NEAR REAL-TIME CLOUDSAT PROCESSING AT THE NAVAL RESEARCH LABORATORY

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Abstract

Only more than a year since its launch in April 2006 as part of the Earth Observing System (EOS) 'A-Train' satellite constellation, the NASA/ESSP CloudSat mission has already made significant contributions toward broadening our understanding of detailed cloud vertical structures across the globe. Realizing the potential benefit of CloudSat to both the research objectives and operational requirements of the United States Navy, the Naval Research Laboratory coordinated early-on with the CloudSat Data Processing Center to receive and process First-Look (FL) 94 GHz Cloud Profiling Radar (CPR) datasets in near real-time (4-8 hr latency) - making the observations relevant to the operational community.

Applications leveraging these unique FL satellite data include demonstrations of CPR cloud profiles matched to conventional two-dimensional views from passive radiometers (e.g., GOES, Meteosat, MTSAT, and Aqua/MODIS and AMSR-E) on the NexSat (www.nrlmry.navy.mil/NEXSAT.html) web page, globally distributed tropical cyclone cross-sections on the TC Web Page (www.nrlmry.navy.mil/tc_pages/TC.html), support of research field programs (including the Canadian CloudSat/CALIPSO Validation Project), validation of the Navy's numerical weather prediction model cloud fields, validation of passive-sensor derived cloud property retrievals, and quantitative precipitation estimation for light rainfall regimes. This paper summarizes those efforts.

INTRODUCTION

Understanding the life-cycle, radiative, dynamic, and thermodynamic properties of global cloud cover is of paramount importance for representing clouds accurately in numerical weather prediction (NWP) and climate modeling. In light of their importance as an integral component of the hydrological cycle, an increasing number of satellite sensors dedicated to the observation of clouds has emerged. Capable of providing the first global-scale cross sections of cloud vertical structure, the 94 GHz Cloud Profiling Radar (CPR) on board CloudSat will collect information beneficial to a diverse assortment of fundamental research and validation efforts (Stephens et al., 2002).

The paper is structured as follows: section 2 briefly describes the CPR observing capabilities, section 3 is a short description of the concepts behind near real-time satellite data processing, section 4 describes the methodology adopted for integrating CPR data sets into the general framework of the Naval Research Laboratory (NRL) automated satellite data processing system, including its use in tropical cyclone monitoring and field program support, and section 5 summarizes this work.

CLOUDSAT'S 94GHZ OBSERVING SYSTEM

As a mission sponsored by NASA's Earth System Science Pathfinder program, CloudSat targets a variety of scientific objectives related to Earth science, and in particular the complex non-linear feedback role of clouds in the climate system (Held and Soden, 2000). Launched in April 2006 as part

of the 'A-Train', CloudSat is in a 705 km altitude sun-synchronous polar orbit with a ground-track repeat of roughly 16 days. Designed to profile cloud structure, CloudSat features a nadir-looking 94 GHz (3 mm) radar with a minimum detectable reflectivity around -30 dBZ, a 70 dBZ dynamic range, and a calibration accuracy of 1.5 dBZ. With a 240 m vertical resolution and a 2.5x1.4 km footprint resolution, the system is well-suited for sensing a wide variety of cloud systems including cirrus and stratus to deep convective systems.

The Air Force Satellite Control Network (AFSCN) located at Kirtland AFB in Albuquerque, New Mexico tracks and receives raw CloudSat data, quality controls and packages it, and sends it to the CloudSat Data Processing Center (DPC) located in Fort Collins, CO (part of the Cooperative Institute for Research in the Atmosphere (CIRA) at Colorado State University). The DPC is responsible for the primary and scientific data integration, processing, and distribution for the CloudSat program (more info at http://cloudsat.cira.colostate.edu). Of interest to this study are the 1B-CPR-FL products.

NEAR-REAL TIME SATELLITE DATA PROCESSING

The Satellite Meteorological Applications Section at NRL in Monterey, CA develops and transitions to United States Navy operational centers a wide variety of applications using both satellite and numerical weather prediction (NWP) data. The extensive use of satellite data for monitoring weather related events is illustrated on NRL's public NexSat web page (www.nrlmry.navy.mil/NEXSAT.html, Miller et al., 2006). In terms of cloud remote sensing, contemporary passive satellite sensors (radiometers) are limited to statements on cloud-top properties, and are for the most part unable to provide accurate information on cloud internal structure. Space-borne active sensors, such as CloudSat, owing to their inherent profiling capabilities, are an invaluable tool for filling in the missing information and validating passive sensor derived products. In addition, data from numerical models such as Navy's Operational Global Atmospheric Prediction System (NOGAPS®) is sometimes used as the ancillary data for satellite-based algorithms.

