6.8 WEATHER CONDITIONS ASSOCIATED WITH JET ENGINE POWER LOSS AND DAMAGE DUE TO INGESTION OF ICE PARTICLES: WHAT WE'VE LEARNED THROUGH 2009

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1. INTRODUCTION

The aviation industry has now connected a number of jet engine power-loss and damage events to the ingestion of ice particles. Ice particle icing related jet engine power-loss and damage events (which will be referred to as "engine events" from here forward) are occurring during flights of large transport aircraft, commuter, and business jets. These events have only recently been recognized as occurring in regions of ice particles aloft within convective clouds. The events have included engine surge, stall, flameout and rollback, as well as engine compressor damage due to ice shedding (Mason et al. 2006). All have been shown to have occurred during flight near convective weather mostly at high altitude. These clouds are thought to contain high concentrations of ice particles. In the mid-1990s, a commuter aircraft manufacturer conducted a flight program which showed that the engine rollback occurred during flight in completely glaciated cloud (Mason et al. 2006). Further, it showed that ice particles do not form accretions on engine parts which are colder than freezing. Rather, the icing occurs in the engine core. As ice reaches locations in the engine where temperatures are warmer than freezing, some ice is melted, and mixed phase conditions are produced. Surfaces that experience impinging mixed phase conditions are cooled to the freezing point and ice can begin to form. More recently, researchers have hypothesized that it is high ice water content (HIWC), which is needed to cool engine surfaces to freezing for ice to form. A previous study suggested that supercooled liquid in the atmosphere is not a requirement for engine events and the ice formation phenomenon is largely driven by ice particles (Mason et al. 2006). In 2005, an industry and government working group identified the technology gaps currently existing in the understanding of the ice particle icing phenomenon. This group recognized that very little is known about the nature of these convective clouds, in particular the ice water content, particle size and horizontal extent needed to create a design standard for engines.

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To address the need for atmospheric data, a partnership led by NASA that includes the FAA, Environment Canada and Boeing developed a science plan culminating in a flight program to measure the microphysical properties of the clouds which are causing engine power-loss events (Mason et al. 2006). The main goal of this flight program will be to gather statistics on ice water content, particle size, and spatial extent and will be used to create a new icing envelope for engine certification.

Most of what is currently known about the engine ice particle icing problem has been gathered from flight data and pilot reports. From these data, researchers are piecing together a picture of the environment which causes engine events. Careful study of these data can benefit the industry by improving the understanding of what type of weather is most commonly encountered during engine events. Plus, study of the events database can help pinpoint where, relative to storm structure, engine events are occurring. For example, pilot reports and radar data have confirmed that the engine events are not occurring in vigorous updrafts or within high reflectivity regions of convective weather. In fact, many pilots report a lack of radar returns and light to moderate turbulence. It appears as though aircraft flights traverse parts of convective anvil clouds on a regular basis while avoiding cores, yet only some engines experience power-loss or damage. Regions within convective clouds that have localized HIWC are currently not detectible by conventional means nor is it fully understood as to what mode of convective weather (or what part of the storm) is associated with HIWC. The intent of this work is to carefully study the engine event database and develop a better understanding of the convective environment associated with engine events. The work may benefit the scientific community and drive hypotheses of the development and decay of high ice water content regions, which will later be confirmed during the flight program. It will also permit the flight program to operate as efficiently as possible by sampling the correct part of the cloud.

2. Overview of Engine Events

Several criteria were used for this study to identify an engine power-loss event connected with convective weather. All events involved power-loss or damage connected with the engine core: an engine instability such as surge or flameout, or damage of compressor blades. To result in an engine core effect, the source of the ice build-up must be in the core, which is typically much warmer than freezing for the event flight conditions. This leads to the assumption that high ice water content must have been present to cool the surfaces to freezing. In all cases considered for this paper, convection was present at the time and location of the event. Other supporting information considered was the presence of total aircraft temperature (TAT) anomaly and lack of response of the Rosemount Ice Detector (RID) when installed. TAT anomalies occur when the instrument ingests a high concentration of ice particles, which blocks the airflow through the heated housing and corrupts the measurement (Mason et al. 2006, Lawson et al. 1998). The RID is designed to detect supercooled droplets. When exposed to supercooled droplets, ice accretes on the exposed rod of the sensor until it reaches a threshold mass, at which point deicing heat is applied to the rod and a 'trip' is registered.

The engine event database analyzed for this paper includes 12 different engine types. These are mostly engines on large jet transport aircraft, however a handful of commuter and business jet engine events have been included. Mason et al. (2006) described the variety of engine power-loss modes which have been associated with exposure to ice crystals, including surge, stall, flameout, rollback, and compressor damage. The flight phase associated with the different events also varies; some occur in cruise when the engine is at high power while others occur in descent where the throttle is at idle. At this time, the exact location of ice formation inside the engine in these events is not known. Researchers believe that the location of ice formation in each engine may be different, due to event temperature and unique geometry. It has not been ruled out that each engine type may be susceptible to a different environment. Each engine, for example, may have particular sensitivities to particle size, temperature, and ice water content.

Lacking in-situ data for particle size and concentration, the authors took a macroscopic approach to try to understand whether the different engine types are experiencing power-loss in the same environment. On the basis of the convective parameters presented in section 3, it was found that all engines experienced power-loss in very similar environments; with no one engine type appearing different from the rest. Therefore, the analysis presented in this paper considering all the engine events in a single database appears to be justified.

The complete engine event data base consists of nearly 100 events, however not all events were used for each of the following analyses, depending on the availability of reliable data for each event.

Ice particle icing engine events have been reported in several regions of the globe. In this paper, "ice particle icing" is defined as when glaciated or mixed phase cloud particles (lacking significant amounts of supercooled liquid and airframe icing) are accreted within the engine. "Classic icing" is defined as supercooled cloud droplet or large drops freezing on contact.

