BOEING COMMERCIAL AIRPLANES

FLIGHT OPERATIONS TECHNICAL BULLETIN

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DATE: April 15, 2011

SUBJECT: Ice Crystal Icing

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APPLIES TO: 737, 747, 757, 767, 777, 787

BACKGROUND

This bulletin summarizes current Boeing information about engine power loss and damage events associated with flight in ice crystal icing conditions. This problem most frequently affects aircraft flying over tropical regions but is <u>not limited to those areas</u>. In 2008, Boeing recorded three events in the United States, two near Chicago O'Hare airport and one near New York's Kennedy airport. All three were at high altitude in convective* weather associated with the remnants of tropical storms which had lost energy but were still producing heavy rain on the ground.

- * Convection occurs when warm moist air rises in an unstable atmosphere. As the air rises, it expands and cools, and water vapor within it condenses to form clouds. Thunderstorms are one type of convective weather that can lift moisture to the tropopause where winds spread the cloud into a recognizable anvil shape. Convective updrafts lift high concentrations of water above the freezing level where the water freezes, and grows to hailstones or falls as rain.

Ice crystal icing affects engine models differently. Engines on Boeing aircraft have experienced flameouts, surges, high vibrations, and compressor damage due to ice impacting the fan blades. Flight crews are not always aware that the engines have been damaged as a result of flight in convective weather containing ice crystals. Data gathered from pilot reports, flight data, and meteorological studies were used to develop the best practices summarized in this bulletin. Our understanding of the ice crystal icing phenomenon and its flight deck effects is evolving. This bulletin may be updated as more information becomes available.

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1.0 A New Threat

Until now, ice crystals at high altitude have not been thought of as a threat to aircraft because they do not lead to airframe icing. However, the industry has identified a condition in which solid ice particles can cool interior engine surfaces through melting and ice build-up. When the ice sheds, it can result in engine power loss or damage. Symptoms of a power loss can be a surge, flameout, or high vibration. Typically, the engine power loss has occurred at high altitude, in clouds, as the aircraft is flying over an area of convective weather where little or no weather radar returns were observed at the flight altitude. In other cases, flight altitude radar returns were observed and pilots followed standard thunderstorm avoidance procedures. Despite pilot avoidance of weather radar returns, engine power losses have occurred. Avoidance of ice crystals is a challenge because they are not easily identified.

2.0 Pilot Reports

Here is a sample report for an ice crystal icing event.

> **J502 YYJ288/30**
> **1420L, FL 350, B747**
> **Intermittent IMC to 330 then IMC up to and at 370.**
> **TAT approximately zero (0).**
> **Winds 330/19, light to moderate turbulence, no icing.**
> **Remarks: TAT indicator wrong. Rain on windscreen at 370 (impossible), suspect ice crystals due to the sound. Heavy returns 5 to 7000 feet below us. Saw tops above 41K before going IMC. No returns at our higher altitude. Got ATC reroute to pass north of heavy returns ahead and below. (passing waypoint) Turbulence increased, asked flight attendants to be seated. Appears Engine 1 rolled back briefly, then recovered.**

3.0 Indications of Ice Crystal Icing

Breaking down the above report and analyzing the weather in similar incidents has increased our confidence in the following traits associated with ice crystal icing:

3.1 In clouds at high altitude

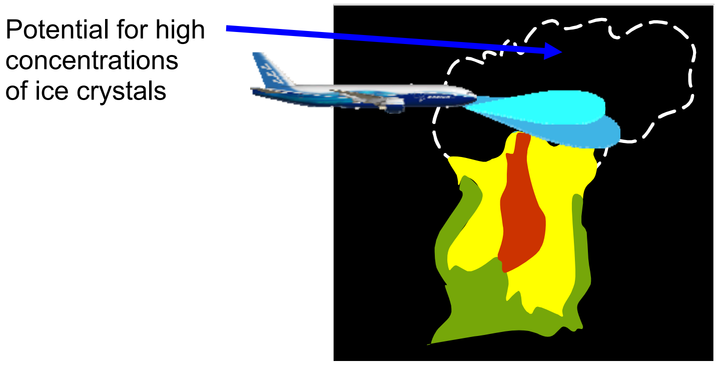
- All pilots report being ***in clouds*** when the ice crystal-induced engine power loss events occur.
- More than 60% of these events occur in the Asia-Pacific region, in a tropical environment, where warm air can hold more moisture. This air rises and cools, forming clouds containing a great amount of ice ***at high altitude***.

