The Ice Crystal Weather Threat to Engines

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The Ice Crystal Weather Threat to Engines

Agenda

- Introduction
- Engine power loss associated with high-altitude ice crystal weather – event data
- Weather description
- Global view of engine events
- Ice particle accretion mechanism in the engine
- Industry activities and challenges
- Summary

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Introduction

- High-altitude ice crystals in convective weather are now recognized to be a cause of engine damage and engine power loss
- This issue affects multiple models of aircraft and engines
- Over 90 events in an industry database 1989-2003
- Leading cause of icing-related power loss
- Power loss – engine surge, stall, flameout or rollback
- Blade damage in some events – tip curls and tears

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High-Altitude Ice Crystal Icing

- High-altitude water is likely to be frozen ice particles rather than super-cooled liquid drops
- Previously, the term “icing conditions” has always been used to refer to conditions where super-cooled liquid drops adhere to cold airframe surfaces – typically altitudes 22,000 feet and below
- “Ice crystal icing” does not affect cold airframe surfaces, only some engine surfaces
- Now believed that ice crystal icing can occur deep in the engine where surfaces are warmer than freezing

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Initial Investigations of Engine Events

- A confusing array of pilot reports with seemingly contradictory information initially misled investigators
- Events usually in the vicinity of thunderstorms or convective storms
- No reports of airframe icing, but rain or heavy rain at very cold temperatures led early investigators to conclude rain, not conventional icing as the cause of many events
- A temperature anomaly initially interpreted as a meteorological phenomenon
- Reports of light-to-moderate turbulence, no radar echoes at event location not consistent with flight through convective core
- Only one event at -40C where supercooled liquid water is not possible
- A mechanism for ice-particle ice accretion not understood

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The Connection of Engine Events to Ice Crystals

- One commuter aircraft type suffered engine rollback events at altitudes between 28,000 – 31,000 feet
- Extensive investigation including flight-testing led to the understanding that ice particles were accreting on warm surfaces in the engine core
- Weather instrumentation conclusively established that the condition that led to engine rollback was a high concentration of ice crystals
- Industry icing committee in 2003 compared the commuter aircraft events to the large transport events
- The industry now recognizes that high-altitude large transport engine events are most likely due to ice-particle icing

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Similarities between Commuter and Large Transport Aircraft Events

1. High-altitude, cold temperature
2. Aircraft in the vicinity of convective clouds/thunderstorms
3. Significantly warmer than standard atmosphere
4. Visible moisture
5. Light-to-moderate turbulence
6. Precipitation on heated windscreen, often reported as rain
7. Aircraft total air temperature (TAT) probe anomaly
8. Lack of observations of significant airframe icing
9. No pilot reports of weather radar returns at the event location (only large transport aircraft pilots queried)

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Weather Connected to Engine Ice Crystal Icing Events

- Convective weather containing ice crystals – isolated cumulonimbus or thunderstorms to squall lines and tropical storms
- Deep convective clouds lift high concentrations of water thousands of feet into the atmosphere
- In a warm atmosphere at the earth's surface, the clouds can contain more water which can be lifted to high altitude
  – Measurements up to 8 g/m^3. The certification standard for supercooled liquid water for engines is 2 g/m^3
- Ice crystals exist from temperatures just below freezing to well below -40C
- Away from the core of the storm, in the anvil, ice particles have been measured to be very tiny – the particle size of baking flour