Event locations have been plotted in figure 1. A scattering of engine events have occurred over the central and southeastern part of the United States, with one event over southern California, and then several more are scattered about east-central South America, central Europe, and central Asia. A more significant region where events have occurred is located from northern Australia northward into Indonesia and Southeast Asia. The region stretching from Hong Kong to Japan has seen a particularly high number of events. It is theorized that this region is experiencing a higher rate of events compared to the rest of the globe due to a combination of favorable meteorological conditions and significant aircraft traffic.

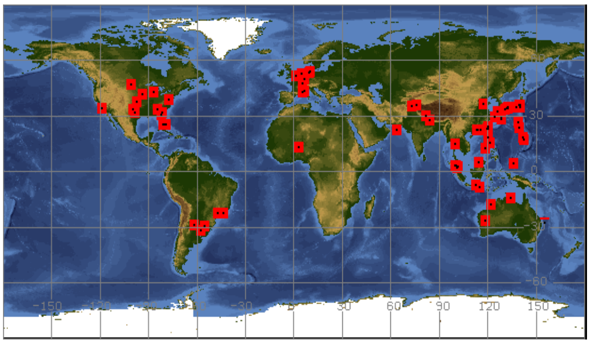

Figure 1. Global plot of engine event locations (in red with black dot) from the database.

Engine events have occurred at a range of temperatures and altitudes as shown in figure 2. Temperatures ranged from -7C to -63C at altitudes that ranged from 9,000' to 41,000' respectively. Fifty percent of the events occurred at ambient temperatures of -29C or colder and 26% of the events occurred at temperatures colder than -40C the theoretical limit for supercooled liquid to be present.

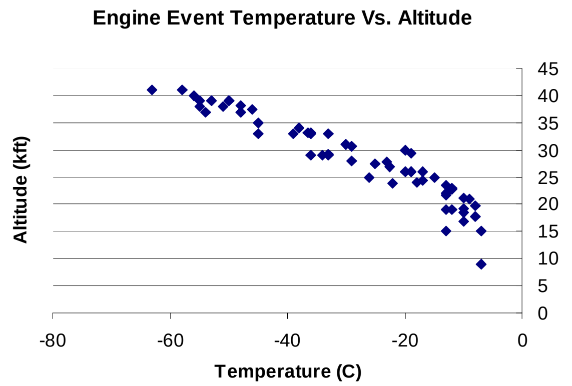

Figure 2. Temperature vs. Altitude for 63 engine events in the Boeing database.

Perkins et al. (1957) conducted an unbiased, in-cloud aircraft icing study where data was collected during reconnaissance flights over oceanic areas. Included in this dataset are samples of clouds in the western Pacific near Japan and the Philippines where many engine events occur. Each engine event temperature in the engine event database has been placed on the icing-to-cloud ratio curve from Perkins et al. (1957) in figure 3. For an event that occurred at a temperature of -29C, for example, only about 6% of clouds were found to be associated with classic icing on the icing-to-cloud ratio curve. The remaining 94% of clouds encountered would have been glaciated. The average probability of encountering classic icing conditions for all events is 12.5%. In other words, assuming that all events occurred in-cloud, there is an 87.5% overall probability that fully glaciated clouds were encountered. We can be certain glaciated conditions existed for events which occurred on aircraft equipped with a RID. When present, this detector never reported super-cooled liquid during any of the engine events. The warmest temperature where an event occurred while at the same time there was no supercooled liquid detected by the RID was -8 degrees Celsius.

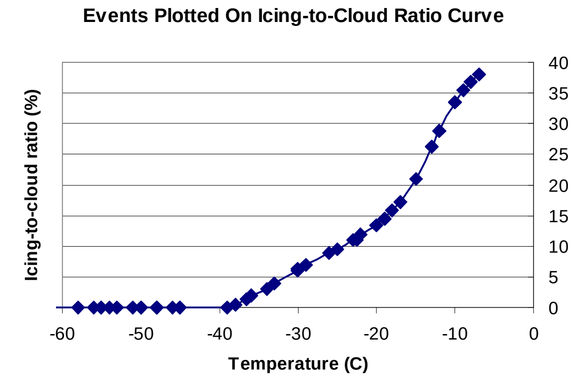

Figure 3. Engine event temperatures have been plotted on the icing-to-cloud ratio curve adopted from Perkins et al.

3. ATMOSPHERIC CONDITIONS

Engine events are occurring exclusively within convective anvil clouds above the freezing level over various regions of the globe. Section 5: “Global Ice Particle Icing Engine Event Weather Threat” discusses the global distribution of environments that are conducive to the development of convection associated with engine events. This section will discuss local conditions associated with engine events by analyzing atmospheric soundings, satellite, and radar data. Pilot reported atmospheric conditions associated with engine events, have many similarities including:

- The aircraft was traversing a convective anvil cloud.
- Pilots were avoiding heavy radar returns at flight level by 20 miles or more.
- Lack of significant airframe icing.
- Only light to moderate turbulence is reported leading up to and during events.
- No hail is reported.
- Little to no lighting was reported.
- Little to no radar returns were observed at flight level (typically scattered light returns).
- Moderate to heavy precipitation was observed below the aircraft and below the freezing level.

3.1 SOUNDING ANALYSIS

Model-derived atmospheric soundings for 49 engine events from the years 1997 through 2009 were analyzed. Data were obtained from NOAA’s Air Resources Laboratory website.

An average thermodynamic sounding was constructed (figure 4) using model-derived data for 49 events where complete sounding datasets existed.

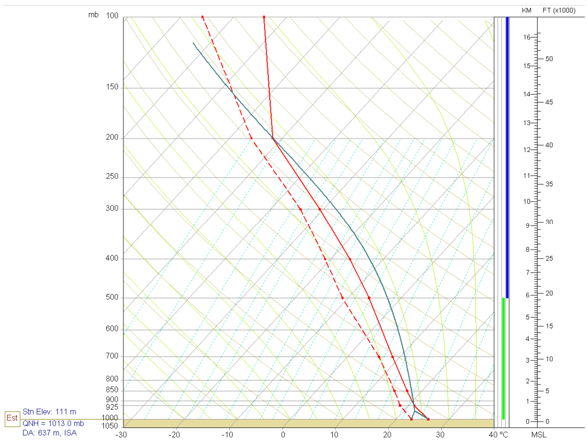

Figure 4. Average event temperature (red solid), dew point temperature (red dashed), and lifted parcel (solid blue) are shown.