In the following sections we explain the strategy adopted for integrating CloudSat data into our automated satellite data processing system for both operational and research and development support.

NEAR-REAL TIME CLOUDSAT DATA PROCESSING

The average data latency of CPR data is on the order of 4 to 8 hours. Whereas CloudSat holds no operational mandate, through a special agreement with DPC/CIRA we currently download the 1B-CPR-FL data almost minutes after the raw data are received at their facility. CloudSat, being a polar orbiting satellite, provides global coverage at the expense of a much reduced temporal coverage (for a given region). From around 15 orbits (i.e. granules) per day that CloudSat produces, depending on the area covered, only a few will intersect one of our established satellite monitoring sectors (stationary or fixed). Whenever that does happen, we superimpose the CloudSat track atop the satellite imagery (geostationary or polar orbiting based) for that sector and plot the corresponding attenuated radar reflectivity profile. In the following subsections we describe some of the near-real time applications using CloudSat data.

First Look Data Processing:

The premise for generating First Look images was that providing a quick, near-real time view of the vertical profile measured by the CPR would be of potential benefit to operational users (e.g. helping better understand vertical structures and cloud layering, information unavailable from the operational satellite datasets). In addition, temperature profiles from NOGAPS® are extracted along the CloudSat's track and over-plotted upon the radar reflectivity profile as contours. It provides a useful (and more commonly used and understood) thermodynamical field giving additional meteorological context to the cloud reflectivity profile. Therefore, one can more readily identify regions prone to have a specific phase (i.e. a cloud type classification), visually estimate in-cloud temperatures and possible inversions, check for the bright band (melting layer) position, precipitation shafts, etc. We currently

process multiple fixed sectors around the world and a variable number of moving sectors tracking TC systems.

