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William J. Hughes Technical Center
Aviation Research Division
Atlantic City International Airport
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The High Ice Water Content Study of Deep Convective Clouds: Report on Science and Technical Plan

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16. Abstract

This report describes a collaborative research project to collect atmospheric data to support engineering issues related to the failure of commercial aircraft jet engines in convective clouds and a variety of scientific issues related to the microphysical properties and structure of deep convective clouds. The aviation sector has compiled information on more than 100 weather-related engine power-loss events and concluded that they are due to flight through areas of high ice water content (HIWC) associated with deep convective clouds. Flight into high ice concentrations has also resulted in failures of air data probes, most notably aircraft pitot probes. As a result, an industry-led working group, the Engine Harmonization Working Group (EHWG), recommended the collection of an in situ data set to characterize the microphysical properties of these clouds, to be used to provide guidance to manufacturers and to substantiate the new Title 14 Code of Federal Regulations Part 33 Appendix D engine icing certification envelope for HIWC ice crystal conditions.

This report provides background information and recommendations on how to conduct flight test operations for these aviation objectives. The objectives of the data collection and the design of the flight experiment were determined during numerous meetings of the EHWG and are consistent with its technical plan. Measurements will focus on the characterization of HIWC regions and the provision of 99th percentile total water content statistics and ice crystal characteristic size as a function of distance scale. These measurements will provide the first extensive modern data set of in situ measurements of the updraft areas of tropical oceanic deep convection and stratiform regions of more vigorous tropical continental convection that can be safely penetrated and will be a unique resource for the industry and science communities. Data will be used by the science community to improve knowledge on basic cloud microphysical processes and numerical cloud modeling and to develop better algorithms for ground- and space-based remote sensors in active convective cells. In addition, the measurements will support the development of pilot's radar and nowcasting tools for the aviation sector to help in forecasting and avoidance of these hazardous cloud regions.

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ARM	Atmospheric Radiation Measurement
AVHRR	Advanced Very High Resolution Radiometer
BoM	Bureau of Meteorology
CDP	Cloud Droplet Probe
CFR	Code of Federal Regulations
CIP	Cloud Imaging Probe
CPI	Cloud Particle Imager
CPOL	C-band polarized radar
CRM	Cloud-resolving model
EC	Environment Canada
EHWG	Engine Harmonization Working Group
EIWG	Engine Icing Working Group
EL	Equilibrium level
FDR	Flight data recorder
FSSP	Forward-scattering spectrometer probe
GEOsats	Geostationary satellites
GISS	Goddard Institute for Space Studies
GOES	Geostationary Operational Environmental Satellite
HAIC	High Altitude Ice Crystals
HIWC	High ice water content
IKP	Isokinetic evaporator probe
IR	Infrared
ISA	International Standard Atmosphere
ITCZ	Intertropical Convergence Zone
IWC	Ice water content
IWP	Column ice water path
JAC	Joint Airworthiness Committee
LaRC	Langley Research Center
LWC	Liquid water content
MCS	Mesoscale convective system
MMD	Median mass diameter
MODIS	Moderate Resolution Imaging Spectroradiometer
MTSAT	Multifunctional Transport Satellites
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council
NTSB	National Transportation Safety Board
NWP	Numerical weather prediction
OD	Cloud optical depth
PPIWG	Power Plant Installation Working Group
PSD	Particle size distribution
RAE	Royal Aircraft Establishment
SAFIRE	Service des Avions Francais Instrumentés pour la Recherche en Environnement
SEA	Science Engineering Associates
SLD	Supercooled large droplets
TAT	Total air temperature

TC	Transport Canada
TRMM	Tropical Rainfall Measuring Mission
TWC	Total water content
TWP-ICE	Tropical Warm Pool-International Cloud Experiment
VPRR	Vertical profile of radar reflectivity
VZA	Viewing zenith angle
WBF	Wegener–Bergeron–Findeisen

EXECUTIVE SUMMARY

This report describes a collaborative research project for the collection of atmospheric data to address engineering and scientific issues related to the failure of commercial aircraft jet engines in convective clouds and a variety of scientific issues related to the microphysical properties and structure of deep convective clouds. The aviation sector has compiled information on more than 100 weather-related engine power-loss events and concluded that these events are due to flight through areas of high ice water content (HIWC) associated with deep convective clouds. Among the power-loss events are temporary multiple engine failures, including two cases of successful landings without engine power, which have resulted in two airworthiness directives related to specific airframe-engine combinations. In addition to the safety concerns of engine power loss, these events can also result in costly engine repairs. Flight into high ice concentrations has also resulted in failures of air data probes, most notably aircraft pitot probes. As a result, an industry working group has recommended the collection of a data set to characterize the microphysical properties of these clouds, which will be used to provide guidance to manufacturers and to substantiate the new Title 14 Code of Federal Regulations Part 33 Appendix D icing engine certification envelope for HIWC ice crystal conditions. Major partners include the FAA, NASA, Transport Canada, The Boeing Company, Airbus, Environment Canada, and the Australian Bureau of Meteorology.

This report provides background information and recommendations on how to conduct flight test operations for these aviation objectives. The objectives of the data collection and the design of the flight experiment were agreed upon during numerous meetings of the Engine Harmonization Working Group and are consistent with its technical plan. Measurements will focus on the characterization of HIWC regions and the provision of 99th percentile total water content statistics and ice crystal characteristic size as a function of distance scale. These measurements will be a unique source, because they provide the first extensive modern data set of in situ measurements of the updraft areas of tropical oceanic deep convection and stratiform regions of more vigorous tropical continental convection that can be safely penetrated. Data will be used by the science community to investigate fundamental problems related to the initiation of ice particles and the development of the mixed phase and precipitation in deep convection. A better understanding of these processes and documentation of the structure and dynamics of active cells of convection will be used to improve numerical cloud model simulations and to develop better algorithms for ground- and space-based remote sensors. The measurements will support the development of nowcasting tools for the aviation sector to help in forecasting and avoidance of regions conducive to jet-engine power loss and air data probe failures due to ice crystals.

Note: The first draft of this HIWC Technical and Science Plan, containing most of the material contained herein, was produced in 2007. The HIWC partnership had been formed in 2006 after the Engine Harmonization Working Group (EHWG) released its Technical Plan. The plan evolved through several meetings with the EHWG, in which objectives and sampling methodologies were vetted. Because of multiple setbacks in securing a research aircraft for the flight program, the completion of this report was continually delayed due to necessary changes to its content, mostly related to the specifics of the aircraft. Though flight campaigns out of Darwin, Australia and Cayenne, French Guiana have already been completed, this report is being published to document early work performed and discussed with the EHWG toward the development of an acceptable data collection strategy. Because of the passage of time, it was necessary to rewrite certain sections in a more generic fashion, most notably the sections related to the specifics of the measurement locations and the details of the research aircraft.

1. INTRODUCTION

1.1 JET-ENGINE POWERLOSS IN DEEP CONVECTIVE CLOUDS

In the mid-1990s, it was recognized that jet engines are susceptible to power-loss events when flying in the vicinity of deep convective clouds. A power-loss event is defined as a temporary uncommanded loss of engine thrust that can occur in one engine, simultaneously in multiple engines, or in all engines. Power-loss events, such as "surge," "stall," "flameout," and "rollback," can be momentary events that may require a manual engine relight or, in the case of rollback, may require descent to melt ice before the engines can be restarted. Though no accidents are attributable to this type of power loss, multiple efforts are underway to find solutions to the problem because of the potential safety threat and the high cost of repairing engines damaged by ice during some events.

The first description of the associated meteorological conditions during an engine power loss event was reported after a series of events on a commuter-class aircraft [1]. In 2003, the Engine Harmonization Working Group (EHWG), an international committee composed of airframe manufacturers, engine manufacturers, regulating authorities, and other government agencies, was assembled to study the effect of a proposed extension of existing icing certification rules to supercooled large droplets (SLDs) and ice crystals for engine icing certification. Approximately 100 engine events thought to be related to icing were investigated; many of these events were in the vicinity of deep convection. These events affected small commuter and large transport aircraft and were observed in many different jet-engine types [2]. The EHWG concluded that the engine power-loss events were caused by a little-known form of icing inside the engine that did not require the presence of atmospheric supercooled liquid water and was largely due to ingestion of a high mass concentration of ice particles. The EHWG proposed a technical plan [3], summarized in section 2.1, to fill the knowledge gaps of this issue. One of the four identified tasks was flight test research of high ice water content (HIWC) environments—specifically, a collection of accurate information on the threat of HIWC in and around deep convective clouds and information on the characteristic size of the particles in those clouds. Accurate information on the total water content (TWC)[1] and particle size in these clouds is essential for engine modeling simulations and ground engine testing for future certification. Discussions were initiated in 2006 with the NASA Glenn Research Center and Environment Canada (EC) to collect these measurements. A partnership with the Australian Bureau of Meteorology (BoM) was formalized to provide knowledge and experience acquired during a series of scientific field investigations focused on tropical convection over the last two decades, with the intent to conduct a flight program in Darwin, Australia that would use existing ground-based facilities, forecasting, and other resources that were developed for these earlier programs. Efforts were launched to improve instrumentation for the measurement of HIWC and to develop an

[1] The term TWC is ambiguously used in the meteorological literature to refer to both water vapor plus condensed water and just condensed water. In this report, it is used to refer to condensed water only; that is, the sum of ice particle mass concentration, also know as IWC, and the liquid drop mass concentration, also known as liquid water content (LWC); i.e. TWC = IWC + LWC.

appropriate aircraft with a suitable instrumentation package for the measurements. Such measurements present a first-time opportunity for scientists to accurately investigate the meteorological properties of oceanic and land-based convection close to the storm's active cells with in situ measurements.

1.2 REVIEW OF HYPOTHESIS ON THE METEOROLOGICAL CONDITIONS THAT CAUSE ENGINE POWER-LOSS EVENTS

The following information on the common observations from commercial aircraft flight data recorder (FDR) data and pilots' reports associated with engine power-loss events has been documented [2]:

- High altitude, cold temperature:
  - Commuter: 28,000–31,000 feet, median 29,000 feet; -20°C to -37°C, median -32°C
  - Transport: 11,500–39,000 feet, median 25,800 feet; -10°C to -55°C, median -21°C
- Aircraft in the vicinity of convective clouds/thunderstorms
- Significantly warmer than standard atmosphere:
  - Commuter: International Standard Atmosphere (ISA) temperature +7°C to ISA+16°C
  - Transport: 5 events ISA<+5°C; 11 events ISA+6°C to ISA+10°C; 13 events ISA+11°C to ISA+23°C
- Visible moisture/Instrument Meteorological Conditions/in cloud
- Light to moderate turbulence
- Ice crystals melting on impact with windscreen, often reported by pilots as "rain"
- Aircraft total air temperature (TAT) probe anomaly
- Lack of observations of significant airframe icing
- No flight-radar echoes at the location and altitude of the engine event (only large transport aircraft pilots queried)

A case study of a transport aircraft engine event was also described [2]. In general, most engine power-loss events have been reported near active deep convection and often in a warm, tropical environment. Power-loss events are observed in the vicinity of both oceanic and continental convection. There are almost no observations of ice buildup on the aircraft or indication of ice accretion by a Rosemount ice detector, if one was installed on the aircraft. The pilot's radar almost always measures reflectivity below 30 dBZ (often below 20 dBZ) at the location and altitude of the aircraft, though in some cases aircraft have been diverted around a high-reflectivity region at altitude. The simultaneous occurrence of HIWC and relatively low radar reflectivity implies that the ice particles are smaller than in precipitation typically found in non-core areas. An aircraft TAT probe anomaly is frequently observed and is known to occur when high mass concentrations of ice crystals are present. The apparent observation of "rain" on the windscreen, sometimes heavy, in the absence of any airframe icing and in regions with no radar echoes above 20 dBZ is now thought to be caused by the melting of small ice crystals on the heated windscreen[2]. This explanation has been supported by one of the few engine-event pilots who have been interviewed, based on his observation of ice crystals out the side window and the distinct sound of the ice particles impacting the aircraft. It has also been verified in industry test flights into HIWC by Airbus [6] and in the first international flight test program for HIWC measurements (see section 7.3). This apparent "rain" observation is now also thought to be another cockpit indicator of HIWC. Additional information was provided by a flight test project in the 1990s, in which a BAe-146 aircraft was instrumented with cloud microphysical probes and deliberately flown near the active cells of continental cumulonimbus clouds in an attempt to induce an engine power-loss event [7]. During one flight, the pilot was able to induce an engine power-loss event while circling to stay within an anvil region with relatively HIWC. This flight test program tied together a lot of the commercial aircraft observations noted above while providing direct measurements of the microphysics of a cloud that caused a power-loss event (at least in this one case). The cumulative evidence suggests that engine power loss is caused by flight in an area of HIWC. Supercooled liquid water content (LWC) is not required. The available data further suggest that ice particle mass may be concentrated at small sizes, though there is no evidence that engines require ice particles to be small to induce a power-loss event. The pilot's radar provides no indication that the aircraft has entered an HIWC region.

From February–May 2010, Airbus conducted a series of flights with their test A340 aircraft out of Darwin, Australia and Cayenne, French Guiana, with the objective of performing exploratory studies of HIWC regions of deep convection [6, 8]. EC and the Australian BoM participated in these studies, providing meteorological expertise and an EC hotwire ice water content (IWC) probe to augment the Airbus optical imaging-based cloud IWC measurement on the aircraft. The Airbus flight program provides invaluable supporting information to the extensive flight program planned with a more heavily instrumented research aircraft optimized for HIWC measurement. Though the Airbus program results are currently being analyzed, it can be stated that the aircraft was able to frequently locate regions of HIWC/low radar reflectivity with estimated peaks in excess of 2 gm^{-3} and possibly as high as ~6 gm^{-3}. Many of the common engine-event observations (e.g., "rain" or splashes on the windscreen, TAT anomaly) were also observed in these HIWC regions.

Figure 1 contains a simplified diagram of a cross section of a deep convective cloud, taken from the Australian Storm Spotter's Guide [9]. More so than any other cloud type, a deep convective cloud has the potential to create areas of high condensed TWC (TWC = LWC + IWC) at high altitude. Near the core area of the cloud are updraft regions that can transport moist boundary layer air, with water vapor mixing ratios that can reach 30 gkg^{-1} or more in a tropical

[2] Using an airborne cloudscope and high-speed imagery, ice crystals are found to melt quickly when impacting a heated surface facing into the airstream [4, 5].

environment, high into the atmosphere where most of that vapor must condense. In theory, this can create undiluted adiabatic updrafts where TWCs as high as 9 gm^{-3} may exist at intermediate altitudes (see discussion in section 3.2). Initially, the condensed water is in the form of water droplets, but ice formation mechanisms and mixing with ice crystals transported from above at temperatures below 0°C can lead to mixed-phase conditions. As the updraft passes through the approximately -38°C level, homogenous nucleation quickly freezes any remaining liquid. The availability of such large local concentrations of hydrometeors results in the production of some larger particles through growth mechanisms, such as aggregation, that fall and produce progressively larger particles and, eventually, heavy precipitation that falls through the freezing level, melts, and forms cells of heavy rain. Deep convective clouds also have a high-altitude cloud outflow region, or anvil, where cloud hydrometeors are transported downwind out of the area of the active cell, sometimes for hundreds of kilometers. The area of the vertically active cell may only be a small fraction of the anvil area as seen by satellite. Anvil regions may also contain relatively large IWC values, though there is evidence that, in general, the IWC drops off with distance from the active cell. Multiple cells may also underlie large anvil areas observed by satellite. Commercial aircraft routinely penetrate these anvils but avoid the active cells if they are detectable by onboard radar at altitude.

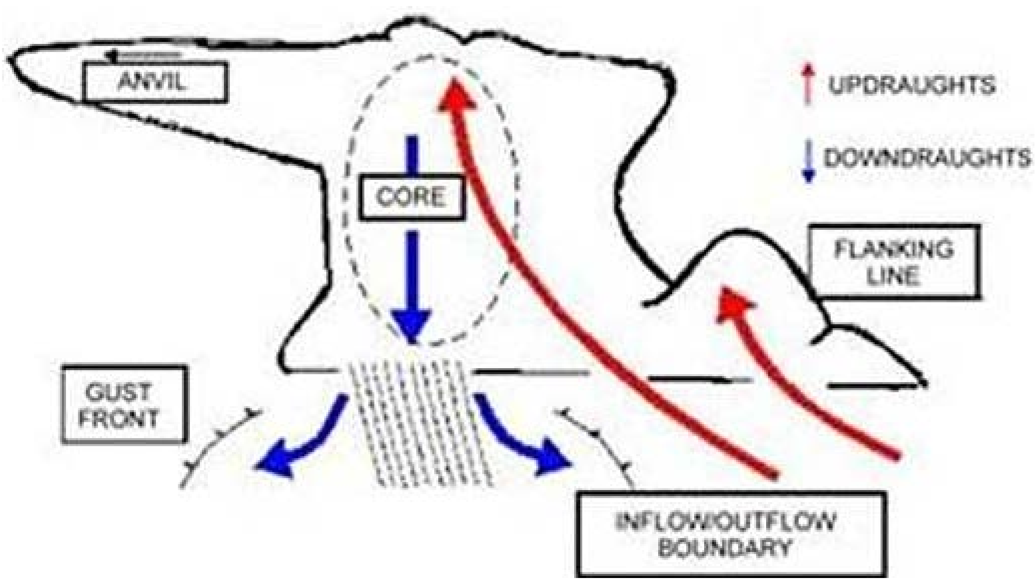


Figure 1. Simplified cross section of a deep convective cloud, from the Australian Storm Spotter's Guide [9]

The EHWG analyzed the engine-event database to provide information on the locations, altitudes, temperatures, and convective cloud types and sizes associated with this issue. It is clear that events occur over a broad range of temperatures from approximately -10°C to colder than -50°C [2]. Events have occurred in both continental and oceanic convection and over a wide variety of cloud scales, such as small, young, isolated convective clouds; large convective complexes; and vast expanses of tropical storms and hurricanes. Events are geographically scattered over most of the areas of congested air traffic in the tropics and subtropics and up to mid-latitudes. There is usually insufficient evidence to determine specifically where a power-loss event has occurred relative to a cell updraft area, though some case studies provide information on location relative to the coldest cloud tops. Essentially, all events have occurred in the general broad anvil areas. Some have occurred while diverting around high-reflectivity regions at altitude, whereas in many cases, no high-reflectivity area was noticed or reported by the pilots. It is suspected that the aircraft was often flying above an area of heavy rain while the radar reflectivity at flight-altitude was low.

A more detailed analysis of engine-event conditions, including additional events since 2003, has been used to develop statistics on the relative frequency of engine events in distinct cloud-system types based on approximately 100 events [10, 11]. It was found that most cases (72%) occurred within mesoscale convective systems (MCSs) of oceanic origin, with approximately equal numbers over land and over ocean. The remaining 28% of cases occurred in other types or scales of convective systems. From the cases with available ground-based or satellite-based radar, it was concluded that reflectivity at flight altitudes was in the 10–25 dBZ range and below the aircraft was in the 30–40 dBZ range. In most cases, the air mass could be classified as warm, humid, and of oceanic origin, with high precipitable water, weak to moderate instability, and moderate wind shear. Events over land were usually associated with an intense cell at flight altitude in the vicinity of the aircraft, whereas cells over the ocean were not observed to have intense signatures at flight-altitude.

All factors were considered in the design of an airborne cloud characterization campaign, including the choice of potential locations of an experiment (see section 5) and the measurement strategies and flight plans (see section 6). Using the time of the onset of a TAT probe anomaly, which is known to occur in regions of HIWC, and the time of engine power-loss events (when available), the EHWG initially concluded that events typically occurred within 20 nm of the suspected initial entrance into an HIWC region. Further analysis [11] suggested that engine events may be more likely when the aircraft has passed through a relatively long distance of deep cloud, implying that exposure time might be an important factor. This resulted in an amendment to the flight plans—the first since the earliest draft flight strategies proposed to the EHWG in 2007.

The fractional distribution of LWC and IWC in deep convective clouds is not well understood and probably depends on factors such as altitude, temperature, location in the storm, period in the storm’s lifecycle, and other, more subtle factors such as aerosol and ice nucleus concentration and composition. There are some observations of high LWC at temperatures as cold as -38°C [12, 13] in strong updraft regions of vigorous continental convection that often produce hail. However, most studies that include in situ properties of deep convection suggest IWC dominates over LWC in the overall subzero degree cloud volume. A 1998 review of thunderstorm anvil measurements available at the time suggested that LWC existed only in isolated regions near the core of the storm [1]. Clouds associated with Atlantic hurricanes were reported to be almost completely glaciated at -5°C or colder [14], with likely rapid conversion of water to ice above the freezing level. Similar conclusions were reached for deep oceanic convection near Taiwan [15]. Intermediate maritime/continental tropical convective clouds in Brazil and maritime convection near the Marshall Islands were found to contain no appreciable LWC, except in isolated areas with significant updraft velocities [16]. All these reports agreed that the stratiform anvil regions were glaciated, and that aggregation was the dominant particle growth mechanism. An Atlantic hurricane in extra-tropical transition was found to contain LWC only in shallow clouds on the east side of the system [17], whereas the west side above the low-level heavy rain region was composed of deep glaciated clouds with relatively high IWC. In summary, it is expected that the broad cloud regions associated with deep convection may contain high levels of TWC mostly in the form of IWC above approximately the -10°C level, except in isolated updraft regions of the convective core where significant LWC may be present.

Tropical oceanic convection has been found to contain considerably weaker updrafts and lower reflectivity than continental convection. A comparison of the maximum 10% vertical velocities in cell updraft for several major field experiments in oceanic and continental regimes was compiled by Zipser and Lutz [18]. Oceanic clouds were found to be characterized by maximum updraft velocities below approximately 5 ms^{-1}, whereas continental updrafts for the one project included were in the 10–20 ms^{-1} range. Maximum cell reflectivity was found to be different in oceanic clouds, especially above the freezing level. Figure 2 contains a plot of the median vertical profiles of radar reflectivity (VPRR) for a sample of tropical oceanic (taken near Darwin), tropical continental, and mid-latitude continental convective clouds [18]. Note that reflectivity drops off sharply above the freezing level in the oceanic convection, and the median cell would not be visible on the pilot's radar (threshold ~20 dBZ) above approximately 7 km. In mid-latitude convection, the median cell exceeds the threshold up to 13.5 km, and red-echoes (~>40 dBZ) on the pilot's radar would be observed to approximately 9 km. Tropical continental convection lies between these two regimes. Furthermore, lightning is much less frequent in monsoon and other tropical oceanic convection than in continental convection [19, 20]. It has been hypothesized that the updrafts in oceanic clouds are too weak to lift large drops and graupel from lower levels in the cloud, leading to relatively small particles and lower reflectivity aloft [18]. The lack of observations of hail and other severe weather in oceanic convection is consistent with the rapid glaciation above the freezing level and the radar observations of rapidly decreasing reflectivity with height [15]. It is not clear whether the TWC values in oceanic convection are lower than continental convection, because there are no directly comparative in situ measurements of both. The deep lift that results in large amounts of condensed water is present in both. However, there is some evidence that rainout below the freezing level from warm-rain production may be more significant in oceanic convection [15, 16].

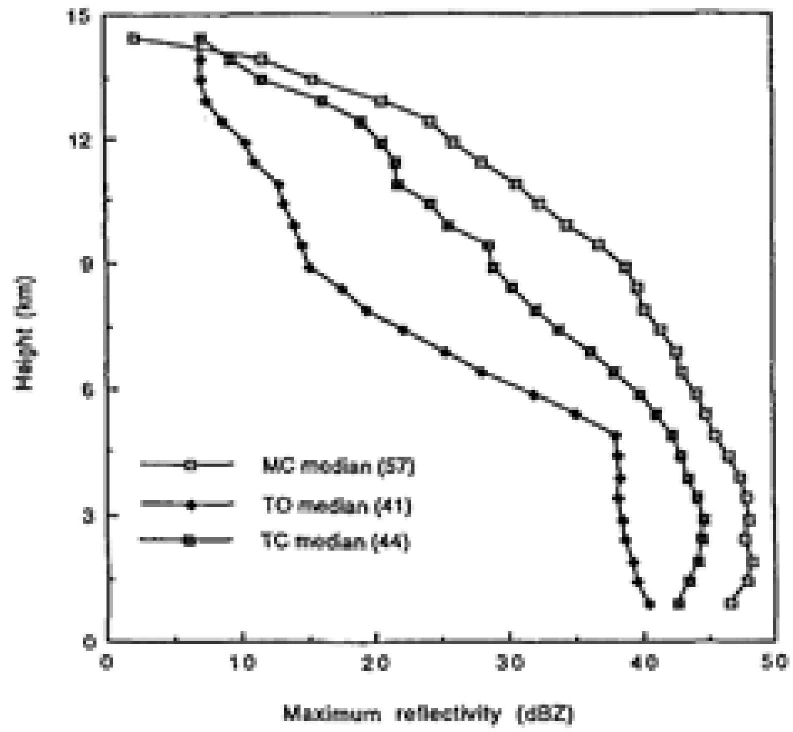


Figure 2. Median VPRR from convective cells in 41 tropical oceanic, 44 tropical continental, and 57 mid-latitude continental MCS events studied [18]

The engine event database is dominated by examples of power-loss events while flying in seemingly innocuous regions in the vicinity of both continental and oceanic convection, with few, if any, observed in strong updraft regions of vigorous convection. Observations supporting the presence of significant amounts of LWC are found in only a few cases, and several of the events were reported at temperatures colder than -40°C, at which supercooled LWC is not possible. It is relatively clear from the available evidence that the engine power loss is associated with high levels of IWC, which are much more prevalent than high levels of LWC in the regions and at the altitudes where the events typically occur. Measurements to support this study would therefore not target expected regions of high LWC near the active cells of vigorous continental convection, but rather regions of expected HIWC in clouds similar to those observed in the engine-event database. It is suspected that such regions would be near convective cells with more moderate updrafts (e.g., weaker continental convection and oceanic convection), in the anvils and the remnants of vigorous convection, and in MCS and tropical storms.

1.2.1 Hypotheses on the Location of HIWC Regions

Engine events occurring in HIWC regions with low radar reflectivity suggests that ice particles are present in high mass concentrations at relatively small sizes. This may challenge the current understanding of the initiation of ice particles in clouds and the development of the mixed phase; though the interactions in a deep convective cloud are complex, and only limited in situ measurements have been collected to date for comparison to theory. Flight campaigns designed for the study of HIWC will provide such comparative in situ data. Many of the science objectives outlined in section 3 are related to improving the understanding of the evolution of the mixed phase. The flight data may identify gaps in the current understanding of mixed-phase development/deficiencies in the conclusions as to the meteorological conditions present during engine events. In view of these uncertainties, it is clear that hypotheses may evolve as data are collected and analyzed. Nevertheless, outlined in this section are two current location hypotheses to be used to guide in searching for potential HIWC regions.

The first simple and general hypothesis is that HIWC regions are found in areas consistent with the locations of engine events; these locations are in the general broad anvil areas of deep convective clouds, often over heavy rain areas, and may be close to or in the updraft areas of such clouds. The HIWC regions can be approximately located within rapidly expanding anvil regions in satellite imagery and from ground radar signatures. More specifically, it is suggested that the presence of a heavy rain area at low altitude is indicative of an updraft area nearby with an associated area of HIWC aloft, and that a general flight survey above a heavy rain area will have a good probability of encountering HIWC in the general vicinity. Heavy rain areas at low altitudes can be identified by ground meteorological radar data or by tilting the pilot's onboard radar down. This is the primary basis for the flight planning strategy detailed in section 6. There is no inherent assumption that HIWC is associated exclusively with low radar reflectivity. However, regions of low reflectivity above the low-level heavy rain regions, if they exist, will be considered possible HIWC regions. Regions of high reflectivity (>30 dBZ) above heavy rain areas will also be considered potential HIWC regions, but will only be sampled from an adequately safe distance.

A second, more specific location hypothesis is that engine events are occurring in relatively undiluted (or quasi-adiabatic) updrafts in deep convection. These cloud parcels ascend from levels low in the cloud, perhaps cloud base, toward the cloud top without significant heat and mass exchange with the rest of the cloud. The ascent stops soon after the parcel reaches the equilibrium level (EL) or level of neutral buoyancy. In deep convective clouds, the EL is usually associated with the height of the anvil top, which may coincide with the general height of the tropopause. If such adiabatic or near-adiabatic updrafts can be found in deep convection, they likely contain high TWC and may also be void of large ice particles. They therefore fit one of the main observations of the EHWG engine-event database—they would be high-TWC regions potentially invisible to the pilot's radar due to the small particle size. These source updraft regions are also of particular interest to many of the scientific objectives outlined in section 3.

There is evidence that some of these updrafts may provide a visible signature. Because of accumulated momentum from ascent, adiabatic updrafts may overshoot the EL. An "overshooting top" is a domed cloud structure extending above the anvil, sometimes protruding into the stratosphere. Photographs of overshooting tops taken from a Learjet at 12.5 km (41,000 feet) are shown in figure 3 [21]. All five pictures illustrate cloud structures above the flat anvil top surface. In some cases, overshooting forms optically dense turrets with sharp cloud interfaces (see figure 3(1–2)). In other cases, overshooting generates cirrus clouds (see figure 3(3–5)). Satellite and aircraft observations show that vigorous overshooting plumes may reach 2–3 km above the anvil top [21–23]. These observations are in general agreement with numerical simulations of convective storms [24, 25]. Overshooting tops can often be identified from satellite imagery. Analysis of National Oceanic and Atmospheric Administration (NOAA)-15 polar orbiter satellite imagery indicates that overshooting is observed in both overland and oceanic convection [26]; the fraction of deep convective clouds with overshooting tops was shown to vary from 30–50%.