3.2 No weather radar returns at flight level

- This ice is thought to be concentrated in very small particles, the size of baking flour - a ***poor reflector of radar energy*** despite the density.

3.3 Heavy weather radar returns below flight level

- From event weather radar analysis, events consistently occur when the aircraft is in Instrument Meteorological Conditions ***(IMC) and over-flying an area which would be amber or red*** on the pilot's weather radar. Ice that has been lifted to high altitude eventually falls through the freezing level and begins to melt. These wet particles are much more reflective and therefore visible (amber or red) to radar. These clouds can be identified by pilots if they ***manually tilt the radar down*** to scan below the freezing level.



3.4 Traversing clouds with tops at high altitude

- Often these clouds lift condensed water to high altitude, even penetrating the tropopause. It is in these ***updraft areas*** where the highest ice crystal concentrations can be encountered.

3.5 No airframe icing

- Ice crystals bounce off cold surfaces such as the airframe, which is why airframe icing is usually <u>not</u> noted. These small particles may accumulate in stagnation areas, so it is possible that a small concentration might be noted on the leading edge of the wiper post.

3.6 Appearance of rain

- Another key indicator of ice crystal conditions is the ***appearance of rain*** on the windscreen at high altitudes. From pilot reports and flight data we have concluded that when small ice crystals in high concentrations hit the heated windscreen, they melt and give the appearance of rain, even when the ambient temperature is too cold for liquid to exist. Several interviewed pilots explained that ice crystals ***sound different*** than typical rain.

3.7 TAT near zero

- For the engineer reviewing event data, the ***TAT anomaly*** (TAT reading near zero °C) is a good indication that an aircraft has flown through ice crystals. This unusual behavior is created when ice crystals collect in the area where the sensor element resides. Some ice crystals melt and the sensor measures ice-water at 0° Celsius. This effect depends on the aircraft model, where the TAT probe is installed on the fuselage, and how TAT is displayed in the cockpit. There are many variations in the Boeing fleet and some aircraft are more susceptible to the TAT anomaly than others.

3.8 Only light to moderate turbulence

- Meteorologists tell us that even though these clouds reach the tropopause, when they form in a tropical environment, they are not as powerful as those that form over land (which more commonly have lightning) and, therefore, they have lower updraft velocities, resulting in only **light to moderate turbulence**.

3.9 Other clues

Pilot reports from events vary and not all the symptoms noted above are reported in every event.

- Another effect which is associated with ice crystals striking the airframe is **St. Elmo's Fire**.
- Several reports referred to increases in **temperature and humidity** in the cockpit preceding the TAT anomaly. This was only present while in IMC and is likely another cue that ice crystals were present.

4.0 Industry Efforts

The industry is working to improve engine capability in ice crystals. There is still much to be understood, including the weather threat and the details of the ice formation inside the engines. Efforts to close the knowledge gap have long timescales, and the ability to apply practical technology to allow robust simulation of these conditions is many years away. Hence in the near term, there has been a focus on providing better information to flight crews in the cockpit to help with weather avoidance.

5.0 Research

Very few instrumented research flights have been made in convective clouds. Very little is known about the concentrations and sizes of ice crystals in these clouds. Knowing the severity of the atmosphere is a key to designing an engine to operate in these clouds. To address this need, a team of government and industry members known as the High Ice Water Content (HIWC) Partnership plans to conduct an instrumented flight program in 2012. At the same time, work is ongoing to better understand the physics of engine ice crystal icing, and develop test facilities where engines can be tested.

