the expense of the requestor. Note: if that same user requests that the data be provided routinely during the course of the mission, those data can easily be transferred via ftp. The intent is to encourage users to request and acquire data in smaller increments over the life of the mission.

Several features of the data ordering system will allow users to request subsets of the larger CloudSat data product list – thus minimizing the volume of data that they will pull over to their local system. Users will be allowed to specify specific fields within a data product that they need for their research. They will also be able to create "custom products" that will combine fields from multiple Standard Data Products into a single file. In addition, users will be able to set filters on the data to select, for example, orbits that contain a higher percentage of water (vs. land) points, or granules that contain less than 30% cloud cover, etc.

All of the CloudSat data products will be available in HDF-EOS (HDF-4) format and can also be output in a user selectable binary format. The CloudSat Data Distribution System interface can be accessed from the DPC website at http://cloudsat.cira.colostate.edu.

Table 1. The CloudSat standard data products

1B-CPR-FL	- Calibrated CPR (First Look-GPS)
1B-CPR	- Calibrated CPR data
2B-GEOPROF	- Cloud Mask
2B-CLDCLASS	- Cloud Classification
2B-TAU-OFF-N	- Cloud Optical Depth (off-nadir)
2B-LWC	- Cloud Liquid Water Content
2B-IWC	- Cloud Ice Water Content
2B-FLXHR	- Radiative Fluxes and Heating Rates
2B-GEOPROF-LIDAR	- Cloud Mask w/Lidar Input
2B-CLDCLASS-LIDAR	- Cloud Classification w/Lidar Input

Table 2. A summary of the AUX products being archived at CIRA

Product Name	Properties	Description
MODIS-AUX	3 X 5 MODIS Level 1B radiance data gridded and centered on CloudSat profile	22 MODIS channels
ECMWF-AUX	ECMWF state variables mapped to each CloudSat bin	3-hr, 50-km interpolated in space and time
CALIPSO-AUX	Closest CALIPSO profiles mapped to CloudSat profile	Cloud Mask and Scene Classification

At the time of writing this description, the CloudSat mission is also exploring adding AMSR radiances and or CERES instantaneous fluxes to these auxiliary data sources.

5. Validation

The CloudSat validation plan relies on dovetailing into both systematic measurement programs (such as the U. S. Department of Energy's Atmospheric Radiation Measurements Program and measurements planned for selected sites within Europe and Japan) and planned field experiments (including NASA validation efforts as part of Aura and Aqua). Research that seeks to use these systematic measurements and field experiments to assess the CloudSat products are encouraged.

Examples of validation studies that could be proposed under this NRA:

- Assess the calibration of the radar. The CloudSat radar calibration plan (ref) includes a routine and detailed system calibration both prior to launch and in flight, vicarious calibration associated with surface returns from the ocean, and direct measurement comparisons with independently calibrated airborne radar volume-matched to the space-borne radar. The expected absolute calibration accuracy is 1.5-2 dBZ.
- Assess the CloudSat radar sensitivity. Emphasis is in the evaluation of the detection characteristics of the CloudSat radar and of how cloud detection is augmented by the other sensors of the EOS constellation.
- Determine the location accuracy of the radar footprint, thereby enabling the merging of CloudSat data with other data sets.
- Quantify both random and bias errors estimated by the retrieval methods. The sources of these two errors types include: *Model errors* associated with the way observations are modeled in the retrieval approach. *Measurement error* related to instrument performance, calibration, noise, etc. *Database errors* due to uncertainties in *a priori* data-bases used to constrain non-unique solutions (e.g. ambiguities associated with attenuated radar reflectivities, etc.). Uncertainties in

databases used to assign model parameters are an often overlooked, additional source of retrieval error.

- Consistency analysis, i.e. comparing retrieved information involving different physical assumptions and thus different forward models.
- Comparison of retrieved data to operational model data.
- Collection of routine, ground-based remote sensing observations for CloudSat and the A-Train. These can be used for validating derived data quantities and amassing climatological datasets that can also be compared to mean satellite data or to improve algorithms.

The key field programs and systematic measurements planned during the operational phase of CloudSat include:

TWP-ICE (http://www.bom.gov.au/bmrc/wefor/research/twpice.htm) – This experiment will be undertaken over a four-week period in January-February 2006 in northern Australia. This will be the first field program in the tropics that attempts to describe the evolution of tropical convection through its life cycle, including the large scale heat, moisture and momentum budgets, detailed cloud observations, and measurements of the impact of the cloud on the environment with a special focus on radiative impacts and cirrus microphysics. A crucial aspect is that the experiment is designed such that a data set suitable for the forcing and testing of cloud resolving models and parameterizations in GCMs is provided as well as the observational validation data for such simulations. Furthermore an extensive set of in-situ validation data for ARM ground-based and NASA space-borne remote sensing systems will be collected. The experiment is a collaboration between the US DOE ARM project, the (Australian) Bureau of Meteorology, NASA, and several US and Australian Universities. There is also possible European involvement.