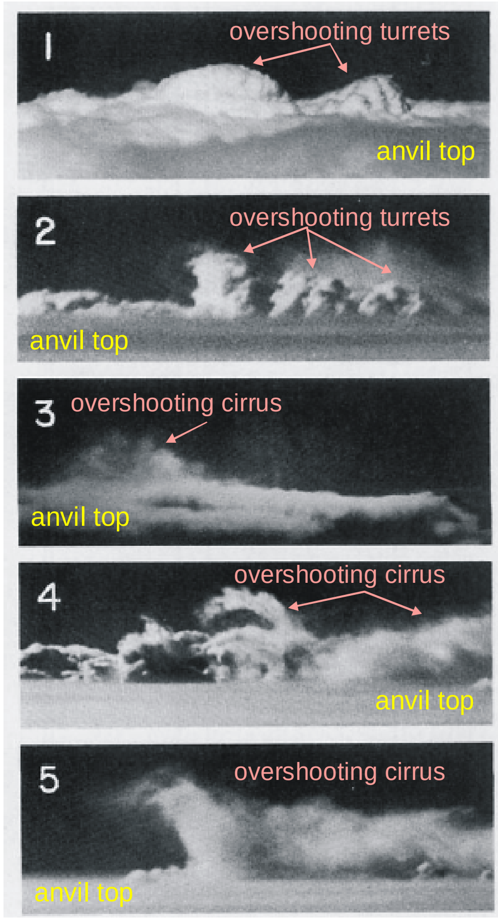


Figure 3. Pictures of overshooting tops (adapted from [21])

An example [26] of NOAA-15 Advanced Very High Resolution Radiometer (AVHRR) visible and infrared (IR) satellite imagery of overshooting tops is shown in figure 4. The coldest IR brightness temperature region was -73.6°C (see figure 4b). The high frequency of occurrence of overshooting tops suggests that inspection of satellite images or, if possible, climbing in the aircraft above general cirrus tops may help in locating regions of HIWC. An overshooting top may be a sign of a strong updraft in a convective storm and may indicate that the storm will have severe weather. In general, real-time, ground-based lightning network data may be useful in avoiding a major fraction of the more vigorous convective cells.

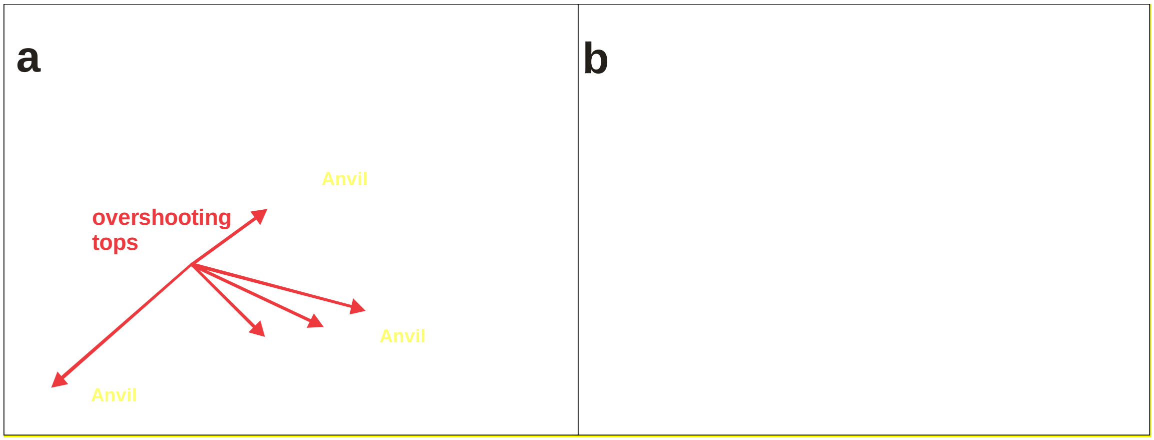


Figure 4. NOAA-15 AVHRR (a) visible and (b) IR imagery from an overpass on June 19, 2001 show the structure of the overshooting tops and cloud-top temperature pattern

Satellite IR image color enhancement has been used in engine event analysis to highlight areas of clouds that are higher than the tropopause [10]. This effectively highlights the broader areas created by overshooting tops. Mason and Grzych [10] found that aircraft are often in these areas of highest cloud when engine events occur. Plans for research flight operations have always considered that such an IR scheme would be used in real time for flight operations to help guide the aircraft to the general area of potential overshooting tops related to active cell updraft areas. It should be noted, however, that the ability to use overshooting top signatures in satellite data will require frequent and quickly available satellite images, which are not available in all measurement locations that are otherwise favorable.

Some detailed results from the Airbus 2010 Darwin and Cayenne flights (see section 1.2) related to general pilot experience and specifically to the use of the pilot's radar further contributes to the operation of the HIWC aircraft close to HIWC regions during the study described in this report. Of special note from the Airbus flights is the fact that regions of HIWC consistent with the hypotheses of the HIWC study are not rare and can be located using identification techniques described in this section.

1.3 MOTIVATION FOR METEOROLOGICAL INVESTIGATIONS IN AN HIWC STUDY

There are significant fundamental cloud physics questions raised by the hypotheses of HIWC cloud properties. The formation of high concentrations of ice crystals with low radar reflectivity and the associated absence of supercooled water droplets within convective clouds is not well understood. The explanation for the occurrence of these conditions and the stage in a cloud system life cycle these extreme characteristics are formed is not yet known. Many other associated atmospheric-science issues remain open due to the lack of data for validation because little in situ data has been collected by the research community in HIWC regions. Research flights to date have been limited by a reluctance to enter HIWC regions and by the lack of instrumentation capable of making bulk IWC measurements to the accuracy required for this project in such conditions. As part of the EHWG technical plan, the HIWC project has developed a new TWC instrument optimized for HIWC measurements up to 10 gm^{-3} at 200 ms^{-1}. The combination of a suite of modern instrumentation with the newly developed TWC probe, and an extensive set of focused flights into previously generally avoided areas of deep convection, will provide a unique data set of great scientific value for addressing a number of atmospheric science questions detailed in section 3. In turn, advances in the understanding of these science issues will also contribute to progress on the EHWG technical plan through better understanding of cloud structure and processes; better description of cloud microphysical parameters such as particle size, shape, and density for engine modeling and ground simulation; and will be a key element in the development of improved pilot radar, pilot recognition, and nowcast and forecast aids for route management. In this regard, technical (aviation safety) and science objectives in this project are highly complementary and interconnected.

2. TECHNICAL (AVIATION) OBJECTIVES OF THE FLIGHT TEST PROGRAM TO SUPPORT THE JET ENGINE ICING ISSUE

2.1 BACKGROUND

The accident of an Aérospatiale ATR 72 aircraft on October 31, 1994 and its subsequent investigation identified gaps in the certification and operating rules for icing, particularly in the area of flight into freezing rain or freezing drizzle. In the process of examining the regulations, it was also noted that mixed phase and glaciated icing conditions were not covered by Title 14 Code of Federal Regulations (CFR) Part 25 Appendix C. One of the National Transportation Safety Board (NTSB) safety recommendations (A-96-54) following the accident investigation states:

> Revise the icing criteria published in 14 Code of Federal Regulations (CFR), parts 23 and 25, in light of both recent research into aircraft ice accretion under varying conditions of liquid water content, drop size distribution, and temperature, and recent developments in both the design and use of aircraft. Also, expand the Appendix C icing certification envelope to include freezing drizzle/freezing rain and mixed water/ice crystal conditions, as necessary [27].

In response to the NTSB safety recommendations, the joint Engine Harmonization and Power Plant Installation Working Groups (EHWG/PPIWG) examined the impact of SLD and mixed-phase/glaciated conditions on 14 CFR 33 (certification rule for engine and power plant installation). In the remainder of this report, EHWG/PPIWG will be referred to as the EHWG for brevity. After fulfilling its Aviation Rulemaking Advisory Committee mandate, most members of the EHWG continued to work together on the mixed-phase issues as the Engine Icing Working Group (EIWG).

The consideration of mixed-phase and glaciated conditions in the sphere of FAA aircraft icing certification exposed an entirely new type of aircraft icing-related problem. The EHWG examined the history of more than 100 engine- and power-plant-related events thought to be due to weather, in which engine damage, compressor stall, power loss, or roll back had occurred. The majority of events occurred in flight during conditions in which conventional icing of supercooled liquid cloud was not suspected or detected, but rather in conditions suspected to be dominated by ice particles. Most engine events resulted in an uncommanded reduction in engine power to idle conditions. In all events, the engines were restarted. For one engine type, it was necessary to descend below the freezing level before the engines could be relit. In one such event, the aircraft lost power on all four engines while cruising at 31,000 feet and was unable to maintain altitude until engine power was restored at 10,000 feet [28]. Since the EHWG study, events have continued to occur. For one particular aircraft type, an event was experienced that resulted in an emergency dead-stick landing [29], which subsequently led to an Airworthiness Directive [30]. More recently, an Airworthiness Directive has been applied to a large transport aircraft due to engine power loss, damage, and vibration events [31]. It has also been determined that aircraft air data probes can be susceptible to failures in the same type of ice crystal weather [32], raising the concern of unreliable airspeed requiring proper pilot response. A separate industry working group is studying the air data probe issue.

The EHWG examined the atmospheric data from the engine events between 1988 and 2003; the scientific and engineering literature; and a flight test program conducted in the 1990s to study engine rollback on one particular aircraft. They concluded that the condition that most likely led to this type of engine event was flight into an HIWC environment normally found near the active regions of deep convective clouds (see section 1.2). Existence of liquid water in the cloud was found not to be necessary. Many of the events were outside the temperature-altitude envelope of 14 CFR 25 Appendix C, and instead tended to be at high altitude in a warm environment. Because engine power loss is suspected to be a result of icing within the engine, the suggestion that such icing could result from ice particles in the cloud rather than supercooled liquid water was surprising. The EHWG further concluded that the current information on the levels of TWC in the engineering and scientific literature is insufficient to accurately describe the expected exposure levels to engine manufacturers, and that the ice accretion mechanism in the engine was inadequately understood. An interim certification envelope for TWC, based on scaled estimates from adiabatic lift calculations and a new temperature-altitude envelope constructed to reflect the engine events, was proposed as Appendix D [33] to 14 CFR 33. This extends the current 14 CFR 25 Appendix C envelope for flight into conventional supercooled droplet icing into a new envelope that is intended to approximate the expected TWC threat, mostly due to ice particles, in the updraft and surrounding areas of deep convective clouds. The new SLD and ice crystal regulations have been issued as a Notice of Proposed Rulemaking by the FAA [34], with a similar notice by the European Aviation Safety Agency [35], both of which came into force in 2015.

The EHWG assembled a technical plan [3] to address the problem of engine power loss that includes the following activities:

- Task 1—Instrumentation development and evaluation for HIWC
- Task 2—Flight test research for characterization of HIWC environments
- Task 3—Experimental testing in support of ice accretion engine model; development and validation for HIWC environments
- Task 4—Test facilities requirements for demonstrating engine compliance with Appendix-D

The current accuracy of instrumentation to measure TWC and IWC is considered inadequate, especially in the HIWC environment. The efforts to evaluate and develop suitable instrumentation (Task 1) are further described in section 4. It is the requirement for the characterization of the HIWC environment (Task 2), which forms the basis for the engine-related objectives of this report, to collect in situ measurements of cloud TWC and other supporting measurements in deep tropical convective clouds to adequately determine TWC threat levels for the assessment of the 14 CFR 33 Appendix D envelope. Such an assessment may lead to modifications to 14 CFR 33 Appendix D as deemed appropriate.

2.2 OVERVIEW OF ENGINE (AVIATION) OBJECTIVES

The technical objectives of the engine-icing component of the research are:

- E1: Characterize the HIWC environment that is thought to cause engine power-loss events, providing distance-scale statistics of TWC, and particle characteristic size.
- E2: Study the potential methods for detecting the HIWC environment onboard conventional aircraft, including pilot external aural and visual cues on the windscreen; the response of the pilot's weather radar; and the response to other onboard sensors.
- E3: Develop tools to nowcast the HIWC environment.

2.3 OBJECTIVE E1: CHARACTERIZATION OF THE HIWC ENVIRONMENT

The primary interests of the EIWG in this project are in acquiring accurate statistics on the expected TWC exposure level, acquiring the characteristic sizes of hydrometeors in high-TWC regions of clouds in the vicinity of deep convection, and determining whether remote sensing can be used to identify regions of engine-icing threat. Despite the significant recent activities in the international research community in collecting high-altitude cloud measurements for climate and other meteorological research, including cirrus near-deep convection, there is still only limited direct information on the microphysical properties of deep convective clouds, especially near or in vertically developing cells where the TWC is expected to be the highest.

2.3.1 TWC Statistics for the EIWG

In situ TWC measurements in the vicinity of deep convective clouds are rare. Early estimates in the 1990s reported maximum IWC at approximately 3 gm^{-3} [1]. A broad area of IWC peaking at approximately 1.5 gm^{-3} was reported in an Atlantic hurricane [17], revealing that HIWC might be expected over relatively long-distance scales. It has now been shown that that the latter IWC estimate may be low by as much as a factor of 2 or more due to the type of instrument used to make the measurement [36]. Airborne measurements by an industry test aircraft instrumented for cloud microphysics have provided in situ properties of an anvil downwind of an isolated continental cumulonimbus near Little Rock, Arkansas [7]. This study is particularly relevant because an engine power-loss event was deliberately induced during the measurements; they form the closest available representation of the conditions conducive to engine power loss. The instruments suggested that the anvil was completely glaciated, and IWC peak values in excess of 1 gm^{-3} were reported (as much as a factor of 2 or more low due to the type of instrument used to make the measurement). Some estimates from more recent atmospheric studies are now appearing in the literature, but HIWC regions have not been emphasized. Still, it appears that values in excess of 1 gm^{-3} have been recently reported (e.g., [37, 38]). As discussed in section 4, the accuracy of all of these previous TWC estimates for an HIWC environment is questionable because of instrumentation limitations.

The most extensive set of TWC measurements in deep convection was made by the Royal Aircraft Establishment (RAE) to provide engineering data after engine failures on the Brittania aircraft in the 1950s. A series of 101 flights out of Entebbe, Darwin, and Singapore were conducted in tropical cumulonimbus and deep-layer clouds in the Intertropical Convergence Zone (ITCZ) [39]. The study examined clouds in the altitude and temperature range of 11,500–28,000 feet and +3°C to -25°C (averages of 19,100 feet and ~ -9°C). TWC values up to 8 gm^{-3} were reported—measured by a simple pitot-type device that captured and melted hydrometeors for subsequent weighing—providing a data set at approximately 30-second intervals. These peak TWC values are in excess of the measurements in the more recent scientific literature but are similar to the maximum TWC calculations for undiluted, non-precipitating adiabatic deep-parcel lift. This study displayed one surprisingly long 20-minute time series of continuous flight in cloud with TWC in excess of 2 gm^{-3}, with a peak 30-second TWC of more than 6 gm^{-3}. The EHWG derived duration statistics from the RAE data set, and results are summarized in figure 5. For example, at an averaging scale of 10 statute miles, the 99th percentile TWC values from the RAE data is 4.6 gm^{-3}. After the measurements were completed, the British Joint Airworthiness Committee (JAC) issued standards recommended for ice crystal testing of aircraft engines [40] (see figure 5, solid line), which are also contained in the FAA Technical Document ADS-4 [41]. Though the short-distance TWC levels in the JAC report are consistent with the RAE data set, the EHWG was not able to determine how values at larger distance scales were derived.

The EHWG concluded that it is necessary to repeat the RAE measurements because the accuracy of the TWC measurement method could no longer be traced, and an acceptable alternative data set from more recent studies does not exist. Furthermore, there was little information on the flight plans adopted by the RAE study; the distance scale rolloff computed from the data by the EHWG was derived by stringing all the data into one long series for each flight. Therefore, it is considered conservative.

A revised figure 5 represents the highest priority deliverable to the EIWG from the proposed future airborne measurement campaigns. It is also hoped that, with sufficient flight time, the relationships of figure 5 can be sub-categorized according to altitude interval or temperature, and perhaps other parameters of interest. Further discussion on the flight procedures to collect this new data set is contained in sections 1.2.1 and is developed further in section 6.

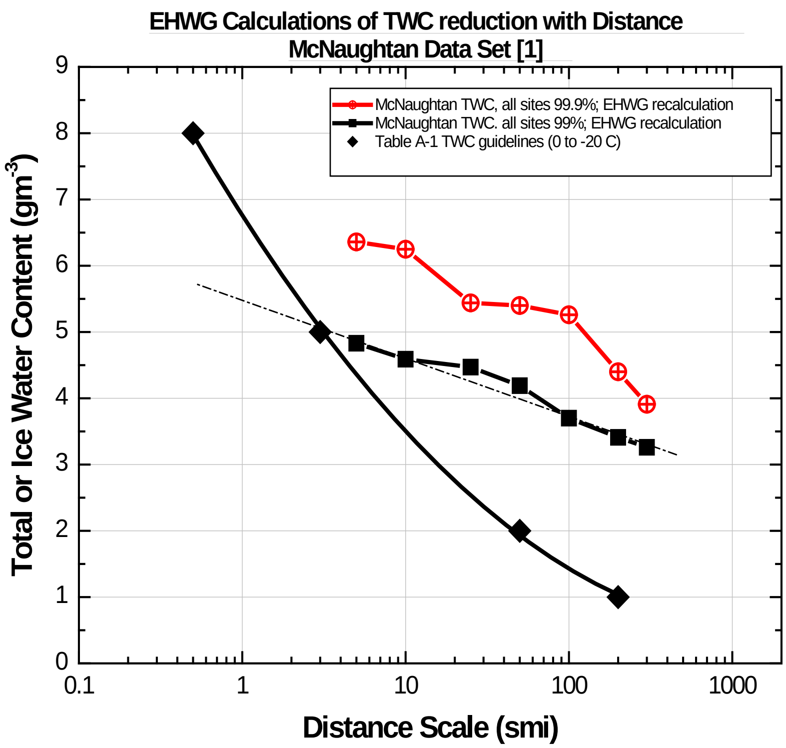


Figure 5. TWC measurements as a function of distance averaging scale [39]

2.3.2 Estimates of Hydrometeor Characteristic Size for the EIWG

Particle characteristic size may be an important parameter for engine modeling and ground engine test simulations. Investigations of microphysical properties of cirrus clouds associated with deep convection have suggested that ice particle distributions in convective clouds measured by in situ instruments on research aircraft may have a small characteristic size. For example, Florida cirrus clouds associated with deep convection were found to have ice particle effective diameters between approximately 10 and 60 μm, as measured by an in situ Cloud Integrating Nephelometer [42]. During the industry flight test program [7], the estimated median mass diameter (MMD) of the ice particle distribution in the anvil of a continental thunderstorm during the engine power-loss event was approximately 40 μm, using in situ measurements from forward-scattering spectrometer probes (FSSP) and 2-D cloud optical array spectrometer probes. Ice particle number concentrations reached in excess of 200 cm^{-3}, and peak IWC exceeded 1 gm^{-3}. Using similar instrumentation, the estimated MMD in the broad anvil from deep convection in extratropical Hurricane Michael was ~185 μm, with ice particle concentrations and IWC exceeding 100 cm^{-3} and 1.5 gm^{-3}, respectively [17]. However, in general, closure of in situ particle size distribution (PSD) measurements with remotely sensed particle size measurements are problematic (e.g., [43, 44]). There is now strong evidence that small particle concentrations may be artificially enhanced from ice-particle breakup on the leading edges of some sampling instruments [45–53], thereby resulting in a low ice crystal characteristic size bias and greatly increasing total ice number concentrations. The effect on MMD measurement is expected to be much less than for number concentrations, but the actual uncertainty for MMD is unclear. Based on the available measurements, and acknowledging these possible measurement problems, the first approximation of MMD < 200 μm in HIWC deep convective cloud was proposed to the EHWG. Measurement efforts in a dedicated flight program (see section 4) would include the use of more recently available instrumentation, some with modifications specifically to address particle breakup issues, which will provide superior measurements in the critical sub-100 μm size range. Future measurements could also include an independent technique to estimate particle effective size in a simple manner from bulk measurements of TWC and extinction [54]. The extinction measurements could also provide important closure information to validate the PSD data.

The flight test program that provides TWC statistics will simultaneously also provide detailed size distributions from which particles' characteristic size and MMD will be obtained. These same measurements will also provide detailed imagery of the cloud particles that will be important for many of the science objectives described in section 3.

2.3.3 Cloud Resolving Model Simulations to Integrate Measurements and Theory

Current estimates of where HIWC regions could occur are limited by the lack of understanding of their causes. Deep convective cloud systems are the most complex of such cloud systems in the atmosphere. Turbulent dynamical structures are closely coupled with microphysical processes that result in the simultaneous formation, growth, transport, and interactions of size-dispersed droplets and ice crystals. The diverse morphological evolution of ice particles complicates the rates at which they grow by vapor deposition, accrete liquid droplets, and aggregate with other crystals. Relatively esoteric processes, such as breakage of delicate snow dendrites from collisions, could have important effects.

Though current cloud-resolving models (CRMs) are no substitute for observational data, they are an indispensable tool for advancing theoretical understanding of cloud physics because of their ability to directly simulate the complex interactions of dynamics and microphysics that ultimately determine the spatially distributed properties of extensive cloud decks. Furthermore, the coherent, physically consistent framework of such models provides a virtual integration platform that has proven critical for identification of suspect measurements in a number of field projects. However, models have been limited in advancement of prediction of deep convection near-core cloud properties, in part because of a lack of observational constraints in a region that is highly sensitive to even small changes in microphysical representation (e.g., [55]).

Past aircraft studies have been limited in several ways. First, comprehensive microphysical measurements obtained in penetrations of updraft source regions of deep convection using aircraft (e.g., [56]) are rare. Most aircraft studies of deep convection intentionally avoid such regions by a wide safety margin. Second, the quality of in situ cloud data has been questionable because of instrument issues, such as ice particle shattering contamination and saturation in high concentrations (see section 4). By addressing these issues and intentionally pursuing high mass concentration regions, the measurements obtained in the HIWC study flight campaigns will provide critical measurements needed to advance theoretical understanding.

A principal objective of cloud-resolving modeling for this project will be to identify the likely causes for the observed collocation of low reflectivity and high ice mass mixing ratio (see section 1.2). The primary modeling tool will be the Distributed Hydrodynamic

Aerosol-Radiation-Microphysics Application (DHARMA) CRM, which is based at NASA Goddard Institute for Space Studies (GISS). As a starting point, the setup of model simulations will borrow from the Tropical Warm Pool-International Cloud Experiment (TWP-ICE) model intercomparison for CRMs [57, 58], in which periodic lateral boundary conditions were used on a 176 x 176 x 24 km mesh with uniform horizontal spacing of just under 1 km, and vertical spacing that varied between 100 and 300 m. Some of the simulations will use a bin microphysics scheme [59, 60], which resolves hydrometeor size distributions, and others will use a two-moment microphysics scheme [61], which imposes a functional form on the size distributions of hydrometeors and is less computationally demanding. Simulations will be initialized and forced with observationally derived data sets, including aerosols on which all cloud droplets initially form and the thermodynamic environment in which clouds develop (e.g., [62]). Results will be compared with all available, credible measurements, including those from the aircraft (e.g., ice particle number size distribution, mass mixing ratio, and cloud radar reflectivity), ground-based remote-sensing (e.g., scanning precipitation radar), and satellite-based remote-sensing (e.g., cloud-top effective radius or reflectance obtained from Moderate Resolution Imaging Spectroradiometer [MODIS] instruments). Results will not only provide a coherent framework to evaluate the consistency of measurements but can also be expected to lead to advances in theoretical understanding beyond what is possible with only data analysis or more simplified modeling.

2.3.4 Linking Characteristics of Sampled Clouds to the Engine-Event Database

Much of what has been hypothesized about the cloud environment that causes engine events has been extracted from an industry flight test program in the mid-1990s [7]; case studies of engine events using data from the aircraft FDR; additional meteorological sources such as upper air, radar, and satellite observations; and general comments from the flight crews [2, 10, 11]. In some cases, flight crews have been specially interviewed. The common observations during engine events have been previously summarized [2] and are listed in section 1.2.

It will be important to establish that the cloud characterization measurements collected in this flight program are made in conditions consistent with those observed and recorded to provide confidence that the new data set is representative of the clouds encountered by aircraft experiencing engine power-loss events. Most of the required links will be provided by particular microphysical instruments on the aircraft (i.e., state parameter probes; wind and gust measurement system; Rosemount TAT probe; pilot’s radar; and research radar) and from visual and aural observations on the flight deck during HIWC encounters. In addition, sampling strategies (see section 6) must be chosen to target cloud types and exposure scales such as indicated by the most recent analyses of engine events [11].

Maintaining these links to the engine-event database will require constant update of knowledge with information from new events, which in turn will require a continued close dialogue with industry partners. Cues from the event database should be incorporated into the aircraft operations plan for the flight program to enhance the connection between the research aircraft measurements and industry’s operational experience.

2.4 OBJECTIVE E2: FLIGHT-DECK RECOGNITION OF THE HIWC ENVIRONMENT

One of the important industry longer-term objectives is to design engines so that they are not susceptible to power loss from cloud-particle ingestion. However, because aircraft with legacy engines may be in service for many years to come, providing onboard means to detect HIWC environments is an important objective so that mitigating procedures can be applied, and pilots can make tactical decisions to exit the environment.

This objective encompasses the investigation of several methods for onboard cockpit detection. These methods use:

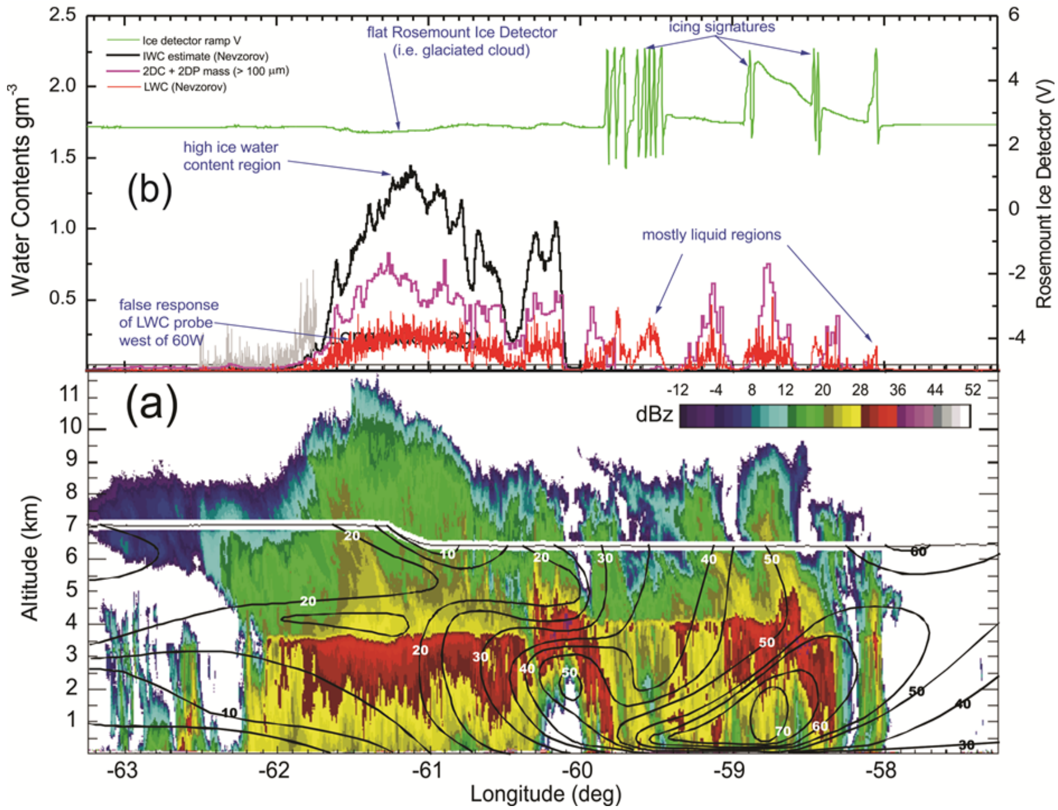
- Visual/aural signatures of ice crystal/water droplet impacts on the wind screen and airframe that serve as cues to pilots.
- Weather radar reflectivity signatures, radar scan patterns, and aircraft location relative to the active convective cell.
- Onboard sensors to identify the presence of HIWC.