The sounding is warm and moist from the surface up to the tropopause. There is a long, thin, positive area for a lifted surface parcel on the diagram resembling a Miller type II (or tropical) sounding (Fawbush and Miller 1954). The following thermodynamic analysis includes consideration of surface-based (SB), most-unstable (MU) and mean-layer (ML) convective available potential energy (CAPE), convective inhibition (CIN), and lifted index (LI). The most unstable layer was equal to a surface based parcel so only SB will be reported. The average sounding has 1,141 J/kg of SBCAPE, -11 J/kg of SBCIN, and a SBLI of -3.5. For a mean-layer parcel, the average sounding has 338 J/kg of MLCAPE, -26 J/kg of MLCIN, and a MLLI of -1.6.

Figure 5 shows “box and whisker” plots for surface lifted index, surface-based CAPE, Bulk Richardson Number (BRN) shear, and precipitable water.

For all 49 soundings analyzed, the median surface lifted index was -3.7, which is shown in the top left panel of figure 5. The middle half of events in the database had LIs between -1.3 and -4.7, the maximum was +1.7, and the minimum was -6.5. A majority (84%) of the events occurred within a marginally (LI between 0 and -3) and moderately (LI between -3 and -6) unstable atmosphere.

A more accurate measure of atmospheric instability is CAPE, which has also been included in the analysis. The top right panel in figure 5 shows a CAPE box plot. The median CAPE for all events was 1,364 J/kg, the middle half occurred with CAPE values between 331 J/kg and 2,017 J/kg, the minimum was 6 J/kg, and the maximum was 3,873 J/kg. Considering that an atmosphere with CAPE values from 0 to 999 J/kg can be considered to be marginally unstable, 1,000 to 2,499 J/kg is moderately unstable, 2,500 to 4,000 J/kg is strongly unstable, and greater than 4,000 J/kg is extremely unstable; 40% of the events occurred in a marginally unstable atmosphere, 48% occurred in a moderately unstable atmosphere, and 12% occurred in strongly to extremely unstable atmosphere.

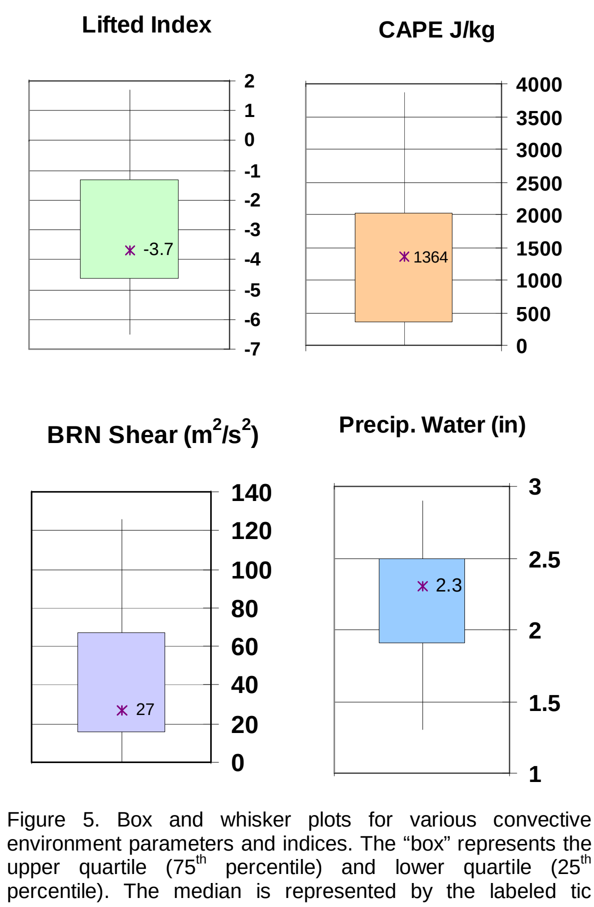

Figure 5. Box and whisker plots for various convective environment parameters and indices. The “box” represents the upper quartile (75th percentile) and lower quartile (25th percentile). The median is represented by the labeled tic marking in the box. The “whiskers” connect to the dataset’s maximum and minimum. Outliers have not been included in the plots. CAPE is in J/kg, BRN Shear is m^2/s^2, and precipitable water in inches.

Bulk Richardson Number Shear (BRNS, figure 4 bottom-left) can be used to evaluate the potential for storm organization given that CAPE values are greater than zero. Strensrud et al. (1997) found that for BRNS values of 40 m^2/s^2 or less, storms become outflow dominated and are likely to evolve into squall lines. They found BRNS values of 40 to 140 m^2/s^2 to be optimal for the development of supercells. For the engine event database, the median BRNS was 27 m^2/s^2, the middle half occurred with BRNS values between 15 m^2/s^2 and 67 m^2/s^2, the minimum was 0 m^2/s^2, and the maximum was 126 m^2/s^2. Furthermore, 61% of the soundings had BRNS values less than 40 m^2/s^2 and the remaining 39% had BRNS values between 40 m^2/s^2 and 140 m^2/s^2. Generally speaking, soundings in the engine event database have a modest amount of wind shear present.

Precipitable water (PW, figure 4 bottom-right) values for the event environments were quite high in most cases. The median PW was 2.3”, the middle half occurred with PW values between 1.9” and 2.5”, the minimum was 1.3”, and the maximum was 2.9”. Precipitable water values were greater than or equal to 2.0” in 71% of the soundings, which are values associated with a very moist and tropical-like atmosphere.

