GPM Cold-season Precipitation Experiment (GCPEx)

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Table of Contents

Executive Summary

Rationale

As a component of the earth's hydrologic cycle, and especially at higher latitudes, falling snow represents a primary contribution to regional atmospheric and terrestrial water budgets. Importantly, falling snow also represents a primary source of snow pack accumulation which in turn provides a large proportion of the fresh water resources required by many communities throughout the world. Falling snow can also have deleterious impacts on society when it occurs in excess; i.e., blizzards or heavy snow events that cause associated disruptions in transportation, commerce, and power supply. Alternatively, rapidly-melting snowpack causes similar societal impacts via flooding. As in the case of rainfall, it is not possible, or even feasible to adequately quantify the total amount of frozen precipitation occurring at any given time over the entire surface of the earth using only ground-based remote sensing. In order to collect information on the complete global precipitation cycle, both liquid and frozen precipitation must be collected via spaceborne instrumentation. Accordingly, the Global Precipitation Measurement mission (GPM) with its core satellite scheduled for launch in mid-2013 has been designed to provide uniform and calibrated precipitation measurements over the majority of the globe at a temporal resolution of 2-4 hours. The GPM core and constellation satellites will carry active and passive microwave instrumentation designed to detect and estimate falling snow.

During the GPM pre-launch period physically-based snowfall retrieval algorithms are in an active phase of development. Further refinement and testing of these emerging algorithms requires the collection of targeted ground-validation datasets in snowing environments. This document describes a field campaign effort designed to provide both new datasets and physical insights related to the snowfall process- especially as they relate to the incorporation of appropriate physics into GPM snowfall retrieval algorithms. The referenced field campaign effort is the GPM Cold Season Precipitation Experiment (GCPEx), a collaboration between the NASA GPM Ground Validation (GV) program and its international partner Environment Canada (EC).

Scientific Objectives

The GPM Cold-season Precipitation Experiment (GCPEx) is planned to occur in Ontario, Canada (Figure 1) during the winter season (Jan 15- Feb 26) of 2011-2012. GCPExwill seek to address shortcomings in GPM snowfall retrieval algorithm by collecting microphysical properties, associated remote sensing observations, and coordinated model simulations of precipitating snow (hereafter "falling snow" and/or "snowfall" will be used interchangeably in reference to precipitating snow). These data sets will be collected toward achieving the overarching goal of GCPEx which is to characterize the ability of multi-frequency active and passive microwave sensors to detect and estimate falling snow.

Figure 1. Location of the GCPEx experiment.

GCPEx expands upon the successful Canadian CloudSat/CALIPSO Validation Programme (C3VP) held the winter of 2006-2007. The C3VP experiment provided GPM snowfall algorithm developers and satellite simulator models (coupled cloud-resolving and radiative transfer models) with a basic set of observations and modeling simulations to use for algorithm development. Perhaps more importantly C3VP provided a benchmark from which GPM GV physical validation strategies could further evolve toward implementation of GCPEx and the addressing of more specific questions/problems related to GPM snowfall retrieval algorithm development. Building upon the C3VP benchmark and subsequent refinements of GPM snowfall algorithm development needs, the primary objectives of GCPEx include:

1) Conduct a complete study of snowfall physics from the ground through the atmospheric column under coverage of a high-altitude airborne GPM satellite simulator. This will be achieved via use of dual-frequency radar (APR-2; Ka, Ku bands) and "frequency-targeted" radiometer (CoSMIR; 50-183 GHz) integrated on the NASA DC-8 aircraft.
2) Provide coordinated in situ airborne and ground-based microphysical platforms to observe single snow crystal and bulk snowfall properties (habit, size distribution, density) that will enable development of models converting microphysical properties of snow to observed GMI brightness temperature and DPR Ka-Ku band reflectivity.
3) Provide multi-frequency/polarimetric radar vertically pointing and volumetric datasets suited to relating particle scale characteristics to bulk snowfall measurements over spatial scales consistent with satellite fields of view.
4) Provide ground-staring multi-frequency radiometer measurements with coincident snowpack water content estimates toward evaluating the impacts of and potential corrections for ground emission on the snowfall retrieval algorithms.
5) Provide tropospheric measurements of thermodynamic quantities such as temperature and water vapor for algorithm and satellite simulator model needs.

Collectively the GCPEx data set will provide a high quality, physically-consistent and coherent data set suited to the development and testing of GPM snowfall retrieval algorithm physics. GCPEx datasets will further our basic understanding of snowfall physical processes across multiple scales. Most importantly the results will elucidate how those processes may be optimally observed using spaceborne remote sensing instrumentation that includes the GPM Dual-frequency Precipitation Radar (DPR), the GPM passive microwave (PMW) imager (GMI) and other existing/planned active or passive microwave (PMW) sensors flying on ancillary platforms (e.g., CloudSat, AMSR-E, AMSU-B/MHS, SSMI/S etc.).

GCPEx objectives will address the process of falling snow events and augment the currently limited database of snow microphysical and radiative properties that form the critical assumptions at the root of satellite retrieval algorithms. GCPEx objectives address significant areas of weaknesses or knowledge gaps in GPM snowfall detection and estimation algorithms to include: (1) lack of realistic representation of snow particles, their bulk density, size and shape distributions, and their associated radiative properties in algorithm forward models; (2) limited physically-based means to assess the behavior and mitigation of surface emission impacts and emission dynamics on satellite PMW measurements over multiple temporal scales and surface types (3) a lack of representative databases for active+passive observations linked to a measurement reference, (4) the low sensitivity to light/moderate falling snow events by passive sensors and sensitivity to tropospheric water vapor profiles, (5) the ambiguity in Ze-S and TB-IWP relationships, (6) near surface clutter contamination for radar observations, and (7) detection and influence of cloud water imbedded in snow profiles.

Specific science questions to be addressed by the GCPEx include:

- What are the minimum snow rates that can be detected (and/or estimated) by current satellite precipitation sensors and the future GPM? What are the differences in detectability for active versus passive instruments? For lake water surfaces versus land surface (including snow covered) snow events? For shallow versus thick snowing clouds? Does detectability and estimation accuracy/approach vary by meteorological regime (e.g., synoptic vs. lake-effect systems)?

- How well can these sensors discriminate falling snow from rain or clear air?
- Can we develop and/or constrain parameterizations between the physical properties of falling snow (e.g., non-spherical habit, particle size distribution (PSD), ice water content; IWC, density) and their radiative properties (e.g., absorption, scattering, asymmetry, and backscattering) in a statistical sense?
- What is the impact of variability in these microphysical assumptions and/or parameterizations and those related to vertical structure and spatial inhomogeneity on random errors on snow detectability or retrieved snow rate?
- What are the detection/estimation impacts of ancillary data such as surface emissivity, surface temperature, and profiles of temperature, water vapor, and cloud water? GCPEx will attempt to collect an adequate description of the thermodynamic environment of the snowfall and the underlying surface.
- Do operational model estimates of tropospheric water vapor and temperature fields provide enough fidelity to satisfy GPM snowfall retrieval algorithm needs? Can we improve cloud resolving model (CRM) simulations of falling snow events? GCPEx will provide snowfall datasets supporting development of satellite simulator models (e.g., coupled CRM, Land-Surface, and radiative transfer models).

Methodology

GCPEx measurements are targeted toward observing the characteristics of individual snow crystals and aggregates (e.g., single-scatter albedo, density, asymmetry parameter) and subsequent relation of those characteristics to the bulk behavior of a given snow field (e.g., density and water mass content) as observed by GPM DPR, GMI and constellation radiometers within both synoptic and lake-effect snowfall regimes. Importantly, snowfall retrieval algorithms also require a quantitative description of the ambient temperature and water vapor in the intervening troposphere, and some radiative characterization of the underlying surface.

The required measurements include combined high-altitude, downward-viewing dual-frequency radar and multi-frequency radiometer observations collected over the top of in situ profiles of cloud and precipitation microphysics and associated surface observations. These measurements will be obtained via coordinated, stacked high-altitude and in-situ cloud aircraft missions sampling within a broader network of ground-based volumetric observations and measurements. The core analysis strategy for the experiment is based on an approach where well-calibrated, multi-instrument (ground, aircraft, and satellite) measurements are used to develop three-dimensional volume depictions of falling snow events. Ground sampling will be focused about a densely-instrumented vertical profiling central location situated at the EC Centre for Atmospheric Research Experiments (CARE) site. The CARE site observations will be augmented by three nearby “secondary ground sampling locations” (SGSL) with some limited profiling capability located within ~10 km of the CARE site. A fourth site similar to the SGSL will be operated in a major lake effect snowbelt closer to Georgian Bay. When combined appropriately, the associated volumetric datasets will be used to characterize the detection characteristics and improve algorithm development for the GPM GMI and DPR instruments, as well as for current PMW imagers and sounders (with channels sets sensitive to snow) and the CloudSat CPR radar. In this way, the measurements can be used to isolate the effects of a wide variety of algorithm assumptions. Further, GCPEx measurements will be catalogued for later use in GPM validation and have the Data Policy as outlined in Appendix A.

International Collaboration and Experiment Coordination

GCPEx is a collaborative effort between the NASA GPM Ground Validation (GV) program, and Environment Canada (EC). The NASA GPM team will lead the overall coordination of the field campaign including planning, execution, and subsequent analysis and archival of results. GPM will provide the NASA DC-8 aircraft with the APR-2 Ka/Ku-band , the CoSMIR radiometer (50-60 (two), 89, 166, 183(three) GHz channels), the University of North Dakota Citation in-situ microphysics aircraft, the NASA Dual-Frequency Dual-Polarimetric Doppler Radar (D3R), a suite of 2D Video and Parsivel disdrometers, weighing snow gauges, Micro Rain Radars (MRR), Hot Plate sensors, a snow video imager, and ground-based L-band snow water equivalent sensors. Environment Canada will provide instrument access, deployment and operations logistics support for the EC CARE facility and ancillary sites, access/use of the King City C-band dual-polarimetric radar, the McGill University vertically-pointing W-band and X-band radar platforms, Precipitation Occurrence Sensor Systems (POSS), a ground-staring 10-89 GHz radiometer, radiosonde operations at the CARE site, University of Manitoba ground-based high resolution imagery of individual snow particles, and ancillary meteorological surface measurements at all sites. A number of organizations will be providing additional measurement capability, most notably the U. Bonn ADMIRARI MRR/90-150 GHz radiometer combination (Appendix B). GPM will also coordinate with the appropriate instrument and algorithm development teams to conduct comprehensive evaluation of the measurements and to maximize the benefits of the collected data for improving future products. The full spectrum of partners, instrumentation, and measurements will be detailed later in the document.