2.4.1 Visual/Aural Signatures of HIWC

The observations during engine events (see section 1.2) of a TAT anomaly, and the pilots' observations of apparent "rain" at very cold temperatures in the absence of airframe icing and significant radar echoes, are important cues to the pilot that they may be in a hazardous HIWC situation. The "rain" observation, reported at temperatures as cold as -50°C, is a peculiar and seemingly impossible observation, particularly in the absence of airframe icing, that resulted in much confusion early in the industry investigations. It has now been concluded that this is due to the near instantaneous melting and coalescing of high mass concentrations of small ice particles on the heated windscreen; it is desirable to corroborate this with a visual record and in situ microphysical measurements. The design of a flight program should include a measurement of a variety of visual and aural cues that may present themselves on the flight deck. High-definition video cameras and audio measurements should be made to support the documentation of HIWC encounters. A camera should image the impacts and subsequent flow of hydrometeors on the heated wind screen of the project research aircraft, and a microphone should record the audio signature of these impacts. These image and audio recordings should be made in various cloud (e.g., liquid, mixed phase, and glaciated) and precipitation (e.g., rain or snow) environments to determine if unique signatures can be identified. Additional video of the wing leading edge, wingtip, and engine inlet is also recommended to document any ice accretion or captured ice particles, and the visibility of the cloud (see section 4, table 2).

2.4.2 Radar Reflectivity in HIWC Regions

The current conventional onboard weather radar on commercial aircraft is intended as a severe weather avoidance tool; the minimum reflectivity presented to the pilot is typically 20 dBZ, though most modern units also include a “maximum gain” setting that provides an additional ~10 dBZ sensitivity. Engine-event data indicates that the cloud regions where the events occurred often have radar reflectivity below ~20 dBZ minimum sensitivity. This may be because the HIWC regions causing engine events are characterized by unexpectedly small ice crystals. Because radar reflectivity can be shown to be related to the fourth power of the size of ice particles, reflectivity is highly affected by the largest particles in the distribution. Though a number of previous studies have provided combined in situ IWC measurements and either ground- or aircraft-based radar measurements, few coupled measurements exist in an HIWC environment. One such example has been provided using an onboard 35 GHz (Ka-band) cloud radar (see figure 6) and IWC estimates from a Nevzorov hotwire probe [17]. The hotwire TWC measurements are likely underestimating true IWC values by at least a factor of 2 [36], implying that the IWC reached a maximum in excess of 3 gm^{-3} in the deep glaciated cloud on the west side of the hurricane. In this same region, the radar reflectivity increased to a maximum of approximately 22 dBZ. Though this may be closer to 27–28 dBZ on a pilot’s X-band radar due to the frequency difference, this reflectivity would still only be within the first threshold (green) of the pilot’s radar and therefore not considered unusual or hazardous and would likely not be avoided. These measurements reveal how HIWC may be encountered near deep convection with little or no indication on the pilot’s radar.



(The top panel shows the estimated IWC from a hotwire instrument [black line], now known to be low by a factor of 2–3. Flight altitude is shown as the white horizontal band across the radar cross section. Isopleths are wind speeds in m/s derived from dropsondes.)

Figure 6. The (a) Ka band radar reflectivity and (b) in situ measurements taken during a flight across Hurricane Michael, October 19, 2000 [17]

Measurements within an HIWC flight test project provide a unique data set to study radar reflectivity in an HIWC environment. Ideally, the flight test aircraft would be equipped with one of the next-generation pilot's radars that will soon be available for commercial pilots. One such radar is the Honeywell RDR-4000, which uses volumetric 3-D scanning and pulse-compression technologies to detect weather with sensitivity superior to today's radars, out to 320 nm ahead of the aircraft. It is recommended that in an HIWC flight test program, the pilots have normal control and standard radar displays (see figure 7), including the identification of turbulence. The in-phase and quadrature data would be digitally recorded and processed to provided researchers with several radar "products" (e.g., radar reflectivity to show low reflectivity signatures, some wind velocity measures [vertical and horizontal], and turbulence measurements (i.e., spectral width of wind velocities). Both the RDR-4000 and a high-sensitivity, onboard research radar would be anticipated to be critical in locating areas of HIWC during the flights.

Efforts should be made to emphasize coordinated observations with ground-based radars whenever possible (e.g., the CPOL radar operated by the Australian BoM near Darwin). It is hoped that such studies will improve the understanding of radar signatures in HIWC regions and provide information for further development of next-generation airborne weather radars.

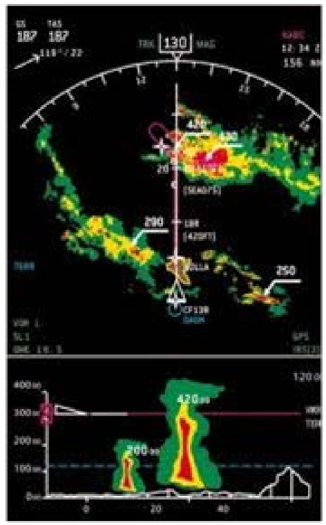


Figure 7. Typical pilot's display of RDR-4000 data

2.4.3 Onboard Sensors to Detect the Presence of HIWC on Commercial Aircraft

For this study, research-quality TWC measurements will be collected from new and existing instruments adapted for the HIWC environment and installed on the aircraft in locations chosen to minimize the effects of the aircraft itself on measurements (see section 4).

The aviation industry is interested in simple measurement techniques that might be adapted to commercial aircraft for detecting HIWC regions. For example, a fuselage-mounted instrument that detected simple threshold levels of IWC in both mixed-phase and glaciated environments, rather than numerical values of IWC, would likely be adequate to aid pilots in decision-making if an HIWC region were encountered. Potential methods to threshold HIWC might include detection of the TAT anomaly (described in section 1.2), detection of pitot-pressure port blockage, and the use of special devices using electrothermal methods. A future HIWC flight test program should collect data from several existing and prototype sensors that use these methods and compare results to the research-quality measurements of TWC to develop the relationships needed for the simple threshold detection algorithms.

2.5 OBJECTIVE E3: DEVELOPMENT OF TOOLS TO NOWCAST THE HIWC ENVIRONMENT

The frequency of HIWC encounters may be reduced by providing weather avoidance strategies to pilots. Forecast and real-time information on the location of HIWC regions derived from various data sources is needed for development of warning tools for the aviation hazard presented by HIWC conditions. Current weather nowcasting tools have typically been developed for mainstream requirements of the public, such as the occurrence of hazardous precipitation/hazardous winds near the ground. Though efforts have been made to nowcast aviation hazards aloft, these have mainly focused on conventional and SLD icing conditions, hazardous winds, and meteorological conditions affecting the efficient movement of aircraft traffic in and out of airports. The diagnosis and forecasting of regions of HIWC is specific in terms of the details of its occurrence and its effect on the public and has received little attention prior to the HIWC study.

Meteorological conditions hypothesized to cause engine power-loss events [1, 2, 10, 11] are summarized in section 1.2. Analyses of multiple engine events have provided variables and criteria for defining areas of risk due to HIWC, and, in some cases, quantitative thresholds for variables are suggested. The list of probable conditions present during engine events can be used to focus a nowcasting system on the proper areas. For example, engine events occur within convective anvil clouds. These areas can be objectively identified within a nowcasting system using satellite data. Most occur within MCSs while traversing the deepest area of cloud. Areas of convection over ocean and over land are currently detected by existing nowcasting systems [63–65], and techniques used in those systems might be applied here. Overshooting cloud tops may be an indicator of the location of an updraft that could produce HIWC conditions. Satellite products exist to objectively identify these features [66]. Radar reflectivity at flight location is usually low (10–25 dBZ) at flight altitude, and moderate to high (30–40 dBZ) below the aircraft during engine events. Though radar data are not expected to be routinely available, this finding provides clues about the vertical structure of the atmosphere during engine events; conditions supporting this type of structure might be discernable in numerical model fields. Other conditions found to be typical of the environment where engine events occur include high precipitable water, weak to modest instability, and modest wind shear. Such information can be incorporated into the design of a nowcasting system. Though the conceptual model remains speculative, this prior research provides a framework on which to base a preliminary nowcasting algorithm, and flight test measurements will provide more specific information for refinement of the algorithm.

Nevertheless, identification of a small-scale, possibly short-lived feature such as HIWC aloft presents significant challenges to the available data sets and tools. Typical operational nowcasting tools include numerical weather prediction (NWP) models, conventional weather network data (e.g., Meteorological Terminal Aviation Routine Weather Reports, radiosondes, pilot reports, and radar networks), and satellite imagery. The detection—or diagnosis, because these conditions would most likely be diagnosed via clues from available data sets rather than be directly detected—of HIWC regions offers special challenges to each of these tools. Numerical models provide some guidance as to the likelihood, general area, intensity, and timing expected for deep convection, but their ability to provide precise timing and location of convective elements likely to be associated with HIWC is limited. Furthermore, the TWC predictions in a model are highly dependent on models of microphysical processes that have not been validated. The low radar reflectivity that is typically observed at flight altitude during engine events limits the use of ground-based and in-flight radars as a direct detection method. The combination of low reflectivity at flight altitude and moderately high reflectivity below may be an important clue, but use of this criterion by itself would likely result in a high number of false alarms. Furthermore, radar coverage is sparse in many continental areas and non-existent over the ocean; space-borne radar is not global at this time.

Identification of HIWC zones from satellite sensors may also be a challenge. Satellite imagery provides a powerful primary tool for observing the development of deep convection on a broad scale and, in some cases, good information on the locations of the active cells of thunderstorms. However, the temporal and spatial resolution of satellite sensors currently may not be well suited for identifying quasi-random convective impulses that may have a characteristic size less than 20 nautical miles and lifetimes of tens of minutes. Furthermore, the high optical depth of deep convection may impede identification of concentrated IWC features in the upper portion of the cloud.

Current limitations of the available data sources for describing the HIWC phenomenon make the data provided by the future HIWC study flight campaigns essential for improving the conceptual model of where and when HIWC regions occur. Data provided by these campaigns will improve model simulations of deep convection and allow investigators to study the ability of the various remote sensors to directly or indirectly detect these regions. Flight campaigns in HIWC regions will provide the first modern extensive data set of properties near and in active cells of deep convection for such purposes. The development of tools for reliable nowcasting of HIWC regions overlaps with some of the science objectives of this study, and further fundamental research related to the performance of models and remote sensors are detailed in sections 3.6–3.8. Finally, development of diagnosis and forecasting tools entails components distinct from science objectives, and these components must work together for a successful outcome: engineering, science, and regulation/policy. Issues related to these components are:

- Engineering: Collection of appropriate data sets in real time, ingestion into algorithms, creation of products that are easily understood by the end-user, and the communications and computing architecture that enables this all to be done quickly and accurately.
- Science: Determination of the information needed to accurately diagnose and forecast HIWC conditions; exploration of additional operational data sets or development of new instruments for diagnosis or detection of HIWC conditions; better understanding of the processes leading to these conditions and application of this knowledge for NWP nowcast/forecast models.
- Regulation/policy: Recognition of HIWC conditions as a serious hazard to aviation and the regulatory and policy changes needed to support development and use of diagnosis and forecast tools.

3. SCIENCE OBJECTIVES

3.1 OVERVIEW OF SCIENCE OBJECTIVES

Convective systems represent a significant aviation safety and operational hazard. There remain fundamental limitations in the understanding of the physics of storms that are significant issues for forecasting and aviation. The observation of highly glaciated clouds with HIWC but low radar reflectivity represents a significant challenge to the understanding of cloud processes.

Convective systems play a major role in the climate by affecting the Earth’s heat, moisture, and radiation budgets. Current attempts to model and predict convection must adequately represent the microphysical structure of these clouds, which is critical to proper understanding and simulation. The measurement of actively growing regions, with possibly quasi-adiabatic updrafts, will improve the understanding of a number of fundamental cloud physics problems, such as the initiation of ice particles and the evolution of the mixed-phase. Statistics of cloud updraft and associated microphysical structure will be generated. The available data sets with this kind of information are limited, and the observations here will include an extension of the height range of such statistics. The validation of model simulations will initially focus on the ability of the models to realistically simulate the basic sampled parameters. Questions that the model validation will answer include whether the models reproduce the probability distributions of the storm draft structures (size, mass flux, etc.) and, in the case of cloud resolving models, the appropriate microphysical structures, and if the cloud resolving models simulate HIWC with low radar reflectivity. The proposed observations will lay the groundwork for improved understanding and modeling of convection and the parameterization of these processes in global forecast models. Therefore, the data sets collected as part of such flight campaigns will provide crucial data for improved forecasting.

Microphysical measurements in deep convective clouds are needed for the interpretation of ground-based and space-borne radars (e.g., CloudSat, Tropical Rainfall Measuring Mission [TRMM]). In situ measurements of cloud microphysics are also critically needed for validation of microwave and IR satellite retrieval techniques. To date, most in situ cloud microphysical data were collected in the anvil or stratiform regions, away from the vertically developing cells of deep tropical systems.

For a flight measurement program in Darwin, Australia, validation of remote sensing would include, but not be limited to, an examination of the polarimetric radar data along the flight tracks. There are several features to be validated. The radar retrievals include the cloud microphysical type, IWC, and, in cases below the freezing level, estimation of rain drop size distributions. If convective cells have regions of HIWC characterized by relatively low radar reflectivity and presumably small ice particles (see section 1.2), the accuracy of existing relationships to derive IWC from reflectivity may not be accurate for these regions. Flights crossing from active convection into stratiform rain areas and anvil cloud will provide detailed cloud observations for testing retrievals from a range of radars operating at various frequencies, including cloud radars and satellite remote sensing. The variability of the tropical ice cloud properties as a function of distance to the convective cells will also be characterized with this flight strategy.

Sections 3.2–3.7 describe the fundamental meteorological science questions to be addressed in this project, which also have direct relevance to the engineering goals and aviation weather forecasting goals outlined in section 2.

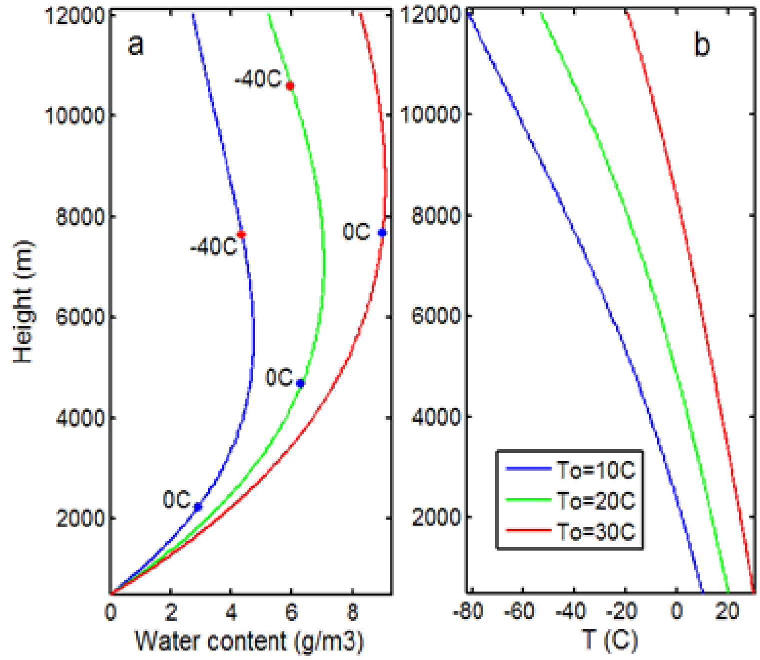
The science objectives to be addressed in this study are:

- S1: Characterize the microphysical and thermodynamic properties of vertically developing cells of deep convective clouds, including cloud LWCs and IWCs; PSDs and particle density; fall speed; and habit.
- S2: Determine the small ice particle formation mechanisms in deep convective clouds and the importance of small ice crystals in bulk microphysical properties; determine how small ice particles form through nucleation (homogeneous or heterogeneous) or through ice multiplication.
- S3: Determine the temporal and spatial evolution of the mixed phase in deep convective clouds; determine how the liquid/ice water fraction changes with time in a convective updraft and at the tops of convective storms. This includes an understanding of the relative humidity in the cloud and how ice particles grow.
- S4: Validate ground remote sensing of microphysical properties of deep convection and associated cloud systems.
- S5: Validate satellite remote sensing of cloud properties and HIWC regions in deep convection.
- S6: Improve simulation of deep convection using cloud resolving models.

3.2 OBJECTIVE S1: CHARACTERIZATION OF THE MICROPHYSICAL AND THERMODYNAMIC PROPERTIES OF VERTICALLY DEVELOPING CELLS OF DEEP CONVECTIVE CLOUDS

One of the highest priorities of this experiment is to identify regions of HIWC in deep convective clouds and conduct microphysical and thermodynamic measurements in these regions. Measurement should focus on characterization of spatial variations of IWC, LWC, extinction coefficient, cloud PSD, ice particle habits, humidity, temperature, vertical velocity, and turbulence along the flight direction at several preselected levels, including in the main updraft regions of some less vigorous convection.

It is hypothesized in this report that regions of HIWC are associated with adiabatic or quasi-adiabatic updraft cores, where cloud parcels are ascending from lower levels with minimal entrainment and mixing with the surrounding cloudy environment so that the condensed water remains undiluted. Figure 8 shows calculations of adiabatic LWC and T calculated for different initial cloud-base temperatures (T_0=10°, 20°, and 30°C). This diagram is a first approximation of the range of maximum condensed water content that may be encountered during a flight campaign. The maximum LWC increases with increasing T_0, and at T_0=30°C it reaches approximately 9 gm^{-3}. The altitude of the maximum adiabatic LWC ranges from approximately 5.5–9 km for a cloud-base temperature range of 10°C < T_0 < 30°C.



(a) (b)

(The altitude of the cloud base, and the lowest *y* value on the axis is H_0=500 m.)

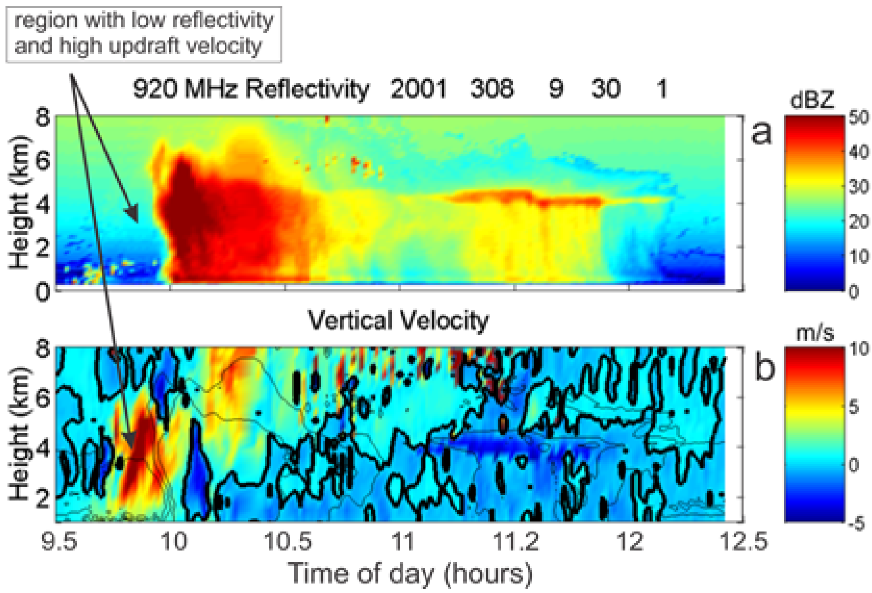
Figure 8. Calculated (a) LWC and (b) temperature during adiabatic lift for three initial cloud-base temperatures: T_{01}=10°C, T_{02}=20°C, and T_{03}=30°C

Because of the current lack of in situ measurements, the existence of such adiabatic cores in deep convective storms is still a matter of debate. Simple calculations suggest that entrainment and mixing will dilute and mix the ascending cloud parcel relatively quickly, reducing the concentration of condensed water, thereby inhibiting the survival of adiabatic regions. However, cloud parcels ascending with an updraft greater than 10 m/s may reach the upper part of the cloud (~10-12 km) in less than 15–20 minutes. If the cloud parcel is large enough, then this time may be insufficient for mixing of the entire parcel, and some regions may remain adiabatic when they reach the cloud top.

The basic questions related to adiabatic updraft cores in convective storms include:

- How does the pacel deviate from adiabatic in such cores (i.e., how adiabatic are the cores)?
- What are the roles of entrainment and vertical velocity in maintaining/dissipating the degree to which a core is adiabatic?
- What is the level of origin of the adiabatic core?
- What are the mechanisms triggering local updrafts in convective storms resulting in adiabatic cores?
- What is the vertical and horizontal extent of the adiabatic core?

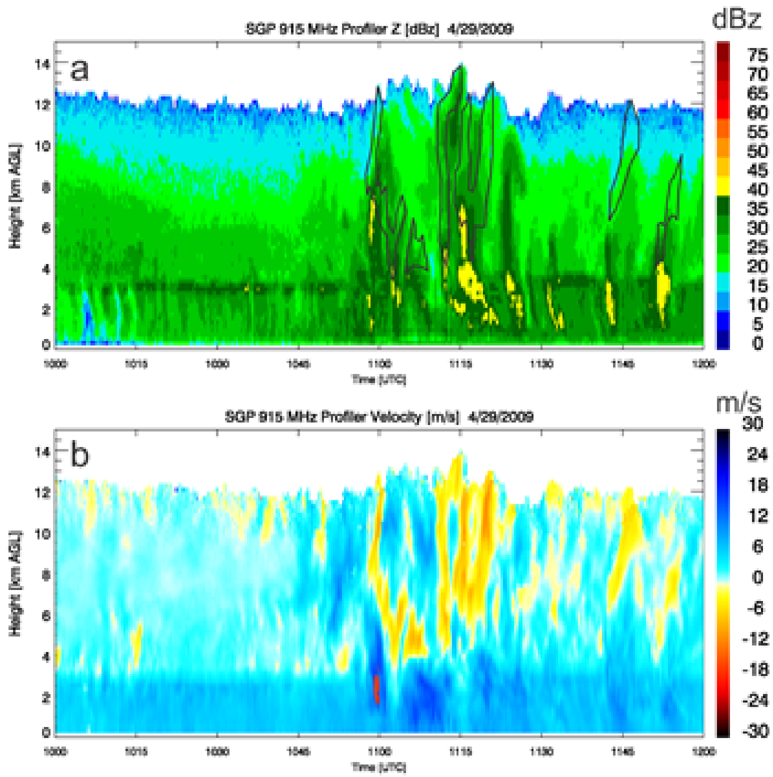
An analysis of UHF 920 MHz radar measurements in convective storms near Darwin illustrates an example of a region with high updraft and low radar reflectivity (see figure 9). The leading edge of the storm had a region between approximately 9.7 h and 9.9 h with a vertical velocity up to 10 m/s (see figure 9b) and a vertical extent from approximately 2–6 km. This cloud region was associated with low radar reflectivity (see figure 9a), which is indicative of small concentrations of large particles. The detection of such regions with a C-band radar is hindered because of low signal return. Numerical simulations suggest that such a high-speed updraft would result in a high supersaturation, activating a large fraction of the cloud condensation nuclei available in the cloud volume. Therefore, it is reasonable to assume that the cloud associated with this leading-edge updraft in figure 9 consists mainly of small droplets or small ice particles.



(Courtesy of Peter May, BoM)

Figure 9. The (a) reflectivity and (b) vertical velocity measured by the Atmospheric Radiation Measurement Department of Energy Darwin site radar wind profiler in an inland convective storm

Figure 10 shows another example of UHF radar measurements illustrating sharp, high-speed updrafts embedded in a deep stratiform cloud layer, this time for a convective storm over Oklahoma. Figures 10a and 10b also show that the regions of the strong updrafts do not always coincide with regions of high radar reflectivity. Note that, in figure 10, the regions of high reflectivity are located underneath the strong updrafts, and the overshooting region (between 11:00 h and 11:20 h) is associated with the region of the strong updraft. This is consistent with the discussions in sections 1.2 and 1.2.1.



(Black contours on the top diagram identify the regions with high updraft velocity from the lower diagram. In the lower figure, updraft velocities are negative.)
[Courtesy of Scott Giangrande, Brookhaven National Laboratory]

Figure 10. The (a) reflectivity and (b) vertical velocity in a convective storm over southwest Oklahoma measured by the Atmospheric Radiation Measurement Department of Energy Southern Great Plains Radar Wind Profiler

Though there are significant differences between oceanic and continental convection, the UHF radar observations of convective storms shown in figures 9 and 10 are presented to support a zero-order hypothesis regarding the location and nature of high TWC regions:

- Regions of strong updrafts form adiabatic or quasi-adiabatic cores with high TWC.
- The adiabatic cores are in the form of jets rather than bubbles with vertical depth of up to 10 km.
- The horizontal scale of the regions of strong updrafts in figures 9 and 10 is estimated as 1–2 km, assuming a horizontal speed of 40–80 km/h.
- The altitude of the onset of embedded strong updrafts (see figure 10) is usually located above the freezing level. Searching and identifying high-TWC regions, which potentially are adiabatic updrafts, is one of the HIWC operational tasks discussed in sections 1.2.1 and 6.

To fulfill science objective S1 while also improving the understanding of the dynamics and evolution of convective storms, the following measurement strategy should be followed:

- Identify regions with adiabatic or quasi-adiabatic condensed water content by comparison to theoretical calculations.
- Measure the horizontal and vertical extent of adiabatic or quasi-adiabatic updrafts.
- Collect statistics of vertical velocity and buoyancy.
- Estimate the characteristic spatial scale of the interface between the adiabatic and non-adiabatic regions.
- Collect measurements of the turbulence and temperature fluctuations from which estimates of mass and heat exchange between adiabatic and non-adiabatic regions of the clouds can be derived.
- Collect measurements to estimate the role of entrainment and detrainment at the cloud interfaces and deep inside the cloud.
- Collect statistics of the spatial variability of bulk microphysical parameters (e.g., extinction, droplet, and ice concentration; LWC; IWC; and particle habit) at different scales from tens of meters to kilometers and their relationship to local cloud dynamics.

The evolution of the microphysical and thermodynamic parameters is closely related to the growth rate of the ice particles and liquid droplets responsible for the balance of water vapor and energy in convective updrafts. The growth rate of cloud droplets and ice particles is governed by supersaturation over liquid water and ice, respectively. The supersaturation in liquid and mixed-phase cloud regions will be estimated based on the quasi-steady approximation [67, 68] from measurements of u_z and the integral radii of ice particles ($N_i\bar{r}_i$) and liquid droplets ($N_w\bar{r}_w$). In glaciated clouds below -10°C, the supersaturation over ice can be deduced directly from humidity (LI-COR and tunable diode laser hygrometer) and temperature measurements with a relatively good accuracy. Information on supersaturation is important for parameterization and validation of numerical simulations.

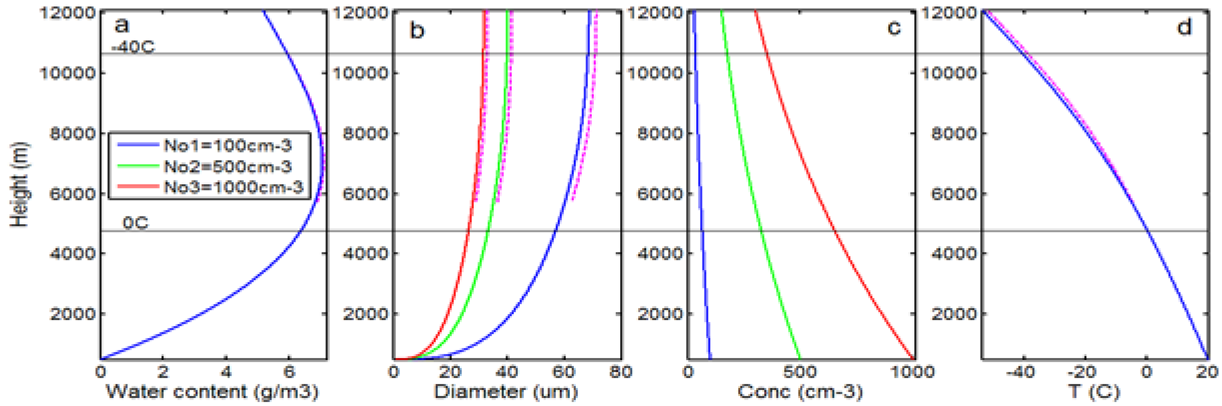
It is possible, and perhaps even likely, that conditions with high concentrations of small crystals are transitory in the evolution of a particular cloud system. Therefore, radar and satellite data will be important for defining the stage of evolution of sampled clouds.

The rate of ice precipitation formation is strongly dependent on the growth mechanism (riming, aggregation, or vapor deposition growth). The relative role of these mechanisms in precipitation formation would be best estimated from high-definition cloud particle Cloud Particle Imager imagery and potentially with polarimetric radar signals, if available.

The measurements will also provide a comprehensive characterization of the HIWC regions and the specific relationships between cloud parameters that will provide an observational basis for the development of nowcasting/forecasting tools using model outputs or satellite measurements.