An example of the CPR quick look radar profile is presented in Figure 1. Collected on January 21 2007 by GOES-East, it shows an area centered at 65 W covering the West Atlantic Ocean and the Eastern part of the US (the "NW Atlantic" overview sector of NexSat). On the right side of the image is a fast moving front crossed by CloudSat. Behind it, cellular cloud structure in the cold-sector of the system as northeasterly winds advancing over warmer waters of the northern Gulf Stream is clearly visible. The red line shows the CloudSat satellite ground track. To facilitate cross-referencing with the GOES image, the black dots overlaid upon the ground track represent one minute of orbit time. The "Start" and "End" labels identify the UTC times when CloudSat enters and exits this geographical area. A "North" or "South" arrow indicates an ascending or descending orbit. The measured radar reflectivity profile is presented using a color bar that ranges from -30 dBZ to +20 dBZ, followed by a horizontal scale bar. Altitude and pressure are shown on the left and right ordinate axes. The corresponding 3 hourly interpolated profile of air temperature from NOGAPS® is also displayed as contours.
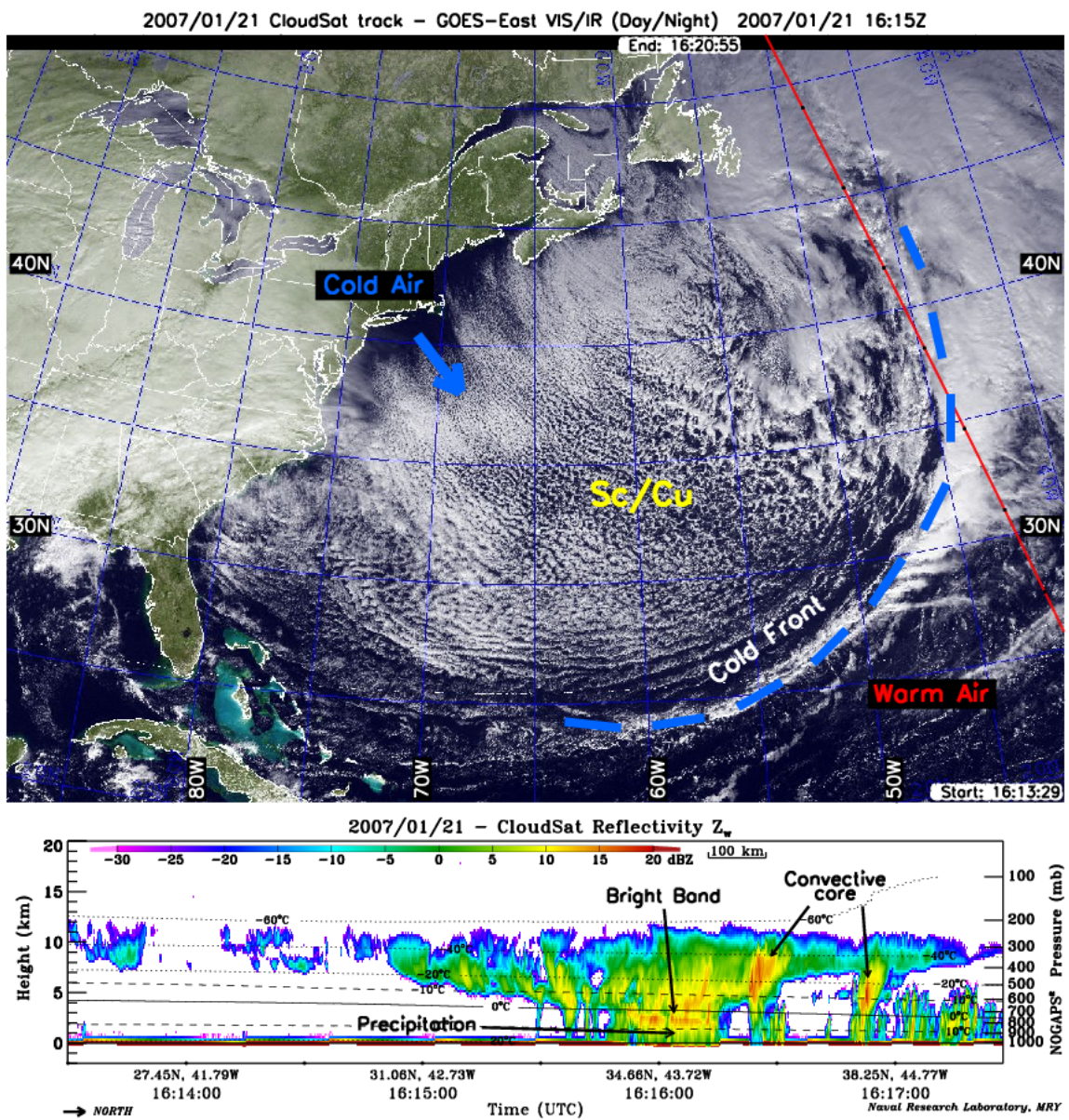

Figure 1: GOES data and CloudSat radar profile for the NW Atlantic sector on 2007/01/21, 1615 UTC.

CloudSat Processing for the Tropical Cyclone Web Page:

CloudSat's sensitivity to cloud droplets has proven very useful in profiling one of the most severe weather phenomena on Earth: tropical cyclones (TC). Due to frequent upper-level clouds, all passive visible/IR sensors are severely limited in monitoring these large and powerful systems that contain high winds and heavy precipitation. Radars, on the other hand, can penetrate deep into the dense cloud/precipitation structure before being attenuated. The TC page's near-real time processing is driven by the 6-hourly updates provided by the Joint Typhoon Warning Center (JTWC, Pearl Harbor, Hawaii), the National Hurricane Center (NHC, Miami, Florida) and the Central Pacific Hurricane Center (CPHC, Hawaii) via the Automated Tropical Cyclone Forecasting (ATCF) system. The full suite of geostationary and polar orbiter digital data sets are then interrogated to see which newly arriving data will be processed to create TC products (Hawkins et al., 2001). During the 2006 TC season, CloudSat had more than 900 TC crossings, and in some cases, through the synthesis with spatial images, it has provided unique views of TC inner-core cloud and precipitation structure.