Expected Outcomes

Given the paucity of observations linking snow microphysics to snow radiative properties, along with the early state of falling snow detection and estimation algorithms, it is anticipated that GCPEx will fill a valuable data gap for falling snow algorithm development. GCPEx will provide:

- Quantitative assessment of the snow detection capabilities of a variety of satellite-based sensors including current PMW imagers and sounders, GPM's GMI and DPR, and the CloudSat CPR.
- An archive of high quality microphysics and snow intensity measurements in high latitude precipitation systems for improving the underlying assumptions in satellite algorithms and to facilitate the development of algorithms for future sensors.
- An overall better understanding of frozen high-latitude precipitation processes and their implications for satellite remote sensing.

These project objectives and snow-centric outcomes are highly relevant to GPM programs, as well as CloudSat.

1. Introduction

1.1 Scientific Motivation

Water is fundamental to life on Earth and its phase transitions among the gaseous, liquid, and solid states dominate the behavior of the weather, climate, and ecological systems. The transport of water in all three phases is a powerful mechanism for re-arranging the Earth's energy budget. As climate forcing changes, precipitation - which converts atmospheric water vapor into rain or snow - can profoundly alter the global energy balance through coupling with clouds, water vapor, atmospheric circulation (via latent heat release), ocean circulation (via salinity dilution), soil moisture, and surface reflectivity of sunlight (via snow cover). Precipitation also has a direct impact on our everyday life. It is the primary source of freshwater and can have tremendous socio-economical impact from natural hazard events such as hurricanes, floods, droughts, and landslides. Accurate knowledge of when, where, and how much it rains and snows is essential for improving understanding of how the Earth system functions and for making better predictions of weather, climate, natural hazard events, and freshwater resources. Often overlooked, precipitation falling in the form of snow is critically important for society and the Earth's climate, geologic and ecosystems. Snowpacks store freshwater and reflect incoming radiation energy. Falling snow disrupts transportation systems and contributes to the overall precipitation record. Yet despite their importance for human activity and understanding the Earth's system, detailed descriptions of the microphysical properties of frozen precipitation systems/regimes are under-represented in the available ground-validation archives.

The GPM Cold-season Precipitation Experiment (GCPEx) will address these issues by making detailed in situ observations of cloud and frozen precipitation microphysics in coordination with (1) a ground-based Polarimetric C-band Doppler radar (King City), (2) a primary heavily instrumented ground site (CARE), (3) three secondary ground sample locations (SGSL) with additional ground instrumentation, (4) the NASA DC-8 aircraft with radiometer channels from 10-183 GHz, and radar channels at Ku and Ka-band, and (5) the University of North Dakota (UND) Citation aircraft with in situ particle sensors. These ground and aircraft instrument measurements will be coordinate to (a) evaluate the falling snow detection characteristics of current and future spaceborne instrumentation, (b) document the macro- and microphysical properties snowfall with detailed ground and airborne active and passive observations of lake effect and synoptic snow events (and any other occurring snow events, e.g., blizzards), (c) establish the implications of variability in the snow, surface, and environmental characteristics for the accuracy in satellite-based snow detection and estimation at high latitudes, (d) explore methods for improving these estimates using future satellite instrumentation and focused cloud-resolving model experiments, and (e) if the measurements exist, extend these analyses to mixed-phase, wet snow events. It is anticipated that the data collected during GCPEx will provide an invaluable resource for resolving challenges in current satellite snow detection and estimation. The eventual outcome of this effort will be to help improve our understanding of frozen precipitation processes in high-latitude environments and their importance in the context of the global hydrological cycle.

1.2 Background

In recent years the capability to quantify liquid precipitation from space has been greatly enhanced with the addition of several measurement capabilities from low-Earth orbit, most notably from passive microwave (PMW) sensors such as the Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI), Earth Observing System (EOS) Advanced Microwave Scanning Radiometer (AMSR-E) onboard Aqua, the Defense Meteorological Satellite Program (DMSP) Special Sensor Microwave/Imager (SSM/I), Windsat onboard the Coriolis satellite, and the SSM/I-Sounder (SSMI/S) onboard DMSP F-16. These sensors commonly referred to as imagers, estimate the vertical hydrometeor profile using top-of-atmosphere (TOA) based on observed upwelling brightness temperatures (T_B) at 6, 10, 19, 37, and 85 GHz.

GPM is an international satellite mission specifically designed to unify and advance global precipitation measurements from a heterogeneous set of research and operational microwave sensors to provide next-generation precipitation measurements from space around the world every 2 to 4 hours. Under the GPM partnership between NASA and JAXA, the two agencies are jointly developing a GPM Core Observatory carrying advanced active and passive precipitation sensors in a non-Sun-synchronous orbit at 65^o inclination to serve as a reference standard for the inter-calibration of constellation microwave radiometers. The Core Observatory will carry the first space-borne Ku/Ka-band Dual-frequency Precipitation Radar (DPR) and a multi-spectral (10 to 183 GHz) GPM Microwave Imager (GMI). The GMI is designed with special attention to instrument accuracy and stability to serve as a reference for developing a transfer standard to unify radiometric measurements by a constellation of microwave sensors. In addition, the DPR and GMI on the Core Observatory will together function as a "precipitation physics observatory" to provide complementary information from active and passive sensors to improve the physical fidelity of precipitation algorithms for the GPM Core and constellation sensors. The increased sensitivity of the DPR relative to the TRMM radar and the high-frequency channels on the GMI will give GPM new capabilities relative to TRMM to take on the challenge of measuring light rain and falling snow, which account for large fractions of precipitation occurrences outside the Tropics, especially in winter seasons over land. The GPM Science Objectives are provided in Table 1.

Table 1. GPM Science Objectives

Science Driver	Mission Objectives
Advancing precipitation measurement from space	• Provide measurements of microphysical properties and vertical structure information of precipitating systems using active remote-sensing techniques over a broad spectral range. • Combine active and passive remote-sensing techniques to provide a calibration standard for unifying and improving global precipitation measurements by a constellation of dedicated and operational microwave sensors.
Improving knowledge of precipitation systems, water cycle variability, and freshwater availability	• Provide 4-dimensional measurements of space-time variability of global precipitation to better understand storm structures, water/energy budget, freshwater resources, and interactions between precipitation and other climate parameters
Improving climate modeling and prediction	• Provide estimates of surface water fluxes, cloud/precipitation microphysics, and latent heat release in the atmosphere to improve Earth system modeling and analysis.
Improving weather forecasting and 4-D climate reanalysis	• Provide accurate and frequent measurements of precipitation-affected radiances and instantaneous precipitation rates with quantitative error characterizations for assimilation into weather forecasting and data assimilation systems.
Improving hydrological modeling and prediction	• Provide high-resolution precipitation data through downscaling and innovative hydrological modeling to advance predictions of high-impact natural hazard events (e.g., flood/drought, landslide, and hurricanes).

With the capabilities of the GPM Core we will address issues associated with retrieving precipitation from space. Furthermore, the GPM scientists must transfer knowledge gained from the active+passive sensors on the Core spacecraft to the constellation passive radiometers. As pointed out by many studies

(Evans et al, 1995; Bauer, 2001) the relationship between precipitation and satellite observations is not unique owing to variations in the vertical distribution of precipitation characteristics (mass content, DSD, melting layer properties, etc.), the amount of cloud water present, dielectric properties of the melting level, and horizontal variability in the large PMW field of view (FOV). These properties can be statistically constrained to some extent with *a priori* information but introduce uncertainty in retrieved rainfall rates. Furthermore, uncertainty in the specification of surface emissivity over land reduce signal to noise thus leading to increased errors in these environments.

Frozen precipitation measurement from space includes the above difficulties associated with liquid precipitation, but in addition, challenges due to the wide variability in snowflake shape that impacts active and passive signals, and the weak signal to noise ratio due to the differing dielectric properties between liquid and frozen precipitation. PMW sounders, such as the National Oceanic and Atmospheric Administration (NOAA) Advanced Microwave Sounding Unit (AMSU-B) and AMSU-B's next-generation sensor the Microwave Humidity Sounder (MHS), offer an alternative for detecting and estimating falling snow based on higher frequency measurements ranging from 150 to 183 GHz. Sounders have the advantage of being sensitive to the ice water path (IWP), (but not necessarily the surface snow) in the cloud and less sensitive to uncertainties in prescribed surface emissivity (Skofronick-Jackson and Johnson., 2011). They also offer smaller FOVs. Ice-phase precipitation detection and retrieval algorithms have been reported and shown to be useful in studying near-surface falling snow (Skofronick-Jackson et al., 2004; Ferraro et al., 2005; Chen and Staelin, 2003; Kim et al., 2008; Noh et al., 2009). These falling snow precipitation retrieval algorithms include those that rely on neural networks, statistics, physical relationships, and/or some combination thereof. The millimeter-wave and sub-millimeter-wave frequencies channels have been exploited in the above approaches. For these reasons, high frequency channels (165.5V&H, 183±3V, and 183±7V) were added in 2005 to the design of the GPM GMI radiometer that already included the 10V&H, 19V&H, 23V, 37V&H, and 89V&H GHz channels.

The network of PMW sensors is enhanced with the current active sensors on CloudSat and TRMM. The TRMM Precipitation Radar (PR) (Kummerow et al, 1998) rarely observes falling snow due to its tropical non-sun-synchronous orbit. CloudSat's Cloud Profiling Radar (CPR) (Stephens et al, 2008) provides information concerning the vertical distribution of hydrometeors, including snow in the atmosphere. Radar observations provide direct observations of backscatter from particles throughout the atmospheric column that can be converted to rain/snow rates given appropriate drop size distribution (DSD) assumptions. However the fact that observed reflectivities depend on the sixth moment of drop size can lead to potentially large uncertainties in retrievals. Drop sizes are even more complicated for snowflakes where a majority of the particles are non-spherical. In addition, with the minimum detectable reflectivity signal of the PR (17dBZ) , CPR (-25dBZ), and the GPM DPR (17 and 12 dBZ for Ku and Ka, respectively) affect their ability to detect snowfall, with CPR being the most sensitive to light snow rates (Kulie and Bennartz, 2009). Furthermore, for the CPR and heavy snow and for the DPR and heavy rain, attenuation can become so large as to completely overwhelm the reflectivity signal and multiple scattering effects, that are difficult to model in retrieval algorithms, can become significant. Finally, all active spaceborne sensors suffer from an inability to detect hydrometeors in the lowest kilometer of the atmosphere due to contamination from the surface return. This clutter results in the need to extrapolate precipitation retrieved at 1 km or higher down to the surface.