Recently, airlines have brought pilot reports and flight data to Boeing's attention where the aircraft TAT is in disagreement with the engine inlet temperature. We believe this can occur in ice crystal icing conditions. A study of TAT anomalies, as well as TAT and engine inlet temperature disagreement, may provide more insight into the type of convection that causes engine power loss and damage events. One interesting finding is that the TAT anomaly is occurring at a higher frequency than previously realized.

Boeing continues to enhance its understanding of what kind of weather causes engine events so the best information can be provided to flight crews. Each engine event is carefully evaluated from a meteorological and engine diagnostic standpoint so that, in the future, we can provide better information to operators.

6.0 Key Points for Flight Crews

6.1 Recognize weather conducive to ice crystal formation

Ice crystals are most frequently found in areas of visible moisture above altitudes normally associated with icing conditions. They are indicated by one or more of the following:

- Rain on the windscreen at temperatures too cold for liquid water to exist, due to ice crystals melting on the heated windows.
- Aircraft TAT remains near 0 degrees C.
- Areas of light to moderate turbulence.
- No significant radar returns at aircraft altitude.
- Heavy rain below the aircraft, identified by amber and red on weather radar.
- Cloud tops reaching above typical cruise levels (above the tropopause).

Note: There is no significant airframe icing. The icing conditions detection system (if installed) is not designed to detect ice crystal icing, only supercooled droplets.

6.2 Avoid ice crystal icing conditions

During flight in IMC, avoid flying directly above significant amber or red radar returns, even with no returns at aircraft altitude.

Use the weather radar manual tilt and gain functions to assess weather radar reflectivity below the aircraft flight path.

6.3 Ice crystal icing suspected

Exit ice crystal icing conditions. Request a route change to minimize time above red and amber radar returns.

7.0 More Information

For more general information please see the MyBoeingFleet web pages below:

- **Air France Training Module**
  Ice Crystals at High Altitude: Engine Powerloss, TAT and Pitot Anomalies
  [A 15 minute computer based training module for flight crews. Follow: “Flight Operations”, “Events, Training & Resources”, “Safety Tools & Training Aids”, “Ice Crystals at High Altitude”.]
- **Symposium Briefing**
  Ice Crystal Threat

["Flight Operations", "Past Flight Operations Conference Presentations", "More", "Regional Operations Conferences" (2008), "Ice Crystal Threat".]

- **AERO magazine**
  Engine Power Loss in Ice Crystal Conditions ["Archive", "2007, 4th Quarter"]
  Avoiding ConvectiveWeather Linked to Ice-crystal Icing Engine Events ["Archive", "2010, 1st Quarter"]

8.0 Ice Crystal Ice Threat - Frequently Asked Questions

Q1. How many engine events have been recorded?

There are more than 100 events in an industry database. This number includes events on Boeing aircraft, events involving engines on other manufacturers' aircraft, a commuter aircraft, and a business jet. In some cases, Boeing has been successful in making procedural changes which have eliminated engine power loss events on some engines.

Q2. How does ice form on warm engine surfaces?

The physics of ice crystal accumulation in the engine is not completely understood, but the mechanism is thought to be the following: Ice particles enter the engine and bombard a warm surface. Thus, a mixture of liquid and ice particles exist on the surface. The liquid slows down the incoming ice particles long enough for heat transfer to take place. Heat is removed from the metal until the freezing point is reached and ice begins to form. This phenomenon means ice accumulation can occur well behind the fan in the engine core. Ice shed from compressor surfaces can cause engine instability such as surge, flameout, or engine damage.

Q3. To date, what is the maximum internal engine surface temperature at which ice has formed?

Industry data has shown that an engine at cruise power, with engine surfaces near 100°F (38°C) before entry into cloud, was able to build up ice.

Q4. Are these events mostly at low power settings?

No. Engine power loss and damage events have been experienced both at high power, cruise conditions and low power, descent conditions.