An analysis of engine event atmospheric soundings reveals that the typical convective environment is largely characterized by an oceanic or tropical atmosphere. The average sounding resembles a Miller type II sounding, there’s marginal to modest atmospheric instability, wind shear is typically in the range to support squall lines, and precipitable water values range from high to extremely high.

3.2 INFRARED SATELLITE ANALYSIS

Infrared satellite data were analyzed for 46 engine events that were found to have sufficiently accurate time and coordinate data. First, a visual analysis methodology was used to place each convective system into one of the following categories: isolated cell, multicellular cluster, mesoscale convective system (MCS), or tropical system (figure 6). An isolated cell was defined as being one that was isolated from other convection and its anvil canopy was not interfered by or in contact with other cells. A multicellular cluster was defined as several or more cells in an area within close proximity to one another and the anvils of individual cells could be separate or touching, but were not merged into one large cloud shield. An MCS category was used for a large region where many cells have merged into one system having a unified convective anvil shield present. Finally, a tropical system was defined by either visually having a notable circulation present or by the author’s experience it was known to be a tropical system. This method of categorizing convective systems may result in some tropical systems, which did not have obvious visual circulations present, being categorized as an MCS, however this potential error source was deemed acceptable for the purposes of this study.

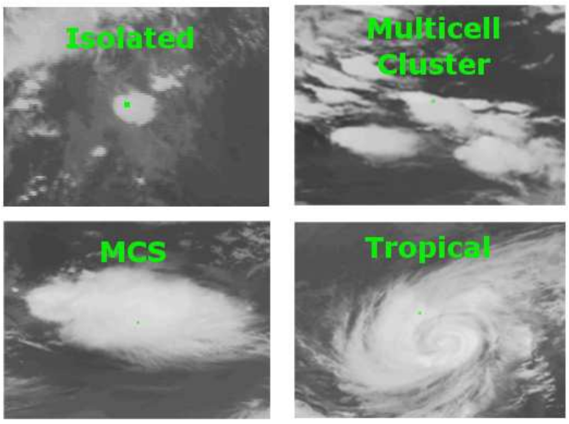

Figure 6. Examples of infrared images for each category in the "visual analysis".

Figure 7 shows the infrared satellite analysis results. The analysis reveals that 60% of the convective storms encountered during engine events were MCS, 22% were multicellular clusters, 11% were of tropical nature, and 7% were isolated cells.

Next, an objective analysis of infrared cloud top temperature was performed using each event location (figure 8). Infrared cloud top temperatures were measured and recorded for each event location. As a result of the analysis, the median cloud top temperature was found to be -63C, the middle half of events had cloud top temperatures ranging from -55 C to -70 C, the maximum temperature was -44 C, and the minimum was -87 C. When considering cloud top temperature, one must take into account the event location and time recorded in the database are the moment the engine power-loss occurred. This is the moment the ice shed. The ice formation must have occurred just prior to the shed, but the duration of the ice formation is not known.

A feature that is commonly observed during engine events is a significant cold cloud top region, usually associated with the deepest and coldest part of the convective cloud, was being traversed by the aircraft

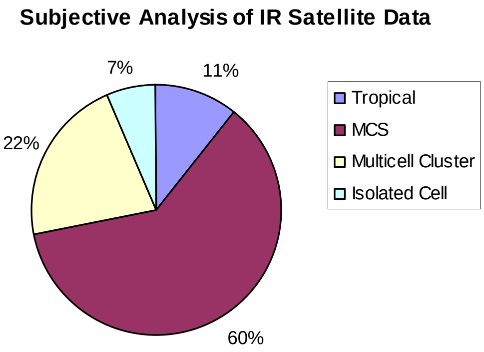

Figure 7. Statistics compiled from subjective infrared satellite analysis.

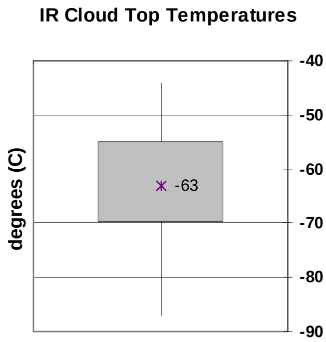

Figure 8. Box plot of engine event infrared cloud top temperatures from an objective analysis.

at the moment of the event. These areas typically appear within the interior region of an MCS. Researchers are interested in the connection between high ice water content regions and the presence of overshooting tops, hypothesizing that overshooting tops may be a sign that strong updrafts are the mechanism to lift high concentrations of ice particles to high altitude. The event data can provide some insight as to whether overshooting tops are present near the event locations. Inspection of visible satellite imagery revealed that in many cases, horizontally stratified cirrus cloud lacking significant cloud shadowing associated with convective overshoots was observed. In a few cases there were shallow overshoots present in the vicinity of the aircraft at the time of the event. The lack of overshoots present in the majority of observations is consistent with relatively weak updrafts that are commonly found in oceanic convection due to marginal/modest instability combined with high water loading – or the prevalent atmospheric conditions for engine events.

3.3 RADAR ANALYSIS

Weather radar data were available for 11 engine events in the database. Archived NEXRAD data were analyzed for 9 of the events, which occurred within the United States lower 48; one radar dataset was acquired from the Hong Kong Observatory, and finally Tropical Rainfall Measuring Mission (TRMM) radar reflectivity data were available on one fortuitous occasion. Vertical profiles of radar reflectivity (VPRR) were developed by analyzing pseudo range height indicator (pseudo RHI) images for each event. The event radar data was categorized here into two types (referred to as Type I and Type II) of VPRR and "average" profiles for each type were constructed.

The least prevalent mode in the event radar database (two of eleven events), type II, as seen in figure 9, has a weak reflectivity region in the middle levels of the atmosphere bounded by a lack of radar returns at lower and higher levels. The two radar images where this profile is observed can be described as an anvil cloud associated ice crystal "blow off" down shear from a convective cell. In this scenario, the peak radar return of 20 dBZ occurred at 25,000 ft of altitude. Both events occurred near the peak reflectivity. Although only a small percentage of engine events in the database have occurred with this scenario, we have developed the recommendation that aircraft avoid flying down shear from convective cells in-cloud, at temperatures below freezing, especially if light returns (20-29 dBZ on aircraft weather radar).