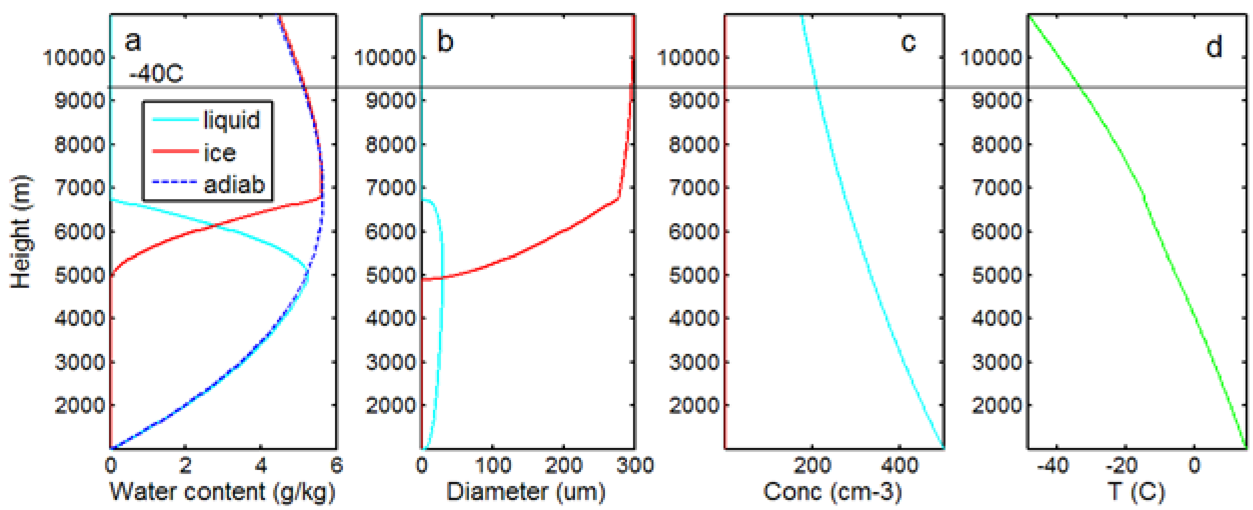
3.3 OBJECTIVE S2: SMALL ICE PARTICLE FORMATION IN DEEP CONVECTIVE CLOUDS AND IMPORTANCE OF SMALL ICE CRYSTALS IN BULK MICROPHYSICAL PROPERTIES

Sections 1.2.1 and 3.2 present the hypothesis that regions of HIWC/low radar reflectivity associated with engine events (see sections 1.2 and 2.4.2) are consistent with small particles and high condensed water contents that may likely be produced in regions of adiabatic lift near and in the active cells of convective clouds. Figures 9 and 10 support this hypothesis. The characteristic sizes and concentration of cloud particles in adiabatic updrafts have been estimated from a parcel model and are presented in figure 11. Because of the small phase relaxation time (τ_{ph}~10^{-1}–10^{0} s) for these droplet sizes and concentrations, the simulation reveals that vertical velocity plays a secondary role in determining the condensed water content and particle sizes as long as it does not exceed $|u_z|$~30 m/s. Figure 11 shows calculations of LWC, *D*, *N*, and *T* for an adiabatic ascent from 500 m to 12 km for three initial droplet concentrations: 100 cm^{-3} (typical of maritime convection), 500 cm^{-3}, and 1000 cm^{-3} (typical of overland convection). As shown in figure 11c, the droplet concentration decreases by a factor of ~3 during the adiabatic ascent from 0.5–12 km because of the air parcel expansion. Depending on the initial concentration, the cloud particle size at 12 km varies from ~30 μm to ~70 μm, a first estimate of the anticipated particle characteristic size in HIWC regions. The horizontal line above 10 km in figure 11 indicates the *T*=-40°C level, above which all droplets not already transformed because of heterogeneous freezing will do so because of homogeneous freezing. The calculations indicated by the dashed lines in figure 11 show the case of instant freezing of all droplets at the *T* = -5°C level. As shown in figure 11b, the sizes of ice particles will only differ by a few percent from the sizes of the liquid droplets. This small difference is the consequence of a relatively small difference between ice and liquid adiabats. However, in the case of partial freezing of the droplet population, ice particles will have the advantage over coexistent droplets and grow more rapidly and deplete water vapor more quickly than the droplets. Their growth rate becomes sensitive to the vertical velocity (see figures 12 and 13). These examples illustrate a variety of possible scenarios for the microphysical evolution in adiabatic updrafts that eventually affects the phase composition and size distribution of ice particles. The characteristic sizes and shape of the droplet size distribution may indicate the level of the onset of the adiabatic updraft. The width of the ice PSD and ice particle habits may trace back to the level of ice nucleation in adiabatic updrafts. If the size distribution is narrow, then any ice nucleation is likely to have occurred during a relatively short time interval. Broad size distributions of ice particles in adiabatic updrafts with no mixing are likely related to more gradual, continuous ice nucleation during ascent.



(H_0=500 m, T_0=20°C. The calculations were performed for three initial droplet concentrations: N_{01}=100 cm^{-3}, N_{02}=500 cm^{-3}, and N_{03}=1,000 cm^{-3}. Red dashed lines show changes of (a) adiabatic IWC; (b) particle diameter; and (c) temperature in cases of instant freezing of all droplets at the level with T=-5°C. Results are for diffusional growth only.)

Figure 11. Calculated (a) LWC; (b) droplet diameter for a monodisperse size distribution; (c) concentration; and (d) temperature during adiabatic lift



(Ice particles were initiated at T=-5°C, ice particle concentration 1 cm^{-3}, vertical velocity u_z=1 m/s; H_0=500 m, T_0=15°C. Results are for diffusional growth only.)

Figure 12. Modeling of changes of (a) LWC and IWC; (b) cloud particle sizes; (c) droplet and ice concentrations; and (d) temperature during adiabatic ascent

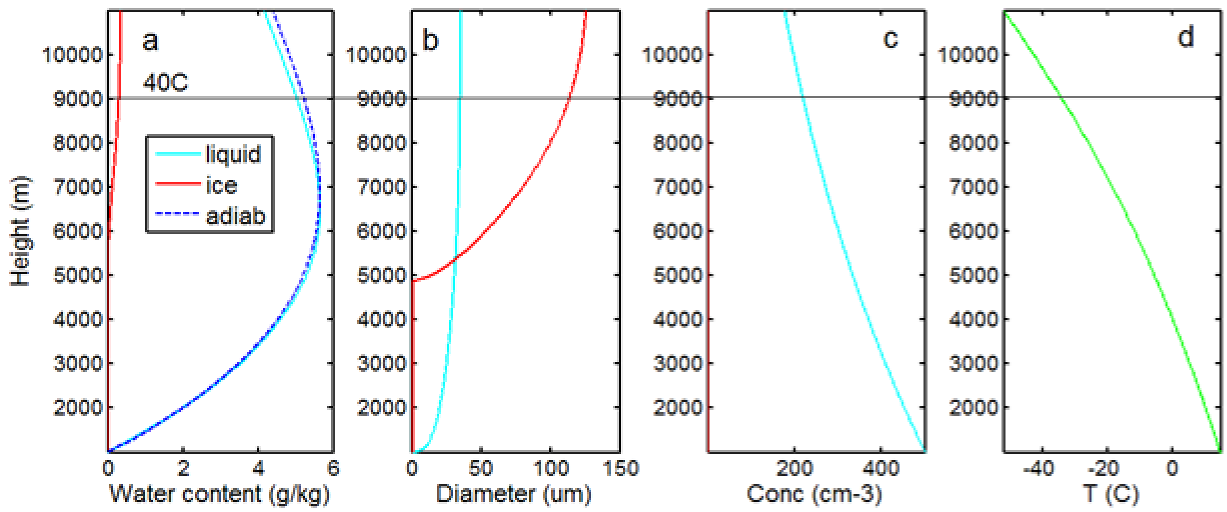


Figure 13. Same modeling of changes as in figure 12, but for u_z=15 m/s

The main goals of Objective S2 are:

- Test the hypothesis of the formation of cloud regions with small cloud particles and high TWC in adiabatic and sub-adiabatic updrafts. For this purpose, simultaneous measurements of TWC, cloud PSD, and vertical velocity are required. A systematic search of active cells of convective storms, identified by proximity to heavy rainfall below, may be used as a general strategy to attempt to locate such adiabatic cores. These cells may also be located by identifying overshooting tops in satellite imagery or from the pilots' visual observation in real time (see sections 1.2 and 1.2.1). Identification of adiabatic updrafts based on maximum TWC alone may be misleading, because high TWC may also be formed in accumulation regions, which are not related to adiabatic updrafts. Accumulation regions are thought to have relatively small vertical velocities and to consist of large particles, and therefore likely have a high radar reflectivity.
- Obtain measurements of the spatial changes of ice PSDs in the anvil region. Convective storm anvils play an important role in the Earth's radiation budget, and the presence of small ice particles may significantly affect the radiative transfer at the cloud top. Anvil tops are also significant in the transport of the water vapor in the upper troposphere and stratosphere. Water vapor is one of the greenhouse gases important for the Earth's climate. Small ice particles having shorter evaporation time will saturate the upper troposphere more effectively than larger ice particles.
- One of the long-standing problems in cloud physics is the understanding of mechanisms of glaciation in mixed-phase updraft regions. Ice formation may occur through: (1) contact or immersion droplet freezing; (2) deposition or sublimation nucleation; (3) one of the mechanisms of secondary ice production (ice multiplication) following an initial ice nucleation process; (4) recirculating ice coming from higher cloud levels and mixing in the updrafts, followed by glaciation due to the Wegener–Bergeron–Findeisen (WBF) process (see section 3.4); and/or (5) freezing of liquid drops below the temperature of homogeneous freezing (~-40°C). In this regard, it is important to identify the altitude of early formation of ice particles in adiabatic updrafts. Measurements of the

changes with height of the concentration and sizes of ice particles in adiabatic updrafts may help clarify the mechanisms of ice formation.

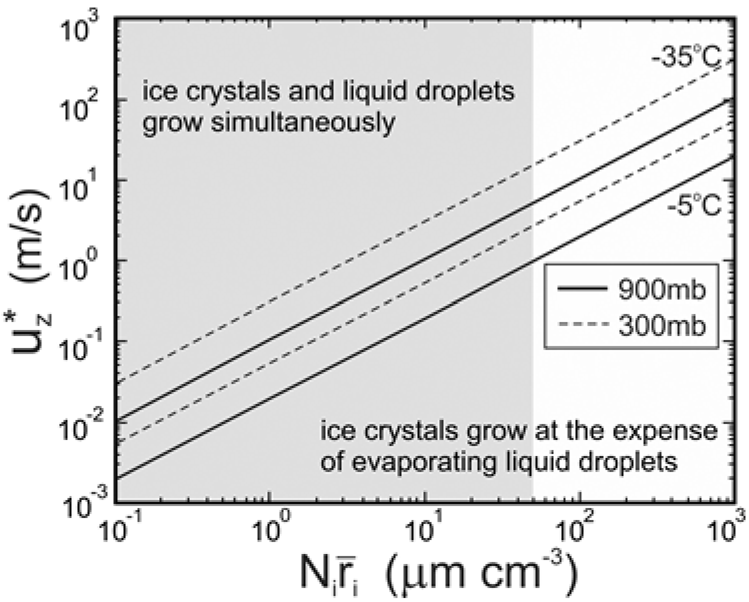
- Perform measurements of the horizontal and vertical dimensions of adiabatic updrafts and obtain microphysical and thermodynamic properties across these updrafts. These measurements are crucial for the estimation of heat and mass exchange between convective and stratiform regions in deep convective clouds. This information is of great value in the understanding of the dynamics of deep convective storms and validation of numerical models.
- Refine the normalized ice PSD for remote sensing cloud-retrieval techniques to include more realistic small ice particle statistics [69].

During flight operations, the sizes and concentration of small (*D* smaller than ~100μm) ice particles will be estimated primarily from measurements of particle probes such as the FSSP, Cloud Droplet Probe (CDP), 2-D stereo optical array spectrometer, and cloud imaging probe (CIP) (see aircraft instrument list, section 4.1, table 2). Recent studies have revealed that large crystals shattering on the tip of the probes can create small artifacts that contaminate the measured spectrum (see section 4 for more details and for special efforts undertaken by EC and NASA to mitigate this and other instrumentation problems for this study).

3.4 OBJECTIVE S3: TEMPORAL AND SPATIAL EVOLUTION OF THE MIXED PHASE IN DEEP CONVECTIVE CLOUDS

Mixed-phase clouds are fundamentally phase-unstable and can only exist for a limited amount of time before complete glaciation as a result of the difference in saturation vapor pressure over ice and liquid. The mechanism and the rate of conversion of liquid phase into ice in mixed-phase clouds is one of the most critical parameters for precipitation formation. Phase transformation in mixed-phase clouds is usually associated with the WBF process in which ice crystals grow at the expense of evaporating liquid droplets. Until recently, the WBF process in convective clouds had been thought to dominate the conversion of liquid into ice and subsequent precipitation formation. However, recent theoretical analyses have shown that the evolution of mixed-phase clouds is closely related to local thermodynamic conditions. The WBF process is just one of three possible processes of a three-phase system and is not necessarily dominant [70, 71]. Depending on the vertical velocity, ice particles and liquid droplets may both grow or evaporate, or ice particles may grow while droplets evaporate (WBF process). During simultaneous growth, liquid droplets compete for the water vapor with the ice particles, which slows down the depositional growth of ice particles instead of promoting their growth at the expense of the liquid, as in the WBF process. It has been shown theoretically that the role of the WBF process in convective clouds can be limited.

Figure 14 shows the dependence of the threshold velocity u_z^*, which separates the WBF regime from the condition in which ice particles and droplets compete for water vapor. For typical ice particle sizes r_i and concentrations *Ni*, the value of u_z^* usually does not exceed a few meters per second. Figures 12 and 13 show modeling of the phase transformation for two cases with the same initial conditions, except that the vertical velocities are 1 m/s for figure 12 and 15 m/s for figure 13. When the vertical velocity is small enough, cloud glaciation occurs relatively quickly (in figure 12 just above 6 km). However, at uz=15 m/s, the presence of ice particles does not greatly affect the behavior of the droplets, and LWC stays close to its adiabatic value. These theoretical results, and the conclusion regarding the limited role of the WBF process in the phase transformation in convective clouds, raise questions about the primary mechanisms of glaciation of deep convective storms (e.g., does the majority of ice result from: (1) homogeneous freezing of droplets in adiabatic updrafts at temperatures below 38°C followed by recirculation throughout the cloud; (2) one of the mechanisms of secondary ice production; or (3) heterogeneous nucleation?) The analysis of the temporal and spatial evolution of mixed-phase clouds in the HIWC study will improve the understanding of the mechanisms of glaciation of convective storms and therefore provide better insight into the mechanisms of precipitation formation in deep tropical convective clouds. Because radar and satellite remote sensing techniques are limited in their capability to identify and quantitatively characterize mixed-phase cloud regions, in situ measurements currently remain the most effective option to characterize the mixed-phase in deep convective clouds.



(The grey area highlights *Nr* typically occurring in stratiform clouds) [70]

Figure 14. Threshold vertical velocity separating two regimes of phase transformation: WBF (below the curves) and simultaneous ice and liquid growth (above the curves)

The main goals of Objective S3 are:

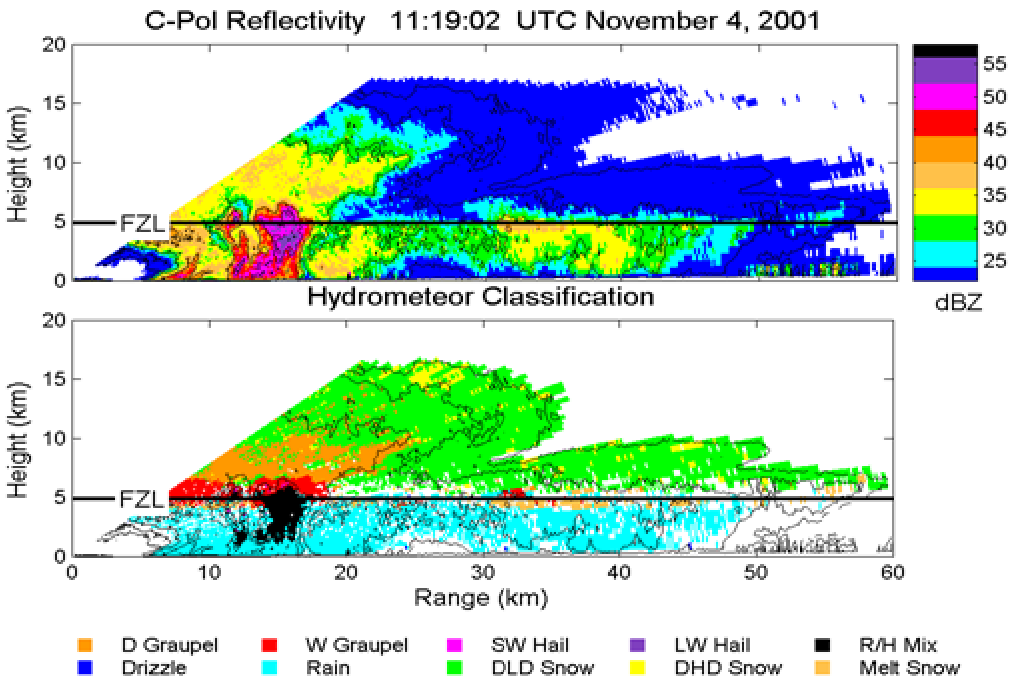
- Perform a detailed analysis of the relationship between vertical velocity and phase composition based on the theoretical approach outlined above.
- Identify spatial characteristics of cloud regions with different phase transformation regimes based on the comparisons of u_z and u_z^*.
- Obtain statistics of the threshold velocity u_z^* and integral radii of droplets $N_w\bar{r}_w$ and ice $N_i\bar{r}_i$. The integral radii of ice particles and liquid droplets are the most critical parameters defining the rate of the phase transformation in mixed-phase clouds [67], assuming no riming or particle fallout of the parcel model.
- Obtain statistics of the phase-composition coefficient $\frac{LWC}{TWC}$ inside deep convective clouds at different cloud levels.
- Obtain statistics of the lengths of liquid, glaciated, and mixed-phase cloud regions.
- If measurements are made in Darwin, estimate the "age" of the cloud, based on the BoM technique using millimeter wavelength cloud radar and C-band polarized radar (CPOL) observations for the additional analysis of the evolution of mixed-phase and cloud glaciation. This technique may provide information on the distance of HIWC zones from deep convective storms, a potentially important objective for the engine-icing component of this study. Presently there are limited data available in the literature about the evolution of the mixed phase in deep convective clouds [72]. The retrieved microphysical properties will also be binned as a function of distance to the nearest active cell to characterize how microphysical properties vary with distance from their parent convection.

4. OBJECTIVE S4: VALIDATION OF GROUND-BASED, REMOTELY SENSED MICROPHYSICAL PROPERTIES OF DEEP CONVECTION AND ASSOCIATED CLOUD SYSTEMS

This section was specifically written for a project location of Darwin, Australia, where a variety of powerful remote sensing measurements are available, though similar objectives may be possible in other locations equipped with similar remote sensing measurements.

A number of radar remote sensing approaches for the estimations of cloud properties are routinely implemented in the Darwin area. These have relevance to both weather and climate applications because they are used for measuring particle size (including hail), separating snow from rain, and estimating IWC of clouds. These are powerful methods, but there is only a small database of in situ cloud property measurements to validate these types of measurements.

The scanning polarimetric radar uses radar returns at centimeter wavelengths in two separate polarizations. These measurements, along with background environmental information, are used to delineate radar echoes from rain, snow, graupel, and hail (see figure 15), including regions where multiple species are present [73–75]. The polarimetric information is also used to provide information on the median size of rain drops in rain [76, 77] and IWC [78] in the upper parts of convective clouds. These additional measurements also allow for more accurate rainfall measurements and superior quality control than conventional radar [79].



This shows an active convective element with a rain-hail mixture and a large area of wet graupel around the cell core. Of particular interest is the narrow layer of melting snow that is resolved in the stratiform region farther from the radar. Contours of radar reflectivity are overlaid on these panels. The line labeled FZL is the freezing level.)

Figure 15. Example of reflectivity and hydrometeor classification from the CPOL near Darwin (RHI scan at 1119 UTC on November 4, 2001 showing the reflectivity [top] and classification [bottom]

There is little published work describing detailed verification of the derived products. This is particularly true for mixed and frozen hydrometeor species. Separating rain and snow regions has been convincingly demonstrated [81], and consistency has been demonstrated between polarimetric measurements and vertically pointing radar measurements with hail present [80]. Likewise, there is consistency between estimates of median volume diameter with polarimetric radar and vertically pointing radar retrievals [82, 83]. The reliability of the polarimetric estimation of IWC is particularly uncertain, and in situ measurements will be vital to refine this.

Very little in situ microphysical data has been collected in the high mass concentration/small ice crystal cloud regime, and both passive and active retrieval methods have not been optimized to detect these situations. How to detect such conditions remotely will be a challenge, and is an important step in providing warnings to pilots. The proposed flight campaign measurements within the HIWC study, including significant statistics of ice type and concentration across a wide range of concentrations, will be an invaluable data set for the purposes of testing and refining retrieval algorithms. The size- and shape-resolved data will be used for scattering calculations to refine retrieval algorithms and providing validation data.

Though the polarimetric radar provides 3-D mapping of the cloud fields, the radar may not be sensitive to non-precipitating clouds that may be climatologically important because of their effect on the radiation balance. These cloud fields may also contain significant amounts of undetected LWC and IWC. Because of this, a number of sites around the world have had millimeter-wave cloud radars and lidars installed to measure profiles of cloud properties. The approaches include the retrieval of size distributions and, in the case of cirrus, IWC, effective radius, fall speed, and visible extinction from combinations of wind profilers, cloud radar, and lidar. One such site is located at Darwin airport, and it would be useful to conclude flight missions with spiral descents over the airport. This was performed during the TWP-ICE experiment [84], but only a limited data set was obtained and with issues regarding the measurement of small particle sizes [49]. Data collected from a research aircraft would be used to assess all of these estimates.

A better understanding of the relationship between IWC, LWC, and updraft intensity in active cells will be the primary objective of the BoM using research aircraft in situ and cloud radar observations. This interest includes the statistics of the drafts, their buoyancy, and the relation to the cloud properties. A better understanding of these properties will improve interpretation of ground-based scanning polarimetric Doppler radar observations from CPOL.

Regarding ice clouds, the BoM has derived a set of IWC, effective radius, and number concentration statistics using the radar/lidar combination (e.g., [85]) or the Doppler cloud radar [86] at the Darwin Atmospheric Radiation Measurements (ARMs) site using past wet seasons. However, a better characterization of the small ice crystal size distributions and HIWCs is needed to improve these radar/lidar and Doppler radar methods in the tropics, as the implicit relationships between cloud parameters in these retrieval methods have not been tailored for these particular cases. This new experiment offers the unique opportunity to substantially extend the range of sizes and concentrations for which these methods are assumed to be valid. In addition, some simple methods rely on statistical relationships between bulk microphysical properties and atmospheric state (e.g., IWC-Z-T[3] method [87], extinction-IWC-T[4] method [88]). However, up until now, because of the limited availability and quality of the small ice particle and HIWC measurements, there is a large degree of extrapolation required when using these methods. A good example of this is the IWC-Z-T relationships in the tropics, which is clearly lacking a good description of the relationship between these three parameters for HIWC. Therefore, an HIWC study flight campaign data set may also help refine such simple analyses, which have proven to be good at describing the statistical properties of ice clouds.

Once these remote sensing methods have been improved and validated using the in situ observations, the main objective will be to produce reference ice cloud climatologies, which will then be used for NWP evaluation and space-borne retrievals assessment (CloudSat and CALIPSO).

[3] IWC = ice water content; Z = radar reflectivity; T = temperature
[4] IWC = ice water content; T = temperature

4.1 OBJECTIVE S5: VALIDATION OF SATELLITE REMOTE SENSING OF CLOUD PROPERTIES AND HIWC REGIONS IN DEEP CONVECTION

Cloud properties derived via satellite remote sensing could be highly valuable for forecasting and nowcasting regions of HIWC in convective storms and for deriving global maps of HIWC frequency of occurrence. However, the relationship between what is observed by the satellite and what is in the flight portion of the cloud volume has not yet been established. At a more fundamental level, there are few comparisons of in situ data and satellite retrievals of cloud properties in deep convective clouds. A few comparisons of cloud optical depth (OD) and effective particle size have been made in convective anvils (e.g., [89]), but the amount of information available to validate satellite retrievals of cloud properties in convective clouds is limited. The capability to monitor the skies over large areas from satellites is compromised by the constraints of temporal sampling and spatial resolution. Geostationary satellites (GEOsats) are the only ones capable of providing the necessary temporal resolution. The Geostationary Operational Environmental Satellite (GOES) series typically takes 4-km resolution imagery every 15 minutes over the continental United States and every hour over the globe, but has the capability of taking data over selected areas every 1–5 minutes. The Japanese Multifunctional Transport Satellites (MTSATs) take 5-km-resolution global imagery over eastern Asia and Australia every hour, but might be scheduled to image the Southern Hemisphere every half hour, if needed. Both the current GOES and MTSAT series have a comparable suite of spectral channels (0.6–0.75, 3.7–3.9, 6.7, 10.8, and 12.0 µm) that are currently being used to estimate a variety of cloud properties in near-real time [90][5]. Figure 16 shows examples of some of the products derived from the MTSAT-2 at 23:33 UTC, January 20, 2006, during TWP-ICE. The pseudo-color red-green-blue (see figure 16a) and the standard IR image (see figure 16b) show the cloud structure over and around Darwin (lower center, shown with a white circle). Several deep convective systems are active just northwest and west of Darwin. These systems rise well above 14 km as indicated by the values of cloud effective radiating height Z_{eff} in figure 16c). The ODs (see figure 16d) exceed 128 directly in those same areas over the active convective cells and fall off gradually in the downstream anvils. These are typically the same clouds with larger effective ice crystal diameters D_{eff} (see figure 16e), though the largest crystals are not necessarily found over the region of active convective cells. The column ice water path (IWP) (see figure 16f) is determined from the product of the optical depth OD and D_{eff} and typically is greatest over the active cells. The actual physical cloud top Z_{top} is generally 1–2 km higher than Z_{eff} because the IR radiance from thick, high clouds comes from an altitude corresponding to OD = 1 from the top of the cloud [91]. With two satellites viewing from different angles, it is possible to estimate the IWC within the uppermost portion of the cloud. However, air traffic is often below the top 2 km of convective clouds, so a different approach would be needed, even if two satellites were available to view the same cloud simultaneously. Therefore, it would be necessary to infer conditions at flight levels based on the D_{eff} in the top of the cloud and the IWP.

[5] Visit http://www-angler.larc.nasa.gov/satimage/products.html.

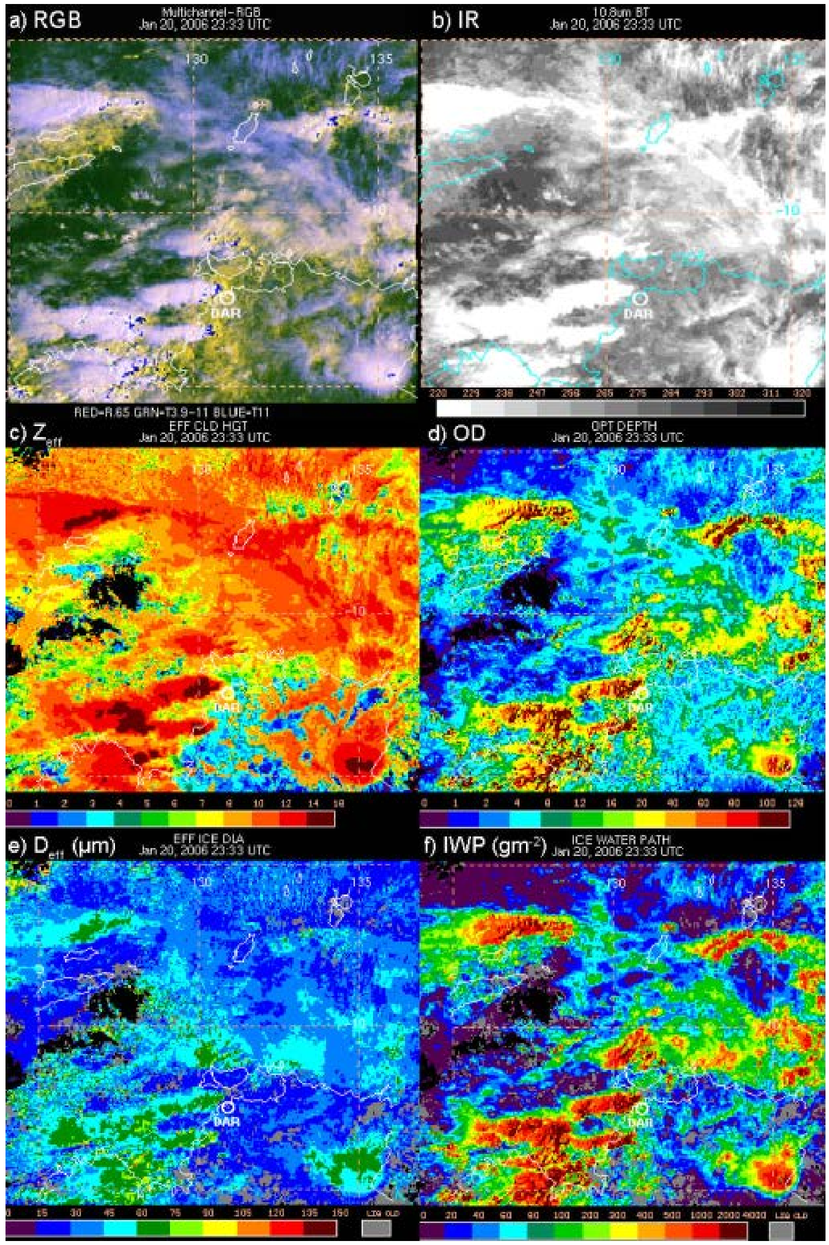


Figure 16. Imagery and cloud properties from MTSAT-1R over the southwest Pacific and northern Australia, 23:33 UTC, January 20, 2006

The statistically reliable relationships needed to make such inferences would require a large number of realizations matching D_{eff} and IWP with measurements of $D(z)$ and IWC(z), where z is the flight altitude. This number would be difficult to achieve using only in situ measurements. However, estimates of the vertical profiles of D and IWC are available from cloud radar measurements, and these profiles are now being derived on a global basis using the CloudSat radar measurements [92]. They can be used to determine cloud IWP, enabling direct comparisons with the passive retrievals from GEOsats. Figure 17 compares the IWP derived from GOES-12 and CloudSat over the northern United States. The GOES-retrieved IWP values are generally close to those from CloudSat, yet D_{eff} is only representative of the top 1–2 km of the cloud. The reflectivity profile in figure 17, however, shows the greatest values deep within the cloud, corresponding to larger particle sizes (not shown). These types of comparisons, including those between *IWP* and D_{eff} with *IWC(z)* and *D(z)*, can be performed using CloudSat and matched Aqua MODIS measurements over the globe, providing a sufficient number of samples to determine whether it is possible to make inferences about *IWC(z)* and *D(z)* based on the passive retrievals. However, the MODIS data matched with the CloudSat footprint have a nearly constant viewing zenith angle (VZA) and will not necessarily provide the relationships that would be operable at other VZAs. Therefore, matched GEOsat and CloudSat data will be needed to establish the VZA dependence of such relationships.