Clearly each of the state-of-the art precipitation sensors has characteristic strengths and weaknesses. This suggests that, despite recent advances in sensor technology, there remain several key areas of space-based precipitation retrieval that are not well understood and their impacts are especially acute at higher latitudes. A significant fraction of the global population resides at latitudes where a significant fraction of the fresh water originates from falling snow or snowpack melt. This point is illustrated in Fig. 2, which presents the fractions of zonally averaged snow and light rain precipitation accumulation derived from the

Comprehensive Ocean-Atmosphere Data Set (COADS) ship-borne meteorological observations between 1958 and 1991. This dataset provides evidence that falling snow contributes up to 80% of the precipitation occurrence in Polar Regions. There is, therefore, a great motivation for improving snow precipitation retrieval algorithms and resolving discrepancies between products from different sensors. Regrettably, for frozen precipitation there is scant and incomplete validation data. Clearly, since the majority of precipitation events at high latitudes are associated with spatially incoherent, shallow cloud layers producing light but persistent snow (and a significant accumulation), detection limitations of current sensors may lead to a substantial underestimate of accumulated snow and its contribution to the associated water cycle. It is, therefore, important to both characterize the abilities of current satellite precipitation sensors to detect and estimate the intensity of frozen precipitation events and an accurate characterization of the microphysical properties of such events upon which to base development of new algorithms for future sensors such as the DPR and GMI that will fly on the GPM core satellite.

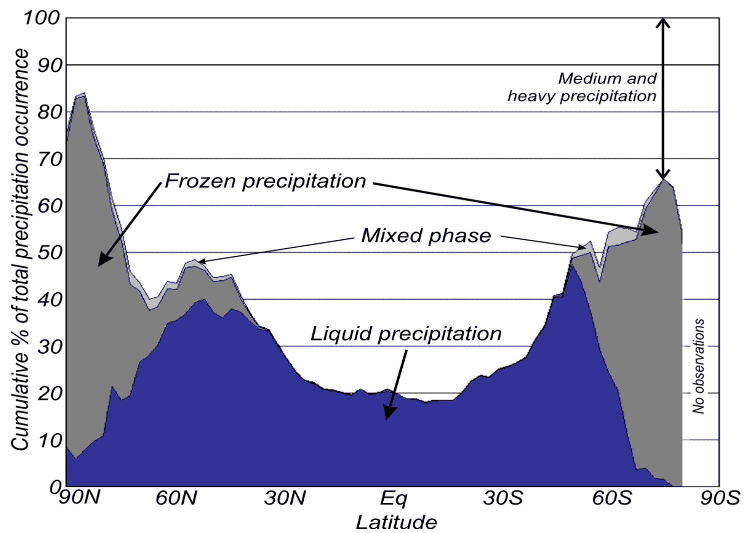

Figure. 2 Zonally averaged fraction of precipitation from 1958-1991 falling in the form of light rainfall (less than 1 mm h^{-1}) and snowfall (adapted from the analysis of COADS ship-borne meteorological observations summarized in the EGPM Report for Mission Selection, ESA SP-1279(5).

1.3 Ontario Climatology

The primary objectives of GCPEx are to obtain coordinated high quality in situ and remote sensing observations of falling snow events in a northern latitude climate. Such systems are prevalent in the Ontario region in the December- February timeframe where monthly mean snowfall amounts are approximately 40, 30 and 25 cm/month for December, January and February, respectively. Furthermore, the primary choice for DC-8 operations (Bangor, Maine) will allow potential sampling of Nor'Eastern Blizzards and heavy snow events over St. Johns Newfoundland (site of current NCAR snowfall measurements supporting aviation research). A deployment to the Ontario region in January 2012 therefore provides an ideal opportunity to observe several types of falling snow events with cloud tops ranging from 1 km to ~9 km.

2. Science Goals

The overarching goal of GCPEx is to characterize the ability of the GPM DPR, and PMW imagers and sounders to detect and estimate frozen precipitation. In addition, GCPEx seeks to provide the snowfall algorithm development community with a database of well-calibrated measurements of the microphysical properties of high-latitude falling snow events and their associated PMW and radar signatures for future algorithm development. The GPM Radar, Combined, and Radiometer algorithm development teams have provided a listing of algorithm issues and assumptions that need to be tested in a GV field campaign in order to constrain the algorithm hypotheses. In order to address these algorithm issues and assumptions, they have requested an associated set of parameters to be measured. These are provided in Table 2.

2.1 GMI and PMW Falling Snow Detection and Estimation Algorithms

Falling snow detection is a function of the snow event's macro- and micro-physical properties, the instrument characteristics/limitations, and the retrieval algorithm employed to extract information from its measurements. In terms of passive radiometer detection and retrievals of falling snow, the problem is difficult due to surface emission, column water vapor, and weak signatures from light snow fall events. A majority of the problem is detection of snow (versus rain or surface noise/snow covered surfaces). Passive instruments inherently measure an integrated quantity of the liquid or ice water along a slant path (LWP, IWP), not range-binned information such as radars. The performance of PMW algorithms depends strongly on how the channels are used: methods for minimizing the noise contribution from the surface emission are important, especially over land surfaces. Nevertheless, progress is being made with the 89, 150/166, and 183 GHz channels. From simple theoretical studies, for example, IWP of ~0.5 kg m^{-2} can be detected using only 150 GHz with reasonable (but not perfect) assumptions. Again using simple back of the envelope calculations and a few assumptions about how the IWP is distributed within a cloud, an IWP of 0.5 kg m^{-2} results in a melted rate of ~1.25 mm hr^{-1}. This is a rather heavy snow rate of maybe 1-2 cm an hour but with better algorithms, detection should drop to lower IWP and, therefore, lower snowfall rates. GCPEx will provide important constraints on detection assumptions by answering the following questions:

- What is the contribution/error due to surface emission? Can we better measure/estimate/model surface emission to reduce its impact, especially over snow covered surfaces?
- Do snow events exhibit a strong relationship between ice scattering aloft and the presence of snowfall near the surface?
- What is the typical vertical structure of high latitude snow systems?
- What are the emission and scattering properties of ice particles in snowing clouds? Ice scattering aloft?
- What are the contributions of super-cooled water to observed T_Bs over the range of sounder and imager frequencies?
- How does spatial heterogeneity in snow events impact detection and estimation from microwave imagers and sounders?
- How does the bulk structure of the snow cloud macrophysics (e.g., IWP, cloud depth, event type) affect the resultant TB and Z and hence detection success?
- How does the character of these frozen precipitation systems, and, therefore, the factors that influence PMW snowfall retrievals, depend on the surrounding environment (and regime variability)?
- Can robust relationships be established that relate snow to observations at high and low frequency T_B signatures or as a function of retrieved parameters such as IWP?
- Does a priori identification of snow system regime type (e.g., synoptic vs. lake-effect) provide any systematic information for partitioning detection and estimation error variances?

Algorithm component, assumptions, or issue addressed for GCPEx	Applicable Measured and/or Diagnosed Parameters																
	Z	Z_{DFR}	S	PSD sfc	PSD col	PID	ρ_b	ρ_p	T	Q_v	Q_{soil}	CN CCN	TW_c	CW	IW	ε/σ_{sfc}	T_B
Path integrated attenuation approach(es)	◆	◆	◆	◆	◆	◆				◆			◆	◆		◆	
Hydrometeor Identification (3D)	◆	◆	◆	◆	◆	◆	◆		◆				◆	◆	◆		
Bulk snow article habit properties	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆			◆	◆	◆		◆
Bulk snow particle size distributions	◆	◆	◆	◆	◆	◆	◆	◆	◆								◆
Detection thresholds for falling snow	◆	◆	◆	◆	◆	◆	◆	◆	◆					◆	◆	◆	◆
Dual-Frequency snow detection	◆	◆	◆	◆	◆	◆	◆	◆	◆					◆	◆	◆	
Near surface rain estimate/rain profile	◆	◆	◆	◆	◆	◆										◆	
Sub-pixel DSD and snow variability (correlation, errors, beam filling)	◆	◆	◆	◆	◆	◆											◆
DSD profile and "ε" adjustments	◆	◆	◆	◆	◆	◆											◆
Column/Land surface emission			◆						◆	◆	◆					◆	◆
Rain/snow discrimination	◆	◆	◆	◆	◆	◆			◆	◆			◆	◆	◆	◆	◆
Ice particle vs. volume extinction	◆	◆			◆	◆	◆	◆	◆	◆					◆		◆
Cloud water profiles/ice water profiles	◆	◆	◆						◆	◆		◆	◆	◆	◆		◆
Ice process, scattering, and snowfall	◆	◆	◆	◆	◆	◆	◆	◆					◆	◆	◆		◆
Regime controls on precipitation process	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆		◆	◆	◆	◆	◆	◆
DSD Gamma-Triplet correlations	◆	◆	◆	◆	◆	◆							◆				
CRM/LSM Satellite Simulator Physics	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆
Land surface emission			◆						◆					◆		◆	◆
Coupling upper cloud ice processes & surface snow rates/detection	◆	◆	◆	◆	◆	◆	◆	◆	◆				◆	◆	◆		◆

Table 2: Algorithm team provided retrieval components, assumptions, or issues (leftmost column) along with needed GV measurements to be used to develop and improve falling snow detection and estimation.