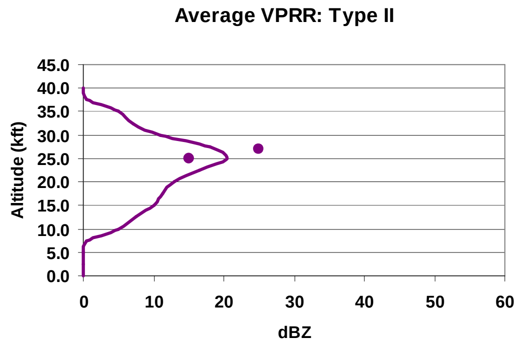

Figure 9. Average vertical profile of radar reflectivity associated with the anvil region down shear from a convective core (Type II). The dots represent aircraft position for the 2 events that comprise this profile.

Vertical radar profile Type I, as shown in figure 10, is an average radar profile comprised of datasets from 9 events. This profile, which is most commonly associated with engine events, has moderate radar returns (35-40 dBZ) from the near-surface level up to approximately 15,000 ft. Above 15,000 ft of altitude (the approximate average freezing level), radar returns quickly decrease with altitude. The type I VPRR closely resembles the "tropical oceanic median" profile from (Zipser and Lutz 1994). They describe the profile as having maximum reflectivity at the lowest levels and a very rapid decrease in reflectivity with height beginning just above the freezing level. They also found that this profile has radar reflectivity less than 40 dBZ at -10 C, the threshold above which is thought to be associated with rapid storm electrification leading to lightning. This observation is consistent with the lack of lightning reports associated with engine events. Szoke et al. (1986) also describe a VPRR similar to our Type I that is associated with tropical MCS's and hurricanes. This profile was also found by LeMone and Zipser (1980) and Gray (1965) to be associated with characteristically weak updrafts in the 3 to 6 m/s range. Pilot's often report weak and occasionally moderate turbulence while flying through convection associated with engine events, which is consistent with weak updraft velocities. Finally, the Type I VPRR also significantly resembles the VPRR from a "newly formed stratiform region" within a tropical MCS as described by (McGaughey and Zipser 1996). The combination of lack of turbulence and lack of radar reflectivity suggest these clouds are not those which pilots are trained to avoid. The industry standard advice for thunderstorm avoidance to pilots is to avoid significant radar reflectivity (amber and red on the aircraft radar screen) by 20 nautical miles. Amber and red on a pilot's radar display ranges from 30-50 dBZ, which are values greater than all reports at flight level in the event database.

A subjective inspection of the lowest elevation plan position indicator (PPI) scans from events in the database reveals that two thirds of the events occurred in stratiform precipitation regions associated with convective systems. The remaining one third of events occurred within or near active convective cells, but in regions associated with light radar reflectivity at flight level.

It is believed by the authors that aircraft flying through the upper levels of convective weather that has a "Type I" VPRR is the most probable locale to encounter high ice water content and the possibility of ice particle icing engine events. Currently the pilot's tools to detect and avoid these regions are limited, since standard aircraft weather radars have a minimum reflectivity threshold of 20 dBZ. Many events occur within regions that have reflectivity less than 20 dBZ; therefore contributing to a seemingly benign weather region in combination with the lack of turbulence, lightning, hail, and airframe icing. Pilots must use a process of deduction to detect these conditions. It is recommended that pilots use their radar's tilt and gain functions to scan below the aircraft while flying in and around convective weather. Regions where moderate to heavy precipitation are present below the freezing level, whether or not returns are present at flight level, should be avoided.

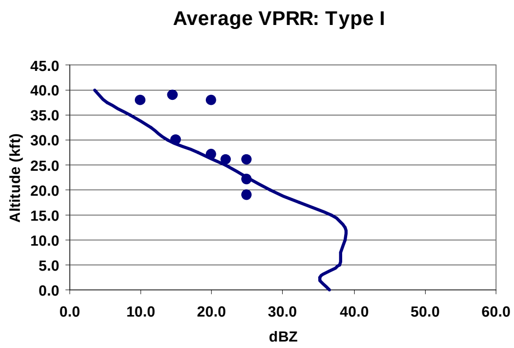

Figure 10. Average vertical profile of reflectivity associated with a majority of the events (Type I). Aircraft positions that comprise the profile are represented by dots.

4. ICE CRYSTAL ICING ENGINE EVENT CASE STUDY

This case study provides a detailed meteorological account of a large transport jet-engine event. This event was chosen because it was found to be representative of a majority of the events having a Type 1 radar profile and occurring within an MCS in a tropical environment. The event occurred during early summer while the aircraft was descending into Hong Kong