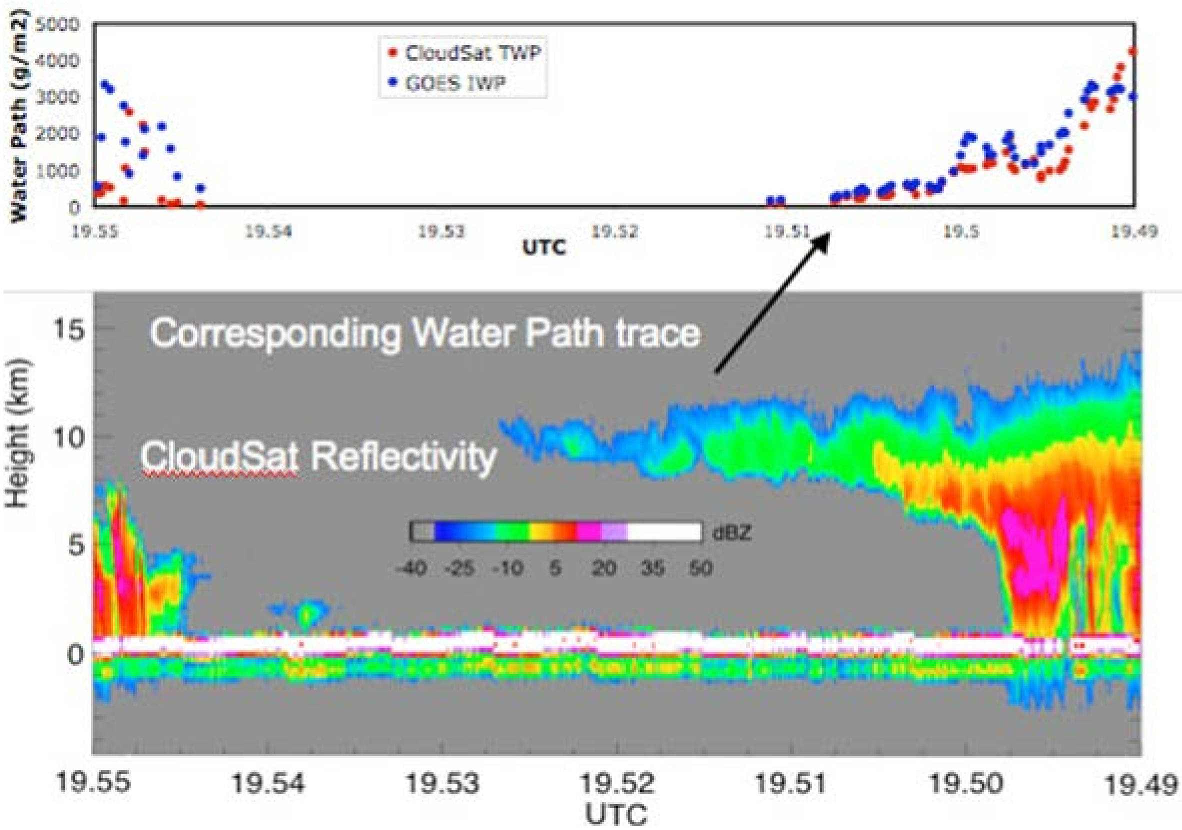


Figure 17. Comparison of cloud ice water paths from CloudSat and GOES-12, March 1, 2007 (lower panel shows the CloudSat radar reflectivity profiles)

Any inference of *IWC(z)* and *D(z)* or an index of HIWC probability from the passive measurements must be verified against in situ measurements. The CloudSat retrievals of IWC and particle size profiles themselves must also be validated, because they have not been developed with databases including HIWC or high-quality measurements of small particle sizes. An HIWC flight program will be ideal for that effort. Whenever possible, the flights should be aligned with the A-Train overpasses coincident with deep ice clouds. The remaining portions of those A-Train flights and other no-A-Train flights should focus on obtaining vertical profiles of *IWC* and *D* to facilitate validation of the direct retrievals of D_{eff} and *IWP* and the inferences of *IWC* and *D* lower in the clouds. Furthermore, efforts to align the flights with *Terra* overpasses should also be made to examine the utility of multispectral retrievals of D_{eff} when inferring *IWC* and *D*. The 1.6 and 2.1-μm channels on MODIS can provide estimates of D_{eff} corresponding to much thicker portions of the cloud top than possible with the 3.9-μm channel. They would provide, in effect, a vertical profile of cloud particle size (e.g., [93]). Though neither of the channels is currently available on either GOES or MTSAT, the R Series of GOES (known as GOES-R), scheduled for launch in 2016, will have 1.6 and 2.2-μm channels that can serve the same purpose.

The A-Train active and passive remote sensors also offer great promise for the development of global maps of the frequency of occurrence of HIWC and a better understanding of the specific environmental conditions that lead to HIWC regions. However, the current methods for the retrieval of IWC from space-borne active and passive remote sensing have not yet been evaluated for these particular conditions, simply because such a validation data set does not exist. Furthermore, they are not expected to be accurate, because they have not been constrained so far by relevant observations. The HIWC measurements produce great expectations in that respect. The existing methods for the retrieval of IWC will be assessed, and new relationships between IWC and the cloud observables of the A-Train will be established using the in situ observations from the HIWC flight campaign.

4.2 OBJECTIVE S6: IMPROVEMENT OF SIMULATION OF DEEP CONVECTION USING CRMS

CRMs provide 3-D and temporal context to the flight measurements to be taken in this experiment, and may in the long-term, if corroborated, provide model-produced TWC statistics for engine-icing objectives. However, a number of fundamental issues, which may be studied in this flight program, affect the accuracy of any such model simulations.

There is a growing recognition that different CRM simulations of deep convection using identical initial and boundary conditions produce significantly divergent microphysical fields (e.g., [94], [62]), and constraining model uncertainties using field measurements is extremely difficult. Perhaps the most widely used measurement for this purpose is radar reflectivity, which can provide a relatively high-resolution statistical description of deep convection that can be compared with simulations. However, measured radar reflectivity is highly dependent on the largest sizes in tail of the PSDs and cannot be uniquely mapped to integrated condensate mass, which is therefore left under-constrained. The challenge of constraining CRMs, which are widely used in many areas of atmospheric and climate research, clearly relates to the problem of heavy condensate mass loadings that are not coincident with high radar reflectivity.

It is natural for CRM modelers to turn to in situ measurements to help fill the gap between radar measurements, which provide coverage of vast volumes of the atmosphere, and condensate mass and PSDs, which are the more fundamental model variables. However, in the case of deep convection, research aircraft actively avoid the regions where they would be most useful: the vicinity of storm updraft cores, where most condensate mass is created and most cloud particles originate. The focus of future HIWC flight measurements on penetrating regions of vertically developing cells with specially designed instrumentation (see section 4 for discussion of instrument problems and mitigation) will therefore provide valuable in situ data to the CRM community.

The fact that the mechanisms controlling ice formation under mixed-phase conditions remain poorly understood, as described in section 3.3, also limits confidence in model fidelity. Because CRMs can resolve some aspects of the complex coupling between dynamical and microphysical processes in turbulent environments, CRM simulations can serve as an important test of hypothesized ice formation mechanisms, at the same time that data is used to improve them (e.g., [95]).

Integrating the data gathered during the HIWC study with detailed CRM simulations can contribute significantly to advancing the understanding of ice formation mechanisms. This objective is further discussed in sections 3.3 and 3.4.

5. MEASUREMENTS TO SUPPORT TECHNICAL AND SCIENCE OBJECTIVES

This section outlines measurement systems required or desirable for a study of HIWC cloud properties.

5.1 RESEARCH AIRCRAFT MEASUREMENTS

The main purpose of the research aircraft is to make in situ and remote sensing measurements in and near the cores of deep convective clouds. These measurements will provide data for aviation technical objectives and science objectives outlined in sections 2 and 3, respectively.

5.1.1 Basic Aircraft Requirements

To collect data in the environment in which engine events are observed, it is recommended that an experienced jet-aircraft flight test group provide aircraft and operational support that meets the minimum requirements outlined in table 1.

Table 1. Recommended aircraft and operator requirements to perform a HIWC flight program

Requirement	Minimum	Desirable
Fundamental measurement agreement	Willingness and ability to fly into expected HIWC conditions with the intention of searching for and making continued in situ measurements in such conditions.	
Aircraft history	No known history of engine, pitot, or other failures in high ice concentration conditions.	
Operational experience	Experience in flight test or atmospheric science airborne experiments.	Previous experience in research or flight test operations in HIWC conditions.
Flexibility	Ability to dedicate aircraft to a flight program in a fixed period, possibly in a remote region of the world, for a period of up to 1 month.	3-month flight program
Aircraft ceiling	No less than FL400.	
Aircraft flight duration for HIWC flights	3.5 hours	6 hours
Cabin volume	Adequate for four HIWC instrument racks	Adequate for six HIWC instrument racks
HIWC instrument operators on board	4	6
Instrumentation requirements	Must be able to accommodate minimum instrumentation list (see table 3) through existing or new aircraft modifications.	Able to accommodate maximum instrumentation list (see table 2) and potential aircraft modifications.
HIWC instrument project power	~12 KW	~25 KW

5.1.2 Aircraft Accommodation of Instrumentation

To provide data that are defensible to both the aviation and atmospheric research communities while fulfilling the objectives described in this document, the research aircraft must meet the following requirements:

- Externally mounted in situ probes: The location of these probes is important. For TWC and PSD measurements, fuselage mounting locations are discouraged, because they are subject to uncertainties due to the particle deflection, size sorting, and debris from upstream surfaces. Under-wing locations are encouraged, with the sampling locations of these probes forward of the leading edge of the wing.
- Research radar: Several scenarios are possible, each of which requires the mounting of relatively large antennae either in external fairings or looking through apertures in the fuselage.
- Fuselage-mounted probes: Several small probes would be deliberately mounted to the fuselage, either to simulate commercial aircraft sensor locations or because the measurements are not sensitive to fuselage-induced errors.
- Pilot’s radar: Recording of pilot’s radar/accommodation of a next-generation pilot’s radar is desirable.

5.1.3 List of Instrumentation

Previous investigators (e.g., [7]) have indicated that the HIWC environment can be hostile to instrumentation. Because of the high cost of flight operations and the possibility of instrumentation failure, instrument redundancy is encouraged, if possible. Such redundancy also allows for comparative measurements between similar instruments for studies of instrumentation accuracy. For this reason, initial plans for an HIWC research aircraft instrumentation list included 12 under-wing locations for probes with overlapping measurement ranges. Several aircraft in the atmospheric science community have such redundant capability.

Table 2 contains such a list, in which all technical and science measurement HIWC objectives are made simultaneously each flight. The aircraft would have 12 under-wing locations for the PSD probes; the new TWC isokinetic evaporator probe (IKP); the wind and gust measurements; and a boom for all hotwire measurements. No in situ cloud measurements would be made on the fuselage of the aircraft unless deliberately so as to simulate commercial aircraft measurements because of the potential for measurement contamination.

Table 2. Highly redundant instrumentation suite for measurement of the HIWC environment

Atmospheric State Parameter Instrumentation	Bulk Microphysics Probes for LWC, TWC, IWC, and all underwing
• TAT probe (standard probe sensitive to TAT freezing) • Solid wire TAT probe (insensitive to TAT freezing) • Background water vapor mixing ratio probe • Chilled mirror dewpoint sensor • Standard static pressure and airspeed sensors • Wind and gust measurement system • GPS position	• IKP for TWC (underwing) • PMS King LWC hotwire probe • Science Engineering LWC hotwire probe • Nevzorov LWC/TWC hotwire probe • Science Engineering TWC “robust” hotwire probe
Under-Wing Cloud Spectrometers (7 of 8 at one time)	Additional Aerosol Instruments (cabin)
• PMS FSSP probes (5–95 um) • DMT CDP • PMS 2D2-C probe (50–1600 µm) • PMS 2D-P probe (200–6400 µm) • SPEC 2DS probe (10–1280 µm) • DMT CIP probe (25–1600 µm) • DMT PIP probe (100–6400 µm) • SPEC CPI probe (2.3–2500 µm) • PCASP-100x probe (0.1–3.0 µm)	• TSI 3772 CN counters (2), >10 and >40 ηm • Scanning Mobility Particle Analyser
Other Important Microphysics Instruments	Audio and Video
• EC Cloud Extinction Probe • Ice detectors (one conventional location, one back fuselage in ice particle shadow zone)	• Cockpit HD windscreen camera • Camera for imaging TAT • Camera for imaging engine inlet • Camera for imaging wing leading edge or wingtip • Microphone for cockpit audio, including ice crystal impacts • General audio recording of ship intercom
Remote Sensing Measurements	
• Research radar, upward, downward, and side fixed antennae, or equivalent • Pilot’s next-generation radar (3-D recorded) • Stormscope for measurement and recording of lightning sferics	
Air-to-Ground Communications	
• Satcom, with voice and data transmission, chat, transmission of satellite pictures, ground radar, with flight track superimposed • Data from aircraft instruments to ground	

Table 3 contains a reduced list that meets all the HIWC technical and science objectives with minimum redundancy using only six under-wing locations (four PSD, one IKP, and one hotwire boom or equivalent). Additional aircraft modifications are also likely needed to accommodate a sensitive research radar.

Table 3. Approximate Minimum Instrumentation Suite for Measurement of the HIWC Environment

<table>
<tr><td>Atmospheric State Parameter Instrumentation:</td><td>Bulk Microphysics Probes for LWC, TWC, IWC, all underwing</td></tr>
<tr><td>• TAT probe (standard probe sensitive to TAT freezing)
• Background water vapor mixing ratio probe
• Standard static pressure and airspeed sensors
• Wind and gust measurement system (underwing or otherwise)
• GPS position</td><td>• IKP for TWC (underwing)
• Science Engineering LWC hot-wire probe (underwing) or equivalent
• Science Engineering TWC “robust” hotwire probe</td></tr>
<tr><td>Under-Wing Cloud Spectrometers
(7 of 8 at one time)</td><td>Additional Aerosol Instruments (cabin):</td></tr>
<tr><td rowspan="2">• DMT CDP or equivalent
• SPEC 2DS probe (10–1280 μm) or equivalent
• DMT PIP probe (100–6400 μm) or equivalent
• SPEC CPI probe (2.3–2500 μm) or equivalent</td><td>• TSI 3772 CN counters (2), > 10 and >40 ηm</td></tr>
<tr><td>Audio and Video:</td></tr>
<tr><td>Others Important Microphysics Instruments:</td><td rowspan="4">• Cockpit HD windscreen camera
• Camera for imaging wing leading edge or wingtip
• Microphone for cockpit audio, including ice crystal impacts</td></tr>
<tr><td>• EC Cloud Extinction Probe
• Ice detector</td></tr>
<tr><td>Remote Sensing Measurements:</td></tr>
<tr><td>• Research radar, upward, downward, and side fixed antennae, or equivalent
• Pilot’s radar (recorded)
• Stormscope for measurement and recording of lightning sferics</td></tr>
<tr><td>Air-to-Ground Communications:</td><td></td></tr>
<tr><td>• Satcom, with voice and data transmission, chat, transmission of satellite pictures, ground radar, with flight track superimposed
• Data from aircraft instruments to ground</td><td></td></tr>
</table>

Note that partial HIWC objectives can be met by research aircraft that do not meet the specifications noted above. For example, the primary 14 CFR 33 Appendix D objective of collecting TWC and MMD statistics can be met, with some risk, with only three particle measurement probes; a pilot’s radar (recorded); the IKP and background humidity measurement; standard state parameter and aircraft position measurements; and proper air-to-ground communications. This would only require four under-wing positions for cloud probes and the IKP. Note that there are situations in which measurements from a less-extensive instrumentation suite may still provide extremely useful data sets that meet important HIWC objectives.

5.1.4 Instrumentation Development and Modifications for HIWC

To address shortcomings in instrumentation that would potentially compromise HIWC measurements, the HIWC partnership made significant investments to improve instrumentation and test facilities for the HIWC environment. Details are included in appendix A, and highlights are listed below:

- A new IKP was designed specifically as the primary measurement of TWC in this project [96–99], in a partnership among National Research Council (NRC) of Canada, EC, Science Engineering Associates (SEA), and the FAA. A downsized version of the IKP (IKP-2) was developed by SEA, NRC, NASA, and the FAA for use on a smaller aircraft than originally intended for first airborne measurements.
- An IWC cloud simulation in the M7 test cell 5 tunnel at NRC was improved for cloud instrument testing, including the development of an absolute IWC reference to approximately 8 gm^{-3} at 150 ms^{-1} at a “hot spot” in the tunnel, and 4 gm^{-3} at tunnel center [100]. The facility was used to help establish the functionality and accuracy of the IKP and other probes.
- Fourteen different probe types were tested in the M7 facilities for de-icing performance and to identify any failures or idiosyncrasies in HIWC conditions. Any resulting probe modifications are described in appendix A.
- Certain probes were identified to be sensitive to electrostatic charging in HIWC conditions. A solution was found and implemented, using Titaniun Nitride coating on external probe surfaces, and the method is now in common use in the instrumentation community.
- EC put significant efforts into designing new probe tips to mitigate the contamination of PSD measurements due to breakup of particles on upwind probe surfaces [101]. Tips were replaced on many of the probes to be used in an HIWC flight program.
- EC developed a new cloud extinction probe for use on an HIWC aircraft. The probe is important for obtaining closure experiments between PSD and bulk parameter instruments and for the fundamental microphysical science objectives, and other objectives in this science plan.
- EC has developed laboratory calibration devices to characterize the performance of particle imagers and to improve their accuracy, particularly for small-particle measurements.

5.2 GROUND OBSERVATIONAL NETWORK REQUIREMENTS

A variety of ground and space-borne measurements are required to efficiently operate a flight program and fulfill HIWC objectives. Some of these have been identified in sections 2 and 3. In this section, these observations are briefly reviewed, and some differentiation between operational and science requirements is provided.

5.2.1 Ground-Based Radar

Ground-based radars provide continuous measurements of cloud precipitation fields in 3-D, offering valuable context to aircraft measurements. Section 3.5 outlines the HIWC science objectives related to improving algorithms of cloud properties from ground-based radars using the unique cloud in situ data that would be provided by this program. The aircraft and radar measurements are clearly complementary. Section 3.5 also describes scientific advances achievable if the aircraft is flown within the range of a polarimetric radar. Radar data sets are also important in fulfilling the HIWC core microphysical and modeling objectives (see sections 3.2, 3.4, and 3.7), and providing an important data set for nowcasting development (see section 2.5). In fact, it is likely that most of the HIWC science objectives would make use of ground-based radar data.

Operationally, real-time access to radar data can be used in locating regions of HIWC. Convective cells of heavy rain identified in radar signatures are likely the result of nearby active cells and HIWC aloft.

It is therefore highly desirable to make HIWC measurements within a network of modern ground-based radars and preferably within coverage of a polarimetric radar.

5.2.2 Other Ground-Based Data

Other ground-based data, such as those collected at airports and meteorological surface sites, are important supporting information for HIWC studies. Upper air soundings, for example, provide important information for modeling studies and for understanding the atmospheric forcing for convection. Opportunities for augmentation of upper air sounding frequency may be advantageous for research and operations. All such data is useful operationally to support forecasting and nowcasting efforts and to make decisions regarding the deployment of aircraft resources.

5.2.3 Lightning Network Data

Lightning network data are of high importance for HIWC aviation and science objectives. Lightning clusters are a key indicator of the location of active cells, where HIWC may be expected to be found. Lightning-intensive cells are also more likely to be vigorous. Therefore, the data are important in defining the overall structure and time evolution of the specific area of a cloud system that is of high interest to this project.

Lightning data are also important to conducting safe flight operations. The data can be used strategically for directing the aircraft to the general area of activity and optimizing the time of sampling once electrical activity subsides. It can also be used to decrease the probability of a lightning strike to the aircraft by avoidance. In this regard, lightning data are important for HIWC flight operations.

Near-global lightning data is available from commercial suppliers in near real-time. Data can also be obtained from an aircraft-based sensing system (stormscope). Either or both systems should be considered to support HIWC flight operations.

5.3 METEOROLOGICAL SATELLITE REQUIREMENTS

Satellite measurements are important for essentially all objectives within HIWC. The primary connection for the HIWC project to the type of cloud that causes engine events has been established through industry case studies, in which satellite is the most important meteorological data set. The industry hypothesis on the location of HIWC conducive to engine events is described through IR satellite imagery, in which the aircraft is likely to have travelled extended distances through clouds topped in the tropopause. This hypothesis, and the use of IR satellite, will be the primary means for vectoring the aircraft into HIWC cloud areas during an HIWC flight campaign.

For HIWC science objectives, satellites provide continuous context for the aircraft measurements. They provide fundamental comparative cloud fields for model comparisons and are a key component of the new HIWC nowcasting system (see section 2.5). Specific HIWC science objectives related to the improvements of satellite cloud algorithms have been discussed in section 3.6. For the most part, any aircraft operations in clouds are likely to be within the domain of the various GEOsats, though the frequency of imaging of these satellites is dependent on the location. In addition to GEOsat coverage, section 2.6 calls for flights coordinated with A-Train overpasses, which are essentially global for the types of cloud systems studied in this project.

As partner in the HIWC project, NASA Langley Research Center (LaRC) would provide near-real-time cloud products from a variety of satellite imagers (e.g., for a Darwin-based project; from MTSAT-1R, FY-2D; Terra and Aqua MODIS; NOAA-15/16/17/18 AVHRR; and possibly the MetOp AVHRR). Examples of some of the relevant products are shown in figure 16. These products and imagery would be made available in a satellite support Web page at NASA LaRC[6]. The raw and parameter imagery would be useful for flight planning and real-time adjustment. Pixel-level results would be matched with flight coordinates for direct comparison with the in situ observations.

The life cycle of individual cells within a typical engine-event-producing convective cloud system is approximately 30 minutes to 1 hour, whereas the overall lifetime of a system may be several hours. Detecting and measuring the short life cycle of individual cells, from which HIWC is thought to be generated and where the most important science measurements can be made, will require satellite imaging at substantially better frequency than the hourly frequency available in some areas of the word. Similarly, for directing the aircraft in real time to suspected areas of HIWC, high-frequency geostationary imaging is highly desirable. A minimum imaging frequency of 30 minutes is recommended.

6. FLIGHT CAMPAIGN LOCATIONS

Deep convection occurs from the tropics to the high latitudes, but the distribution of engine events indicates that they are more likely in the tropics and subtropics. A high frequency of engine events is found in the region of Southeast Asia. Though there are several possible contributing factors, it is noteworthy that this is the region of the highest sea-surface temperatures in the world, and therefore is conducive to high atmospheric vapor content and

[6] Visit http://angler.larc.nasa.gov/tc4/.

deep convection. Though deep oceanic convection is not limited to this warmest of oceanic regimes, there is good reason to consider that such an environment would be favorable for HIWC.

It is established in section 6 that HIWC flight campaigns should emphasize measurements in oceanic deep convection, for which it is thought that updraft regions can be safely penetrated. Measurements should be made in a location where such clouds are abundant, reachable on a daily basis for extended periods, and where adequate support facilities and measurements are available. Meteorologically, oceanic deep convection is abundant along the ITCZ, which seasonally moves north and south of the equator around the entire Earth's circumference, and therefore can be found at different time periods at different locations throughout the world. Surges in oceanic convection can also be found in regional monsoons associated with the ITCZ. Early aircraft measurements of cloud TWC in the 1950s by the RAE were made at Darwin, Singapore, and Entebbe, in association with the monsoon and ITCZ migration in each location.

The selection of a measurement location should take into account the following factors:

- The frequency of oceanic convection and overall duration and predictability of suitable conditions. Suitable locations would typically have a rainy season and precipitation annual totals in excess of 300 mm, occurring during a rainy season. Maximum monthly precipitation during the rainy season may exceed 100 mm.
- The frequency of large MCSs with anvil diameters larger than 100 nm (see section 6). These are target systems, as per engine event case studies.
- Idiosyncratic features of such storms, such as their intensity (e.g., can they be sampled with aircraft?), diurnal effects (e.g., are they night-time features?; at what time of day is the convective maximum?), and regional influences (e.g., coastal interactions).
- The existence of supporting meteorological ground measurement facilities that are either essential for HIWC measurements or desirable enhancements (e.g., radar network, lightning network, forecasting support, and special meteorological research facilities [see section 4]).
- Satellite measurements: the quality and frequency of satellite imagery available for the area of operation.
- Aircraft operational issues (e.g., suitable airports, distances to alternates, hangars, transit time to base of operations, Air Traffic Control, and diplomatic clearances required for operation in the area).
- Regional air quality and the potential effects of aerosol loadings on microphysical measurements.

The following list of regions of the world has been suggested in discussions with the HIWC team and its partners as likely to have a high frequency of the meteorological conditions conducive to HIWC oceanic sampling:

- Northern Australia/Indonesia during the January–March monsoon. There have already been several atmospheric science flight programs and at least two aviation programs out of Darwin devoted to ice crystal studies. Land-based convection is also prevalent and reachable.
- Northern South America on the Caribbean coast, during the rainy season. The aviation industry has conducted successful flight operations during a rainy season peak in the month of May. Land-based convection is also prevalent and reachable.
- Costa Rica/Panama in the June–August rainy season. This period is associated with the location of the ITCZ and local geographical effects leading to increased convection in the "Panama Bight". Several atmospheric research projects and one aviation flight test program have been conducted out of San Jose, Costa Rica. Land-based convection may also be prevalent and reachable.
- South China Sea area up to southern Japan, during the regional monsoon (May, June), with convection forming along the persistent Meiyu front. Land-based convection is unlikely to be workable because of political boundaries and sensitivities.
- West Central Africa during the summer rainy season. This region experiences both oceanic ITCZ convection and large, intense, land-based convective systems. Several atmospheric research projects have been conducted in the region.
- Off the east coast of Brazil in the ITCZ, during the January–March period.
- West/Central Pacific Ocean (several large atmospheric science projects have been conducted in this area, and U.S. government radars exist on Kwajalein).
- Bay of Bengal and Arabian Sea west of India, during the Indian summer monsoon.

Practical considerations (e.g., local facilities, political boundaries, and satellite imagery) increase the difficulty of operations in many of the locations listed above. The first four locations above are presently considered to be the most likely locations for HIWC flight operations.

Early discussions in the HIWC partnership were focused on a flight program centered in Darwin, and some of the HIWC science objectives are linked directly to Darwin facilities. In section 5.1, a description of the highly suitable facilities in Darwin is given, and a short description of the first international flight program partnered with the European High Altitude Ice Crystals (HAIC) project [102] is given in section 7.

6.1 THE DARWIN LOCATION

The Darwin area hosts one of the most suitable meteorological observatories for this project anywhere in the tropics (see figure 18). The BoM operates a network of operational radars in the project area (see figure 19) and two weather radars systems near Darwin. One is fully polarimetric [103], and the other is an operational Doppler. They have a baseline of approximately 25 km and a dual-Doppler lobe over the open ocean. This combination allows for the measurement of the 3-D wind field within the precipitation region and the thicker cloud region of the convective systems. Both radars complete a volume scan every 10 minutes. This allows for the observation of the generation of cloud structure within complex convective systems. Therefore, they provide the key baseline observations for the interpretation of other data sets. The polarimetric radar has the capability for estimation of cloud microphysical habit; water and ice content; and winds. These radars can also provide crucial data for directing the aircraft into regions of interest and documenting the stage of evolution of the cloud systems being sampled. These radars are capable of measuring clouds at an early stage of their development. The polarimetric radar also provides a regular analysis of the microphysical habit of the hydrometeors that are detected by the radar. This classification uses a combination of the polarimetric and thermodynamic variables with a fuzzy logic approach. This product is generated in real time and is archived by the BoM. A sample of the data is shown in figure 20. This is a time/height cross section of the data above the profiler site for a period of two days during the 2002/2003 monsoon. This was from a particularly active monsoon period, but does highlight the potential for rain to persist for several hours at a time, though heavy rain is relatively brief.