Q5. Does increasing thrust help prevent ice build up?

Unlike conventional icing (supercooled liquid water), which builds up on cold engine surfaces, ice crystal icing can occur on engine surfaces that are initially warmer than freezing. When power is increased, the engine surfaces that are susceptible to the formation of ice change but ice formation is not eliminated. Further, if on descent, setting higher power would result in a slower descent and longer exposure to the threat.

Q6. In what temperature range do ice crystals exist?

Ice crystals exist from temperatures just below 0°C to well below -40°C. Note that convective storms have strong mixing effects so all supercooled liquid is efficiently converted to ice or ice crystals, even near freezing temperatures.

Q7. Explain the significance of ice crystal mass concentration compared to supercooled liquid?

For engine certification, the engine is exposed to a maximum of 2 g/m^3 (grams per cubic meter) of supercooled liquid droplets. In these conditions, ice builds up on the front of the engine – the fan, spinner, and core splitter fairing. When ice sheds, some of it will pass harmlessly through the fan duct. Measurements suggest that convective clouds can hold up to 8 g/m^3 of ice crystals. Not only is that four times the mass of supercooled liquid but ice is also able to form on core engine surfaces.

Q8. Why do some engines stall, some flameout, and some have damage?

The ice crystal icing phenomenon is not completely understood. Every engine also has different margins in its compressor and combustor, plus different geometry. The combination of design margins and geometry seem to result in different effects on each engine.

Q9. In these conditions, should engine anti-ice be turned on for all aircraft?

Not for all aircraft. Engine anti-ice supplies heat to the cowl and, in these conditions, that is not where ice is forming. Engine anti-ice also has other effects: Accelerating the engine to approach idle, providing ignition, and promoting a higher fuel-to-air ratio in the combustor. We have recommended using engine anti-ice for only those engines where we believe these effects are beneficial – those engines that have a power loss during low power. If the power loss or damage problem occurs during cruise, none of these effects prevent icing-related power loss.

Q10. What about turning on engine ignition?

On engines without auto-relight protection, continuous ignition could help the engine recover more quickly if the combustor flames out.

Q11. Would the relights be faster if the engine is at approach/high idle?

Yes, as long as ignition is available.

Q12. Are events still happening?

Yes. Across the industry, there is roughly one power loss and one damage event every four months.

Q13. At what altitudes have events been identified?

We have seen events from 9,000 feet up to 41,000 feet, all above the freezing level in a convective storm.

Q14. Are both large and small turbofan engines affected?

Yes. In the 1990s, commuter aircraft suffered rollbacks due to ice accumulation "blocking" the core. This phenomenon has not happened on large turbofan engines because the sizes of the engine passages make it more difficult to build up enough ice to block the core. Most of the large turbofan engine events are a result of ice building up and shedding, causing a surge, flameout or damage.

Q15. Do all engines recover?

As of today, all large turbofan engines have recovered. Commuter aircraft engines were not restarted until the ice melted at lower altitude. On large turbofan engines which have suffered power losses, all have been restarted quickly. Once the ice has shed, the engine is immediately able to restart.

Q16. Are both low and high bypass ratio engines affected?

Yes. We have events on older, low bypass engines as well as on brand new, large high bypass ratio turbofan engines.

Q17. Are deteriorated engines more susceptible?

Not necessarily, we have had events on old and new engines.

Q18. Why aren't there flight crew procedures for all engine types?

Not all engines have ice crystal 'problems' and the behavior of engines with problems differ. We provide engine-related procedures for only those engines where they are needed.

Q19. What is the TAT anomaly?

The aircraft Total Air Temperature (TAT) probe erroneously reporting zero °C can be an indication of ice crystals in the atmosphere.

This anomaly is due to ice crystals building up in the area near the sensor element, where ice crystals are partly melted by the heater, causing the zero °C reading. In some cases, TAT has "flat-lined" at zero during a descent and may be noticeable to pilots. In other cases, the error is more subtle and may not be a reliable indicator to provide early warning to pilots of high concentrations of ice crystals.