Figure 2, which highlights a CloudSat overpass of hurricane Ileana (maximum sustained wind of 54 m/s) on August 23 2006, at 2100 UTC reveals a complex horizontal and vertical structure. The top part of the image shows the 2-D horizontal cloud distribution as captured by Aqua MODIS visible sensor at 1 km resolution, with the CloudSat track superimposed in red (dots denote 15 second flight track intervals), while the bottom part depicts the CPR's vertical profile. The cloud tops created by the vigorous convective activity reaches about 16 km and spans over more than 800 km with spiraling bands clearly visible. The CloudSat vertical cross-section provides a wealth of information: a) upward sloping of cloud tops towards the TC eye or storm center, b) a rain-free region associated with both the eye and a "moat-like" region to the south located between the inner eye-wall and an outer rain-band, c) ready identification of intense rain areas along the radar's nadir only ground track, d) cloud-base measurements to the south as the cirrus cloud bases get progressively higher away from the convective source region, and e) mapping of the upward sloping "bright band" (BB), an indication of a melting layer. NOGAPS[®] thermal structure is included as isotherms.

Another illustrative example is a CloudSat overpass of western pacific typhoon Durian, on September 07 2006, at 0210 UTC while at an estimated intensity of approximately 40 m/s (see Figure 3). Here, Durian is caught in a highly explosive stage (after reaching its maximum intensity earlier) that highlights the value of CloudSat's unique profiling capabilities. The Aqua MODIS IR imagery includes a massive cirrus canopy, but does not permit the analyst to ascertain much information pertaining to the organization of rain-bands or storm structure beneath it. However, CloudSat details a small, but explosive convective region that is responsible for the mushroom-like cloud appearance that spans over 180 km around it. Huge convectively active regions like this one are called "hot towers" and are one of the mechanisms that create and sustain the TC warm core. In fact, Durian did intensify shortly after this particular convective burst event. Similar hot towers can be viewed by the TRMM precipitation radar (PR) since the precipitation signature is so large and involves very large droplets. Note that Figure 3 also detects low and mid-level cloud and rain structure both north and south of the convective cells that are extremely difficult to extract from the IR image alone.

Data extraction is also done along the CPR tracks for all TC crosses, creating a comprehensive data base (www.nrlmry.navy.mil/archdat/tropical_cyclones/CPR_TC_Intercepts). It contains radial information along CloudSat track about CPR's reflectivity, AMSR-E brightness temperature and derived products (wind, SST, precipitation, LWP, humidity), as well as NOGAPS[®] data fields.

Near-Real Time Support for Field Programs:

While validation is an important utility of the CloudSat dataset, it is recognized that CloudSat itself must be validated. Intensive field campaigns aimed at gathering as much in-situ data from as much complementary/redundant instrumentation as possible over a target area during a limited time range is one way to accomplish this. The Canadian CloudSat/CALIPSO Validation Project (C3VP) Experiment (www.c3vp.org), for example, sought to collect datasets to evaluate cloud, precipitation, and aerosol products from CloudSat and CALIPSO associated with cold-season weather systems in the great
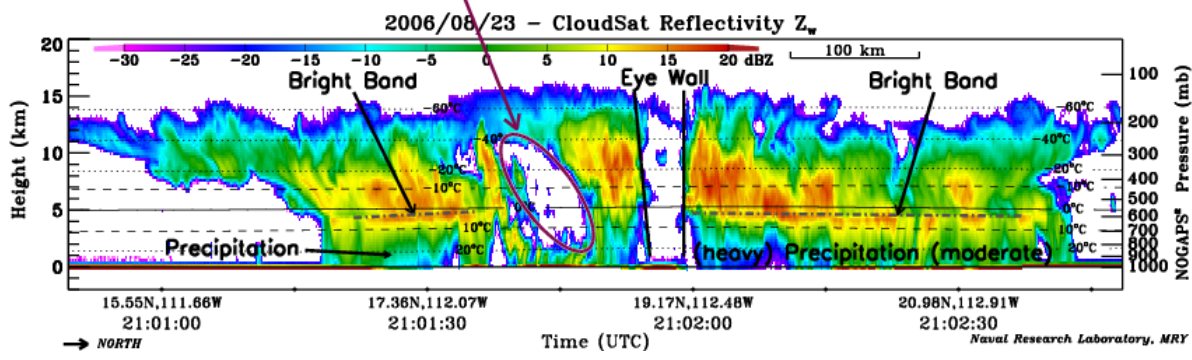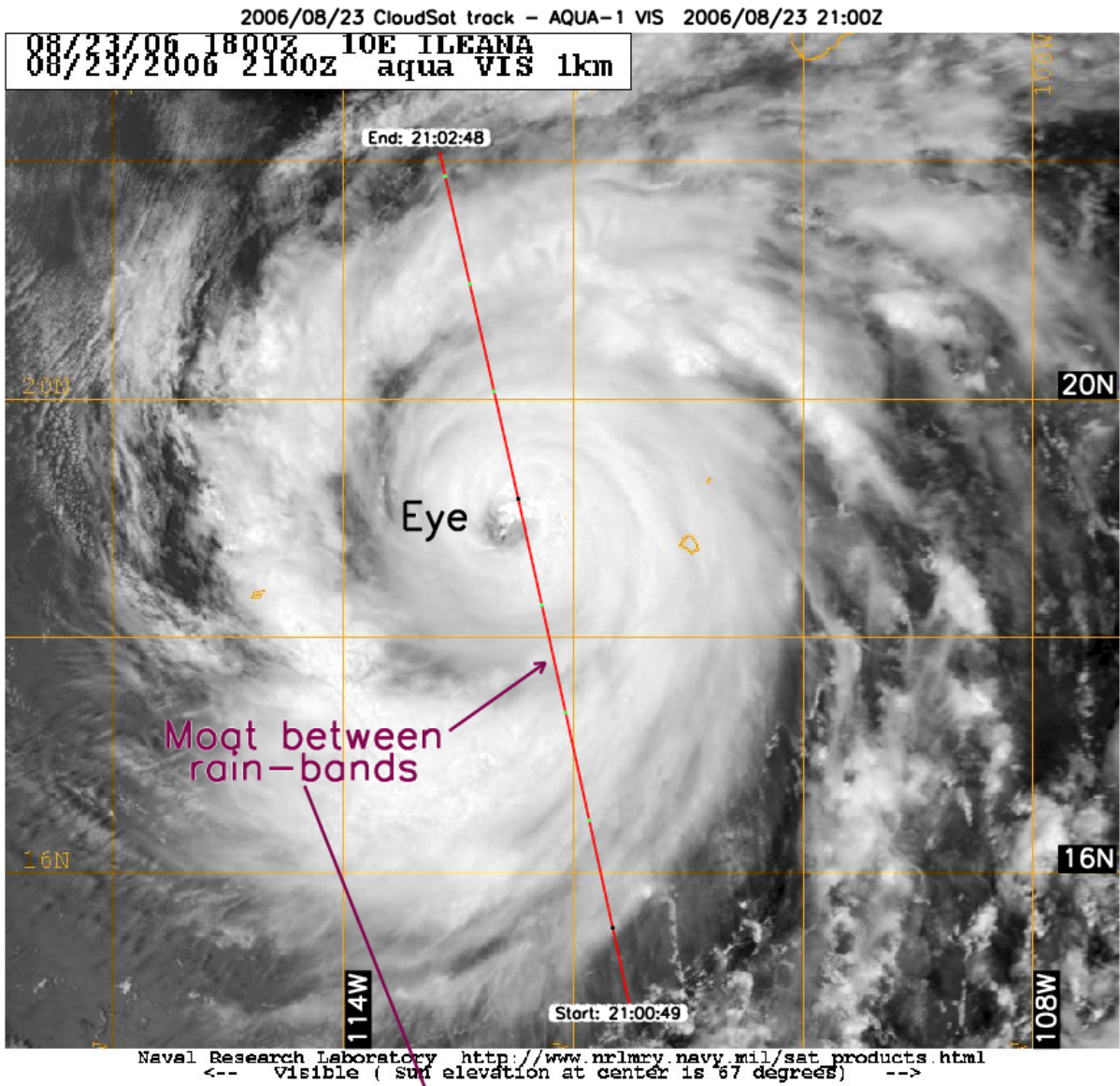
Figure 2: **'A-Train' (Aqua-VIS and CloudSat) view of hurricane Ileana on 2006/08/23, 2100 UTC.**

lakes region of Canada. The experiment yielded several high quality datasets from ground-based and airborne X-, C-, W-, Ka-, and Ku-band radar, in situ observations of cloud particle size distributions, water contents, and precipitation rates, and a suite of passive remote sensing instruments. These measurements, often collocated with satellite overpasses, cover a wide range of cold-season cloud systems featuring light rainfall, snowfall, multi-layer, and mixed-phase clouds. The availability of

