

The Canadian CloudSat/CALIPSO Validation Project (C3VP)

Science Plan

February, 2005

1. Introduction

Space-based remote sensing of the atmosphere is the key to providing global observations necessary to improve our understanding of the role of clouds in climate, and thus climatic change and variability. This is particularly true for a country like Canada, which extends from middle to polar latitudes and encompasses a diversity of climatological regimes spread over vast tracts of data-sparse regions.

While no previous measurement systems were demonstrated to be capable of acquiring such observations, a space-borne system that uses a combination of active radar, lidar and passive radiometer measurements is believed to be capable of observing vertical profiles of cloud properties. These active-passive observing capabilities have been incorporated into the [NASA/CSA CloudSat](#) satellite mission. CloudSat, with a 94 GHz cloud profiling radar, will be launched together, and fly in formation, with the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations satellite ([CALIPSO](#)) that houses a dual wavelength lidar. As part of the so-called [A-train](#), these two satellites will also fly in formation with the [Aqua](#) satellite, which has a suite of passive radiometric and sounder instruments.

The CloudSat mission objective is to provide, from space, the first global survey of cloud vertical profiles and cloud physical properties, and to show their seasonal and geographical variations. It is intended to provide estimates of vertical profiles of cloud physical properties, specifically to support research activities in meteorology and climate. The CloudSat radar represents a step toward future more ambitious NASA and European Space Agency ([ESA](#)) missions. An overview of the CloudSat mission is given in [Stephens et al \(2002\)](#).

The aim of this project is to carry out a detailed validation study of CloudSat data products. The retrieval algorithms are leading edge but have not been applied to satellite measurements. These techniques make simplifying assumptions about cloud microphysical parameters. Therefore, the quality of CloudSat products requires thorough and careful evaluation by comparisons with independent measurements made from other platforms including both in-situ and remotely sensed observations. The applicability of CloudSat products to Canadian climate will be emphasized in the study. This will then enable the Canadian atmospheric science community to confidently use CloudSat observations in climatological and meteorological applications.

Many CloudSat products derive from coincidental use of observations from CALIPSO. Since several CloudSat products will incorporate CALIPSO data, and since several CloudSat scientific

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objectives require measurements from CALIPSO, there is a clear link, and little distinction, between CloudSat and CALIPSO validation activities.

The project covers a five-year period through 31 March 2009, although analyses of results will continue for some time thereafter.

2. Background

A unique feature of the CloudSat mission is the *formation flying* as part of the so-called A-train. This allows nearly simultaneous views of Earth from distinct instrument payloads. The Aqua, [PARASOL](#), and [Aura](#) satellites are already in orbit. CloudSat and CALIPSO are expected to be launched from Vandenberg Air Force Base in California during July 2005. Data from both CALIPSO and Aqua are used together with CloudSat data in order to produce some of CloudSat products.

CALIPSO will provide a global data set on aerosol and cloud properties, radiative fluxes, and atmospheric state. Aqua is focused on the multi-disciplinary study of Earth's interrelated processes (atmosphere, oceans, and land surface) and their relationship to changes in the Earth-atmosphere system.

The [formation flying orbit](#) is sun-synchronous (~ 1330 MLT ascending node) at an altitude of 705 km and an inclination of 98.2°. The mean separation of Aqua and CALIPSO is 74 s. The mean separation of CloudSat and CALIPSO is 15 s with CloudSat in front. The CloudSat radar footprint is expected to overlay CALIPSO's lidar footprints at least 50% of the time and will fall within the swath of Aqua's [MODIS](#) radiometer. The A-train orbit repeats its ground track every 233 orbits or 16 days.

On a parallel path, the ESA has essentially given the green light to the [EarthCARE](#) satellite mission. This mission is basically the components of the A-train referred to thus far, but with radar, lidar, and radiometers housed on a single satellite. As part of the EarthCARE programme, an end-to-end numerical simulator was developed. Its purpose is to streamline communication between aerospace engineers, optical engineers, and the scientists who effectively design the mission.

The simulator begins with data obtained from either ideal settings (e.g., homogeneous cuboidal clouds) or from complex cloud system-resolving models. Based on these data, optical properties are defined consistently for all wavelengths applicable to EarthCARE instruments. Then, radiative transfer calculations are then performed which essentially simulates radiation arriving at the receivers. Instrument imperfections are then added thereby rendering synthetic data. These data are then acted on by retrieval algorithms to produce inferred cloud properties. These can be compared directly to the input fields. Also, radiation calculations at climatologically significant wavelengths can be done on both input and inferred fields. This produces radiative flux errors that stem from the measurement/inversion process. Clearly, not only EarthCARE, but CloudSat, and indeed all proposed observational studies, including those that aim at validation, could benefit from such a tool.