Although TAT is an engine control system parameter, the TAT anomaly has not been determined to be a contributor to the surge, stall or flameout events. Under these conditions, the engine control system compensates for the loss of TAT. Note that the 757 has never had a TAT anomaly event due to its location on the fuselage.

Q20. Can we tell flight crews to use the TAT anomaly to avoid iced crystal icing conditions?

The TAT anomaly is not a reliable indicator of ice crystal icing conditions because it does not occur on all aircraft and it sometimes occurs after the engine event.

Q21. Is anyone building an ice crystal detector?

Boeing and the industry are working to develop better methods of detecting ice crystals.

Q22. What is the industry doing to better understand this problem?

An industry committee has developed a Technology Plan which includes:

- Improved instrumentation to measure atmospheric conditions
- Flight trials to characterize ice crystals (particle size, concentration and extent)
- Fundamental physics testing of ice accumulation and shedding
- Improving engine test methods and facilities

Government and industry partnerships are funding this work.

Q23. What is the FAA doing to make sure engines are capable of operating in ice crystal icing?

The FAA is a partner in the technology plan mentioned above. In addition, the FAA has new regulations under review.

Q24. If I have had an ice crystal icing event, **would Boeing be interested in hearing about it, and receiving data?**

Boeing would greatly appreciate hearing details of the event. We have a questionnaire (included in this bulletin) you can fill out. In addition, if the flight data is still available, we have a standard request for engine and airplane data, including questions for the pilots. This would be very valuable to our continued investigation

9.0 Ice Crystal Encounter Pilot Questionnaire

Most information about ice crystal icing has been gathered from meteorological studies, airline-provided pilot reports, and flight data. If you suspect you've experienced an ice crystal encounter, even if it hasn't resulted in an engine event, we'd like to hear about it. In addition, it would be helpful to receive Flight Data Recorder (FDR) or Quick Access Recorder (QAR) data, if available.

Please complete the questionnaire on the following pages or online at http://vovici.com/wsb.dll/s/6640g3bab0. It should take less than 10 minutes of your time.

If you have had more than one encounter, please complete a questionnaire for each encounter.

Thank you in advance for your assistance.

Ice Crystal Encounter Pilot Questionnaire

Ice crystals have been associated with engine power loss, vibration, and damage. Power loss can be a surge, stall, flameout, or failure to respond to throttle input.

Please review the Engine Anomalies in Part 1 and the Conditions Associated with Ice Crystal Encounters in Part 2. If you have experienced an engine anomaly in IMC *or* one or more of the conditions, please answer the Questions about Ice Crystal Encounters in Part 3.

Part 1. Engine Anomalies

- Engine surge or stall (may have been momentary)
- Engine failed to respond to thrust lever inputs (may have been momentary)
- Engine flameout
- Engine vibration

Part 2. Conditions Associated with Ice Crystal Encounters

- No ice detected on Rosemount ice detector
- Aircraft in the vicinity of convective clouds or thunderstorms
- TAT anomaly (or TAT / T12 disagree)
- Flight above freezing level
- No weather radar returns at the event location
- Tropical atmosphere
- Visible moisture
- Light to moderate turbulence
- No observation of significant airframe icing
- Heavy rain or rain on the windscreen at SAT below -20°C
- St. Elmo's Fire
- Lightning
- Sounds of precipitation

Part 3. Questions about Ice Crystal Encounters

Please take a few minutes to provide as much of the following information as possible about your experience. Feel free to include any additional information you think may be of interest.