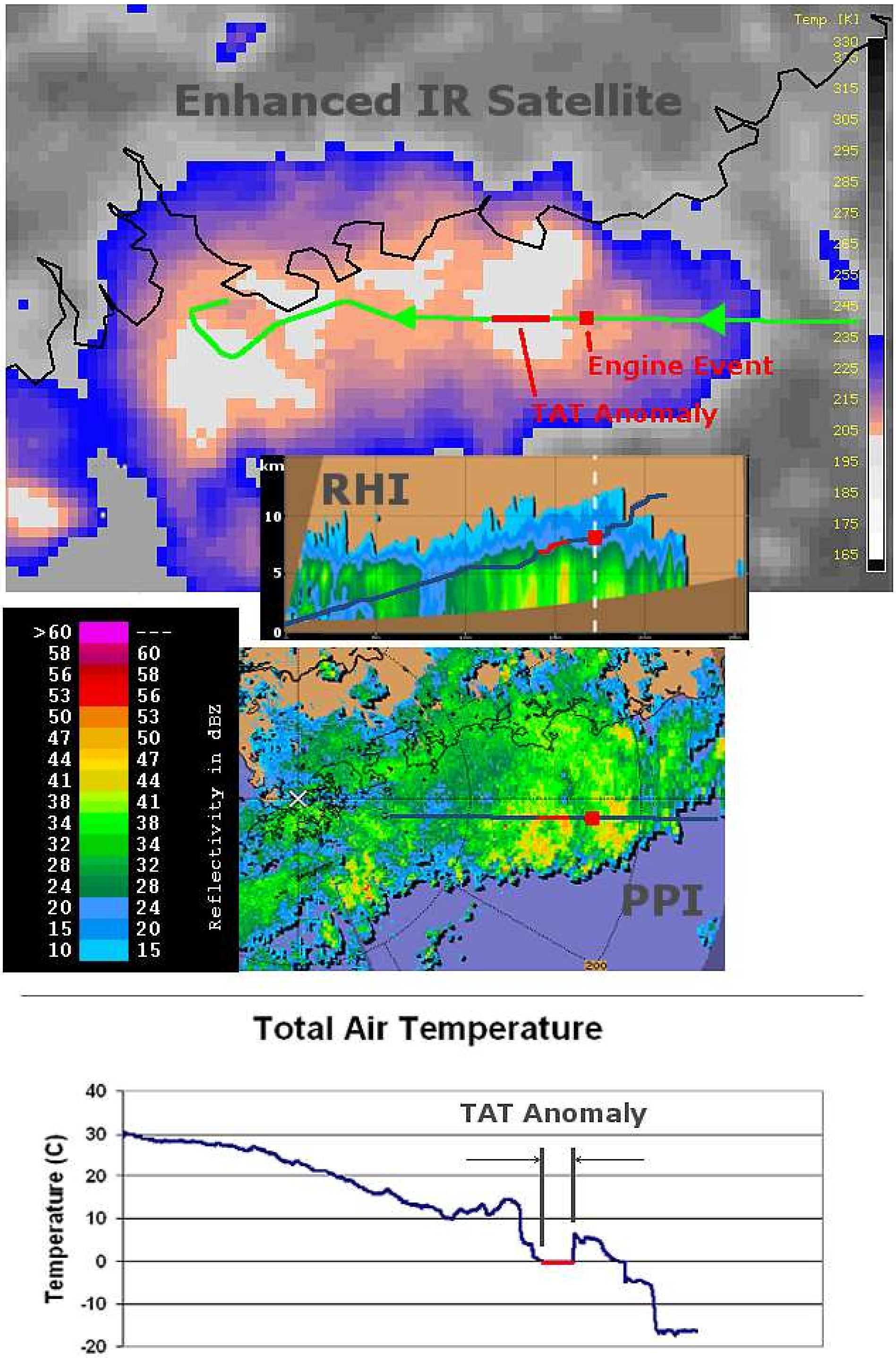

Figure 11. Enhanced infrared satellite, radar RHI, PPI, and total air temperature for the engine event case study near Hong Kong. Aircraft track is in green on the satellite image and blue on all other plots.

at an altitude of 26,000'. The aircraft was traveling westbound and arriving from Japan. Figure 11 is a collage including a color enhanced satellite image, a pseudo-RHI radar scan, a PPI radar scan, and a total air temperature (TAT) plot all of which are aligned vertically such that the x-axes approximately match.

The infrared (IR) satellite image shows a tropical MCS positioned along the southern coast of China. Blue, beige, and white have been used to highlight deep convective clouds. The transition between beige and white signifies an IR temperature of 205K (-68C), which was the approximate temperature of the tropopause in this location. Bright white areas are associated with the deepest clouds and coldest cloud tops, which were up to an altitude of 51,000 ft. As the aircraft began its descent into Hong Kong, it entered cirrus cloud associated with the MCS's anvil at 36,800 ft of altitude with an ambient temperature of -39C (figure 12). On the far eastern side of the MCS, the cloud was diffuse, but gradually thickened westward as precipitation increased at lower levels. Winds at cruising altitude were light and out of the east-northeast at 15 kt (figure 12). As they continued westbound and descended through 31,000 ft, the cloud continued to thicken and they entered a 10 dBZ radar return region with 30-40 dBZ returns directly below the aircraft and below the freezing level (figure 11, RHI). The ambient temperature at aircraft elevation was -25C (figure 12). Radar reflectivity values continued to gradually increase as the aircraft descended. The engine event occurred at an altitude of 26,000 ft where the ambient temperature the sounding was -15C (but could have been theoretically as warm as -11C in an updraft core considering moist adiabatic ascent of an air parcel). Radar reflectivity at flight level during the event was ~20 dBZ with ~35 dBZ below the freezing level. An examination of the PPI from the radar's lowest elevation angle shows that, just prior to the engine event, the aircraft had passed over an area of heavy precipitation (40 – 49 dBZ). This analysis suggests that if the pilots had used the aircraft radar's tilt and gain function to scan below, they would have observed areas of heavy (red on aircraft radar display) returns. The event occurred near the deepest part of the system after the aircraft had traveled roughly 50 nautical miles (~90 km) through convective anvil cloud.

Following the short duration engine event, a TAT anomaly was recorded. The TAT anomaly, in this case, can be seen at the bottom of figure 10 where the temperature reading flat-lines at 0C for a period of 140 seconds. The aircraft was passing through the deepest part of the convective system when the TAT anomaly occurred and it was centered within an "enhanced" IR region as seen in the satellite imagery. The aircraft was descending from 25,300 ft through 22,900 ft during the duration of the TAT event and ambient temperatures ranged from -13.5C to -10C. On the RHI image, the aircraft was passing through ~25 dBZ radar reflectivity at flight level. A convective core can be seen below the freezing level near the TAT anomaly with radar reflectivity of ~45 dBZ. The aircraft landed in Hong Kong without further incident.