2.2 GPM DPR Falling Snow Algorithm Evaluation and Improvement

The dual-frequency GPM DPR represents a significant technological advance over the TRMM Precipitation Radar (PR) providing, for the first time, active remote sensing wavelength diversity on precipitation-measuring satellite platform. The most important benefit of having wavelength diversity for snow retrievals is the significantly improved particle size distribution (PSD) and hydrometeor phase information provided by differential attenuation in the measurements at each frequency. With a minimum detectable signal of 12 dBZ, the Ka-band channel also provides more sensitivity than the TRMM PR. Nevertheless, initial results from CloudSat also that suggest that, with a sensitivity of 12 dBZ, the GPM Dual-wavelength Precipitation Radar (DPR) may miss a significant fraction of snow occurrence (see Figure 3). It is not clear what fraction of snow water equivalent will be missed. However, these results are very sensitive to methods used to convert W-band reflectivity observations to Ka/Ku-bands. The extent to which W-band reflectivities 'saturate' due to non-Rayleigh effects is also unclear motivating the use of theoretical studies and ground radar networks to investigate the frequency and detectability of heavy snow events at W, Ka, and Ku bands and to fully populate the PDF in Figure 2. More generally, challenging regions at the limits of snow detectability for radars such as the DPR should be targeted for more comprehensive study using ground, aircraft, and spaceborne radars. GCPEx will provide insights into to the snow detection characteristics of the DPR and establish uncertainty estimates in DPR snow intensity retrievals in challenging high latitude environment:

- What are the anticipated minimum detectable snow rates for the DPR given the additional sensitivity afforded by the lower minimum detectable signal of the Ka-band?
- How does ground-clutter affect our ability to detect shallow snow systems?
- How much improvement in DSD and snow accuracy can be realized by adding the Ka-band observations in high latitude environments?
- What fraction of falling snow is missed by the DPR as compared to the CPR? That is, evaluate the results presented in Kulie and Bennartz (2009) and in Figure 3. While frequency of occurrence may be undersampled by DPR as indicated by Fig 3, it is not clear what fraction of the

total snow water equivalent will be missed. Can we estimate that fraction for the regimes sampled during GCPEx?

- How do spatial heterogeneity and associated environment characteristics of differing snowfall system types impact the detection and estimation statistics of the DPR retrieval algorithms?
- Can current numerical weather prediction models provide tropospheric water vapor and temperature profiles with enough accuracy and fidelity to be useful to falling snow retrievals?

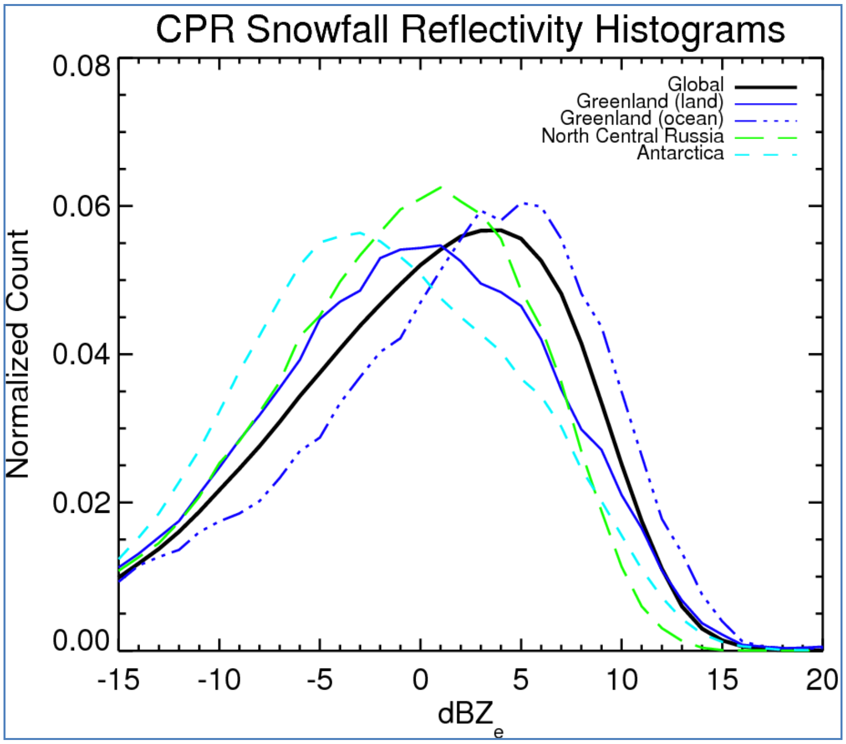

Figure 3: CloudSat W-band (94 GHz) Cloud Profiling Radar (CPR) reflectivity histograms for snowfall in several different regions (courtesy Mark Kulie).

2.3 Process Studies

Analysis of high quality in situ microphysical property datasets along with associated surface precipitation measurements and temperature, humidity, and aerosol information for context will contribute to our understanding of the processes that govern the development of frozen precipitation in high-latitude environments. Moreover, the analysis will produce microphysical databases that provide a framework from which to conduct basic instrument simulator studies for algorithm testing. Specific process questions that will be addressed include:

- Do lake effect snow bands produce fundamentally different snow water equivalents relative to synoptic snowfall systems for equivalent reflectivities or TBs at similar surface temperatures?
- Can properties of the snow size distribution including bulk density be adequately modeled as a function of the vertical profile of temperature and humidity?
- Can systematic Z-SWE relationships and associated density-diameter relationships be developed as a function of snowfall type?
- How prevalent is cloud water in synoptic vs. lake effect snow systems and what is its typical profile?

- To what extent do discrete layers in tropospheric temperature and humidity control crystal habit type and tendency to aggregate? When layers exist, does their impact on the snow morphology impact our interpretation of remote sensing properties?

3. Experiment Strategy

The observing strategy framework is designed to use a combination of multi-frequency radar, particle imaging and water equivalent-measuring surface instrumentation in conjunction with airborne dual-frequency radar, high frequency radiometer and in situ microphysics observations arranged in stacked altitude patterns to provide the most complete coupled sampling of surface and in-cloud microphysical properties possible. The resulting 3D volumes will be combined to provide a fundamental description of snowfall physics at the ground and through the atmospheric column, and to create an associated database of scenes for evaluating and developing satellite snowfall retrieval algorithms. This "algorithm laboratory" can be used to test the fundamental capabilities of current and proposed sensors for detecting and estimating falling snow over complex land and lake surfaces. Furthermore, CRM simulations of snow events occurring during GCPEx will augment the observations. With this experiment strategy, GCPEx can be used to quantify the impacts of assumptions in current algorithm formulations, and to explore new retrieval techniques. The instruments and parameters to be measured are listed in Table 2, while specifics about each instrument are found in Appendix B.

3.1 Ground and Air Measurement Strategy Synopsis

The expected GCPEx instruments and parameters to be measured are provided in Table 3. The experiment will consist of DC-8 and UND coordinated flights within a domain covered by one primary (CARE) location and four secondary ground sampling locations in Ontario, Canada about 70 km north of Toronto, and surrounded by the Great Lakes (see Fig. 4). The measurement strategy is denoted in Fig. 5. The ground instruments at the primary and secondary sites will be used to collect coordinated point source microphysics under the broader volumetric or vertically-pointing coverage of multi-parameter radars (Table 3; instrument complement at CARE). The King City C-band dual-polarimetric radar is situated as shown in Fig. 4 and will provide continuous volumetric (3-D, broad-area) and RHI (Range Height Indicator; vertical profile) coverage of the entire area, with special emphasis for RHIs placed directly over the surface measurement sites. At the CARE site, scanning Ka-Ku band radar coverage in volumentric, RHI, and vertically pointing modes will be combined with vertically pointing W, K, and X-band radar measurements and also coordinated with airborne sampling. The ADMIRARI radiometer/MRR combination will be located at the CARE site to collect combined K-band and radiometer data oriented along RHIs of either the D3R or the King City radar to facilitate studies of snow and cloud water content detection. Radiosonde profiles of temperature, pressure, humidity and wind (T, P, RH, U) will be collected prior to and after airborne missions to quantify tropospheric thermodynamic structure. At CARE for atmospheric profiling, we will have a vertically pointing TP3000 microwave radiometer and a dual channel vertically pointing lidar (1064 and 532 nm – 532 channel). Finally, the surface characteristics of the snowpack and underlying land surface will be continually sampled at the surface sites using the Environment Canadapassive microwave radiometer (1.4, 19, 37, 89 GHz) at the CARE site, and Duke University L-Band/γ-sensor surface measurements at all sites for assessing land/snow surface impacts on emission properties. The Environment Canada ground-staring radiometer will provide measurements from a 5 meter platform during the months of October – March (through freeze-thaw period). Both the radiometer and L-band surface measurements will be augmented by regular snowpack measurements (depth, density, SWE, stratigraphy, grain size etc.) which will be used to evaluate layered snow model simulations and microwave snow emission models.

For airborne sampling the DC-8 will a single radiometer spanning the 50-183 GHz and a Ku/Ka radar. The DC-8 serves as a GPM satellite simulator. The UND will carry in situ microphysics sensors and will provide vertical information on the distribution of snow clouds. Where possible, flight legs will be aligned along an RHI scan axis of the King City radar and/or in stacked profiling spirals (Citation) or orbiting patterns (DC-8) over the heavily instrumented primary/secondary ground sites to provide a direct connection between in situ microphysics observations, surface snowfall intensities and PSDs, and multi-frequency radar observations. Aircraft flights will occur during snow events, with the exception of several planned DC-8 missions designed to measure surface emission during intervening cloud free periods of the campaign. Occasionally these aircraft operations will occur during NOAA (or potentially CloudSat) overpass times (air traffic concerns and weather objectives permitting) for coincident measurements of high frequency passive microwave precipitation estimates from the AMSU-B/MHS instruments and from the CloudSat. In such cases, cloud radar and in situ observations from a direct satellite underflight at the time of overpass will be supplemented with in situ sampling at multiple altitudes within a satellite footprint box around the satellite ground track to assess detection capabilities and relate errors to heterogeneity within the satellite field of view and algorithm assumptions concerning the vertical distributions of ice hydrometeors. More details about the ground observations will be provided in Section 4, while Section 5 describes the aircraft observations.

Figure 4: Layout of the primary (CARE) ground site along with the secondary sites GCPEx East (SkyDive), GCPEx South (SteamShow Fairgrounds), GCPEx West (B. Morton), and Huronia airport. Distances between sites and CARE are indicated. Location of the King City Radar with azimuth and range to CARE site is also indicated. Green lines indicate approximate GCPEx "pie slice" of airspace for working science operations with Nav Canada.

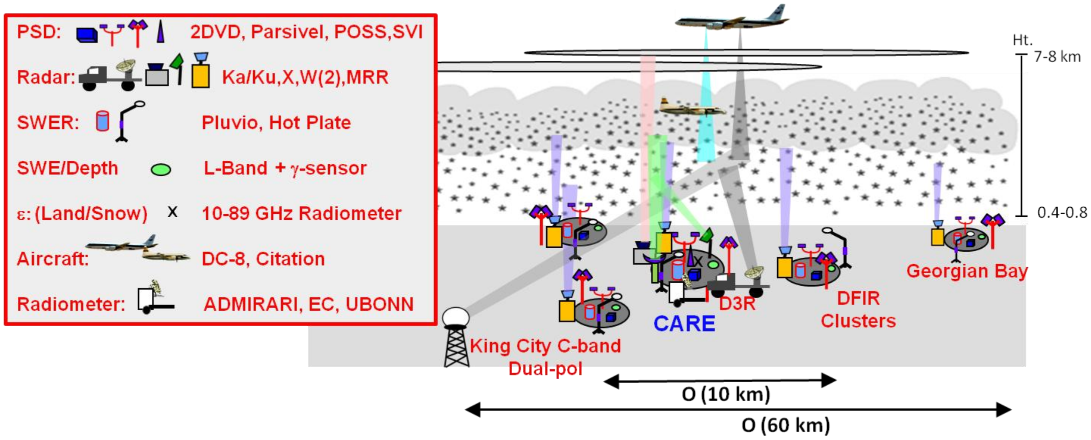

Figure 5: Measurement strategy concept.