There have been two MSC projects that have collected data that have direct application to CloudSat research objectives. The most comprehensive was [AIRS](#) (field projects in 1999/2000

and 2003/2004). AIRS focused on winter cloud and storm conditions over Mirabel, Quebec with extensive aircraft and ground-based measurements. Data from these studies are being used to augment parameterizations of cloud microphysics properties. The second project was the [Mackenzie GEWEX study](#) that conducted field measurements in the fall, winter, and spring of 1998/1999 at Fort Simpson, NWT. Data from this study are being used to assess radar sensitivity limitations, subpixel inhomogeneity, and cloud macroscopic properties. Both studies are addressing the issue of remotely sensed determination of precipitation occurrence and type. Such studies are potentially applicable to the design and validation of CloudSat algorithms.

3. Satellite Data

The satellite data products that will be used in the analysis originate at the [CloudSat Data Processing Center](#) (DPC). The input data include cloud profiling radar data and spacecraft engineering data from CloudSat, numerical model analysis data from [ECMWF](#), MODIS data from Aqua, and lidar data from CALIPSO. The standard products are given in [Table 1](#). Additionally, there will be a number of experimental products available for evaluation; the most significant are given in [Table 2](#).

In addition, CALIPSO data products can be directly validated. These products focus on both aerosol and cloud properties such as height and thickness of layers of a various optical thickness, as well as more complex products like backscatter profile, extinction profile, optical depth, and phase.

4. Science Challenges

Radiation and microphysics

What are the relationships and interactions between cloud microphysical processes and radiative processes? How can we improve the representation of radiative transfer in climate and weather models? How important are cloud geometric properties that are systematically neglected by current radiative transfer algorithms?

Detectability of clouds

Can CloudSat and other A-train satellites observe the majority of clouds over Canada? If not, which clouds are missed, what are their frequencies of occurrence, and how important are they to the water and energy budgets? What is the effect of the sub-pixel variability, both vertically and horizontally, on CloudSat algorithms?

Macroscopic properties

What are the macroscopic properties of the clouds (type, amount, and thickness)? How does cloud cover vary as a function of altitude? This is a very commonly used parameter that is poorly defined and understood; yet it is of first-order importance for calculating radiative and moisture fluxes.

Microscopic properties

What are the vertical distributions of cloud microphysical properties such as liquid water content, ice water content), and effective particle size? Many clouds over Canada are mixed phase, containing both ice and liquid particles. How will this effect the retrievals? Which phase is most important to the radiation budget as a function of time and space scale? How can vertical distributions of cloud properties be characterized for use in, and assessment of, NWP or GCM models?

Aerosols

What are the direct effects of aerosols on the radiative forcing budget? The uncertainty in current measurements and the weak ability of models to predict the radiative role of aerosols provides the motivation to improve our understanding of their optical budget. What are the relationships between aerosol vertical profile information and the variability of passively derived optical parameters such as aerosol optical depth? What are the most appropriate observations needed to verify model predictions of cloud-aerosol interactions and their ultimate impact on water and radiative budgets at regional and global scales?

5. General Approach

When validating satellite measurements and the resultant data products from ground-based or aircraft platforms, there are a number of complicating factors. For instance, ground-based remote sensing equipment, such as radar or lidars, are below cloud looking up, but corresponding satellite sensors are above clouds looking down. Signal attenuation by atmospheric constituents needs to be explicitly taken into account. Also, the vertical resolution and horizontal footprint size of data will be unique for each instrument. This is not only a factor in comparing ground-based and satellite data but also radar and lidar data from a common perspective. For aircraft measurements, huge sampling volume discrepancies with remotely sensed data (e.g. 8 orders of magnitude) need to be accounted for.

The main sources of error that need to be considered (apart from retrieval algorithm errors) are precision of measurements, sample volume mismatch, space/time offset in the measurements, and representativeness of measurements. Their relative importance, and whether they are dominated by a random or systematic component, needs to be determined.

A numerical simulator that builds the one used by EarthCARE as an aid at the mission-planning stage will be developed. We believe that its role can be expanded to aid in the planning and interpretation of a validation programme. For the purpose of this CloudSat validation, the EarthCARE simulator is being extended to include sampling by aircraft (i.e., in situ sampling as well as active and passive radiometric sampling), and surface-based sampling by sensors already included in the simulator and with the addition of microwave radiometer and precipitation radar.