This particular aircraft was equipped with a RID. This sensor did not report any supercooled liquid during the entire event. The lack of supercooled droplets implies a rapid conversion of liquid droplets to ice crystals took place above the freezing level as discussed by Black and Hallett (1986), Jorgensen and LeMone (1989), and Stith et al. (2002).

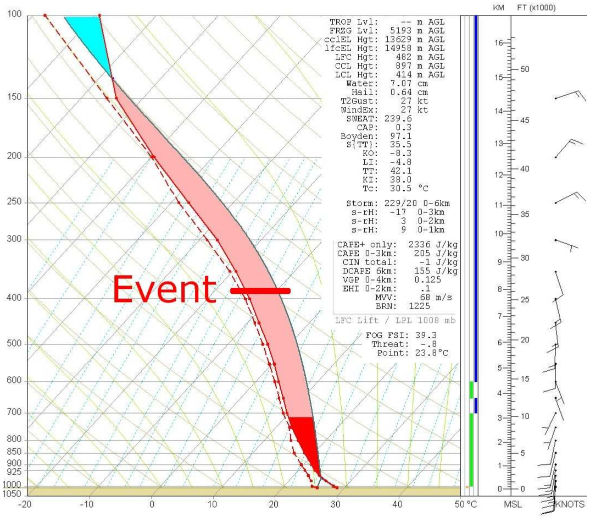

Figure 12. Model derived atmospheric sounding for the engine event case study. Surface-based CAPE is represented by red and pink area.

A model-derived atmospheric sounding sampling the "inflow" region south of the MCS is shown in figure 12. The sounding has a long, thin area of CAPE resembling a Miller Type II sounding. There was 2,336 J/kg of surface-based CAPE present, which is in the ~80th percentile relative to all other soundings in the engine event database. The surface-based lifted index was -4.8, which is the 78th percentile. The atmosphere was moderately unstable during this event from a global perspective. A warm and nearly saturated thermodynamic profile from the surface to the tropopause contributed to a precipitable water of 2.78 inches (7.07 cm). This is an extremely high value, tropical in nature, and is a 99th percentile value.

5. GLOBAL ICE PARTICLE ICING ENGINE EVENT WEATHER THREAT

Global probabilities of the environment favorable for convection associated with engine events have been calculated and were plotted in figure 13. For each event in the database, precipitable water, surface-based LI, and 1000-500mb wind shear (VWS) were derived from the NCEP-NCAR Global Reanalysis (NNGR) dataset (Kalnay et al. 1996, Kistler et al. 2001). The percentage of the time that conditions were favorable for the development of convection that has been associated with engine events was plotted. This was done by finding the average and standard deviation

PW, LI, and VWS value for each event and then calculating the percentage of time that PW, LI, and VWS for each NNGR grid point simultaneously had values that were within the range of plus or minus one standard deviation from the average for each variable. More precisely, the percentage of time that PW was between 36 and 60 mm; LI was between -4.5 and 0; and VWS was between 5 and 20 m/s was plotted for each season. Plots represent the seasonal occurrence of atmospheric conditions supportive of convection associated with a majority of the engine events in the dataset.

The plots in figure 13 show that favorable conditions generally exist in tropical and subtropical regions between 30 degrees north and 30 degrees south latitude. Variations do exist both seasonally and longitudinally, however. Seasonally, the band of occurrence fluctuates north and south slightly following the Earth's tilt. The band drifts north during the northern hemisphere's summer and south during the southern hemisphere's summer. Longitudinal variations appear to be influenced by variations in sea surface temperature (SST) and arid continental regions. Areas of highest occurrence are mostly over or adjacent to warm oceanic regions. In particular, the areas of highest occurrence annually are located over and near the Indian Ocean; western Pacific near Southeast Asia, Indonesia, and northern Australia; Central and northern South America; the Pacific intertropical convergence zone (ITCZ); and equatorial regions of Africa. During the northern hemisphere summer, a large area of modest occurrence rates develops over the southeastern and south central United States and an area expands into Japan and eastern China as well.

By comparison of figure 1 and figure 13, it is apparent and expected that not all events fall into the range of typical atmospheric conditions favorable for events. A tropical environment is favorable, but not a requirement for engine events. Engine events can occur wherever convection and air traffic coexist. As mentioned previously it appears as though lower ice water content clouds can produce engine events due to the nature of the ice build up process inside the engine.

To investigate the seeming lack of events in South America (figure 1) despite the presence of a tropical environment during northern Hemisphere autumn and winter (figure 13), one aircraft type was analyzed more closely. When the rate of events on that aircraft per flight was calculated by region, South America (southern Brazil) and the Asia Pacific had similar rates.

Some of the engine events, in particular, those in Europe (figure 1), did not occur in a tropical atmosphere or in regions that have been found to be conducive for engine events (figure 13). Even so, in all these cases, convective cloud was present. For one of these cases in Europe, the theoretical maximum ice water content was calculated for the event altitude and found to be 3 g/m3. This ice water content still exceeds the typical water contents found in cloud containing super-cooled liquid and defined in the certification standard for engines. The power-loss mechanism in the large transport engine events is the result of ice build-up and shedding and this mechanism is still possible in lower ice water content clouds. The Ice may build-up more slowly in these cases but can still shed at a size which will result in engine power-loss.