GCPEx GV measurements			Applicable Measured and/or Diagnosed Parameters																
Instruments		Measurable	Z	Z_{DFR}	R	PSD sfc	PSD col	PID	ρ_b	ρ_p	T	Q_v	Q_{soil}	CN, CCN	TW_c	CW	IW	ε/σ_{sfc}	T_B
Ground Radar and Profiler	C-band Dual-Pol	Z, Vr, W, ZDR, Φ_{DP}, ρ_{hv}	☒		☒	☒	☒	☒											
	D3R Ka/Ku Dual-Pol	Z, Vr, DFR, W, ZDR, Φ_{DP}, ρ_{hv}, LDR	☒	☒	☒	☒	☒	☒											
	X-band profiling	Z, Vr, W	☒		☒			☒											
	MRR2 profiling	Z, Vr, W	☒		☒	☒	☒	☒											
	W-band profiling	Spectra (Z, Vr)	☒		☒	☒	☒	☒								☒			☒
	Dual freq. LIDAR	σ					☒												
Ground Gauge and Radiometer	2DVD/Parsivel/POSS	DSD, shape, fall spd	☒		☒	☒		☒											
	Pluvio2 SWE Gauges	SWE Rate			☒														
	TPS 3100 Hot Plate	SWE Rate, Wind, T			☒						☒								
	Soundings	P, T, RH, wind									☒	☒							
	ADMIRARI Radiometer, MRR	T_B 19, 37 Z 24 GHz	☒		☒											☒			
	EC TP3000 Radiometer	TB 23-59 GHz									☒	☒				☒			
	EC Ground-Staring Radiometer	TB 10-89 GHz															☒		☒
	EC Surface Met. Inst.	P,T,RH, wind									☒	☒							
Aircraft	APR2 (Ka/Ku Radar)	Z, Vr, DFR, W, ZDR, Φ_{DP}, ρ_{hv}, LDR	☒	☒	☒		☒	☒										☒	
	CoSMIR (Radiometer)	T_B 37,89, 165.5,183 H/V															☒	☒	☒
	CPI/2D-C/CIP, HVPS	Precip. Image	☒		☒		☒	☒	☒	☒					☒		☒		
	CDP	Cloud Water/Spectra					☒									☒			
	Nevzorov	Total water							☒						☒	☒	☒		
	King Probe	Cloud water bulk														☒			
	Rosemount Icing Probe	Supercooled water														☒			
	Aircraft T/RH/Gust	Air T, RH, wind									☒	☒							

Table 3: Instrumentation and measurements for GCPEx. The parameters measured link to the needs of algorithm developers indicated in Table 2.

3.2 Development of Three-Dimensional Volumes and Databases

In situ microphysics information measured both in the air and at the surface combined with the multi-frequency vertical profiling radar information will be placed in a common spatial/temporal reference frame and used to constrain broader domain scanning King City radar microphysical property retrievals to expand the more limited-area in situ sampling to the full King City radar sampling volumes for synthetic testing of other satellite rainfall algorithms. Coincident scanning via the University of Bonn Advanced Microwave Radiometer for Rain Identification (ADMIRARI) radiometer/MRR platform will provide associated information on cloud water contents. This approach involves careful reconstruction of the full 3D volume of cloud and precipitation hydrometeor information (measured and diagnosed properties) using all available in situ airborne and ground-based observations. For example, in a column over the CARE and external sites all associated/relevant airborne and ground based observations will be placed in a common vertical grid to include the basic instrument measurement parameters (e.g., T, RH, reflectivity, radiance/TB, PSD, snow water equivalent, particle habit etc.) and diagnosed variables (e.g., IWC, IWP, bulk density etc.). For intervening locations, between the surface sampling sites, the airborne and scanning ground radar measurements will be combined in a common gridded product that collocates the datasets at the position of both the DC-8 and UND aircraft.

This information will be augmented with associated temperature, humidity, and surface wind speed information from both radiosonde and regional analyses and used as input to satellite simulators that model appropriate satellite geometry and antenna patterns to generate PMW T_Bs covering the range of radiometer frequencies from 89 - 183 GHz and Ka- and Ku-band radar reflectivities. This empirical database can, in turn, be used as input to snowfall retrieval algorithms of varying complexity to study both the detection characteristics and retrieval uncertainties of current and proposed satellite precipitation sensors. This approach allows all relevant algorithm assumptions to be varied over appropriate ranges observed during GCPEx to assess the impact of individual assumptions on retrieval performance.

3.3 Cloud Resolving Model (CRM) Simulations

To augment the observations and provide additional test cases for synthetic algorithm development and satellite simulator testing, a number of modeling activities are also planned. Cloud resolving model simulations of frozen precipitation events using the GSFC-Weather Research and Forecasting (WRF) and model will be performed, initialized and forced by appropriate NWP forecast models. The GSFC WRF has single-moment Goddard Microphysics and spectral-bin microphysics. All of the microphysical schemes have their own set of unique capabilities and assumptions, and all will be tested by the GPM groups. In turn, the simulations will be critically constrained by the ground- and aircraft-based in-situ measurements of PSD and density, by aircraft active and passive observations, as well as C-band reflectivities and polarization measurements. This modeling activity will proceed as it did for C3VP (e.g., Shi et al., 2009) and LPVEx, albeit expanded via the enhanced observational capabilities afforded by the instruments provided during GCPEx (Table 3).

Provided reasonable agreement can be obtained through statistical evaluation against in situ and radar observations, analysis of these model runs will also provide a CRM-based satellite algorithm testbed for evaluating snowfall retrieval algorithm sensitivities. Application of simulators for all relevant satellite precipitation sensors to output from these simulations will then allow a database of snow scenes to be constructed. Since such scenes are generally lacking in current PMW rainfall retrieval algorithms that tend to be tropics-centric, these simulations will provide a valuable tool for tailoring current retrievals for application at higher latitudes.

Advantages of CRM databases include: a) provision of a seamless high-resolution 3D volume; b) vertical and horizontal resolution can be adjusted on request. Disadvantages include a) CRM simulations will have forecast errors to some degree; and b) CRM databases will be biased to some degree even after calibrating assumptions (which are also not perfect in any empirical database) are applied to the CRM microphysics.

3.4 Ancillary Opportunities

As an alternate to sampling over/near the CARE site if conditions are abnormally dry, and/or in the event that additional DC-8 flight time is available, flights to measure heavy snow events over St. John's, Newfoundland or over Nor'Eastern blizzards along the east coast of the U.S. may be considered.

Ensuring a capability for alternate sampling if needed is the reason that the preferred deployment site for the DC-8 is Bangor, Maine as opposed to a location very close to the CARE site. Sampling over St. John’s, Newfoundland will be coordinated with Dr.’s Roy Rasmussen and Paul Kucera of NCAR. NCAR is conducting extensive surface snow water equivalent and PSD measurements in St John’s as part of their FAA icing research program. Alternatively, if a strong Nor’Eastern blizzard occurs during the GCPEx operations, sampling such an event would provide measurements of very intense snow rates that would be useful in setting thresholds of detection for falling snow events. Indeed, a heavy snowfall or mixed snow/rain line event occurring as far south as NASA Wallops Flight Facility would be a consideration in order to leverage NPOL radar measurements at Wallops and to examine algorithm response in the mixed phase environment of a rain-snow line. For any of the aforementioned ancillary opportunities it would be preferred to have DC-8 aircraft flights occurring during satellite (NOAA or CloudSat) overpasses.

4. Ground Observing Network

4.1 Primary Site: CARE

The Centre for Atmospheric Research Experiments (CARE) is an atmospheric research facility operated by the Air Quality Research Branch of the Meteorological Service of Canada. It is located 80 km north of Toronto, Ontario, Canada in a rural agricultural and forested region (Egbert, Ontario, lat = 44° 13' 58.44"N = ~44.23, lon = 79° 46’ 53.28"W = ~-79.78). CARE was designed as an integrated multi-disciplinary facility to promote atmospheric research. The CARE site was the major site for the C3VP ground operations in 2006-2007 (see Fig. 6). The expected instruments at CARE during GCPEx include:

- NASA D3R Ka-Ku band radar
- McGill U. Vertically pointing X, and W-band radars
- EC Precipitation Occurrence Sensing System disdrometer (POSS)
- Duke L-band snow water equivalent/rate measurement system
- EC 10-89 GHz ground staring radiometer
- NASA or EC Micro Rain Radar (MRR)
- NASA 2D Video and Parsivel disdrometers
- NASA Snow Video Imager (SVI)
- NASA OTT Pluvio2 200 and 400 cm^2 snow weighing gauges
- NASA TPS-3100 Hot Plate sensor
- U. Bonn ADMIRARI
- EC/CARE Radiosondes
- EC Geonor weighing gauge (climate reference)
- EC Surface met tower
- EC TP3000 microwave radiometer
- EC dual channel vertically pointing lidar
- Snow tube measurements to infer snow density
- U. Manitoba high resolution imagery of individual snow particles
- Weekly physical snowpack measurements (depth, density, SWE, stratigraphy, grain size)
-

These measurements will provide combined and redundant surface remote sensing of falling snow water equivalent rates, snow pack water equivalent, microwave surface emission properties, PSD’s, snowfall bulk density and snow particle habits. Collectively the surface measurements will enable basic studies of snowfall characteristics to be completed at the ground, and will provide for redundant calibration (with uncertainty) of multi-frequency/polarimetric radar/radiometer sampling/diagnostics of similar bulk properties observed in the column.

4.2 Secondary Sites

Measurements conducted at the secondary sites represent a slightly reduced capability to that available at the CARE site. The intention is to provide a suite of basic measurements to enable measurement of precipitation profile, snow water equivalent rates, snow pack water equivalent, PSD and bulk snowfall density information. These measurements provide a means to extend and calibrate volumetric radar products over the broader domain sampled by the King City radar (more appropriate to the scale of satellite footprint) and also a means to connect airborne measurements to locations at the ground other than the CARE Facility. Another benefit of the secondary sites is to allow for better chances to sample lake effect events which tend to be localized and spatially fine-scale (thus not necessarily always over the CARE facility.