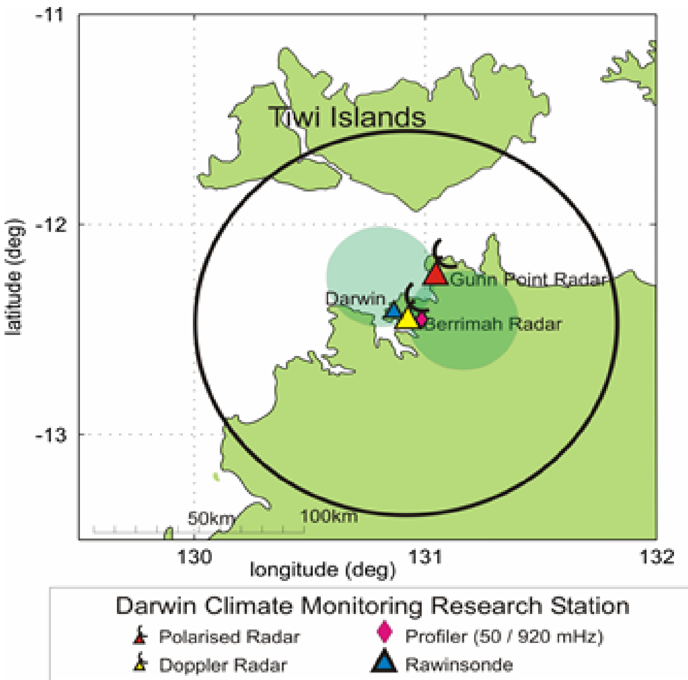
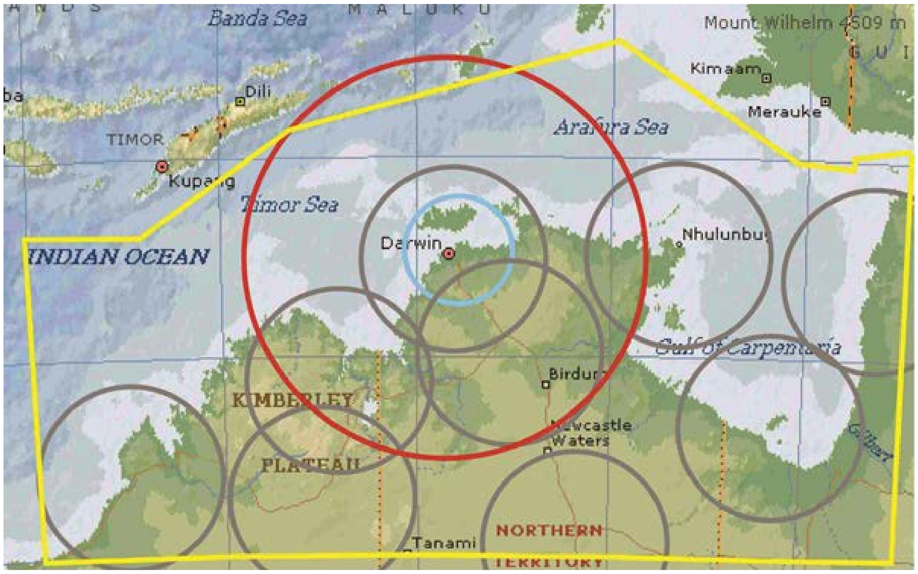
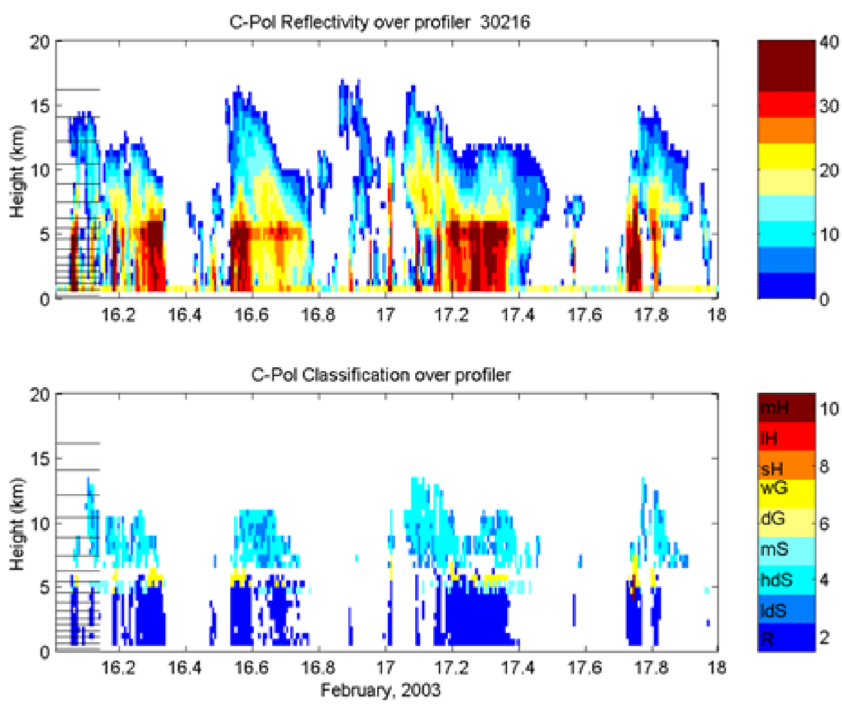


Figure 18. BoM observing network in the Darwin region including the Department of Energy Atmospheric Radiation and Cloud Station (range ring is 100 km radius centered on the Berrimah radar)



(The 300 nm radius red ring provides a distance reference. Most flights will be over the Timor Sea, Arafura Sea, and Gulf of Carpentaria. Preference will be given to flights within the meteorological radar coverage [grey rings], especially the research CPOL [blue ring].)

Figure 19. Proposed outer boundaries of research aircraft project flights for the HIWC study (yellow) out of Darwin



(Dark blue is rain, yellow is graupel, and blue is snow) [104]

Figure 20. Time-height cross section of CPOL reflectivity and hydrometeor polarimetric classification

BoM also operates 920 and 50 MHz wind profilers approximately 5 km from the airport.

The BoM Observing Office at Darwin Airport launches radiosondes twice a day at 00:00 and 12:00 UTC and wind soundings at 06:00 and 18:00 UTC. If there is funding for sonde packages, the wind soundings can be upgraded to full soundings. This should be considered to support any HIWC flight operations.

BoM's Observing Office at Gove Airport launches a radiosonde once a day at 00:00 UTC and wind soundings at 06:00 and 11:00 UTC with volumetric scanning by the Gove weather radar interrupted during these launches. For an HIWC study, the BoM would propose to implement full-time volumetric scanning by the Gove radar to support flight operations and the radiosonde/rawindesondes would be replaced with Global Positioning System sondes.

BoM's forecast office is also located in Darwin and has full access to satellite data, including MTSAT1-R data hourly. In mid-2015, BoM began receiving 16 channels of Japan Meteorological Agency Himawari-8 satellite data at 10-minute intervals, including IR channels at 2 km resolution. An L-band satellite ground station is located in Darwin providing local access to NOAA AVHRR data and an X-band satellite receiver has been recently installed providing local access to MODIS and Atmospheric Infrared Sounder (AIRS) data. A suite of NWP products from the BoM Australian Community Climate and Earth-System Simulator system is available.

7. AIRBORNE MEASUREMENT STRATEGY AND FLIGHT PLANS

7.1 TYPES OF CONVECTION AND DISTRIBUTION OF FLIGHTS

In this section, a flight measurement program is described assuming a base of operations in Darwin, Australia, as originally conceived in early discussions within the HIWC partnership. The principles are transferable to other locations, including specifics of the flight operations, though certain details may require adjustment to suit the location. Darwin provides arguably the most advanced ground measurements and operational support anywhere in the tropics. Other locations may not meet all the HIWC science objective requirements, but still may be suitable for a valuable subset of the HIWC objectives.

The Austral summer swings from periods of vigorous continental convection, which must be sampled by the aircraft with great caution, to periods of monsoon convection, for which it is expected that many convective updraft areas can be safely sampled at altitude over the water and, perhaps, over the land. Scales may vary from single-cell systems with characteristic sizes of 10 km to tropical storms with characteristic sizes of hundreds of kilometers.

Figure 19 shows the proposed overall project area for this study. Most of the flights would be performed over the warm waters of northern Australia (Timor Sea, Arafura Sea, and the Gulf of Carpentaria), and all flights would be performed within the irregular area described by the yellow boundaries. It would be desirable to perform a significant fraction of the flights within the CPOL coverage (blue circle) to collect coincident in situ and remote sensing data, and for flight-safety reasons.

The primary objective of the aviation technical component of this project is to collect statistical information on the levels of TWC in deep convective clouds, in a form similar to that shown in figure 5. Ideally, the EHWG would like to obtain unconditional probabilities of TWC, which cannot be achieved within a realistic project flight period because it would involve flying the aircraft in a random manner for a long time, including through clear sky for a large fraction of the time. Providing probabilities of TWC levels at different distance scales would be realistic, conditional on being in the vicinity of a deep convective cloud.

The EHWG had initially concluded that the majority of engine events occur within 20 nm of the start of an HIWC encounter (see section 1.2). The EHWG further concluded that statistics on TWC should be provided at the 99th percentile level within a statistical TWC uncertainty of 20% at an event distance of 17.4 nm, consistent with the 14 CFR 25 Appendix C distance scale for conventional supercooled liquid cloud icing, and just within the typical 20 nm distance scale initially defined for engine events.

More detailed analyses of the engine event database were subsequently performed after the EHWG study [10, 11], which included new events after 2003. These analyses concluded that the "signature" engine event most often occurs in a MCS embedded in an oceanic air mass. The aircraft is typically traversing a broad area of cirrus cloud with a characteristic length scale of greater than 100 nm where the satellite IR temperature is colder than the tropopause (i.e., the area of the MCS with the highest cloud tops). Furthermore, there is some evidence that the length of the traverse through deep cloud may be an important factor in engine events. These engine events in MCSs were approximately equally divided between systems over land and systems over the ocean, the former being more vigorous and more likely to exhibit intense radar cores at altitude. Because of this updated information on event conditions, the EIWG agreed to amend the original flight plans to collect data in MCS systems whenever possible, while attempting to collect 99th percentile average TWC with acceptable sampling statistics. This is further discussed in section 6.2.5.

Figure 21 shows a typical monsoon oceanic convective cell measured in the dual Doppler region of the CPOL and Darwin radars. This example illustrates a number of features of oceanic convection that make it favorable for sampling within updraft areas of active convective cells. Note that monsoon convection may be shallower than continental convection; cloud tops here as indicated by the radar are approximately 14 km, and anvil heights should be well within the reach of an HIWC research aircraft. The highest IWC values are expected to be in the main updraft area here, over the heavy rain area below 5 km. Reflectivity that would be seen on the pilot's radar as amber (greater than 30 dBZ) or red (greater than 40 dBZ) is only observed below approximately 7 km and 5 km, respectively. A more representative analysis of the vertical profile of reflectivity in oceanic convective cells (see figure 2) has been provided with similar results [18]. Because hail and lightning are rare in monsoon convection, figures 2 and 21 suggest that the active cells of these clouds could often be safely over-flown for altitudes above approximately 7 km, though significant airframe icing must not be ruled out in updraft regions. See section 1.2 for more information.

More vigorous convection is observed over the land during monsoon periods and especially in break periods between monsoons. Convective cells may often be isolated during break periods, but may also be embedded in MCSs. During monsoon periods, MCS convective cells are often observed to be more vigorous over land than over water; therefore, this report has included break period convection and over-land monsoon convection in the same category of continental cells.

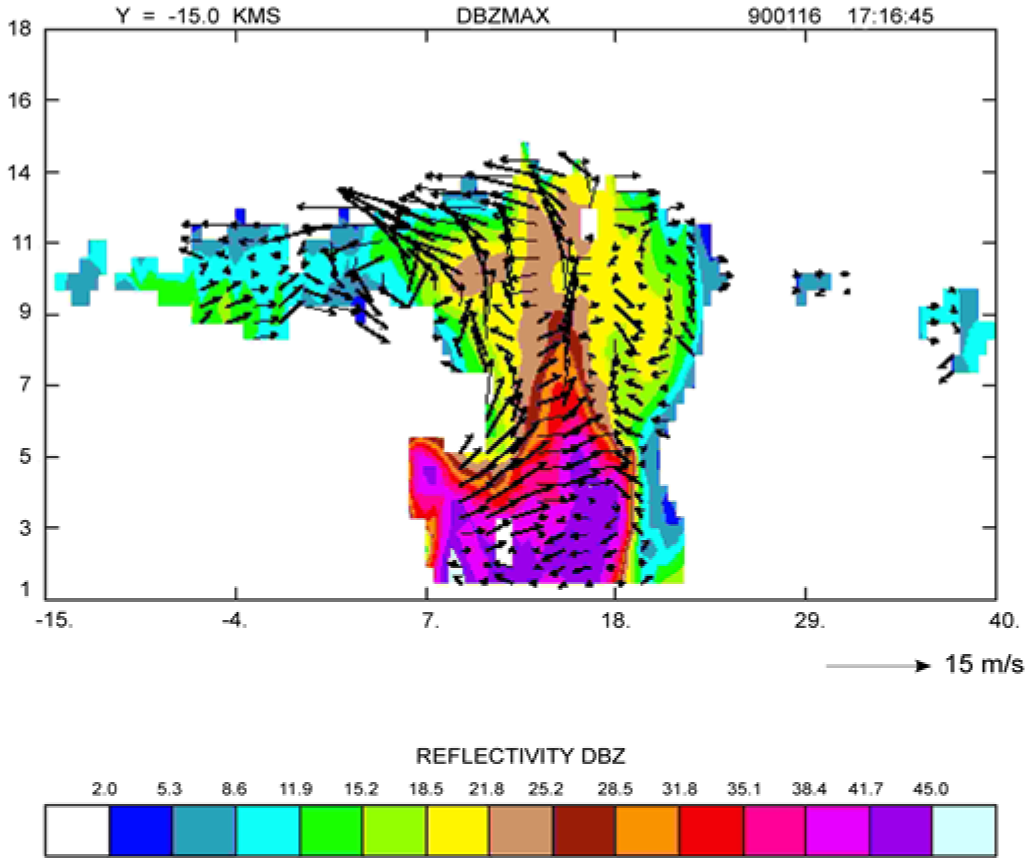
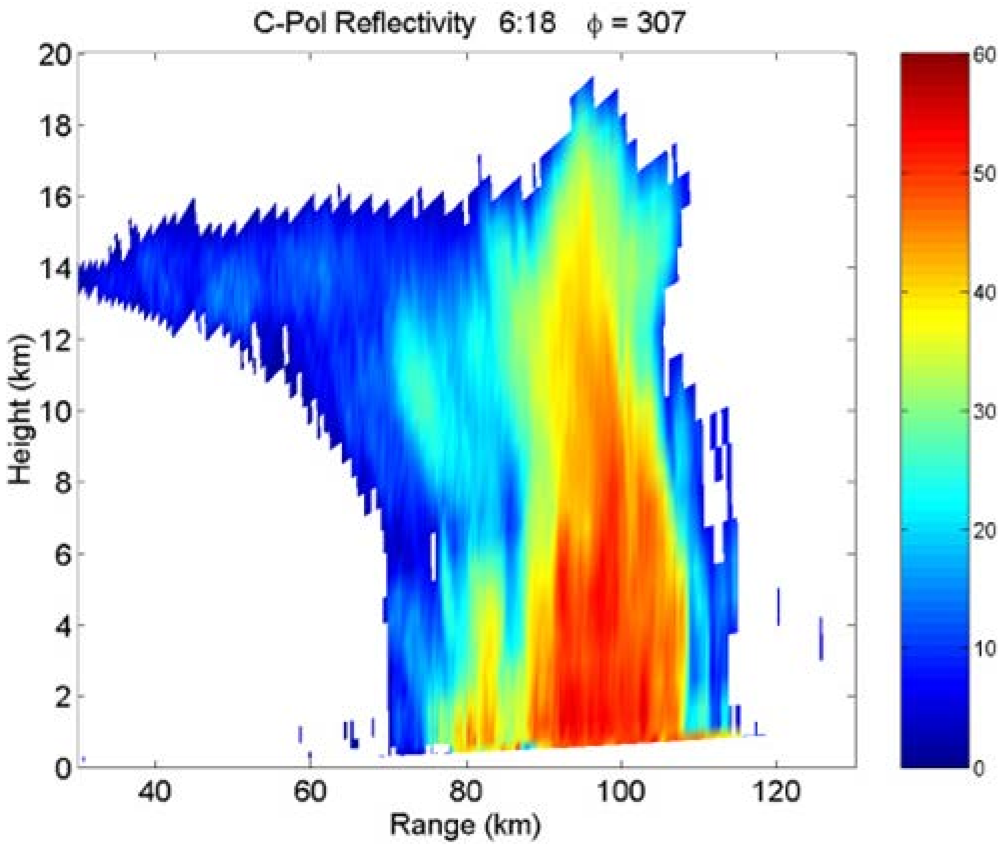


Figure 21. Example of a monsoon oceanic convective cell in the dual-doppler region of the CPOL and Darwin radars (radar reflectivity and wind fields are shown) [104]

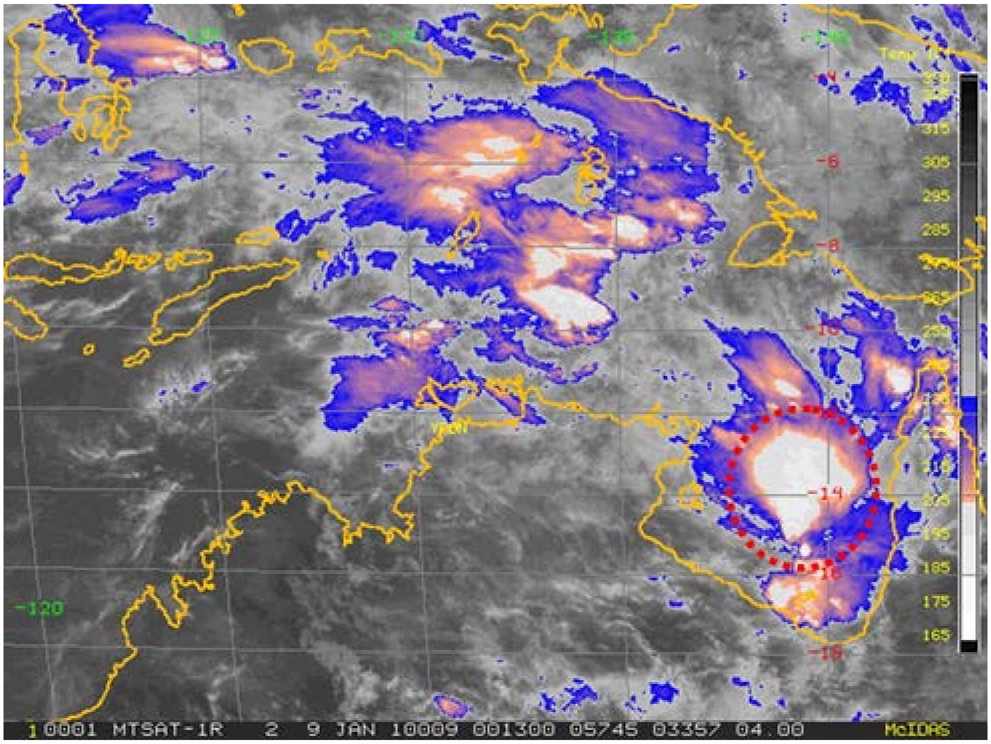
Figure 22 shows a cross section of a fully developed deep convective cell that reoccurs over the Tiwi Islands near Darwin, locally known as "Hector." Though this cloud is a hybrid of oceanic and continental convection, it exhibits the vigorous nature of tropical continental convection. Typical tops for these clouds are in excess of 18 km, with trailing anvils situated between 11 km and 16 km. Note that at the estimated -50°C level (~12.4 km), the highest sampling level requested by the EIWG, there is a core of reflectivity exceeding 40 dBZ (red on the pilot's radar) persisting to the ground. Cells of this nature generally will be characterized by high updraft velocities (~20+ ms^{-1}), abundant lightning, and a significant probability of graupel and hail. Therefore, it would likely not be possible to penetrate the vertically active regions of such a cloud at any of the three altitudes suggested by the EIWG. However, HIWC values may be found in the stratiform anvil region downwind of and close to the active cells. Therefore, it is desirable to sample the regions downwind of these cells. The edges of such convection have previously been sampled in the Darwin area by a Proteus aircraft and an Egrett aircraft during the TWP-ICE experiment [84]. Their in-cloud sampling strategy was to measure only within the downwind stratiform anvil as close to the convective sources as deemed safe by the aircrew [105]. In an HIWC flight program, a similar approach would be adopted, working the anvil region inward toward the most active storm area, with the proximity of the closest pass to be determined on a case-by-case basis. In addition, it may be possible to sample less vigorous convection that has advected from over-land to over-water, or in convection clearly in the dissipating stage. The life cycle of a convective impulse is expected to be approximately 30–60 minutes.



(Note that the reflectivity color scale is different from figure 21)
[Courtesy of Australian BoM]

Figure 22. CPOL vertical cross section of a well-developed "Hector" storm looking approximately northward from Darwin at 15:48 local time on November 15, 2001

Because nearly three out of four engine events occur in MCSs with characteristic scales of greater than 100 nm, the EIWG also decided that emphasis should be placed on sampling such MCS clouds whenever possible. To ensure that these cloud systems exist with adequate frequency in the Darwin area during the project period, MTSAT data were examined for the first 70 days of the year (January 1–March 11) for the period of 2008–2010. It was found that on 47% of the days, at least one MCS with a characteristic size of approximately 100 nm or larger was observed within the project domain described in figure 19. One such example is shown in figure 23, in which the cloud in question is circled in red. In this representation, the IR temperatures colder than the tropopause are shown as embedded white areas, following previously defined IR color-enhancement procedures [10]. A target MCS for this experiment would have a characteristic white area of ~100 nm or greater.



(Regions where the cloud top is colder than the tropopause are enhanced as bright-white.)

Figure 23. MTSAT IR image of a MCS over the Gulf of Carpentaria, typical of the type in which engine events are observed

Overall, the EIWG decided that the target breakdown of flights should be approximately as follows (with specific comments related to a Darwin-based project):

- 60% of hours in monsoon convection over the ocean (less vigorous MCS):
  - Sample MCS systems with characteristic size ~100 nm or larger whenever possible
  - Sample smaller systems when MCS are not present or practical
  - Emphasize flights within CPOL coverage when suitable oceanic convection is within CPOL range
  - Attempt to sample three tropical storms with long traverses
- 25% of hours in over-land MCS (more vigorous):
  - Sample MCS systems with characteristic size ~100 nm or larger whenever possible
  - Sample during monsoon periods
  - Consider sampling break-period MCS on case-by-case basis
- 15% of hours in continental break convection:
  - Sample within CPOL or network radar coverage

Because MCSs or other smaller cells or cloud systems over the ocean are expected to be less vigorous than those over land, this project would strive to collect the major fraction of data (60%) in oceanic systems over the water where it is expected that the aircraft can fly through updraft areas of active convective cells where the highest IWC is expected. For a Darwin-based flight program, a significant fraction of the flights would be dedicated to flights in monsoon or break MCS over land (25%), flying a safe distance downwind of these more vigorous active cells in the anvil region. Finally, a small fraction of the flights (15%) would sample anvils of continental cells during break periods.

The more benign oceanic convection provides the opportunity to safely sample a larger number of potentially HIWC areas in actively growing cells to collect a large database of the properties of these storms. Though the relative levels of maximum TWC in over-water versus over-land storms is unknown, the heavy rainfall from both suggests that HIWC may be expected aloft in either case. It is clear that engine events are occurring in oceanic clouds and likely that commercial aircraft are flying through or close to active cells and traversing associated updraft areas. If it is found during the continental cloud sampling that TWC values are consistently higher than oceanic convection, proportions of flight hours may be adjusted on consultation with the EIWG and the flight operations group.

It is also important to perform flights specifically in oceanic convection to fulfill primary science objectives, which would require the aircraft to fly in the updraft regions of convective cells at multiple altitudes. It is assumed that this can only be accomplished in the less vigorous cells over the ocean. Most, if not all, of the over-land MCS and isolated cell studies would be flown in the stratiform anvil region, which is of secondary interest to the science objectives. Only the flights in the updraft areas of oceanic cells would provide the unique data set to the scientific community.

Though it would be necessary to fly a large fraction of the oceanic flights remote from Darwin, it is desirable to sample a significant fraction of the oceanic flight hours within CPOL to provide 3-D context to the aircraft measurements and to provide data for the remote sensing objectives of the study. Whenever such opportunities arise, they should be given priority consideration.

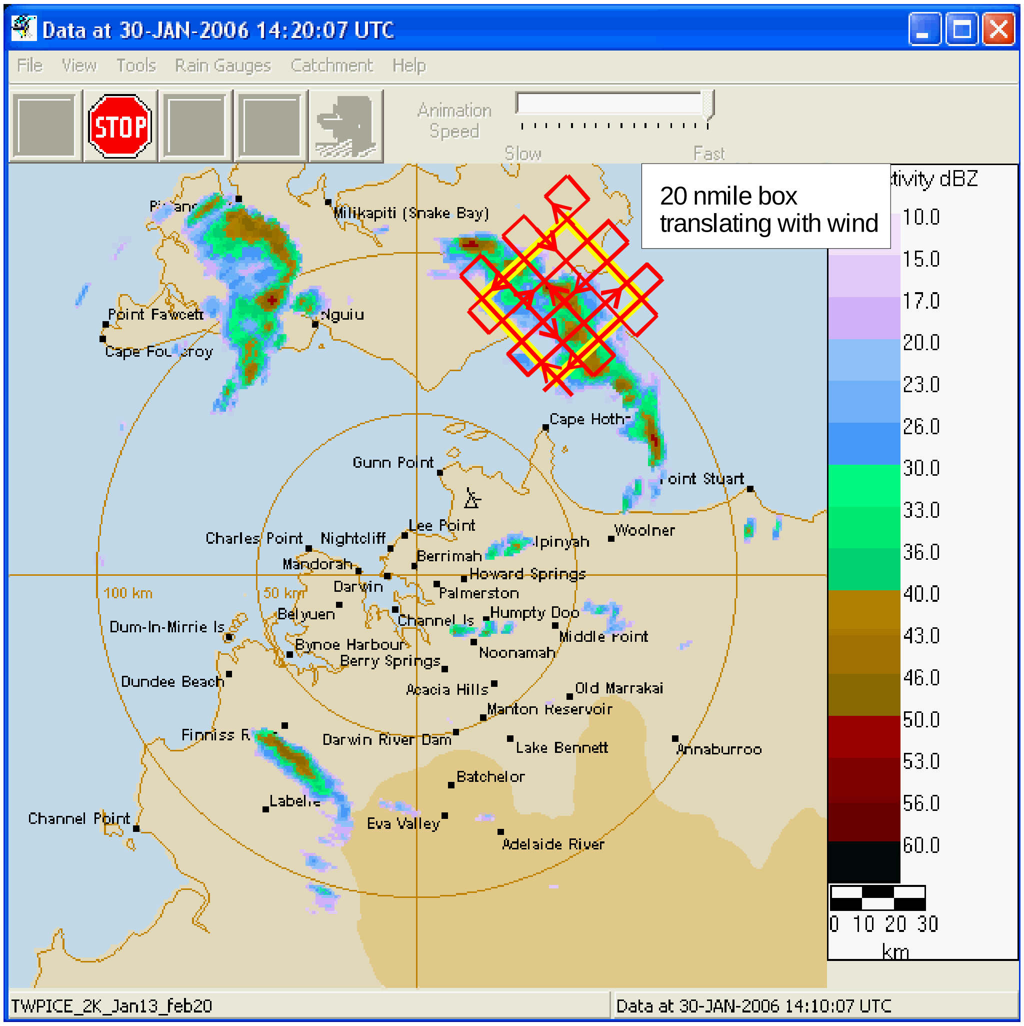
A number of the EIWG power-loss events have occurred when the aircraft were flying across tropical storms, typhoons, or in the remnants of Atlantic hurricanes. Therefore, it is desirable to sample these organized systems to collect additional data in cloud with possibly different characteristics. Tropical storms would be sampled on an opportunity basis, to provide relatively long transects in large-scale cloud systems with a long lifespan.

Section 6.2 describes the sampling strategies to be used to obtain 99th percentile TWC at length scales up to 17.4 nm or longer if possible, from this variety of convective cloud systems.

7.2 FLIGHT SAMPLING STRATEGIES

7.2.1 Idealized Flight Plans: Small Convective Systems Over Water

Figure 24 shows the initial idealized flight plan designed to provide the kind of statistics required by the EIWG. This scenario is for a monsoon convective system with a characteristic size of approximately 25 nm. Subsequent investigations of the event database have refocused the sampling strategy to larger MCS systems (see section 6.1), the flight sampling strategies for which are described in sections 6.2.2 and 6.2.3. The small-system scenario is presented in this section first to introduce the framework of the sampling statistics described in section 6.2.4. It is expected that this small-system scenario would be flown only when larger MCS clouds are not present in the area, and when emphasis on the science objectives is given priority.