It is envisaged that the simulator will be able to help address several key issues. For instance, a crucial question with respect to aircraft flight planning is whether the aircraft should fly in, above, or below cloud before, during, and after the satellite overpass. Of course, the intention is to maximize the unique sampling properties of the aircraft, and it has many sensors which greatly complicates the solution. With the simulator it is straightforward to determine optimal flight paths conditional upon meteorological conditions. Also, as alluded to elsewhere, all of the

instruments involved in the A-train as well as on the aircraft and at the surface sample the atmosphere at different spatial resolutions. This influences both the retrieval and the validation process. The simulator can be used to help interpret the ramifications of the expected myriad of data mismatches.

In broad terms, there are two aspects of the validation process. The first, termed ground truth (GT), deals with the independent verification of the products from the algorithms. This activity assumes there is more confidence in the ground measurements than in the product being validated. The measurements will be analyzed on a statistical basis to identify egregious errors in the products, both random and systematic, and set the meteorological context of the observations. GT will be used to assess the overall uncertainty of effects not directly measurable but that affect the retrievals. The second aspect, physical validation (PV), is concerned with verification of the physical basis of the algorithms. In this case, testable assumptions in the forward model of the individual algorithms will be examined. Specifically, the activities in the overall validation will involve: 1) assessment of random errors, biases, a priori errors, and measurement errors and their effects on the final derived products; 2) identification of conditions under which the retrieval algorithms do not work; 3) testing of steps in the retrieval algorithms; and 4) refinement or development of new retrieval algorithms.

[Figure 1](#) summarizes the data collection strategy to carry out this methodology. The three types of information to be gathered consist of: 1) surface [MSC network](#) observations (radar and surface measurements); 2) [enhanced measurement sites](#) (EMS) with advanced surface and remote sensing instrumentation; and 3) targeted field campaigns involving cloud physics research aircraft. Long term measurements from the network and EMS will be used in GT studies to develop cloud statistics, understand measurement error structure, assess sub-pixel variability and sensitivity issues, and describe various climate regimes. The EMS and research aircraft measurements will also be used to assess the algorithm retrieval assumptions. This can be done even without concurrent satellite measurements. However, the most complete source of data collection will be in targeted field campaigns when the satellite is in the vicinity of EMS. The EMS and research aircraft measurements will attempt to describe the cloud properties in sufficient details with the help of the radiation simulator so as to recreate the satellite observation and assess the whole retrieval process.

[Table 3](#) summarizes the sources of data that will be used to help assess the various CloudSat data products. The detailed C3VP verification strategy matrix is shown in [Table 4](#).

6. Research Activities

The C3VP timeline is depicted in [Figure 2](#).

6.1 Radiation Simulator

Currently, the EarthCARE simulator is being extended to include production of synthetic data obtained from instruments mounted on aircraft and at the surface. Once completed, we will be in a position to essentially simulate the entire CloudSat-CALIPSO-Aqua overpass coupled with under-flying aircraft and fixed surface instruments. The simulator will be initialized with fields that are both idealized and produced by cloud system-resolving models (CSRMs). The idealized

fields serve to address very specific problems such as: how will various configurations of mixed phase cloud impact observations and retrievals? Data from CSRMs serve to put the suite of instruments in a realistic setting. Datasets that we expect to use come represent generic cloud scenes as well as simulations performed with boundary conditions that represent the region where observations are to be made. It is the later that could be potentially the most informative. For example, simulation of Arctic air over Ontario and the resultant snow squalls that often engulf the observation area. Such situations are bound to occur during the experiment, represent a distinct winter precipitation process, and will be a challenge to sample optimally.

6.2 MSC Surface Network

Data from the MSC operational surface network of [radar](#) (Fig 3), [cloud](#) (Fig 4) and [precipitation](#) (Fig 5) observations within a given (but as yet unspecified) swath of the orbit path will be gathered throughout the lifetime of the CloudSat mission. The elements to be considered include the vertical profile of C-band radar reflectivity (10 min time resolution), cloud amount base height and type (hourly), and precipitation type and amount (hourly and daily). At selected POSS sites, precipitation information including particle size distribution at a one minute time resolution will be available. These fields will provide additional information for validation across the many climatic regimes of Canada.