1. Did any of the following engine anomalies occur during the event?

	Yes	No / Don't know
Engine surge or stall (may have been momentary; engine may have recovered automatically)	☐	☐
Engine failed to respond to thrust lever inputs (may have been momentary; engine may have recovered automatically)	☐	☐
Engine flameout (may have been momentary)	☐	☐
Engine vibration	☐	☐
Other (please describe below)	☐	☐

Additional comments:

____

____

2. Please provide information about the event.

Aircraft Type ______________________
Engine Type ______________________
Date ______________________
Time (UTC) ______________________
Location (latitude/longitude, nearest waypoint or navaid) ______________________
Altitude ______________________
Temperature (SAT °C) ______________________

3. Was the flight in the vicinity of convective clouds or thunderstorms?

☐ No / Don't know
☐ Yes (please indicate the location of the weather in relation to the aircraft)

Additional comments:

____

____

4. Was the flight through visible moisture or in Instrument Meteorological Conditions (IMC) at the time of the event?

- ☐ No / Don't know
- ☐ Yes (please describe)

Additional comments:

____

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5. Was there rain on the windscreen or ice melting on the heated windscreen?

- ☐ No / Don't know
- ☐ Yes (please describe)

Additional comments:

____

____

6. If the aircraft was equipped with an ice detector, did it indicate ice?

- ☐ No / Don't know
- ☐ Yes
- ☐ Not equipped with an ice detector

Additional comments:

____

____

7. Was there a TAT anomaly (TAT reading zero or tending toward zero erroneously)?

- ☐ No / Don't know
- ☐ Yes (please explain)

Additional comments:

____

____

8. Were there any radar returns in the area?

☐ No / Don't know
☐ Yes (please provide the location [above or below, in front of, behind], size, color, and any additional information describing the returns)

Additional comments:

____

____

9. Were there any sounds of precipitation?

☐ No / Don't know
☐ Yes (please describe)

Additional comments:

____

____

10. Was there any visible airframe icing?

☐ No / Don't know
☐ Yes (please describe the icing type and severity)

Additional comments:

____

____

11. Was there any turbulence?

☐ No / Don't know
☐ Yes (please describe the turbulence)

Additional comments:

____

____

12. Was there any lightning?

- ☐ No / Don't know
- ☐ Yes

Additional comments:

13. Was St. Elmo's Fire visible?

- ☐ No / Don't know
- ☐ Yes

Additional comments:

14. Was the cockpit warmer or more humid than normal?

- ☐ No / Don't know
- ☐ Yes

Additional comments:

15. Was there any smell in the cockpit?

- ☐ No / Don't know
- ☐ Yes (please describe)

Additional comments:

16. Did the autothrottle automatically disconnect?

- ☐ No / Don't know
- ☐ Yes (please describe)

Additional comments:

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____

17. Please provide any additional information about the event to help us better understand this weather phenomenon.

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____

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Thank you for taking the time to complete the questionnaire.

If you have any questions or would like to provide additional information, contact Jeanne Mason at jeanne.g.mason@boeing.com.

10.0 Information for Dispatchers

10.1 On IR satellite image

Look for large (>180KM) region of cloud tops at or above the altitude of the tropopause

Events typically happen in deep convection identified on an IR satellite image by a large round or oval "enhanced" region of cloud on the order of 180 km or greater. The enhanced region is where cloud tops are at the tropopause* temperature (obtained from nearest observed or forecast sounding see figure B) or colder. Approximately 80% of the events we've seen have occurred in mesoscale convective systems (MCS*).

10.2 Warm season thunderstorms

ISA +5 to +20C

The events are often found in MCSs with a tropical-like moist atmosphere. Events are occurring with equal frequency over land and water. A majority of the events tropical and subtropical regions, but they can occur anywhere convection is found. The temperature profiles are 5 to 20C warmer than ISA during events showing that this is a warm season or warm climate phenomena. The events recorded in 2008-2010 in the USA occurred in remnants of hurricanes and tropical storms.