NexSat products throughout the experiment helped in rapid assessment of weather conditions during the campaign.
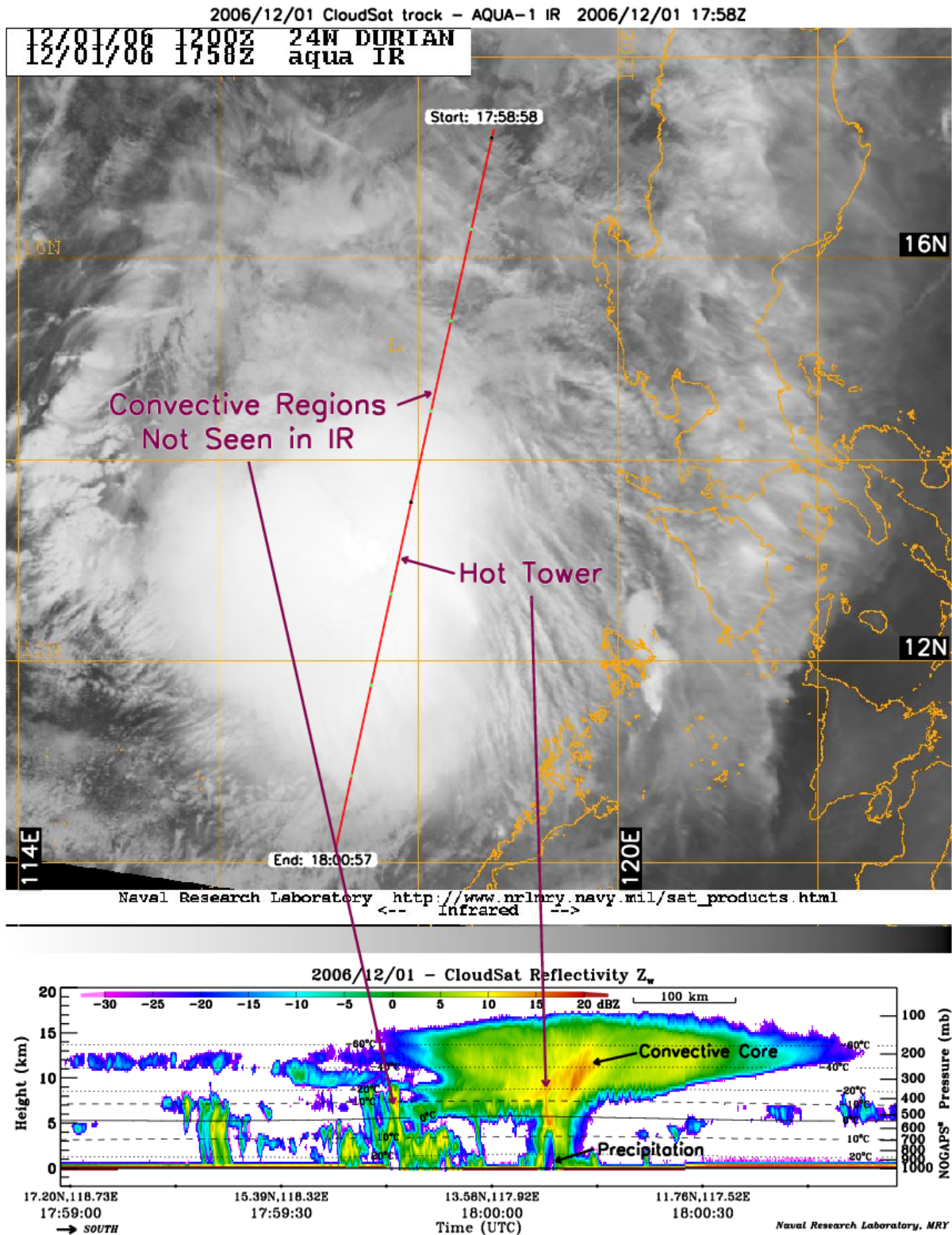

Figure 3: 'A-Train' (Aqua-IR and CloudSat) view of typhoon Durian on 2006/12/01, 1800 UTC.