(These flight patterns would be performed at 3 temperature [altitude] levels above 7 km. Radar reflectivity shown here is for a low altitude and does not extend up to flight altitudes at intensity above 30 dBZ.)

Figure 24. Idealized flight plan for smaller-scale monsoon convection, with 20 nm straight-and-level flight transects over the core of the storm

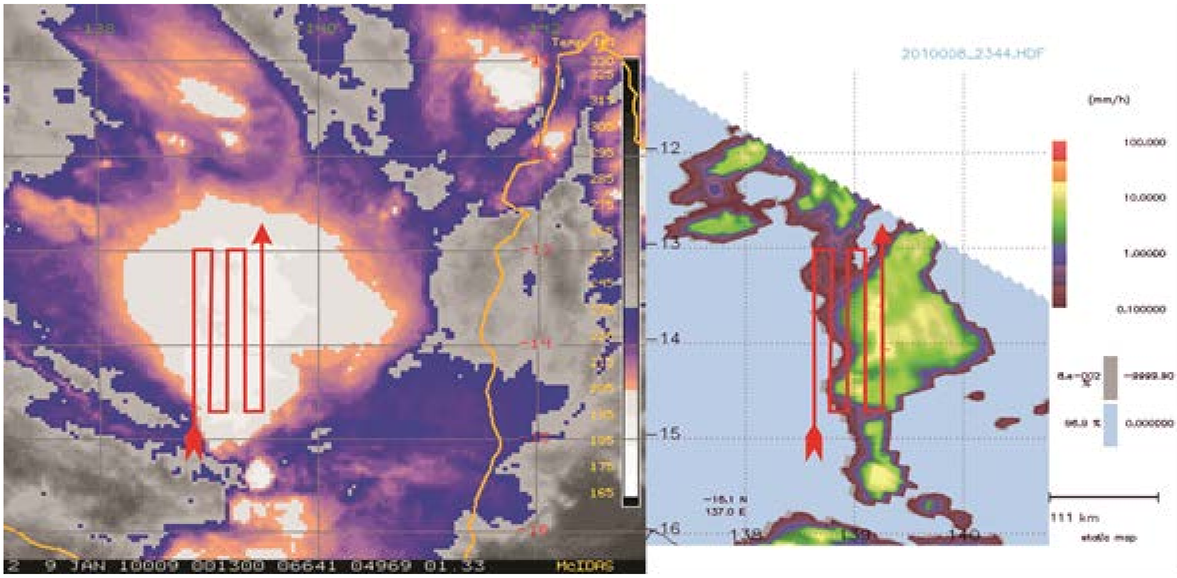
The example shown is a case of multi-cell monsoon convection that has traveled over the ocean from the west, for which it is expected vertical profiles of reflectivity would be similar to figures 2 and 21. For this system, a series of straight-and-level parallel flight transects would be performed above 7 km in an expected area of HIWC. The transects would be adjusted to maintain their horizontal separation relative to the feature as it moved downwind. In the case shown, a low-level region of high rainfall rate identified by a surface-based radar has been used as an expected indicator of HIWC aloft, but other criteria, such as images from the pilot's radar tilted downwards or satellite signals (e.g., rapidly building cold tops, overshooting tops), may be used during the experiment to identify these potential HIWC regions. The legs are straight and level to simulate the typical track of a commercial aircraft, and are rounded up to 20 nm for practical reasons to provide the necessary minimum 17.4 nm distance statistics required by the EIWG. Because the time and location of new cells and their associated updraft areas are unknown, it is assumed that the aircraft would occasionally and randomly penetrate updraft areas above the reflectivity cores by following such a flight pattern. The parallel transects provide a spatial and temporal survey of the system, hopefully through the lifetime of one or more random cell growths and decays. Ideally, the experiment would target an adequate number of cloud features that have a characteristic scale of at least 17.4 nm, as in the case shown in figure 24, and a feature-lifetime in excess of 1 hour. During a 1-hour investigation of a cloud feature, it is estimated that approximately 10 such transects could be flown. A sufficiently large number of these transects (see section 6.2.5) through a number of independent clouds would provide the desired 99th percentile TWC values, for which the statistics are conditional on the aircraft being within approximately 20 nm of the suspected convectively active regions of such clouds.

From the perspective of the science objectives, it is important to sample some convective cells with relatively short flight legs. With a transect of 20 nm (3–4 minutes), it may be possible to sample the same updraft area in the same cell at several different altitudes, tracing the evolution of the cloud properties with height. For the long leg lengths proposed for MCS investigations (see sections 6.2.2 and 6.2.3), the length of individual legs will approach the lifetimes of individual cells, making detailed cell-evolution investigations unlikely.

7.2.2 Idealized Flight Plans: MCS Over Water (Less Vigorous)

The following flight plan is suggested for non-vigorous MCS over the ocean, where high-reflectivity cores are not observed at flight altitude, and the updraft area can be traversed. It could also be used for similar MCS over land if they are observed, though it is expected that over-land MCS would be more vigorous and not allow sampling of the updraft area.

The HIWC project would place the highest emphasis and flight-hours fraction on this scenario (see section 6.1 for a discussion on the rationale for targeting these systems). Figure 25 shows an example MCS, with figure 25a showing the satellite IR image and figure 25b showing the low-altitude radar pattern. Such an MCS would be characterized as highly suitable for the HIWC study if the diameter of the central region of IR cloud tops higher than the tropopause (white area) was greater than approximately 100 nm. As in the previous scenario, it is expected that the vertical profile of reflectivity in the cells would be similar to figures 2 and 21, which would allow for flight over the precipitation core below and through the updraft areas.



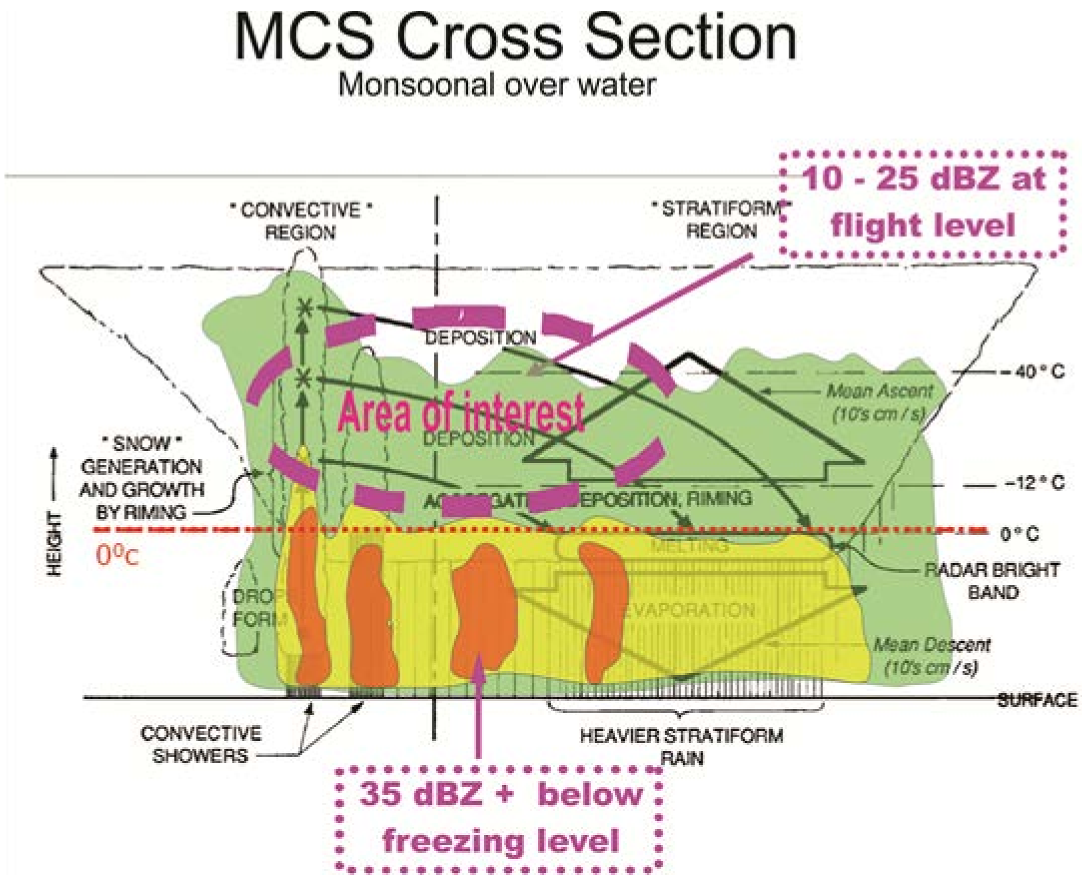
(b)

Fig. (a) is a satellite IR image as in figure 23. Fig. (b) is a depiction of low-level radar reflectivity, in this case from TRMM. The flight track is shown as the red line.

Figure 25. Sample flight plan for MCS over water

A proposed flight track is superimposed in red on the MCS satellite image. The track is chosen to: 1) survey the region of the coldest cloud tops as indicated by the satellite IR image; 2) overfly the area of low-level heavy precipitation along the long axis of the precipitation pattern; and 3) attempt to intersect regions of updrafts and active convective cells. In this case, the lines are approximately 10 nm apart and 100 nm long, but in practice the line spacing, length, and direction would be chosen to optimize the run length and probability of overflying the cells with the precipitation cores below. The flight time of each leg would be ~30 minutes, implying that in a system that persisted 3 hours, approximately six flight legs could be accomplished.

Figure 26 shows a conceptual cross section of such a system with expected pilot's radar intensity patterns (colors) overlaid. Active convective cells are depicted on the left side of the storm, with reflectivity greater than 30 dBZ penetrating only to lower altitudes. The target area for flights in this case, shown as the dotted area on the figure, would be immediately above these active cells and hopefully within main updraft regions.



(The area of interest for flight transects is shown above the low level. The background picture is from [106])

Figure 26. Conceptualized cross section of a MCS over water, with the three color levels of the pilot's onboard radar (green 20–30 dBZ, amber 30–40 dBZ, and red > 40 dBz) overlaid

The risk in flying such long flight legs is that fewer can be performed within the allocated number of flight hours, detrimentally affecting the uncertainty in the 99th percentile TWC values. Furthermore, one might speculate that HIWC may only be observed directly over active cells, and long periods of low-IWC values might be observed for a large fraction of the length of the run. After discussion with the EIWG, it was concluded that if long exposures to HIWC were experienced on these 100 nm runs, this is an important observation, and at least some long-run sampling should be accomplished. If HIWC regions were confined to relatively short regions along the track, and the rest of the run was dominated by low IWC values, it then would be desirable to shift to a sampling strategy closer to that described in section 6.2.1 for smaller cloud systems. In this case, after determining that HIWC was confined to smaller cells along a long run, the sampling would be changed to adopt shorter (e.g., 20 nm) runs in the vicinity of these HIWC cells throughout the lifetime of a cell, and then repeat the pattern in newly developing cells elsewhere in the MCS. An idealized depiction of this type of flight plan is shown in figure 27. In either case, the sampling would include at least two long runs (100 nm) to determine the IWC variability within the MCS cirrus canopy.

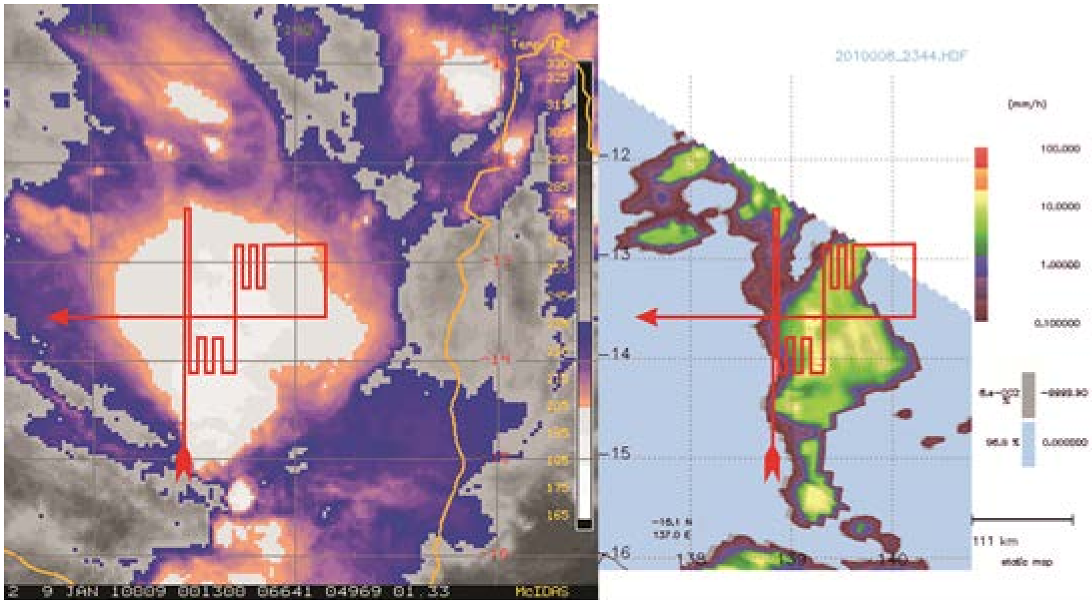


Figure 27. The same sample flight plan for MCS over water as figure 25, but with shorter legs (e.g., 20 nm) focused on smaller regions of HIWC, and longer legs to document variability of IWC across the MCS cirrus canopy

These flight plans may provide different conditional probabilities from the flight plan in section 6.2.1. One way of expressing the TWC percentiles produced by such a scenario might be, for example, as: "conditional on being over the heavy rain region within an over-water MCS with a scale of 100 nm or greater."

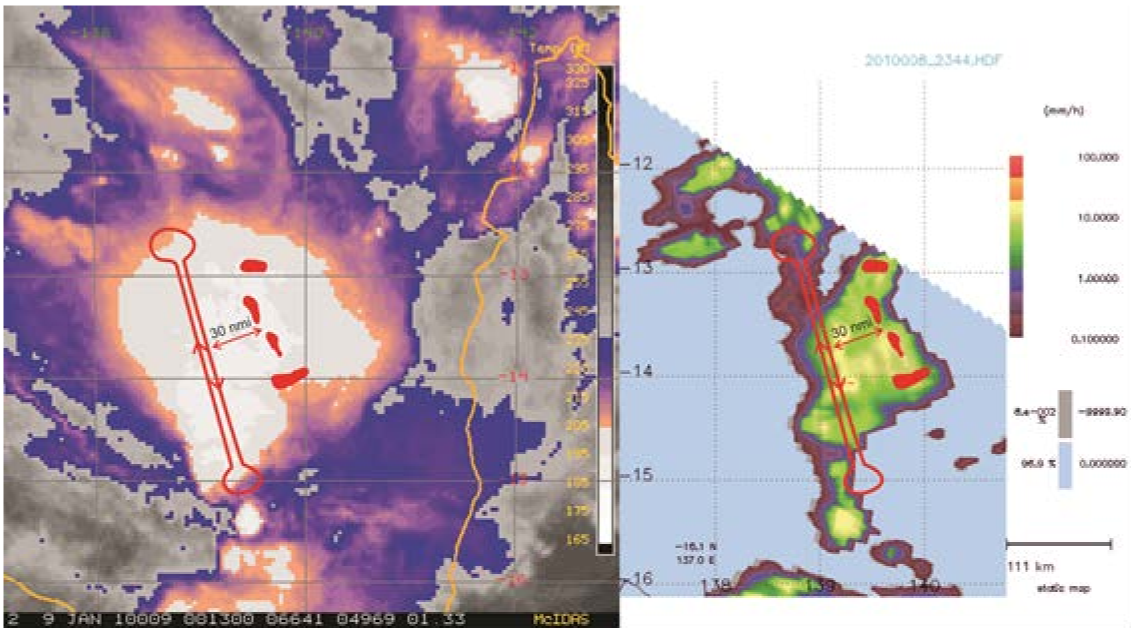
7.2.3 Idealized Flight Plans: MCS Over Land (More Vigorous)

The following flight plan is suggested for more vigorous MCS over the land, where high-reflectivity cores may be observed at flight altitude, and the updraft area cannot be traversed. It could also be used for similar MCSs over ocean if they are observed, though it is expected that over-ocean MCS would often be less vigorous and allow sampling of the updraft area.

The satellite investigation performed by the HIWC team to investigate MCS with scale diameters greater than 100 nm in the Darwin area revealed that approximately half were observed over land**,** in systems originating in oceanic air masses. In monsoon periods, MCS over land may be more vigorous than those simultaneously observed over water[7], with high-reflectivity cells reaching to higher altitudes that cannot be penetrated by aircraft for safety reasons. Radar reflectivity profiles of these cells might be similar to figure 22, or as summarized for maritime continental cells in figure 2.

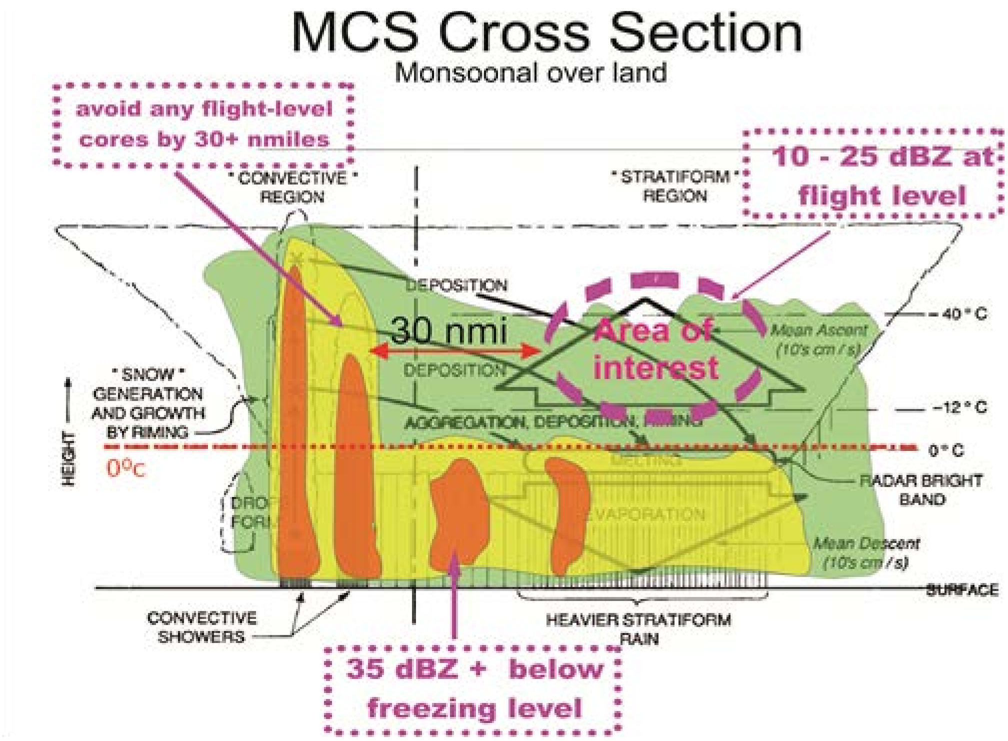
[7] Operational experience during the Airbus A340 high IWC flights in Darwin in February 2010.

Figure 28 shows an idealized flight plan for an MCS over land. The flight plan is similar to that of the over-water case (see figure 25), except that the aircraft would avoid penetrating vigorous cells >30 dBZ at flight altitude, flying long lines downwind of these cells as close to them as safety permits. Figure 29 shows a conceptual cross section of such a system with expected pilot's radar intensity patterns included. Active convective cells are shown on the left side of the storm, penetrating to high altitudes. The target area for flights in this case would be displaced from the active cells, probably within 30 nm of the high-reflectivity cores at altitude.



(Flight-level high reflectivity cells are added here as red-filled regions for illustration. Flight track in red shows the aircraft repeatedly traversing downwind of the cells at altitude at a distance of 30 nm or less if safety permits.)

Figure 28. A hypothetical MCS over land, where vigorous cells (>30 dBZ) are observed at flight altitude



(The area of interest for flight transects is shown ~30 nm downwind of flight-level cores.) [106]

Figure 29. Conceptualized cross section of a MCS over land, with the three color levels of the pilot's onboard radar (green 20–30 dBZ, amber 30–40 dBZ, and red >40 dbz) overlaid

Because of the apparently more vigorous nature of MCS cells over land, there is good reason to sample clouds associated with these cells, because they may be postulated to potentially have higher IWC within the active cells than over-water systems. The cloud should be sampled as close to the flight-level radar-core as safety permits, because it is expected that the TWC levels will diminish with distance from the core. However, because such flights would presumably not penetrate the vertically active regions of the convection, it should be noted that they would not provide ideal data for those HIWC science objectives seeking to understand the properties of the updraft regions and trace the evolution of the cloud microphysics.

These flights would also contribute to EIWG statistics on TWC levels by providing additional segments as data points at a variety of length scales. Similar to the case of the over-water MCS, it is anticipated that the TWC statistics produced would be "conditional on being over the heavy rain region within an over-land MCS with a scale of 100 nm or greater," or might be modified slightly to reflect that flights are in anvil regions adjacent to active cells.

7.2.4 Idealized Flight Plans: Tropical Storms

Tropical storms may not be observed in all potential HIWC measurement locations, but if they are present, they offer a unique opportunity to collect larger distance scale data. For example, approximately three tropical storms would typically pass within research-aircraft range of Darwin during the months of January and February. Because these storms contain active convective cells for periods of days, flights would be considered to collect TWC measurements for the EIWG, if it can be done safely.

A flight transect across an Atlantic hurricane is shown in figure 6, exhibiting a broad area of HIWC greater than 100 nm wide, in which the reflectivity was always green (20–30 dBZ) or lower on the pilot's radar, and in which IWC probably reached levels in excess of 3 gm^{-3}. The flight plan for tropical storms would be similar to that of the over-water or over-land MCS, depending on whether vigorous radar-cores were observed at altitude. If none were observed, the aircraft would fly a straight and level track over general areas of heavy rain below, as in the case of the over-water MCS (see section 6.2.2, figures 25–27). If vigorous radar-cores existed at altitude, the aircraft would fly straight and level in the stratiform region within 30 nm of these cores, as in the case of the over-land MCS (see section 6.2.3, figures 28 and 29). Depending on the low-altitude rain pattern (and safety permitting), the flight plan might track through the center of the storm across its full diameter, returning at a second altitude. Alternatively, the track might be concentrated over a smaller area in the storm where the convection is most active.

7.2.5 Optimizing Flight Methodologies for Non-Vigorous Clouds

Engine events usually occur in clouds with low reflectivity at flight-altitude and relatively high reflectivity below. This is conceptually shown in figure 30. The following section outlines recommended detailed flight procedures to optimize sampling such a system within 20 nm of the precipitation area below.

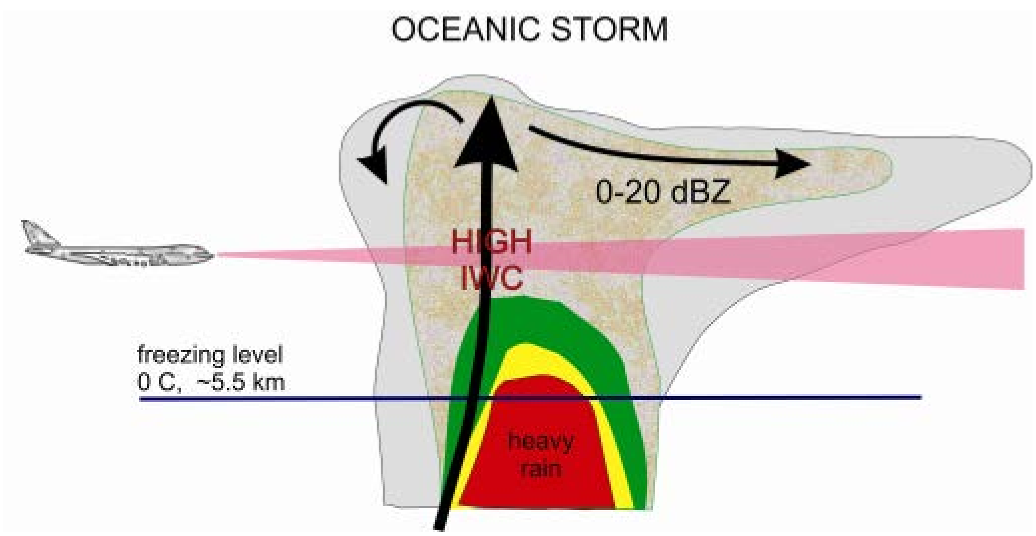


Figure 30. Conceptual depiction of aircraft flying through a non-vigorous cloud with low radar reflectivity at altitude and stronger returns below

An initial proposed track would be determined by the inspection of satellite images and transferred to the pilot. On arrival at the cloud, the pilot would take responsibility for positioning the aircraft, with input from onboard scientists involved in the flight. The pilot would initially tilt his radar down to identify the area of maximum precipitation below and modify this initial proposed track to pass over this area (see figure 31a).

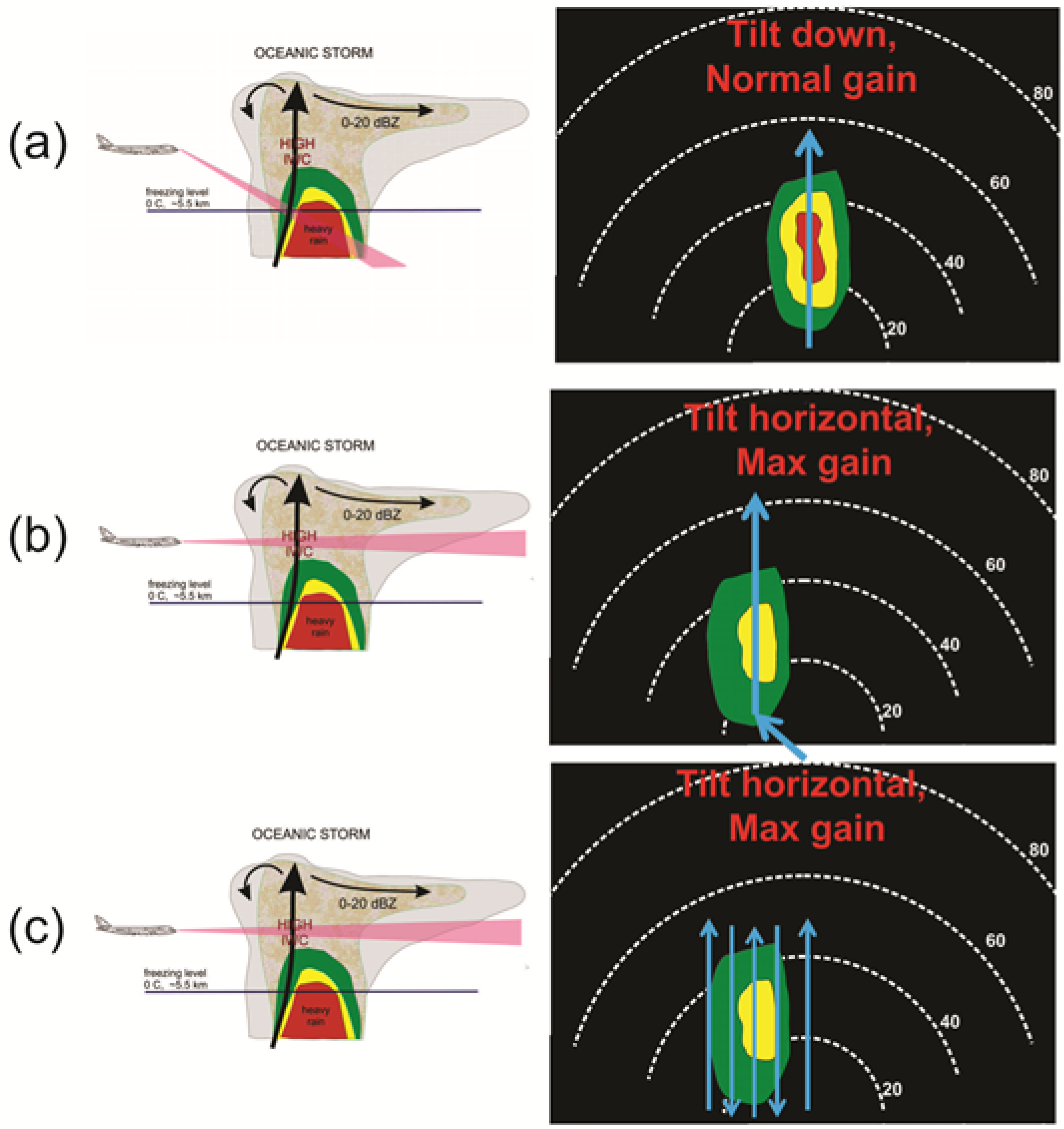


Figure 31. Recommended pilot procedures for 14 CFR 33 Appendix D sampling to (a, b) maximize general location for HIWC sampling and then (c) survey the immediate region

Once lined up for the first pass, the pilot would tilt the radar back to horizontal and switch to maximum gain to identify the region of flight-altitude maximum IWC (it is assumed that maximum gain will detect regions of HIWC that normal gain will not and that higher reflectivity will be indicative of higher IWC). Another adjustment to the track position may then be made by the pilot to stay within the higher reflectivity area at flight altitude (see figure 31b). If HIWC is observed, and it is possible to continue sampling, the pilot would then set up a survey pattern with some appropriate spacing, depending on the situation (see figure 31c). Nominally, 5–10 nm spacing may be a good first choice. Occasionally, the pilot would tilt the radar down again, as in figure 31a, to attempt to keep runs within 20 nm of the heavy precipitation area below.