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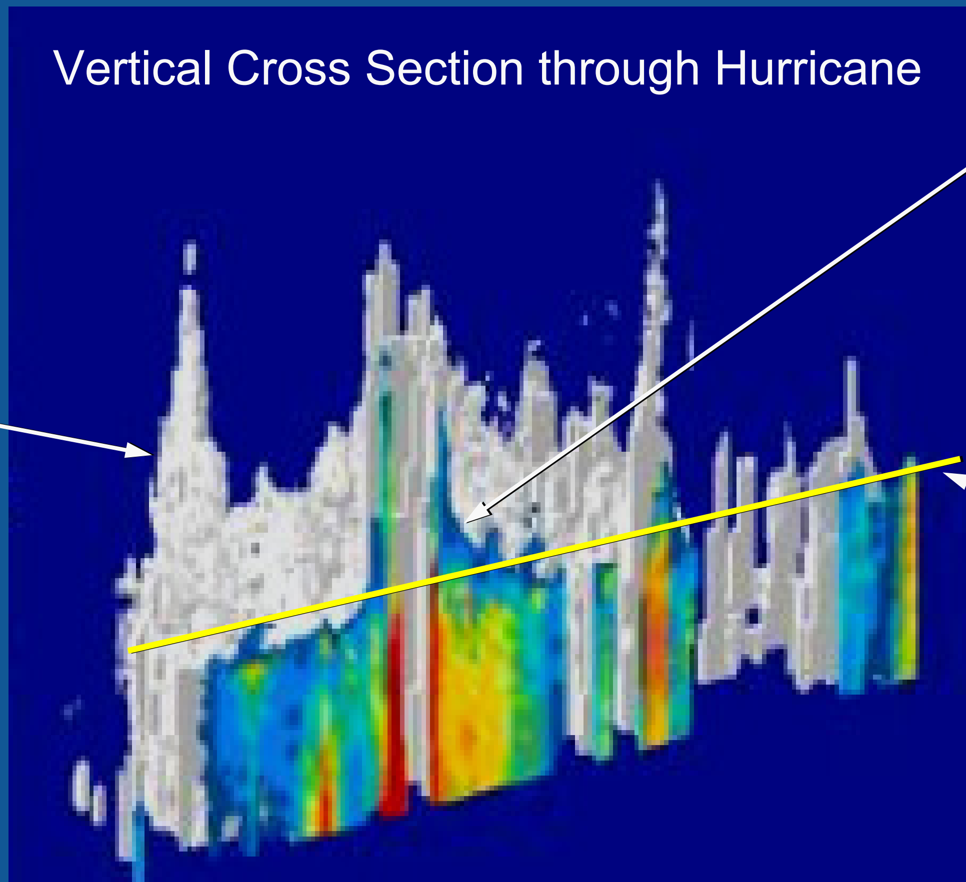
Satellite/Radar Can Detect Ice Crystals

NASA TRMM Satellite/Radar Combined Space-borne Sensors Show The Nature Of A Convective Storm

White indicates regions of particles with low reflectivity such as ice crystals



Region of high reflectivity (heavy precipitation, hail)

Freezing level

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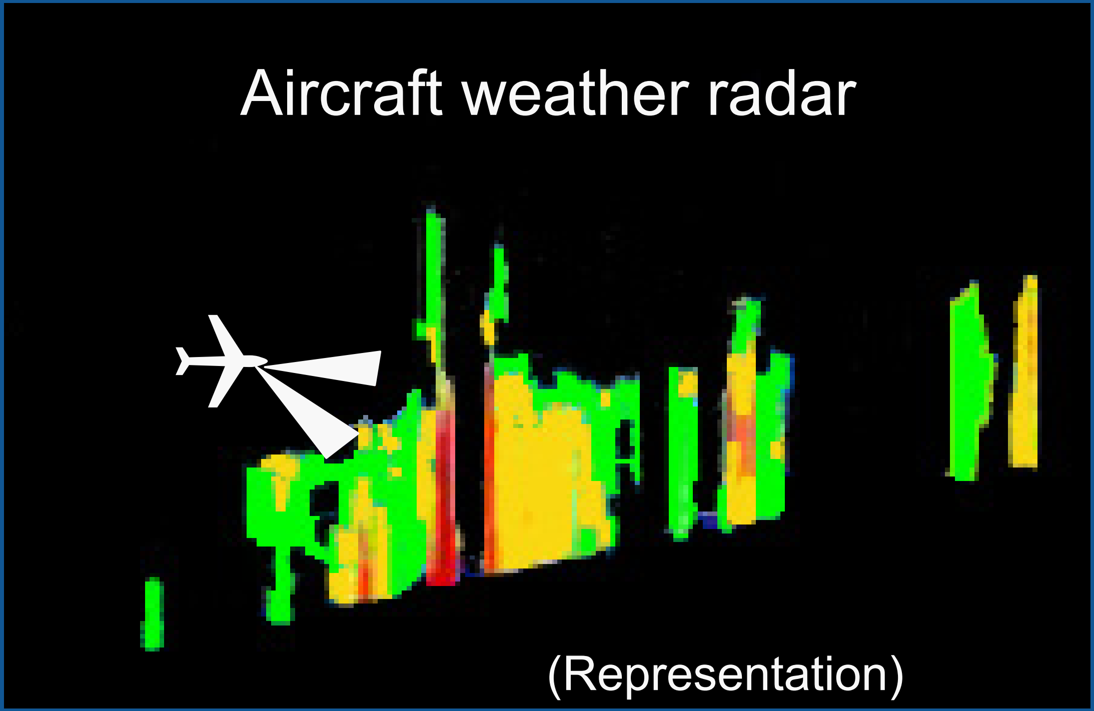
Satellite/Radar Can Detect Ice Crystals