Each of the sites will contain the following set of basic instruments placed in a wind abatement fence designed around the notion of the WMO Double Fence International Reference standard (DFIR).

- EC Precipitation Occurrence Sensing System disdrometer (POSS)*
- Duke L-band snow water equivalent/rate measurement system*
- NASA or EC Micro Rain Radar (MRR)
- NASA 2D Video and Parsivel disdrometers
- NASA OTT Pluvio2 200 and 400 cm^2 snow weighing gauges
- NASA TPS-3100 Hot Plate sensor
- EC Surface met tower
- Aceilometer and a visibility/present weather sensor at the secondary snow site

*Space limitations may not enable this system to be deployed at Bob Morton site.

4.2.1 Southern Site: Steam Show Fairgrounds

Steam Show Fairgrounds (Fig. 6) is considered the Southern site and is located 7.8 km southeast of the CARE site (44°10'48.30"N = 44.1801; 79°43'7.78"W = -79.7188). At this location there will be at least 100'x100' of clear wind fetch conditions in the RV parking area. Accordingly, a "wind abatement fencing setup" e.g., DFIR (will be set up here during the summer of 2011 in preparation for GCPEx).

Figure 6: An image of the Steam Show Fairgrounds (Southern) site.

4.2.2 Eastern Site: SkyDive Toronto

The SkyDive Toronto location (Fig. 7) is considered the Eastern secondary site and is located 11.2 km east of the CARE site (44°14'14.20"N = 44.2373; 79°38'26.96"W = -79.6408). At this location there will be at least 100'x100' of clear wind fetch conditions on the grassy apron of the airstrip and accordingly a "wind abatement fencing setup" e.g., DFIR (will be set up here during the summer of 2011 in preparation for GCPEx.

Figure 7: An image of the SkyDive Toronto (East) site. [SCALE?]

4.2.3 Western Site: Bob Morton’s Ham Radio Tower Location

Bob Morton, a ham radio operator, has a "sheltered valley" rural residence (Fig. 8) that can serve as the Western site. This location is located 12.6 km west of the CARE site (44°10'35.29"N = 44.1767; 79°55'9.13"W = -79.9192). At this location the agreed upon area is a roughly 50'x50' space. While a full DFIR will not fit in the 50’x50’ space, the location is within natural bowl with surrounding trees that should dampen harsh winds thus reducing the need for wind fencing (Fig. 9).

Figure 8: An image of the Western site.

Figure 9: A picture of the Western site depressed area that reduces the need for DFIR wind abatement. (Courtesy Peter Rodriguez)

4.2.4 Huronia Airport (Snowbelt Site)

The Huronia site is located approximately 52 km northwest of the CARE site (Fig. 4), close to the Georgian Bay of Lake Huron and situated at the Huronia Airport (44°41'24.26"N, 79°55'51.94"W; Fig 10). Instrumentation will be similar to that found at the other secondary sites to include a visibility and present weather sensor. The location should be subject to more frequent, heavy lake-effect snow.

Figure 10. Huronia airport secondary site location off the Georgian Bay of Lake Huron. (Snowbelt site)

5. Aircraft Observations

The NASA DC-8 aircraft will serve as a high altitude GPM core satellite instrument simulator for GCPEx. Accordingly it will carry the cross-track scanning APR-2 Ka-Ku band radar and the Conical Scanning Millimeter-wave Imaging Radiometer (CoSMIR; cf. Table 4). The DC-8 will fly patterns in a stack over the top of the University of North Dakota (UND) Citation in situ microphysics aircraft (straight legs or orbits over the top of a UND spiral ascent/descent) and one clear-air pattern for surface emission measurements (Figs. 11-14). Collectively the combination of high altitude satellite "proxy" instruments sampling over the top of the in situ sampling of the UND Citation and given surface sites will provide a top to bottom representation of the snowfall process and physics.

5.1 DC-8 Aircraft

The DC-8 aircraft was selected for the GCPEx due to its compatibility with the desired instrument payload, its altitude ceiling (~12.5 km) and its ability to fly long duration missions if needed (e.g., 10 hours based the expected GCPEx payload). Its typical cruise speed at the nominal 10 km altitude is of order 400 kts (TAS) and it will execute a 15 degree bank angle turn at this speed with a radius of approximately 8.5 nautical miles. The DC-8 will be based out of Bangor, Maine with an approximate flight time to the CARE site of one hour. Flight time to St. John's, Newfoundland will be on the order of 1.5 hours (Verify). The DC-8 on station time will typically range from 4-8 hours depending on the mission and transit time.

The nominal DC-8 instrument complement for GCPEx includes the APR-2 radar and CoSMIR radiometer (Table 4).

Table 4. DC-8 Instruments

DC-8 Instrumentation	
CoSMIR (Passive) H+V polarizations	
Frequencies	50, 89, 165.5, 183.3+/-1, 183.3+/-3, 183.3+/-7 GHz
Resolution at 20 km range	1.4 km footprint at nadir
APR-2 (Active)	
Frequency (inner/outer beam)	13.4, 35.6 GHz (HH, HV)
Transmit peak power	200 W (Ku), 100 W (Ka)
3 dB beam width	3.8º Ku, 4.8º Ka
MDS (dBZ_e, 6 dB pulse width of 60 m., 10km range)	+5.0 / +5.0 dBZ_e
Range gate	30 m
Beam swath	+/-25°

5.2 UND Aircraft

The UND Citation will serve as the in situ microphysics sampling platform with emphasis placed on sampling the column of snow/ice from ~800 m AGL to 7000 m AGL or as the depth of cloud and precipitation dictate. The aircraft is a versatile platform with a service ceiling of 12km and typical cruising speed of 220-240 kts (TAS). During sampling the aircraft speed is typically of order 100 m s^{-1} and descent/ascent rates are of order 750 ft/minute.

The Citation data will serve as a reference microphysics data set for assessing the scattering properties of snow and ice viewed within the swath of the DC-8 instruments and for validating hydrometeor retrievals and ice contents diagnosed by ground-based radars. As such, microphysical data collections will be conducted in close coordination with the DC-8.

The Citation will carry (cf. Table 5) a standard suite of meteorological instruments (T, p, humidity) together with microphysical instrumentation consisting of CDP, CPI, FSSP,CIP, 2D-C, HVPS, Rosemount Icing probe, King probe, and a Nevzorov total water content probe (final complement still TBD as of June 2011).

Table 5: Citation instrumentation

Probe	Range	Notes
CDP	2 – 50 μm	30 bins
2DC	30 – 960 μm	30 μm resolution
CIP	25 – 1550 μm	25 μm resolution
HVPS-3	150 μm – 19.2 mm	150 μm resolution
Nevzorov	0.003 – 2.0 gm^{-3}	Total water, liquid water content.
King LWC	0 – 5 gm^{-3}	Liquid water content
CPI	2.3 – 2300 μm	Particle images, fuselage mount
Rosemount Icing Rate Meter	Detection of Supercooled Liquid Water	
Temperature	-65°C to +50°C	Rosemount total temperature
Dew Point	-60°C - + 40°C	Chilled mirror
Water Vapor	125 – 30,000 ppmv	Maycomm Laser hygrometer
Pressure	0-1034 mb	Pressure
3-D Winds		Gust probe, Applanix inertial system
CN Counter	10 nm cut	Alcohol condensing
GPS Position		Applanix
Orientation (pitch, roll, yaw)	Orientation (pitch, roll, yaw)	Applanix inertial system

5.3 Flight Plans

During GCPEx a majority of the flight operations will be confined to a pie-sliced shape of territory enclosed in the 325° - 040° radials from the CARE site that extends to the northwest over the Lake Huron and to the northeast adjacent to Lake Simco. One or more flights may, however, sample near Newfoundland or along the northeast coast of the US, as dictated by the location of interesting weather, especially on days when AMSU-B/CloudSat is underflown. The final location and execution parameters of the flight patterns are still in coordination with Nav Canada. This selection of flight plans covers all desired modes of aircraft sampling and will be chosen to maximize flexibility to adapt to given weather conditions and avoid potential air traffic restrictions. The following options will be available:

- **Lake Effect Sampling Mode** (Fig. 12) designed to sample lake effect snow events. The goal is to focus on at least one lake effect band per flight operations with the DC-8 aircraft sweeping back and forth while the UND makes steps or porpoises through the layers to obtain in situ data. [DC-8 400 kts ~ 4.5 - 6 minutes to complete a leg; Citation 220 kts; ~ 9 minutes to complete a leg.] Where possible two separate lake effect bands can be sampled; this is useful when the each band exists over separate primary or secondary ground sites and/or the King City field of view.
- **Synoptic Sampling Mode** (Fig. 13) designed to sample widespread synoptic snow events. The DC-8 aircraft will orbit above the event while the UND makes spirals through the layers to obtain in situ data. [preliminary estimates of flight parameters: DC-8 400 kts; 15^{o} Bank; ~8 minutes per orbit as f(radius); Citation 220 kts; descent rate (~500 ft/min; ~45 minutes to complete)]. These spirals, if possible, should occur over the primary or secondary ground sites and/or the King City field of view.
- **Surface Emission Sampling Mode** (Fig. 14) will be used by the DC-8 only if flight hours are available or if feasible before/after the lake effect sampling mode. The objective is to have observations from the radiometers and radars in order to retrieve clear air surface emissivity from

those observations, e.g, sampling land surface backscatter and emission characteristics. If at all possible, it would serve the experiment well if the GCPEx grid/satellite footprint space could be mapped early in the flight operations. No UND aircraft operations are needed for this sample mode nor is King City coordination needed, however, NOAA satellite coordination would be useful to link aircraft fine resolution observations to satellite footprints.

- **Ancillary Opportunities** As described in Section 3.4, ancillary opportunities for the DC-8 to fly over Newfoundland or over US northeast coast blizzards will be determined during GCPEx operations. It is not expected that the UND would fly during these ancillary opportunities. Coordination with NOAA and CloudSat overpasses would be useful.

A typical day of operations will consist of a mission scientist pre-flight planning session, weather briefing and plan of the day discussion (flight plans for mission). The specific options chosen will depend on weather conditions and must be approved by the local aviation authority prior to takeoff. Satellite overpasses of NOAA-15, 16, 17, and 18 and CloudSat will be predicted in order to enhance aircraft flight timing.