With help from our colleagues at National Center for Atmospheric Research (NCAR) in Boulder CO, we are currently examining various satellite algorithms and modeling tools for characterizing aircraft

icing potential and intensity (e.g. Bernstein et al., 2005; Minnis et al., 2004), a serious concern for aviation safety. Initial results from such collaboration, described in more detail in another paper (Lee et al., 2007), are currently being posted on NexSat.

Taking advantage of CloudSat's ability to range-resolve cloud top and base, we have also started a near-real time comparison – (posted on NexSat), between our passive sensor (GOES) derived cloud top heights retrievals and those detected by the CPR. Figure 4, showing a cross-section through a fast moving frontal system over the NE Pacific on January 30 2007 at 2248Z, provides a good example of how CloudSat can reveal caveats to our passive retrieval approaches. Three distinct regions are identifiable. On the first (left part of the figure), the passive sensors cloud top height algorithm does a relatively good job in assigning a correct top altitude since the simplified model closely matches the observed clouds. As the cloud becomes more transparent (mid section of the figure), errors in retrieved optical depth manifest as increasing differences between GOES and CPR-retrieved cloud top heights. The disagreement is most pronounced when the cloud vertical structure as seen by CPR shows a multilayer structure that contradicts the model assumption of one-layer cloud (right part of the figure). These comparisons will help us in correcting, accounting for errors, and understanding limitations of the physical cloud model used for GOES based height retrievals, leading to improvement in the retrieval of other microphysical and optical parameters. Moreover, qualitative comparisons between CloudSat's reflectivity field and other passive sensor output can be done. As such, some of the CloudSat's derived products - available through DPC/CIRA, like cloud class, LWC/IWC, precipitation rates, can also be compared against numerical model output and/or other satellite based techniques. However, all these efforts are currently work in progress and therefore will be discussed in more detail sometime in the future.
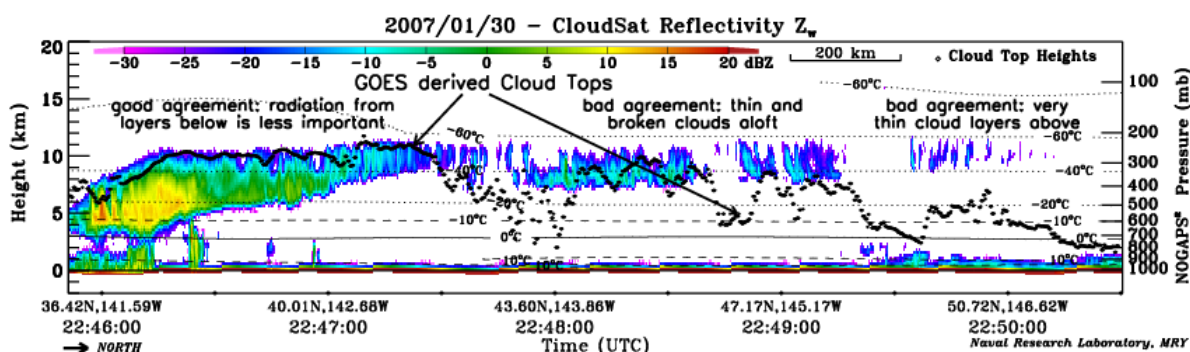

Figure 4: **GOES derived Cloud Top Heights vs. CloudSat for a region over NE Pacific on 2007/01/03, 2248 UTC.**

SUMMARY AND CONCLUSIONS

Designed for profiling the vertical structure of clouds, CloudSat's 94 GHz CPR adds a third dimension of information needed for assessing the influences and feed-backs that clouds exert on our climate system.

While CloudSat is a research satellite, the present work offers such a glimpse into the "operational" (i.e. near real-time) use of CloudSat data in combination with the more widely used (and perhaps better understood) data from passive sensors. Presented here are some applications that combine passive data from sensors on geostationary (like GOES) or polar orbiting satellites (such as Aqua), that only have limited ability of characterizing cloud vertical structures, with CloudSat that by design resolves such a structure. In addition, due the ranging ability that active sensors offer, although somewhat limited to only some cloud types as explained above, radar profiles are extremely useful for validation/comparison purposes. Support provided for the C3VP Experiment and validation for GOES derived Cloud Top Height algorithm represent just some applications illustrated here.

It is also important to note the educational benefits of CloudSat. Training will likely become available from the Cooperative Program for Operational Meteorology, Education and Training (COMET), at www.comet.ucar.edu.

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