6.3 Enhanced Measurement Site

The geographical foci for the enhanced measurement program, reflecting both the expertise of the Canadian research team and the relevance to the science objectives is stratiform “cold” season cloud systems in the Great Lakes area of Canada as shown in [Figure 6](#). The widespread and slowly changing nature of these systems is particularly well suited to validation studies. The spatial and temporal differences between the satellite track and the enhanced measurement site and research aircraft observations are manageable in these circumstances. Therefore, during the enhanced measurement phase, emphasis will be placed on winter cloud systems and on other stratiform cloud systems such as would be found in the spring and fall seasons.

The enhanced measurement program will take place from the beginning of November until the end of April for the years 2005-06 and 2006/07 at the MSC Centre for Atmospheric Research at Egbert ([CARE](#)) in southern Ontario. At a latitude of 44°N, the adjacent satellite passes will be separated by approximately 120 km. Weather systems in this region, included systems spawned by the Great lakes, represent cloud environments that have not been targeted for validation by any other CloudSat Science Team research groups.

The CARE sites will be instrumented with a large array of active and passive remote sensing and direct observation instruments (see [Table 5](#)). Long term ground-based remote sensing observations are an integral part of the validation approach. The main platforms will consist of a two-wavelength lidar with a cross-polarization channel, a cloud radar, a C-band dual polarimetric precipitation radar, and a microwave radiometer.

The cloud radar will provide high resolution information on cloud occurrence and contribute to issues related to the sensitivity and sub-pixel inhomogeneity of the CloudSat radar. Parameters from the polarimetric radars such as differential reflectivity (Z_{DR}) and specific differential phase

(k_{DP}) will be used to infer cloud phase and precipitation rate. The microwave radiometer will be used to deduce the presence of liquid in the cloud systems. The liquid water path measurements will be a key variable in assessing the CloudSat LWC algorithms. In concert with cloud radar measurements, an estimate can be made of the precise location in the vertical of the liquid water layers.

The lidar allows the measurement of both aerosol and cloud properties over widely varying scales. Lidar returns will carry information about the phase of the cloud particles and highly accurate cloud height information. The advantage of using a two-wavelength lidar with a cross-polarization channel is to provide a sensitivity to particle size and shape. In addition to cloud measurements, the lidar is well suited for aerosol measurements both within the boundary layer and the free troposphere, allowing one to measure the transport and optical properties of the aerosol and its radiative impact.

Lidar and radar measurements performed in tandem will be essential in validating the CloudSat algorithms of microphysical properties. In addition, simultaneous lidar and radar measurements will provide an opportunity to measure the indirect effect of aerosols on clouds.

From January to April, 2006, a Convair-580 research aircraft, owned and operated by the National Research Council of Canada ([NRC](#)) and instrumented for atmospheric research by the MSC and NRC, will be used to make in-situ and remote cloud measurements. Its instrumentation consists of a comprehensive suite of in-situ measurements and both upward and downward pointing cloud radar and lidar (see [Table 6](#)). Of special note, the NRC currently plans to install on the Convair-580 a new up/down/side looking dual polarized Doppler W- & X-band radar (see [Appendix 1](#)). The strategy that will be employed is to collect data along the satellite overpasses within the Great Lakes area of Canada where the weather is suitable. Also, provision is made to collect data during significant cloud and weather conditions over the enhanced measurement site, during or outside satellite overpass times.

In-situ measurements and remote sensing measurements made by research aircraft and by ground-based instruments will provide estimates of LWC, IWC, cloud phase, and both liquid and solid particle size distributions. This is exactly the nature of the information required to validate all the CloudSat algorithms dealing with cloud microphysical properties.

Although the emphasis is on cloud measurements, aerosol measurements will be emphasized on cloud-free days during satellite overpasses. This maximizes the scientific value of the intensive campaigns particularly since the CloudSat/CALIPSO tandems are interested in both clouds and aerosols measurements. In the absence of clouds, aircraft flights will still be carried out with the emphasis on lidar and in-situ aerosol measurements in support of CALIPSO. This will address one of the secondary objectives to improve our understanding of the indirect effect of aerosols on clouds.

6.4 Arctic activities

There is an initiative by the Canadian research community that has relevance to the validation project. The Canadian Network for Atmospheric Change ([CANDAC](#)) plans to deploy a cloud radar and a suite of lidars to Eureka, Nunavut in the Canadian high Arctic. Eureka, at 80°N, is

ideally situated near the apex of the A-train orbit to carry out validation studies of high latitude cloud systems. The observations at Eureka will be carried out both in the town of Eureka and at the Polar Environment Atmospheric Research Laboratory ([PEARL](#)) some 12 km away commencing in the summer of 2006. The deployment at PEARL will be performed in conjunction with the NOAA [SEARCH](#) program. The MSC personnel involved in C3VP will provide in-kind support to these studies. A detailed plan for the observational strategy and the resultant analysis as it pertains to C3VP is still under development.