10.3 Storm cloud top temperatures

Typically from -55C and colder (elevations above typical cruise altitudes)

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

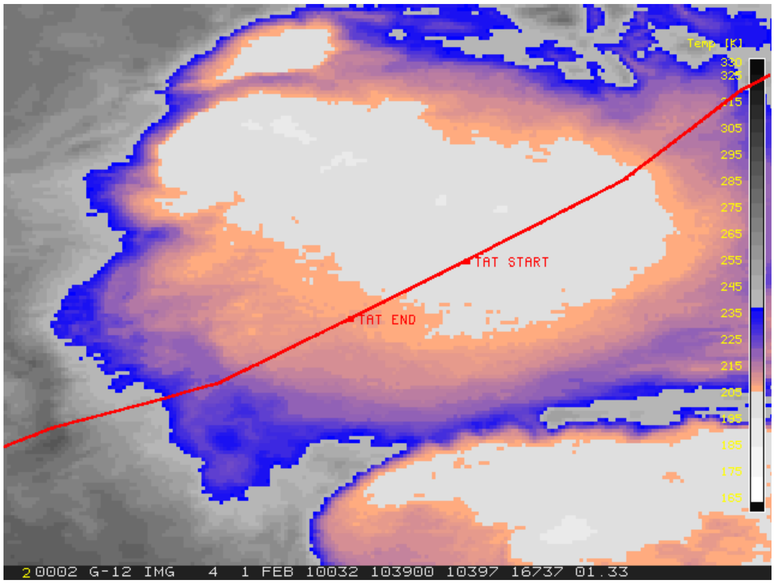

Figure A: Enhanced infra-red satellite image showing clouds at or above the tropopause in grey and white colors. The airplane track is shown in red. An engine damage event occurred during a TAT anomaly, noted by TAT start and TAT end notations. In the flight deck, the flight crew observed an auto-throttle disconnect associated with the TAT anomaly.

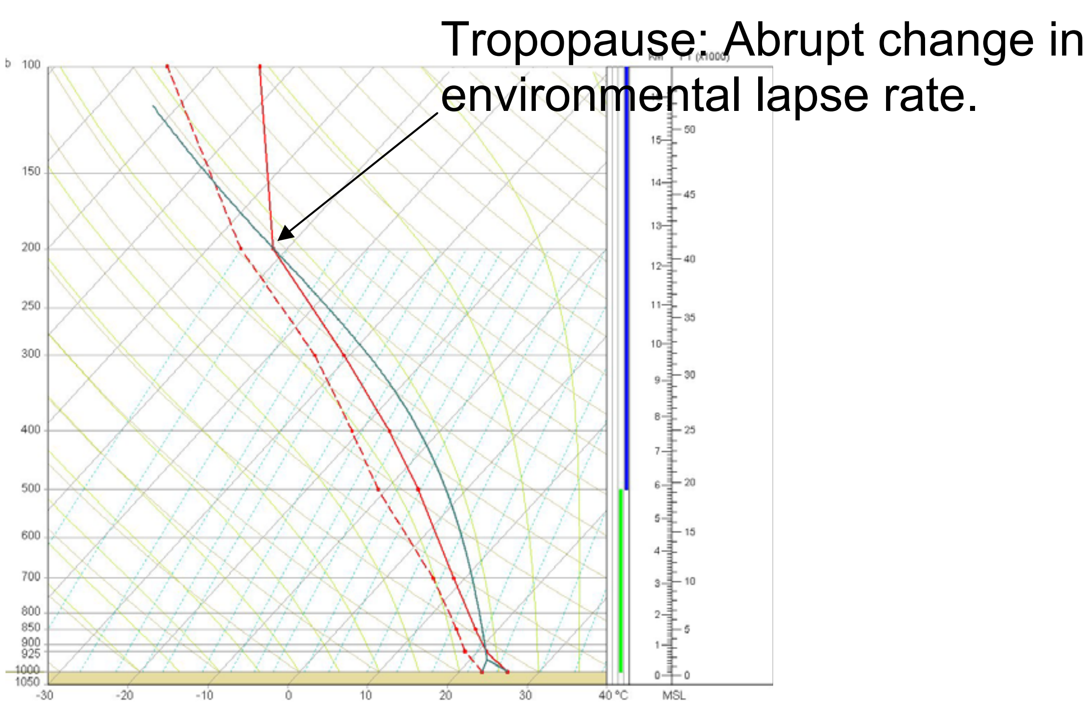

Figure B: An average sounding compiled from engine power loss and damage events up through 2009