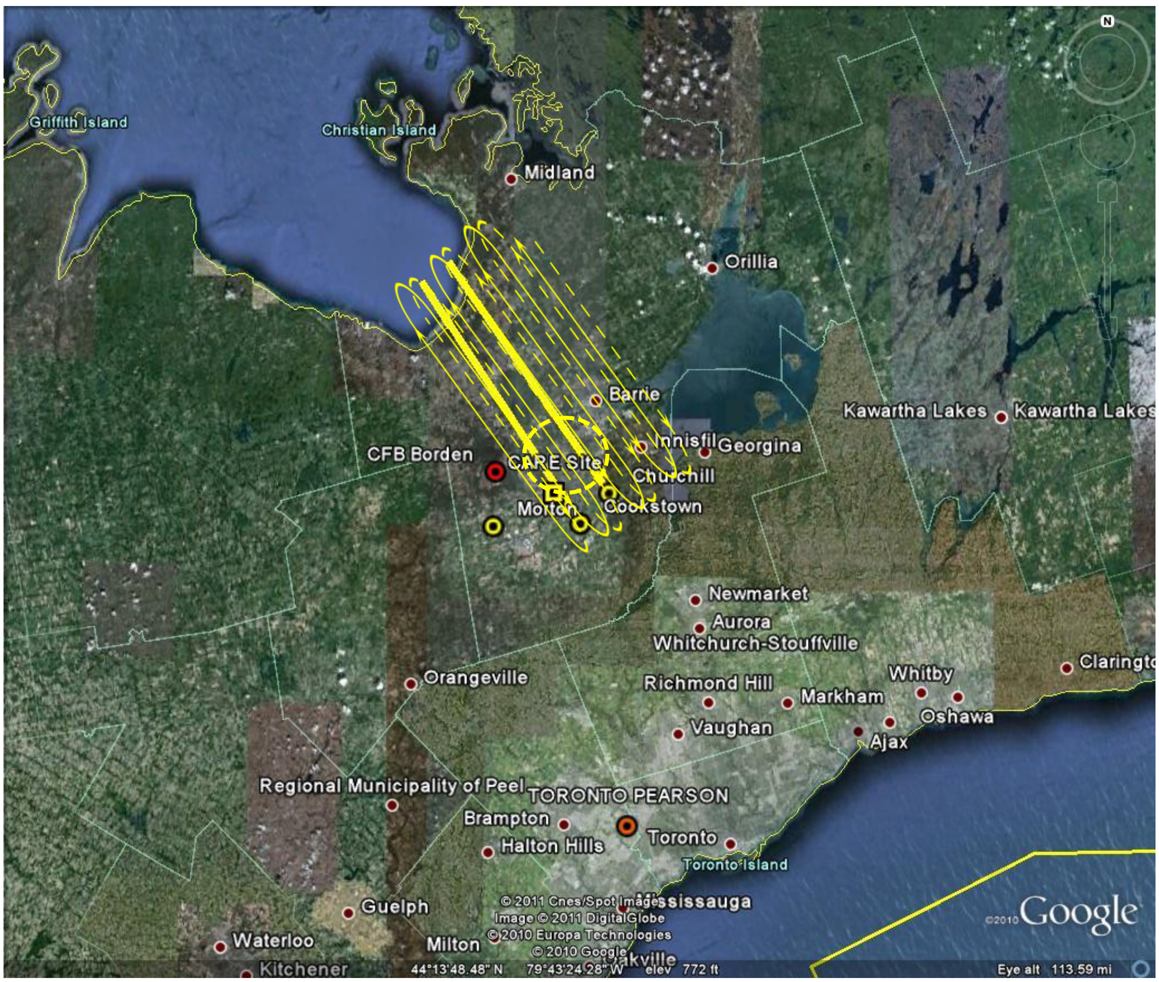

Figure 11: Approximate notion of aircraft observations near CARE site. TO BE UPDATED: Must operate in "pie slice" of Fig. 4; also note that we will work pre-determined rectangular area within the pie-slice to facilitate smooth communications with Nav Canada. This figure will be Update this figure based on most recent discussions with NAV CANADA

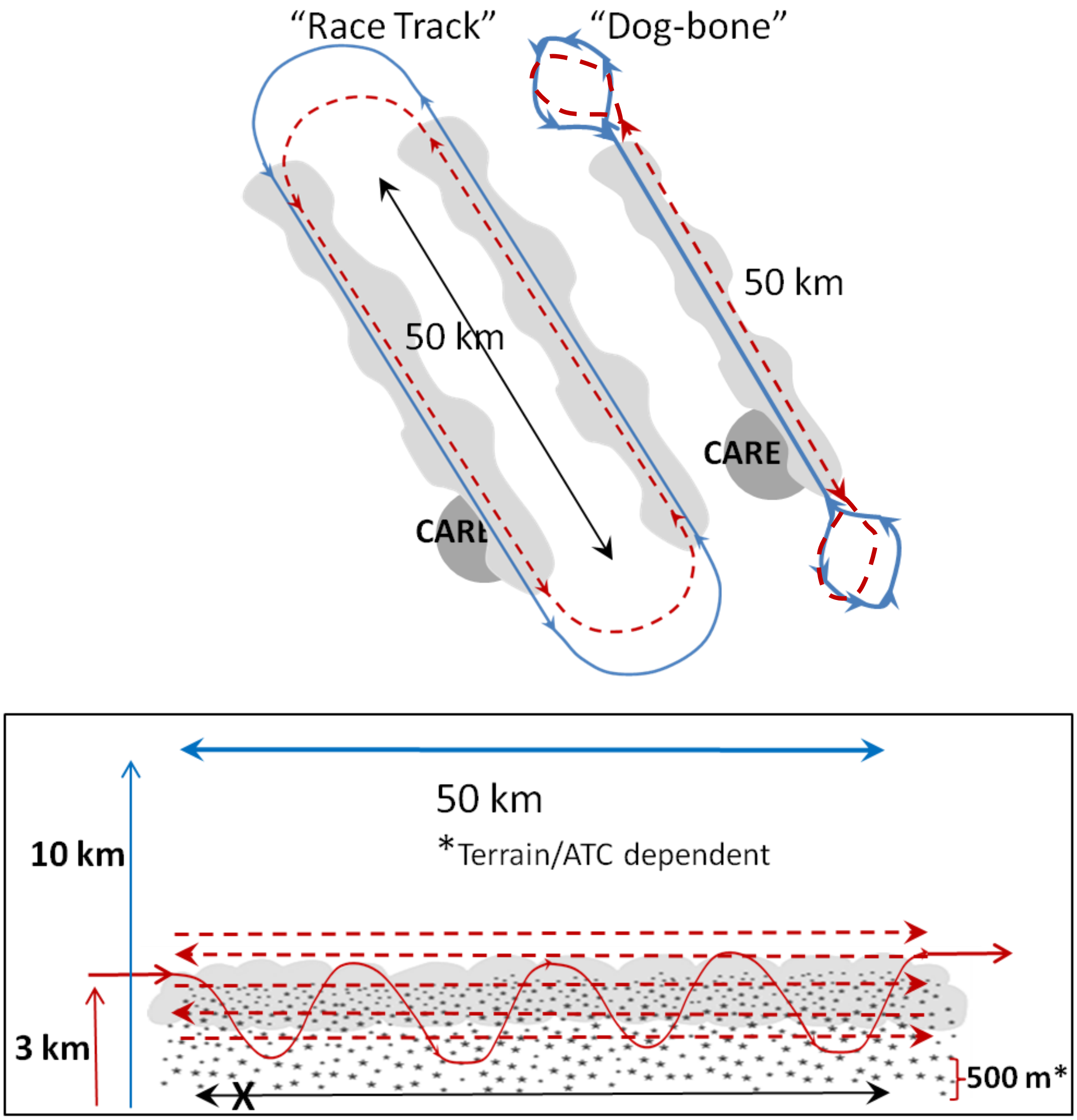

Figure 12: Sample coordinated aircraft observations for Lake Effect Snow sampling. Citation (red dash)-porpoise or stair step in altitude over 50 km leg from 1.5 kft – 10 kft (~500 m to 3000 m). DC-8 (blue solid lines) constant altitude oval orbit over Citation (DC-8, 50 – 75 km leg; altitude 33 kft (10 km) nominal). Legs stretch to the north-northeast with CARE site at southern end (hit other sites as possible). Note that porpoising pattern is not to scale (exaggerated to illustrate concept).

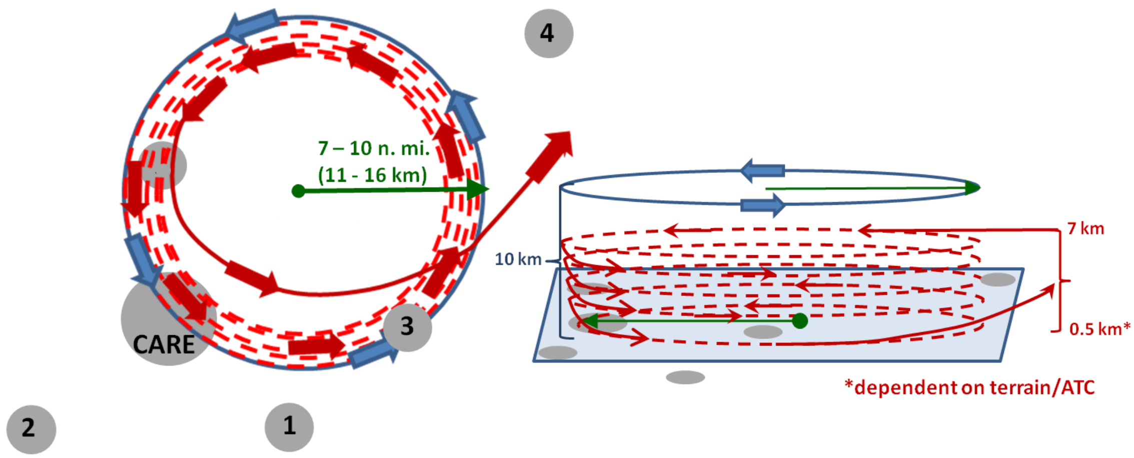

Figure 13: Sample coordinated aircraft observations for Synoptic Snow sampling. Citation (red dashed lines)- Spiral descent from TBD altitude 7 km (24 kft nominal) to 0.5 km (1.5 kft). DC-8 (blue lines) fixed circular orbit over Citation (DC-8 altitude 33 kft nominal)