- Flight in ice crystals will look like visible moisture, but will not produce significant aircraft radar returns
- Using tilt feature on radar should identify heavy rain below – a good indicator that dense ice crystals may exist above



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Recommendations for Flight Near Convection

- It is not practical to avoid all ice crystal conditions; crystals may not be detected by aviation radar
- Normal thunderstorm avoidance procedures may help avoid regions of high ice crystal content
- These include:
  - Plan a flight path that avoids storm cells by at least 20 nautical miles
  - Fly upwind of the storm
  - Avoid flying over a storm cell. A fully developed thunderstorm can reach altitudes of more than 50,000 feet
  - Even when there are no radar returns, there may be significant moisture in the form of ice crystals at high-altitudes
  - Utilize the radar antenna tilt function to scan the reflectivity of storms ahead. Recognize that heavy rain below likely indicates high concentrations of ice crystals above

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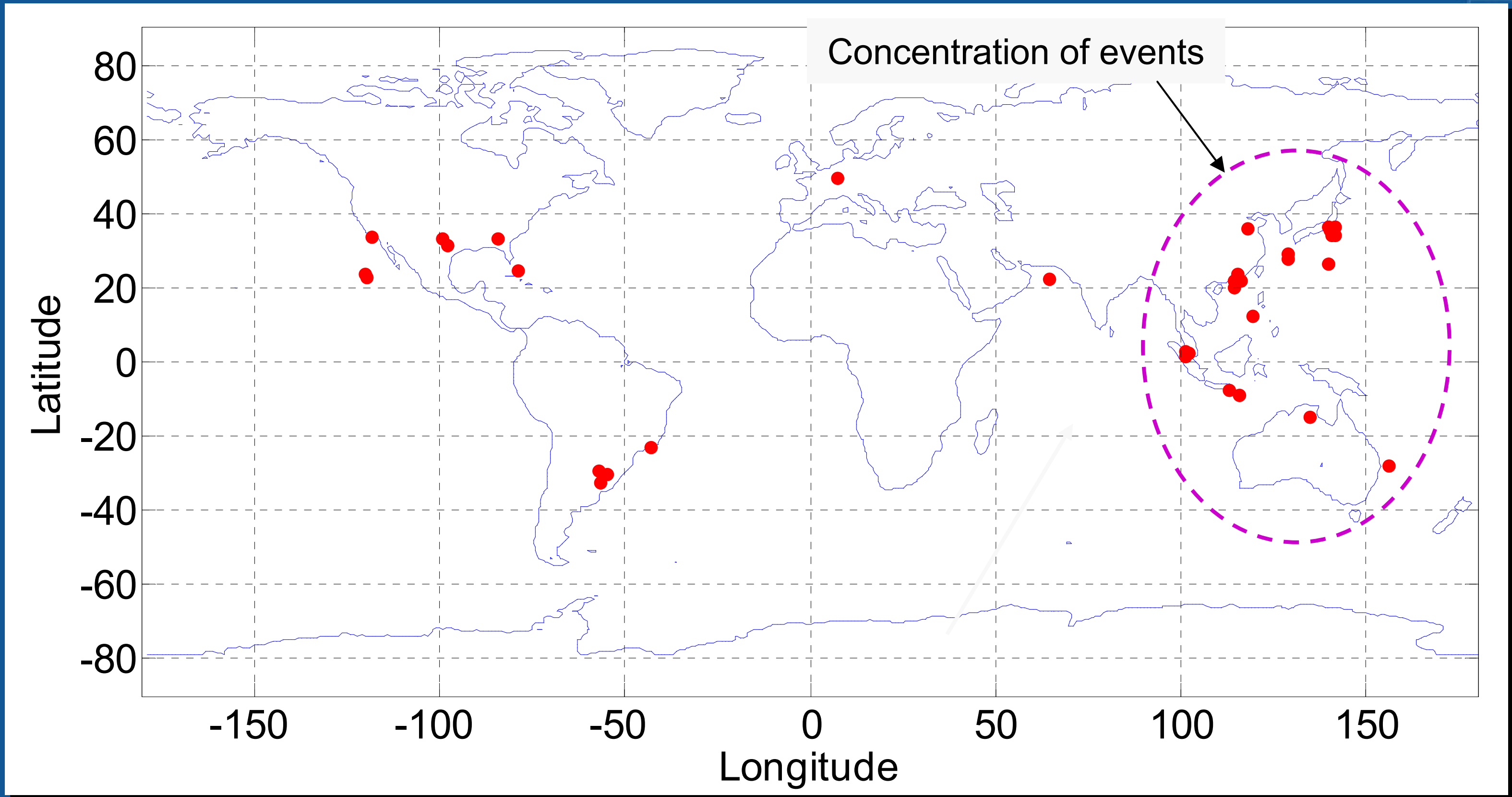
Global View of Engine Powerloss Events