7. Related Research Activities

After the field project is completed, analysis of the data will take approximately two years during which time the data users will evolve from a primarily observationally-based group to a primarily applications-based. This will require a team of observational and modeling specialists (i.e. radar meteorologists, climate parameterization developers, climate modelers, etc.), and involve the following activities: 1) assessment of gaps in the measurements; 2) derivation of physically-based relationships in cloud properties from the extensive data sets collected; 3) assessment of GCM cloud and radiation algorithms; and 4) validation of cloud schemes and cloud predictions in NWP and climate models; 5) the development of conceptual models of the relationship between cloud and the atmospheric water and energy budgets.

It is recognized generally that the unsatisfactory representation of clouds in large-scale models is responsible for much uncertainty in predictions of climatic change. As such, the Canadian Foundation for Climate and Atmospheric Sciences ([CFCAS](#)) has funded the Modelling of Clouds and Climate ([MOC2](#)) initiative over the past 4 years. The objectives of MOC2 are simply to improve the representation of clouds and radiation in the Canadian Global Climate Model ([GCM](#)). This is achieved through pure research, modelling, and observations. As MOC2 comes to a close, there are plans to extend it via a new proposal to CFCAS that focuses on the representation of cloud-aerosol-radiation interactions in the Canadian GCM. Key to this proposal is the use of CloudSat-related data, for they will be the only means of performing global assessments of crucial cloud-related properties that seem essential for GCMs to simulate properly if they are to produce reliable predictions of climatic change. NASA's CloudSat-CALIPSO-Aqua is also prime testing ground for the more ambitious and orchestrated ESA EarthCARE mission which is expected to fly near 2011. Presumably, the ESA mission stands to learn much from the NASA mission with respect to both operations, retrievals, and application. Any work that aids in the understanding of the NASA mission will be almost directly transferable to the ESA mission.

Other studies that will contribute resources to the field work and the resultant analysis include Cloud Layering Experiment ([CLEX](#)) and [EGPM+](#)/EarthCARE. Projects within MSC that have relevance to C3VP and will contribute in-kind support include the King City dual polarization studies, Airport Vicinity Icing and Snow Advisor (AVISA) project, and the Precipitation Occurrence Sensor System (POSS) enhancement work.

8. Operations Considerations

The enhanced measurement site at CARE will collect data during interesting cloud events from November 1 to April 30 during the winters of 2005/06 and 2006/07. During satellite overpasses

(ascending node day 1 and descending node day 15) and whenever the research aircraft is in the vicinity, manned observation will also take place. Data will be archived on site on a weekly basis for transfer to the project data archive.

The Convair-580 will be operated out of Ottawa during the period for January to April 2006. For a given [16-day CloudSat cycle](#), the ascending node afternoon satellite overpasses on days 1, 3, 5, 10, and 12 and the descending night-time node overpass on day 15 are candidates for aircraft coordinated satellite operations. Four such 16-day cycles during the aircraft operational period will be carried out. A preliminary schedule is to concentrate on every other 16-day cycle, with intermittent flights in-between. The result would be 20 satellite underpass flights (8 near CARE) and 4 additional non-coordinated flights over CARE (weather dependent). This amounts to approximately 90 h of aircraft operations.

A detailed operations plan is under development.

9. Project Personnel

The Principal Investigators (PIs) for this project are David Hudak, Howard Barker of the Cloud Physics and Severe Weather Research Division of MSC. Leading the lidar component of the project is Kevin Strawbridge from the Experimental Studies Division of MSC. The lead for NRC aircraft activities is Mengistu Wolde of the Institute for Aerospace Research. There is, however, a strong mix of MSC and university scientists committed to this validation project. They have the necessary experts in radar meteorology, radiation modelling and simulation, cloud and precipitation physics, lidar measurements, aircraft measurements, remote sensing measurements, integrated data sets, and in-situ-model-satellite measurement intercomparisons. They have extensive experience in conducting meteorological- and climate-related observational based field projects. They are well linked to the Canadian GCM and NWP science communities.

[Table 7](#) is a contact list of individuals associated with C3VP.