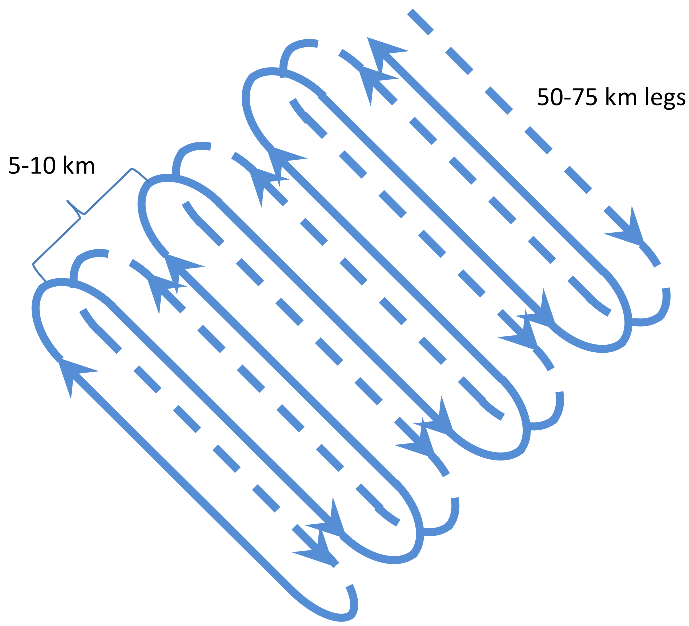

Figure 14: Sample DC-8 aircraft observations for surface emission sampling. Single, nominal altitude 33 kft (10 km). Patterns flown in single ladder, or staggered (to increase surface sampling/resolution).

5.4 Coordination

Coordination of aircraft operations will occur in daily consultation between the Mission Scientist(s), weather forecasters, the UND Citation Mission Manager, and the DC-8 Mission Manager. Guidance for aircraft operations during each mission will be conducted from the EC CARE facility (or other TBD location) via VHF radio, telephone and/or X-Chat depending on the airborne platform and final arrangements made with Canadian authorities. Real time tracking and situational awareness for the aircraft operations will be facilitated via use of the MSFC Real Time Mission Monitor (RTMM) tool. The RTMM will be used by the mission scientist and aircraft crews (esp. DC-8) to guide and follow the aircraft track in the framework of weather radar and satellite surveillance updates.

6. Modeling Support

Modeling activities are an important component of GCPEx both for placing findings into a broader meteorological context and to improve our understanding of the relevant microphysical processes for falling snow development. Toward these ends, GCPEx will leverage large-scale temperature, humidity, winds, and precipitation forecasts from operational models running at both the MSC and NCEP. During the experiment these models will be used for flight planning purposes (TBD) and for subsequent analysis of the results. In addition, these datasets will be used to initialize finer-scale CRM simulations (e.g., GSFC WRF satellite simulator) of several events sampled during the experiment to (a) test the ability of these models to represent this type of precipitation system and (b) provide a deeper understanding of the underlying dynamic, thermodynamic, and microphysical processes.

7. Satellite Datasets

Satellite datasets for overpasses occurring over the sampling domain will be collected and archived by the CloudSat data center located at CIRA in Fort Collins, Colorado. At a minimum these datasets will include AMSU B and MHS measurements from polar orbiters NOAA 18, 19, Aqua AMSR-E datasets and CloudSat with other sensors as needed.

8. Summary

The GCPEx will be conducted over and near the Ontario, Canada/Great Lakes Environment Canada CARE site from January 17 to February 29, 2012. The experiment is designed to measure properties of falling snow for understanding frozen precipitation processes in association with improving and quantifying the detection limits and estimation errors of snowfall retrieval algorithms being developed for GPM. GCPEx will address topics related to satellite algorithm development including assessment of minimum detectable snow rates, discrimination of rain and falling snow, discriminating falling snow from snow-covered land surfaces, microphysical assumptions in the algorithms, spatial heterogeneity of precipitation and its relationship to the aforementioned topics.

To address the above objectives a cross-validated 3-D characterization of precipitation processes in falling snow events will be created. A total of five locations approximately centered on the CARE site (to include one location in the lake-effect snow belt adjacent to the Georgian Bay of Lake Huron) will be heavily instrumented to observe both lake-effect and synoptic-scale snow events. Instrumentation deployed at these sites will include collocated disdrometers, rain gauges, precipitation occurrence sensor systems, L-band snow water equivalent sensors, and micro rain radars. In addition, the central CARE facility site will host the ADMIRARI scanning radiometer, the D3R Ka-Ku band radar, ground staring radiometers and soundings. All of the instrumented sites will be sampled under the coverage umbrella of the King City C-band dual-polarimetric radar, and two aircraft, the UND Citation and NASA DC-8. The UND Citation will carry a full suite of microphysics probes for profiling snowfall above the ground locations while the DC-8 will serves as a GPM satellite proxy- carrying the APR-2 Ka-Ku band radar and CoSMIR radiometer.

Collectively the measurements will be coordinated to provide a database of snowfall characteristics including particle sizes and shapes with attendant bulk and particle-scale water equivalents from the ground through the depth of the cloud, including the melting layer if it exists. These observations will be quality assured and prepared for use in forward radiative transfer models designed to simulate radiometer frequencies spanning the 89 – 183 GHz range, and radar reflectivities at Ka-Ku bands (GPM DPR) and W bands (CloudSat). The GCPEx data set will provide the means to conduct sensitivity studies to assess cold-latitude snow regime microphysical impacts on the fidelity of satellite retrieval algorithms.

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Appendix A: Data Access

All data collected during GCPEx as well as ancillary satellite, NWP, and CRM datasets will be accessible through the GPM GV Data Archive Site and web portal (website in development). This website will provide a running log of all precipitation events sampled during the experiment and provide tools for searching and downloading the corresponding ground, aircraft, and satellite datasets. Many of the GCPEx datasets will be collected and archived centrally on the GPM GV archive hosted by the GHRC DAAC and will be accessible via the NASA PMM Website or GCPEX Portal. Every effort will be made to ensure that individual instrument PIs provide quality controlled datasets to the central archive within six months of their collection. Datasets are considered "open" and will be made freely available to the science community upon completed quality control. PI's may request to be coauthors on any publication using datasets they have prepared and data "readme" files should communicate this request to all users.

NASA policies maintain an open data policy for datasets collected using NASA instruments and/or instruments funded under NASA contracts. These datasets will be made publicly available on the GPM Ground Validation web-site to (or links to relevant datasets) once the data have been quality controlled (typically within 6-months of the end of the experiment).

Appendix B: Instruments and Contacts

Instrument	Qty	Purpose	Provider	Comments
GROUND				**Locations, etc**
		NOTE: Continual Updates are expected		
C-band Dual Pol. Radar (scanning)	1	4-D Precipitation	EC King City Radar	D. Hudak/Paul Joe
W-band vertically pointing	1	Cloud/hydrometeor profiles	McGill U.	P. Kollias
X-band vertically pointing	1	Hydrometeor profiles	McGill U.	P. Kollias
Ground-Staring Radiometer	1	1.4, 19, 37-89 GHz snow pack water equivalent	EC Climate	C. Derksen
Dual Polarization Radiometer	1	89 and 150 GHz (scanning ground and atmos)	U. Bonn	P. Savedra
2DVD	5	DSD/Radar Cal.	GPM	3rd Gen./ W. Petersen
Parsivel Disdrometers	12	DSD/precip. Rate/variability	GPM	2 spares; W. Petersen
Snow LWE probes	5	SWE/rate on/at ground	GPM (Duke U.)	PI Ana Barros
ADMIRARI Radiometer/MRR	1	Combined cloud and rainwater retrievals	U. Bonn/Leicester	PI A. Battaglia
MRR	5	DSD profiling, precip rate, melting layer	NASA/EC	W. Petersen/ P. Joe/A. Battaglia
OTT Pluvio2 Weighing Gauges	9	Precip rate	GPM	GPM (Petersen/Tokay)
Automatic Sounding System	1	T/P/RH profiles	EC CARE	CARE Site; D. Hudak
Twice-daily Soundings	1	T/P/RH profiles at Tallinn, St. Petersburg, and Jokioinen	University of Wyoming webpage http://weather.uwyo.edu/upper air/sounding.html	Otherwise data should be available from FMI
POSS	2	DSD/precip rate	EC	Hudak
Profiling Lidar	1	Backscatter at 2 wavelengths	EC CARE	Hudak
Aircraft				45 flight hours
UND Citation				
King Hot wire	2	Cloud liquid water	UND	Poelllot/Heymsfield
2DC	1	Particle size distribution and type (0.1 – 0.8 mm)	UND	Poelllot/Heymsfield
CPI	1	Cloud Particle Imager	UND	Poelllot/Heymsfield
CIP	2	Cloud Imaging Probe (0.15-1.5 mm)	UND.	Poellot/Heymsfield
CDP	1	Cloud droplet spectra (2 – 50 m)	UND	Poellot/Heymsfield
Nevzorov	1	Liquid and Total water content	UND	Poellot/Heymsfield

HVPS-3	1	Particle sizing (0.15-19.2 mm)	UND	Poellot/Heymsfield
Rosemount icing rate meter	1	Detection of super cooled water	UND	Poellot/Heymsfield
Dew point (chilled mirror)	1	Dewpoint T (-60° to 40°C)	UND	Poellot/Heymsfield
Temperature	1	-60° to +40° C	UND	Poellot/Heymsfield
CN Counter	1	10 nm cut	UND	Poellot/Heymsfield
Winds	1		UND	Poellot/Heymsfield
Water Vapor	1	125-30000 ppmv	UND	Poellot/Heymsfield
Pressure	1	0-1034 mb	UND	Poellot/Heymsfield
DC-8				
APR-2	1	Ka-Ku Ze + Dual-pol moments	GPM	Durden/Tanelli
CoSMIR	1	50-183 GHz TB	GPM	Skofronick-Jackson
Satellite			**CloudSat**	**To be archived for sampling area throughout experiment**
CloudSat	1	W-band reflectivity, Cloud geometric profile, LWC/IWC profile, precipitation type/rate		L'Ecuyer
MODIS	1	IR TBs, visible TBs, cloud mask, LWP, IWP, effective radius		L'Ecuyer
AMSR-E	1	Polarized TBs (6.9-89 GHz), SST, CWV, LWP, rain rate		L'Ecuyer
AMSU-B	1	TBs (89-183 GHz), rain/snow incidence, rain rate		L'Ecuyer
Model Analyses			**TBD**	