The length of the legs would likely be decided by the scientists responsible for the flight and would depend on the duration of HIWC and the length of the precipitation region below.

7.2.6 Sampling Statistics: Small Convective Systems Over Water; MCS Over Water and Land; and Tropical Storms

Small convective systems over water; MCS over water and land; and tropical storms are all expected to provide straight-and-level flight leg segments from which average TWC values can be computed at contiguous length scales from ~200 m up to more than 100 nm. Data from these types of cloud systems, flown in a manner similar to commercial aircraft flights, would be used to produce the TWC statistics required by the EIWG. They would provide the necessary segment lengths required to provide the 99th percentile TWC statistics to the EIWG at the requested length scales of up to 17.4 nm, and higher if possible. Flights in isolated convection during break periods (see section 6.2.7) are expected to provide additional anvil TWC data, possibly only on distance scales shorter than 17.4 nm, for a cloud type that contributes only a small percentage of engine events. These latter data will be available for inclusion in the EIWG TWC statistics if they are deemed suitable after collection.

The number of 20 nm flight segments (rounded up for practicality from 17.4 nm) required to provide 99th percentile TWC values with a statistical uncertainty of less than 20% has been estimated by Pratt & Whitney Co. (Grant Reinman, personal communication) using the RAE TWC data set [34]. Reinman found that the frequency distribution of TWC closely matched a Weibull distribution. By sub-sampling the RAE data set repeatedly, and comparing the 99th percentile TWC statistics provided by groups of the same sample size, Reinman estimated that, for a 20 nm distance scale, at least 100 samples were required to get unbiased 99th percentile TWC values. Furthermore, the standard deviation of the 99th percentile TWC estimates using 100 samples was approximately 8% of the best estimate of the true 99th percentile TWC, suggesting that the 2-standard deviation uncertainty in the 99th percentile TWC using 100 samples would be approximately ±16%. Reinman concluded that it was also important to collect data from clouds with smaller characteristic lengths than 20 nm and to collect companion statistics of the cloud widths.

Because of the absence of any other extensive TWC data sets from deep convective clouds, the EIWG will use the above estimates as a planning guideline for the design of the HIWC study cloud sampling. The project will endeavor to collect at least 100 individual straight-and-level 17.4 nm transects within the regions of deep convective clouds containing active cells to obtain 99th percentile TWC values within an acceptable ±20% uncertainty and will attempt to do this at each of three altitudes described in section 6.2.7.

In the case of the MCS and tropical storm flights (see sections 6.2.2–6.2.4), individual legs may be up to 100 nm long or more, permitting estimation of TWC statistics at length scales longer than 17.4 nm, though with more uncertainty.

As discussed in sections 6.2.2–6.2.5, the 99th percentile TWC values produced will represent values conditional on the aircraft being in cloud in the vicinity of deep convection. On completion of the data collection program and inspection of the tracks of the aircraft relative to convective cells, the project will be able to more precisely define the conditions under which clouds were sampled.

7.2.7 Temperatures (Altitudes) of Flight Transects

The EIWG has recommended that in situ sampling be performed at the following three temperature/altitude levels in the following order of priority to obtain 99th percentile TWC values with a statistical uncertainty less than 20% for distance scales ≤17.4 nm at each level (safety permitting):

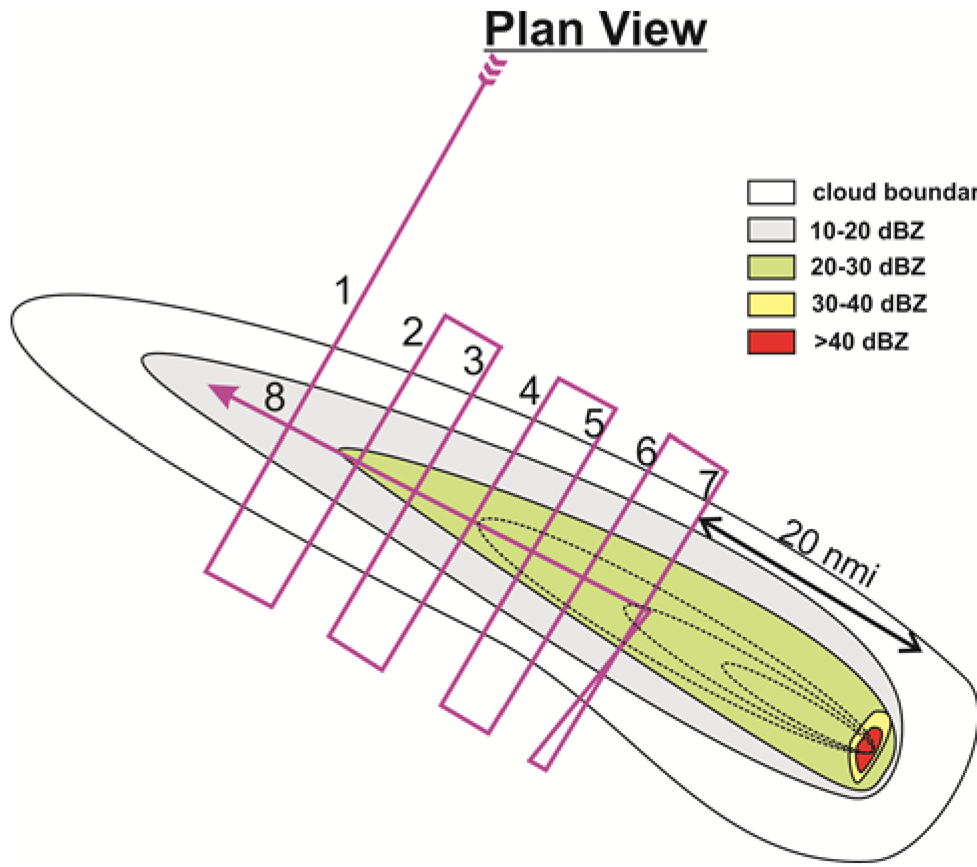
1. -50°C ±3°C (a typical cruise altitude for commercial jet aircraft and at a temperature at which any remaining liquid water in updrafts will have frozen due to homogenous nucleation). The -50°C level is approximately 12.4 km above ground, or approximately 38.0 kft pressure altitude (ISA+6°C).
2. -10°C ±3°C (a compromise between the desire to sample the cloud just above the melting layer, where particles will be approaching their maximum size before melting, and the desire to sample where engine events frequently occur). The -10°C level is approximately 6.9 km above ground, or approximately 21.4 kft pressure altitude (ISA+22°C).
3. -30°C ±3°C (the midpoint altitude between the two levels above, with possibly intermediate particle size, and closer to the approximate height of maximum adiabatic TWC in gm^{-3} shown in figure 8). The -30°C level is approximately 9.8 km above ground, or approximately 30.0 kft pressure altitude (ISA+21°C).

It is possible that significant levels of supercooled LWC may be encountered on runs at -10°C. Though the recovery temperature of the aircraft impingement surfaces are likely to be above 0°C at typical jet true airspeeds, it may be necessary to adjust this sampling level to warmer temperatures (e.g., -5°C, likely giving a recovery temperature of above 5°C) to avoid hazardous airframe icing. Though the project is not expecting conditions of significant airframe icing at -30°C, based on industry experience and limited measurements with instrumented aircraft from the atmospheric science community, one must consider that such conditions may exist and will be hazardous if encountered. This may result in limitations to the sampling or modifications to the flight plan for the runs planned for the -30°C level.

The height of the freezing level is roughly 5.0 km above ground, or approximately 15.6 kft pressure altitude (ISA+19°C). The same idealized flight patterns shown in figures 24–29 would be used as a guide for sampling at each level. Height estimates of temperature levels above are from average radiosondes for Darwin in the wet season [107].

7.2.8 Additional Idealized Flight Plans: Isolated and Multi-Cell Continental Convection

In isolated continental storms, it is proposed to work the trailing stratiform anvil inward toward the radar-core of the storm, subject to safety limits determined by the pilots. Figure 32 contains a plan view of an idealized flight plan for isolated vigorous convection, characterized by a radar-core region on the pilot’s radar exceeding 30 dBZ (amber) at flight altitude. In this figure, the anvil outflow region trails to the northwest from the vertically active region of the cloud. The flight plan illustrates a series of crosswind transects (1–7) across the anvil moving progressively closer to the radar-core. Once the flight crew has determined that no further transects can be safely accomplished any closer to the core, a transect down the center of the anvil (8) would be recommended.



(The red-echo core of the system is shown in the lower right side of the cloud, with a trailing anvil to the northwest. Consecutive parallel tracks across the anvil would be flown from the outside toward the core as far as safety permits. This example shows tracks to within 20 nm of the core. Conceptual TWC isopleths are shown as dotted lines.)

Figure 32. Idealized flight plan for isolated break convection

Continental anvils would typically be observed in a height interval between approximately 11 km and 16 km, corresponding to a pressure altitude range of approximately 34,000–50,000 feet. Therefore, it should be possible for the research aircraft to reach the altitude of the anvil and sample it away from the core, though perhaps not at its highest extent. Because most commercial aircraft cruise between 35,000 and 40,000 feet, anvil measurements appropriate to engine events should be possible.

Flight plans for monsoon MCS systems over land are discussed in section 6.2.3. It is anticipated that the same flight patterns would be used in over-land MCS during both break and monsoon periods, the details of which would be determined by the flight crew in real time according to the specifics of the case.

7.2.9 Additional Flight Plans Variations to Support HIWC Science Objectives

Many of the science objectives outlined in sections 3.2–3.6 would be met under the standard flight plans that have been developed for the engine-icing objectives (see sections 6.2.1–6.2.5 and 6.2.7). Flights in oceanic cells are particularly important for studies of microphysics evolution because they will penetrate updraft regions at more than one altitude. However, the following supplementary maneuvers are desirable to support certain science objectives:

- Spiral ascents or descents over the ARM/profiler sites in Darwin, especially in HIWC regions when ice particles may be small, to support ground remote sensing objectives (see section 3.5).
- Spiral ascents or descents in oceanic updraft regions in growing cells to measure the variation of the properties of these regions with height (virtually all science objectives).
- Flights within the CPOL/Darwin operation radars' dual-doppler lobe, especially above vertically active cells, for verification of radar-derived wind fields and updrafts.
- Flights in deep convection coincident in time and along the track of the A-train satellites, focusing on vertical profiles of IWC and particle size, and flights aligned with the Terra satellite overpasses, to support satellite product validation (see section 3.6).

8. FLIGHT PROGRAM OPPORTUNITIES

This section summarizes dedicated flight programs for the collection of HIWC data and recommendations for further studies.

8.1 RECENT INDUSTRY FLIGHT-TEST PROGRAMS

In 2010, Airbus instrumented a flight-test A340 aircraft and made in situ, high-altitude measurements in deep convective clouds in Darwin, Australia and Cayenne, French Guiana. A total of 23 flights were performed in 2010 [6, 8]. The primary cloud instrumentation consisted of an Airbus nephelometer, which imaged cloud particles and provided PSDs and TWC estimates through image analysis, and a SEA "robust" probe, which had been developed for the HIWC environment in the NRC M7 tunnel to map the distribution of ice in the tunnel. The efficiency of the robust probe for measuring IWC (efficiency = ratio of measured-to-true IWC) had been estimated at approximately 40% from the wind tunnel measurements, though its efficiency in natural clouds is yet to be verified. The program was conducted with the assistance of EC and the Australian BoM and used methodologies similar to those described in this report.

The Airbus measurements were important in providing substantiating evidence for some of the hypotheses described in this report, including the existence of HIWC in regions with low radar reflectivity, and some of the more obscure but important details, such as the appearance of apparent "rain" on the windscreen in HIWC conditions. The flight demonstrated that HIWC conditions in excess of 3 gm^{-3} (corrected for estimated robust probe efficiency of 0.4) were relatively common, and that measurements could be made safely in such clouds. The measurements also provided the first indications of the maximum IWC values in these clouds and how these measurements compared to the new proposed 14 CFR 33 Appendix D regulations. With new characterization of the robust probe in the HAIC-HIWC flight campaign (see section 7.2), it will be possible to examine the A-340 measurements to determine to what extent they can be used to augment TWC measurements to support the 14 CFR 33 Appendix D assessment described in this report.

In 2012, the A-340 conducted further flights out of Santiago, Chile, many over large continental systems. The same instrumentation was used for in situ cloud measurements. Some flights were conducted at warmer temperatures and reportedly exhibited markedly different PSDs relative to the Darwin and Cayenne Airbus A-340 flights [8]. Work is ongoing with Airbus and its partners to incorporate the results of this study into the HIWC knowledge base.

8.2 THE HAIC-HIWC DARWIN 2014 FLIGHT CAMPAIGN

In 2012, the European Commission approved funding for HAIC, a major research program for the study of ice crystal icing. The HAIC project includes many work packages related to the improvement of knowledge of ice crystal accretion and included an objective to characterize the cloud environment.

After the HAIC project award, discussions were initiated to form a partnership with the HIWC project for an intended first flight program in Darwin in 2013, for which HAIC would provide a second aircraft (the Service des Avions Français Instrumentés pour la Recherche en Environnement [SAFIRE] Falcon-20) to complement the HIWC measurements. After a setback cancelled the plans for the primary North American aircraft, it was decided to form a close partnership between the HAIC and HIWC teams and perform the entire flight program solely with the European SAFIRE Falcon-20 aircraft. The program was named the HAIC-HIWC project to reflect the European lead in securing and operating the aircraft within their established HAIC project. HIWC made several key contributions to the partnership through existing partnerships with the Australian BoM and the Japan Meteorological Agency, leading to access of Darwin facilities and data and rapid-scan MTSAT data from Japan. HIWC also provided the expertise of the HIWC team and key instrumentation, notably a downsized IKP (specifically redesigned to suit the constraints of the Falcon-20 aircraft) to make the fundamental TWC measurement.

For the regulatory objectives of the HAIC-HIWC flight program, the project adopted the flight plans and methodologies described in this report (see section 6). Science objectives were merged between the HAIC and HIWC teams.

The results of the first HAIC-HIWC flight program will be summarized elsewhere. The project was successful and corroborated many of the hypotheses contained in this plan, but also revealed some complexities not anticipated in advance of the flight program. The project was terminated early because of maintenance issues on the aircraft after having flown approximately half of the intended research hours. It is intended to complete the project with the same team in a follow-up effort.

8.3 OTHER FUTURE CAMPAIGNS

On completion of the first flight programs, the data must be assessed to determine if the objectives of 99th percentile statistics have been achieved for the three focus temperature levels and whether auxiliary data sets can be added (e.g., research radar remotely estimated TWC) to augment the primary in situ measurements. The need for further measurements will depend on the success of these first data collection efforts. In addition, it is recommended that a review of the data be performed by the scientific team to solicit opinions as to whether the data are globally representative or if measurements in other locations or situations are recommended based on reasonable scientific hypotheses.

8.4 MEASUREMENTS FROM COMMERCIAL AIRCRAFT

Though the measurement efforts described in this report are designed to collect a data set recommended as appropriate by an industry specialist group, a limited number of dedicated flight programs may not measure certain extremes that may be important for ice crystal accretion, by virtue of the low probability of encountering such extremes. For example, it has been postulated that the length of exposure may be an important factor affecting the occurrence of engine icing events [10, 11], and very long exposures may be more difficult to sample in a flight program than simply exposures to HIWC levels. One way to collect data on the most extreme exposures is from commercial aircraft, and there are projects underway to include small sensors on the aircraft fuselage to provide real-time in situ data for pilot awareness and, perhaps, the management of engine parameters. Though it is anticipated that the location of these sensors will be far from ideal for providing accurate absolute TWC measurements, adequate estimates may be derived through empirical scaling to account for mounting location biases. Furthermore, valuable information on distance scales of HIWC encounters could be derived, possibly independent of the need for location scaling. Therefore, it is desirable to encourage the collection of data from commercial aircraft to augment the research-quality data set described in this report.

9. HIWC PROJECT PARTNERS

The main partners in the HIWC study, their roles and interests, and the primary active contact persons are:

- Engine Icing Component:
  - FAA (regulatory use of data)
    - Tom Bond (lead), Chris Dumont, and Jim Riley
  - NASA Glenn Research Center (cloud characterization, flight deck recognition, engine monitoring)
    - Tom Ratvasky (NASA Glenn Principal Investigator)
  - The Boeing Company (cloud characterization, flight deck recognition, engine monitoring)
    - Jeanne Mason (Senior Propulsion Specialist) and Matt Gryzch (meteorologist)
  - Airbus Ind. (cloud characterization, flight deck recognition, engine monitoring, supporting Airbus A340 cloud measurements)
    - Alice Grandin (Ice and Rain Protection Specialist)

- Transport Canada (TC) (regulatory use of data)
    - David Johns, Antoine LaCroix, and Chris Baczynski
- EC (cloud characterization, flight deck recognition)
    - Alexei Korolev
- Australian BoM (cloud characterization, local support)
    - Rodney Potts
- Met Analytics Inc. (cloud characterization, flight deck recognition)
    - J. Walter Strapp (HIWC Science Team lead)
- National Center for Atmospheric Research (Nowcasting HIWC)
    - Julie Haggerty
- NASA GISS–applications of CRMs
    - Andy Ackerman (NASA GISS Principal Investigator) and Ann Fridlind
- Science Engineering Associates (cloud characterization, flight deck recognition)
    - Lyle Lilie

- Meteorological Science Component:
    - Met Analytics Inc.
        - J. Walter Strapp (HIWC Science Team lead)
    - FAA
        - Jim Riley
    - EC
        - Cloud microphysical processes: Alexei Korolev (lead)
    - Australian BoM (Cloud microphysical processes, ground remote sensing validation)
        - Rod Potts (lead), Alain Protat, and Peter May

- NASA GISS (Cloud modeling, cloud microphysical processes)
  - Ann Fridlind (lead) and Andy Ackerman
- NASA LaRC
  - Pat Minnis (Satellite cloud product validation)
  - Steve Harrah (pilot weather radar)
- National Center for Atmospheric Research (Nowcasting)
  - Julie Haggerty

- Major Funding Agencies of the HIWC project:
  - FAA
  - NASA Aviation Safety Program
  - TC
  - The Boeing Company
  - EC
  - Australian BoM

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APPENDIX A—EFFORTS UNDERTAKEN BY THE HIGH ICE WATER CONTENT TEAM TO CHARACTERIZE AND IMPROVE INSTRUMENT PERFORMANCE FOR THE HIGH ICE WATER CONTENT ENVIRONMENT

Table A-1 lists the efforts made to characterize and improve instrument performance for the high ice water content (HIWC) environment.

Table A-1. Efforts made to characterize and improve instrument performance for the HIWC environment

Instrument Issue	Comments	Efforts and Solutions
Lack of accuracy of HIWC measurements		
Lack of a facility for performance testing and absolute calibration of instruments in HIWC/high-speed environment	• Wind tunnel with reference methods for "absolute" calibration methods exist for LWC instruments, but not IWC.	• NRC and EC have developed an ice-cloud simulation at the NRC M7 engine test cell and determined an "absolute" calibration of IWC up to approximately 9 gm^{-3} at 150 ms^{-1} [A-1].
Lack of a reference IWC instrument	• No instrument has been specifically designed to operate in the HIWC/high-speed environment.	• NRC and EC developed an isokinetic evaporator TWC measurement probe, targeting operation up to ~ 10 gm^{-3} at 200 ms^{-1} [A-2–A-5]. • NRC and EC test and calibrate in ice cloud in M7 engine test cell to approximately 9 gm^{-3} at 150 ms^{-1}.
Incomplete capture of IWC by hotwires	• Wind tunnel testing of hotwires at relatively low airspeeds of some hotwire probes revealed bouncing of particles out of capture volume [A-6–A-8] and underestimation of IWC by up to a factor of 3.	• New sensor geometries developed by EC to lessen the particle loss [A-9]. • NRC and EC tested and calibrated new sensor geometries in calibrated ice cloud in M7 engine test cell to approximately 9 gm^{-3} at 150 ms^{-1}. • Flight testing of new hotwire geometries was conducted during dedicated flight project April 2009 on NRC Convair-580 aircraft.
Saturation of IWC devices in HIWC	• Many hotwire devices saturate at water contents below 3 gm^{-3}; CSI is known to saturate at levels less than 2 gm^{-3}, depending on airspeed (e.g. [A–8]).	• Modifications of SEA TWC hot wire electronics have been made to increase the saturation limit to 10 gm^{-3} at 200 ms^{-1}. • NRC and EC develop new isokinetic TWC device to operate up to 10 gm^{-3} at 200 m/s [A-2–A-5]. • NRC and EC to test in calibrated ice cloud in M7 engine test cell to approximately 9 gm^{-3} at 150 ms^{-1}.

LWC = liquid water content; IWC = ice water content; NRC = National Research Council; EC = Environment Canada; TWC = total water content; CSI = Cloud Spectrometer Impactor; SEA = Science Engineering Associates

Table A-1. Efforts made to characterize and improve instrument performance for the HIWC environment (continued)

Instrument Issue	Comments	Efforts and Solutions
Small ice crystal distribution contamination by shattering		
	• Optical array and forward scattering probes may produce spurious enhancements to small particle distributions due to shattering of larger particles on forward surfaces of probe [A–10], [A-11A-19].	• EC incorporated design changes (e.g., new tips/arms) to 2D-C, 2D-P DMT CIP, DMT CDP, and PMS FSSP to mitigate shattering. New designs were tested in wind tunnels and in dedicated NRC Convair-580 airborne program in April 2009 [A-18, A-20]. Best designs are to be implemented for the HIWC study. • EC develops a Cloud Extinction Probe to provide a direct bulk extinction measurement immune to sampling artifacts [A-21]. This can help constrain the particle measurements and, in combination with the isokinetic TWC probe, will provide an independent measurement of ice particle effective diameter [A-22].
Degraded performance of instrumentation in HIWC environment		
Breakage of hotwires in HIWC/high-speed environment	• During industry flight testing in deep convection in the 1990s, the Nevzorov TWC probe failed repeatedly because of ice particle impact damage [A-23]. Failures of other hotwires have also been observed by EC and NASA in tunnel testing in HIWC.	• EC developed stronger Nevzorov sensors, and tested them at the NRC M7 tunnel up to approximately 9 gm^{-3} at 150 ms^{-1}. • SEA, EC, and NRC have developed a "robust" solid TWC hotwire sensor that has survived M7 testing at up to approximately 9 gm^{-3} at 150 ms^{-1}. This probe also survived Airbus A340 testing in Darwin and Cayenne in HIWC regions to 5+ gm^{-3}. • Multiple hotwires, the isokinetic evaporator, and indirect measurements from optical array probes and forward scatter probes will provide redundancy in IWC measurements.
Electrostatic failure of particle probes	• In the HIWC environment, NASA and EC have observed temporary complete failure of PMS 2D-C, 2D-P, and FSSP probes. Behavior has been replicated in the M7 engine test cell.	• EC and NRC diagnosed and fixed electrostatic problems on PMS FSSP, 2DC, AIMMS-20, and FSSP using the M7 test cell to create failure conditions. • EC and NRC tested other particle spectrometers (e.g., CIP, 2D-S, and CDP) to determine if similar problems exist. • Most important surfaces of most probes coated with titanium nitride to mitigate electrostatic charging problems.

EC = Environment Canada; 2D-C = 2-D Cloud Particle Optical Array Spectrometer; 2D-P = 2-D Precipitation Particle Optical Array Spectrometer; DMT = Droplet Measurement Technologies; CIP = cloud imaging probe; CDP = cloud droplet probe; PMS = Partical Measuring System; FSSP = Forward Scattering Spectrometer Probe; TWC = total water content; NRC = National Research Council; AIMMS = Aircraft-Integrated Meteorological Measurement System; 2D-S = 2-D Stereo Optical Array Spectrometer;

Table A-1. Efforts made to characterize and improve instrument performance for the HIWC environment (continued)

Instrument Issue	Comments	Efforts and Solutions
Degraded performance of instrumentation in HIWC environment (continued)		
False hotwire LWC response to IWC	• False response on King and Nevzorov LWC wound hotwires may be as high as 40% of the IWC in the HIWC environment [A-23]. Others have shown false responses of 10-20% at lower LWCs and airspeeds [A-24, A-25].	• The HIWC research aircraft would fly an unwound 0.5 or 2 mm solid wire in addition to other wound hotwires. There is some evidence that unwound wires have smaller false response to IWC. EC and NRC will test this hotwire probe in the NRC M7 engine test cell to check false response.
Total air-temperature anomaly	• Many Rosemount TAT probes exhibit an anomalous behavior in HIWC conditions [A-26, A-27, A-23]. This is a common symptom in the engine event database, so no changes are proposed to the Rosemount sensors.	• The HIWC aircraft would fly, in addition to the standard Rosemount TAT probe, a solid temperature sensor originally from an HS-125 aircraft, expected to be immune to IWC ingestion, but presumably with its own wetting problems.
Rosemount Ice Detector erosion	• The Rosemount Ice Detector is the only instrument capable of measurement of trace amounts of LWC, especially in the mixed-phase environment. Wind-tunnel testing reveals that ice shapes can be severely eroded by ice crystals. Similar effects are hypothesized by EC on the Rosemount Ice Detector.	• EC and NRC characterized the response of Rosemount (old) and Goodrich (new) ice detectors to erosion by ice crystals, using the calibrated NRC M7 tunnel. Erosion was important at HIWC and high speed. Old design Rosemount probes subject to failure in mixed phase. New Goodrich probes more capable. • EC and NASA each purchased new Goodrich ice detectors. • EC and NASA would propose to fly a second ice detector on a window blank in a zone less exposed to ice crystals but equally exposed to LWC.
Failures of wind measurement system	• Wind measurement systems that use pressure ports are prone to failure in heavy icing or high ice crystal concentrations due to blockage of the ports.	• The HIWC aircraft primary winds system (Aventech AIMMS-20) has been modified by Aventech/NASA to incorporate additional heat for deicing and a purge system to blow out accumulated water from ice crystal melting. System has been repeatedly tested and improved at the NASA Icing Research Tunnel and at the NRC M7 wind tunnel, in high LWC and HIWC. • System was prone to electrostatic failures. System has been titanium nitride coated and tested, and failures have been eliminated.
Failures of aircraft pitot	• Pitots are prone to failure in heavy icing or high ice crystal concentrations due to blockage of the ports.	• Aircraft pitot system checks were planned for NRC M-7 and the NASA Icing Research Tunnel. Remedies to failures to be determined.

LWC = liquid water content; IWC = ice water content; EC = Environment Canada; NRC = National Research Council; TAT = total air temperature; AIMMS = Aircraft-Integrated Meteorological Measurement System

Table A-1. Efforts made to characterize and improve instrument performance for the HIWC environment (continued)

Instrument Issue	Comments	Efforts and Solutions
Degraded performance of instrumentation in HIWC environment (continued)		
Particle probe fogging	• Some conventional particle probes are known to fog in a tropical environment after cold-soaking at altitude.	• EC has designed a purge system for the PMS FSSP, 2D-C, and 2D-P, PCASP, and potentially other probes. The system would purge with dry N2 overnight and dry air during flights. • The SPEC 2D-S would be purged preflight in a manner suggested by the manufacturer. The sealed DMT CIP and CDP would initially be purged with dry air and subsequently monitored and the purging repeated. • The procedures would be tested in the flight trial campaign and updated as required.
Miscellaneous		
Poor optical array probe accuracy < 100 µm	• Accuracy of optical array probes for measuring ice particles smaller than approximately 100 µm is poor for older technology spectrometers [A-28A-36] and has not yet been established for some of the newer technology probes.	• EC is working on developing size corrections for the out-of-focus images measured by 2-D probes. Early laboratory and theoretical studies indicated that the measured particle size increases when particles move away from the center of the arms. This oversizing may reach a factor of two for those particles in the fraction of the sample area close to the edge of the depth-of-field. In particular, this problem becomes significant for probes with high pixel resolution and large distance between the arms (e.g., CIP and 2D-S). A theoretical algorithm for retrieval of particle sizes from their out-of-focus imagery has been developed [A-36]. EC is undertaking efforts to validate and make necessary adjustment of these newly developed size retrieval techniques using spinning disc calibrations.
Optical array probes maximum slice sampling rate	• Legacy PMS OAP-2DC probes must be limited to approximately 4 MHz clock rate. EC probes initially set up at 25 µm. • DMT CIP limited at 15 µm at high airspeeds. EC probe resolution initially 15 µm.	• EC 2D-C probe magnifications changed to 50 µm. • NASA 2D-C already at 50 µm. • EC CIP magnification changed to 25 µm.

EC = Environment Canada; PMS = Partical Measuring System; FSSP = Forward Scattering Spectrometer Probe; 2D-C = 2-D Cloud Particle Optical Array Spectrometer; 2D-P = 2-D Precipitation Particle Optical Array Spectrometer; PCASP = Passive Cavity Aerosol Spectrometer Probe; DMT = Droplet Measurement Technologies; CIP = cloud imaging probe; CDP = cloud droplet probe; 2D-S = 2-D Stereo Optical Array Spectrometer;

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