10.4 Moderate and/or Heavy rain below the freezing level (> 30dbz)

Radar data from events show that below the aircraft there was heavy rain identified by greater than 5.5 mm/hr (30 dBZ) or amber or red on the on board weather radar (1 mm/hr = 23 dBZ, 10 mm/hr = 37 dBZ, and 100 mm/hr = 50 dBZ)

10.5 From the flight deck: Little or no radar at flight level (<20dbz)

Little to no radar reflectivity is typically detected at flight level during events. Reflectivity values have ranged from 10-25 dBZ at the engine event altitudes. Pilots can only detect 20+ dBZ, which make these areas mostly transparent to pilots.

10.6 Be aware of CAPE, Lifted Index* and Precipitable Water* values along the route*

A study of environmental parameters indicates engine events occur with moderate instability (median CAPE of 1,141 J/kg & median lifted index of -3.7), high moisture (median precipitable water of 2.3") The highest risk areas will be MCS's that occur within an environment that has PW values of 2" or greater.

10.7 Guidance for flight crews:

Avoid flying over the deepest convection in IMC, at temperatures below freezing. Pilots should also be advised to avoid flying down shear from convective cells in-cloud, at temperatures below freezing, especially if light returns (20-29 dBZ on aircraft weather radar).

10.8 Summary of Key Points for Dispatchers

- MCS with clouds over tropopause height 180km in size
- ISA +5 and greater
- Cloud top temps < -55
- Moderate and/or Heavy rain below the freezing level (> 30dbz)
- Precipitable Water values of 2" or greater

Forecasters should be aware of any MCS's along the route and minimize (or avoid) routes through enhanced cold cloud top regions.

10.9 What the flight crews will notice and actions to take

- Little or no radar at flight level (<20dbz)
- Amber and red returns below the flight level

Advise pilots to tilt radar down and scan below airplane. Highest risk areas will have a combination of heavy rainfall below aircraft (likely no returns at flight level) and enhanced infrared region on satellite within MCS.

10.10 Glossary*

Tropopause: The boundary between the troposphere and stratosphere, usually characterized by an abrupt change of lapse rate. The change is in the direction of increased atmospheric stability from regions below to regions above the tropopause. Its height varies from 15 to 20 km (9 to 12 miles) in the Tropics to about 10 km (6 miles) in polar regions. In polar regions in winter it is often difficult or impossible to determine just where the tropopause lies, since under some conditions there is no abrupt change in lapse rate at any height. It has become apparent that the tropopause consists of several discrete, overlapping "leaves," a multiple tropopause, rather than a single continuous surface. In general, the leaves descend, step-wise, from the equator to the poles.

Mesoscale Convective System (MCS): A cloud system that occurs in connection with an ensemble of thunderstorms and produces a contiguous precipitation area on the order of 100 km or more in horizontal scale in at least one direction. An MCS exhibits deep, moist convective overturning contiguous with or embedded within a mesoscale vertical circulation that is at least partially driven by the convective overturning.

Convective Available Potential Energy (CAPE): The maximum energy available to an ascending parcel, according to parcel theory. On a thermodynamic diagram this is called positive area, and can be seen as the region between the lifted parcel process curve and the environmental sounding, from the parcel's level of free convection to its level of neutral buoyancy.

Lifted Index (LI): is the temperature difference between an air parcel lifted adiabatically Tp(p) and the temperature of the environment Te(p) at a given pressure height in the troposphere (lowest layer where most weather occurs) of the atmosphere, usually 500 mb. When the value is positive, the atmosphere (at the respective height) is stable and when the value is negative, the atmosphere is unstable.

Precipitable Water: is the depth of the amount of water in a column of the atmosphere if all the water in that column were precipitated as rain. As a depth, the precipitable water is measured in millimeters or inches.