AMMA (http://www.joss.ucar.edu/amma/) – African Monsoon Multidisciplinary Analysis (AMMA) is an international project to improve our knowledge and understanding of the West African monsoon (WAM) and its variability, with an emphasis on daily-to-interannual timescales. AMMA is motivated by an interest in fundamental scientific issues and by the societal need for improved prediction of the WAM and its impacts on West African nations. AMMA promotes international coordination of ongoing activities, basic research and a multi-year field campaign over West Africa and the tropical Atlantic. At this time scientists from more than 20 countries, representing more than 40 national and pan-national agencies are involved in AMMA, and funding is largely secured in Europe (mainly in France, Germany, the United Kingdom, and the European Union) up to

2010. Other international efforts are underway to help mobilize the extra funding needed to achieve all the AMMA aims.

Canadian validation experiment (http://c3vp.org) – The Canadian contribution to CloudSat validation will undertake a thorough and careful evaluation of the quality of the CloudSat products as they apply to Canadian climate. The Meteorological Service of Canada (MSC) is the lead agency developing the validation implementation plan, with support from the Canadian Space Agency. The program will focus on stratiform cold-season cloud systems. These are frequently mixed-phase in nature and occur throughout Canada much of the year. The widespread and slowly changing nature of these systems are particularly well suited to validation studies. Ground validation will be carried out over both winters that CloudSat is in orbit. The aircraft campaign will focus on the first winter, i.e. winter of 05/06. The tentative dates for the aircraft component are January to April, 2006.
The goals of the experiment are to:

- Provide the independent verification of the products;
- Verify of the physical basis of the algorithms of the data products as they apply to cold season cloud systems;
- Contribute to the development of new 'mid/high latitude products' e.g snow retrievals;
- Put this analysis into the perspective of weather systems and large-scale circulations.

There will be four main foci involved in this activity. The first is the development of an end-to-end radiation simulator. Similar activities associated with EarthCARE will be built upon to include data from ground-based and aircraft platforms. The second focus involves carrying out detailed field measurements in south central Ontario. This will include ground-based measurements at the Centre of Atmospheric Research Experiments (CARE) with an array of in-situ and remote sensing instrumentation that includes a lidar, a cloud radar, a wind profiler, a precipitation radar and a microwave radiometer. Also, the NRC Convair-580 research aircraft, containing a suite of in-situ and remote sensing sensors, will fly missions along CloudSat's ground track. The goal is to fly from two to four missions for each 16 day cycle of the satellite orbits. The enhanced surface measurements will take place from November to April during the two-year lifetime of the mission. The aircraft campaign will encompass approximately 80 hours of flying. The third focus is to collaborate with the PEARL initiative to obtain addition information, similar in scope to that obtained at CARE, on high latitude cloud systems at Eureka. The Arctic aspect will not have an aircraft component. And the fourth component of the validation exercise will take advantage of the MSC weather observing network, the POSS observing network, and the Doppler radar network.

Japanese-sponsored field experiments (web site TBA)

Subject to approval of funding, the Japanese may contribute airborne radar flights and shipborne radar, lidar and microwave observations.

European contribution: RALI flights (Site in French: http://www.dt.insu.cnrs.fr/rali/rali.php) – A CloudSat/CALIPSO simulator, the RALI payload is a combination of a 95 GHz multi-beam Doppler radar and a 355, 532, and 1064 nm high-spectral-resolution lidar on the same high-altitude research aircraft (Falcon 20: speed 200 m s^{-1}, ceiling 42 kft, endurance 5 hours). Three to four RALI flights, funded by CNES, will occur beneath the A-Train swath from September–December 2005 for validation of CloudSat/CALIPSO Level 1B products. RALI, supplemented with in-situ microphysics, is also planned to fly during the CIRCLE-2 German/French supported campaign in October-November 2006, to study cloud-radiation interactions in southern France.

Systematic Measurement Sites:

1. CESAR (Cabauw Experimental Sensing Area) (http://www.cesar-observatory.nl/)
   Sponsor: KNMI and other Dutch institutes (Delft, RIVM, etc.)
   Instrumentation: Including (but not limited to....)
   - Wind-profiler
   - IR radiometer
   - 3-GHz radar
   - 35-GHZ radar
   - Raman Lidar
   - Scanning elastic scatter lidar
   - Fixed elastic scatter lidar
   - GPS receiver
   - Microwave radiometer
   - Tethered balloon

2. ARM Program (http://www.arm.gov/)
   ARM, funded by the US Dept. of Energy, focuses on obtaining continuous field measurements and providing data products that promote the advancement of climate models. ARM has funded the development of several highly instrumented ground stations for studying cloud formation processes and their influence on radiative transfer, and for measuring other parameters that determine the radiative properties of the atmosphere. Key instruments include one of the few operational Raman lidars in the world; millimeter-wavelength cloud radar; radar wind profilers; and total sky imagers. More recent additions to the suite of ARM instrumentation are the microwave radiometer and the advanced rotating shadowband spectrometer.