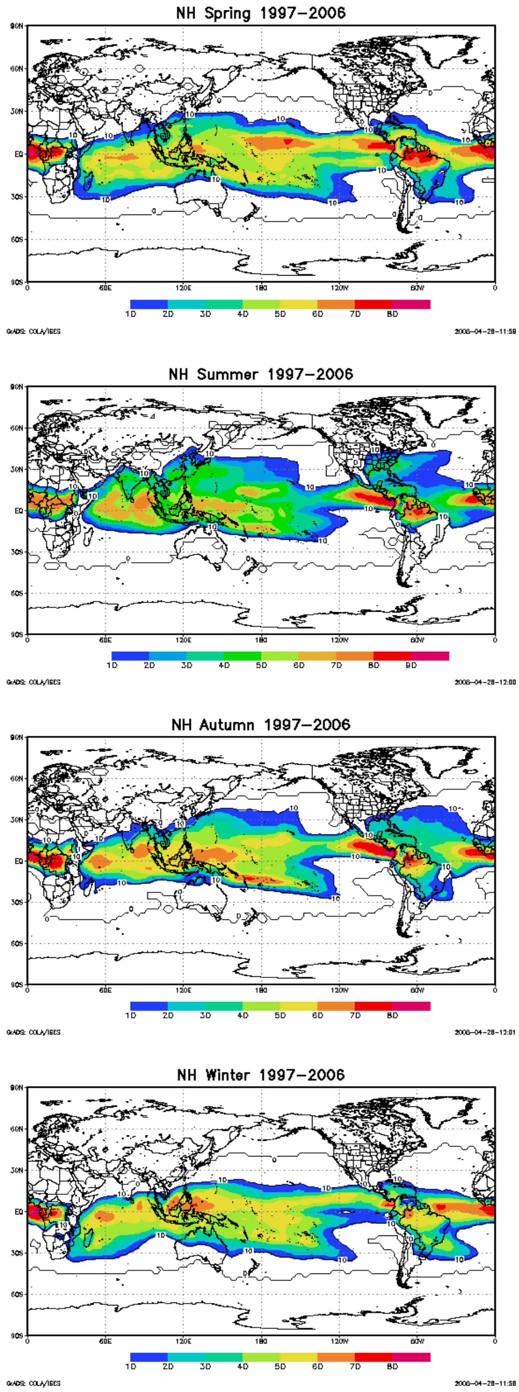

Figure 13. Percentage of time that NCEP-NCAR Reanalysis grid points had favorable conditions for the development of convection associated with engine events.

6. CONCLUSIONS

Jet engine power-loss and damage events are occurring within glaciated regions of convection anvil clouds. While no accidents associated with this phenomenon have been reported to date, there have been several multiple engine power-loss events and the FAA recognizes it as a serious safety concern. Engine events have been reported in various regions of the globe occurring with greatest frequency over the western Pacific and Southeast Asia. Events are also occurring with a lower frequency over the eastern half of the United States, southeastern South America, Europe, central Asia, and Australia. The conclusions developed from the analysis of meteorological data for engine events in the database, are as follows:

- All engine events occurred within convective anvil clouds.
- Of the 46 cases where satellite data were analyzed, 60% occurred within mesoscale convective systems, 22% occurred within multicellular clusters, 11% occurred within tropical systems, and 7% occurred within isolated convective cells.
- The average atmospheric thermodynamic profile resembles a Miller Type II (tropical) sounding.
- The typical environment where engine events have occurred is characterized by high precipitable water, weak to modest instability, and modest wind shear that is supportive of squall lines and MCSs.
- The average vertical profile of radar reflectivity associated with 9 engine events resembles both tropical MCS and hurricane vertical profiles.
- Radar reflectivity values have ranged from 10-25 dBZ at flight altitude and 30-40 dBZ below the aircraft and freezing level during engine events.

The title of this paper reflects the perspective that the understanding of the atmosphere in which engine power loss and damage events occur is a developmental process, which will continue in the future. A considerable amount of research needs to be conducted addressing both ice formation in engines and microphysical properties and structure of convective clouds associated with ice particle icing. This is the first step in the process that will hopefully lead to the ability to forecast and avoid regions conducive to jet engine power-loss and damage. However, enough has been learned through 2009 to offer flight crews advice for assessing and potentially avoiding weather associated with ice particle icing engine events, which includes:

- Avoid flying through or near the deepest part of convective clouds whether or not radar returns are present at flight level.
- While flying through known convective clouds, use the aircraft radar's tilt and gain function to scan below the freezing level. Avoid flying over regions of moderate to heavy precipitation (amber or red returns on a pilot's radar).

A better understanding of ice particle accretion in engines is needed to support the atmospheric investigation. The dependence of an engine capability on the atmospheric microphysical properties such as particle size and ice water content must drive the science goals of the atmospheric characterization effort.

This study suggests that a flight program targeted to sample primarily tropical-like mesoscale convective systems (over land or water) with Type I VPRRs that are characterized by weak updrafts and form in an atmosphere associated with high preciptiable water values (generally 2 inches or greater) and a Miller Type II sounding will result in weather conditions representative for engine certification standards. A small fraction of a flight program sampling should be conducted in continental convective cells downshear from heavy cores at altitude. A flight program does not necessarily need to sample the continental cells downshear from heavy cores, even though they contribute to a small fraction of events, as the extreme ice water contents will likely be measured by sampling convection in a tropical environment.

It has been previously stated that lower ice water content clouds can contribute to events, so an explanation of the reason for the industry focus on "high" ice water contents is needed. The current understanding of the accretion mechanism involves ice and liquid impinging on warm surfaces in the engine. This process reduces the surface temperature until the freezing point is reached and ice can form. Therefore, there is a direct relationship between the amount of ice content needed to cool a hot surface to freezing (i.e. the more ice water content available the hotter the surface can be and still cool to freezing). In an engine, temperature increases with air compression as it moves aft. The implication is that higher ice water content clouds can theoretically form ice deeper in the engine. To develop an engine which is not susceptible to this kind of ice formation, the designer must know the maximum ice water content likely to be encountered to evaluate where in the engine ice has a potential of forming. The value of understanding the extent of the high ice water content region is to determine the size to which an ice formation can grow.

The mechanism for development of high ice water content regions in convective clouds is still not well understood. The authors have shown that high ice water content regions do not appear to be linked in the majority of events with overshooting tops. Events do appear to be linked to flight through the coldest, deepest part of convective systems, however. Future research is needed to develop and test theories of the processes leading to high ice water content regions.

At this time, engine events still occur on a regular basis. Careful analysis of future events may shed light on techniques to identify high ice water content regions and allow for forecasting, detection, and avoidance.

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