- There is large concentration of events in the Asia Pacific region – this may be due to the fact that the highest sea surface temperatures are also found in this region



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Ice Crystal Accretion in an Engine

- Frozen ice crystals bounce off cold surfaces; thus airframe icing is not noticed during aircraft operation in high-altitude ice crystals
- The physics of ice crystal accretion in the engine is not completely understood, but the accretion mechanism is thought to be:
  - When ice particles enter the engine and bombard a warm surface, a mixture of liquid and ice particles can 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 accretion 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

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TAT Anomaly

- Total air temperature (TAT) anomaly has occurred in many cases near the time of the engine power loss events
- The airplane total air temperature probe (TAT) erroneously reporting zero degrees C is known to be evidence of ice crystals in the atmosphere
- This anomaly is due to ice crystals building up in the area where the thermocouple resides, where they are partly melted by the heater, causing the zero degrees 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 not a reliable-enough 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 not to be a contributor to the power loss events. Under these conditions, the engine control compensates for loss of TAT

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Industry Challenges – Designing a Robust Engine

- Zones of high ice particle concentrations are not easily identifiable by pilots
- High concentrations of ice particles are being penetrated, even those storms being tracked by meteorological agencies
- The most effective solution is to make the engine capable of flight in these conditions
- Experimental data characterizing the ice crystal environment is limited – flight measurements are needed
- Test methods for creating representative ice particles do not exist
- Facilities for testing engines in these conditions do not exist
- The ice particle accretion and shedding mechanism is not fully understood

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Industry Committee Activities

- Development of Regulatory Requirements:
  - – Created Appendix D to Engine Certification FAR Part 33 – ice crystal envelope – similar to Appendix C, built with theory and experimental data
  - – Wrote draft rules for engine compliance to ice crystals
- Technology Plan developed to address unknowns:
  - – Improved instrumentation to measure atmosphere
  - – Flight trials to characterize atmosphere (understand particle size, concentration and extent)
  - – Fundamental physics of ice accretion and shedding
  - – Test methods and facilities
- Government/Industry partnerships needed to fund this work

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Communication

- Most of what we currently understand about the environment associated with engine events is based on pilot reports and flight data
- More pilot reports of high-altitude ice particle encounters (with or without engine events) would be valuable to:
  - Make sure our hypotheses about of the conditions associated with engine events continues to be supported by flight data
  - Make sure the flight program is directed into the appropriate flight conditions
  - Help develop cues for these flight conditions
- Boeing is considering publishing a tech bulletin summarizing ice crystal weather conditions that are associated with engine power loss – would appreciate airline feedback

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Summary / Conclusions

- Ice crystal icing conditions have been recognized as a hazard to turbofan engines
- Ice can accrete deep in the engine core where temperatures above freezing exist prior to the cloud encounter
- More detailed research on characterizing the atmospheric conditions and on the thermodynamic processes of ice accretion in the engine are needed
- Airline awareness of the potential for ice-particle icing on all airframes may provide additional information which will help Boeing and the industry understand this phenomenon

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Appendix

- DO NOT PRINT THE LAST THREE DOCUMENTS IN THE BOOK, KEEP FOR THE PRESENTATION

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Case Study of an Engine Event

- Aircraft on descent into Taipei, weather and TAT anomaly immediately encountered at 38000 ft (-42C), moderate turbulence, and some lightning in vicinity
- Brief power loss event occurred at 30,000 ft – engines restarted quickly
- Pilot reported heavy rain at -25C
- No radar echoes at the altitude and location of the aircraft
- Ice Detector – no response – indicative no super-cooled liquid present
- Rain on windscreen – tied to particles melting, later confirmed by pilot not rain

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Case Study of an Engine Event

- Figure shows heavy precipitation below aircraft altitude, obvious convection of fully developed typhoon
- Lack of radar echoes on pilot’s radar consistent with lack of rain, and with small ice particles at aircraft altitude