3. CloudNet (http://www.met.reading.ac.uk/radar/cloudnet/index.html)

   CloudNET is a research project supported by the European Commission under the Fifth Framework Programme. This project, which started on 1

April 2001, aims to use data obtained quasi-continuously for the development and implementation of cloud remote sensing synergy algorithms. The use of active instruments (lidar and radar) results in detailed vertical profiles of important cloud parameters. CloudNet consists of a network of three already-existing cloud remote sensing stations in the Netherlands, the United Kingdom, and France.

Types of Studies of Interest to CloudSat

1. Development of Enhanced Cloud Information

There are a number of unexplored areas that present the research community with exciting opportunities for developing new observational approaches and providing new scientific information. Some of these areas that warrant research include:

- Cloud liquid water in the presence of precipitation. The incipient stages of precipitation confounds the retrieval of cloud water contents. CloudSat provides an opportunity to address this observing problem through a combination of radar data with other satellite radiance data, including the microwave radiance data provided by AMSR.
- Properties of mixed-phase clouds: The cloud radar data, combined with other data of the constellation, such as the depolarization information from the lidar and polarimetric reflectances from PARASOL, provides an opportunity to focus some attention on both the observational challenges associated with mixed-phase clouds as well as on the parameterization of the mixed phased processes in global models.
- Categorization and quantification of precipitation: Solid and liquid precipitation is readily detected by the CloudSat radar. Liquid precipitation exceeding about 10 mm hr^{-1} at the surface will fully attenuate the radar signal.
- The relationships between the atmospheric circulation and the consequent cloud properties: Since clouds form and decay primarily as a result of vertical air motions, which are very difficult to measure, cloud vertical structure is a key indicator of this aspect of the atmospheric circulation. Moreover, the vertical variations of the cloud microphysical properties (particle phase, number density and size) show how the atmospheric circulation affects cloud properties. Thus, one goal of the analysis of CloudSat/CALIPSO observations of cloud vertical structure is to characterize the variations of cloud vertical structure with variations of meteorology to elucidate the connections between them.
- The effects of aerosols and precipitation processes on cloud microphysics and structure: Cloud systems evolve very differently depending on whether or not precipitation forms. Thus, one goal of CloudSat/CALIPSO data analysis is to

determine the conditions (atmospheric state and circulation, cloud properties) that result in precipitation. Most notably, CloudSat will provide unique new information about snowfall, a key missing component of the observed water cycle.

- Atmospheric Dynamics and Total Diabatic Heating: Given vertical profiles of cloud properties and precipitation, the total diabatic heating that drives atmospheric motions can be determined. Thus, one goal of CloudSat/CALIPSO data analysis is to diagnose the synoptic variations of the total diabatic heating induced by the formation of clouds and to study the relationship of cloud/precipitation and diabatic heating with the atmospheric circulation to reveal how cloud processes alter the general circulation. Connecting the cloud properties to precipitation and radiation, diabatic heating to atmospheric circulation, and atmospheric circulation to cloud properties constitutes the main cloud-climate feedback process loop, which is key to accurate model representation of climate sensitivity.
- Interaction of Clouds and Aerosols: Subtle aspects of the relationship between air parcel cooling rates and cloud microphysical properties and precipitation are influenced by the characteristics of the background aerosols that clouds form on, but the aerosols are also affected by cloud and precipitation processes. Understanding how this tightly linked set of interactions can be altered by human-induced changes in aerosols is one of the most uncertain aspects of the climate change problem. The CloudSat and CALIPSO combination, especially when augmented by other instruments in the A-Train, provides a much more detailed look at this problem. Key to separating out the several possible effects on clouds is vertical profile information to discriminate the aerosols at or just below cloud base and the properties of clouds near cloud base. Thus, one goal of CloudSat/CALIPSO data analysis is to characterize the variations of cloud/precipitation properties with variations of aerosol characteristics.

2. Modeling and Data Assimilation

Studies involving:

Global climate models

NWP models

Regional models

Cloud process and cloud resolving models

Exploratory assimilation studies applied to any of the above.

3. Cloud-Climate diagnostic studies

Studies that seek to combine CloudSat data with other data sources are encouraged

4. Application-oriented research