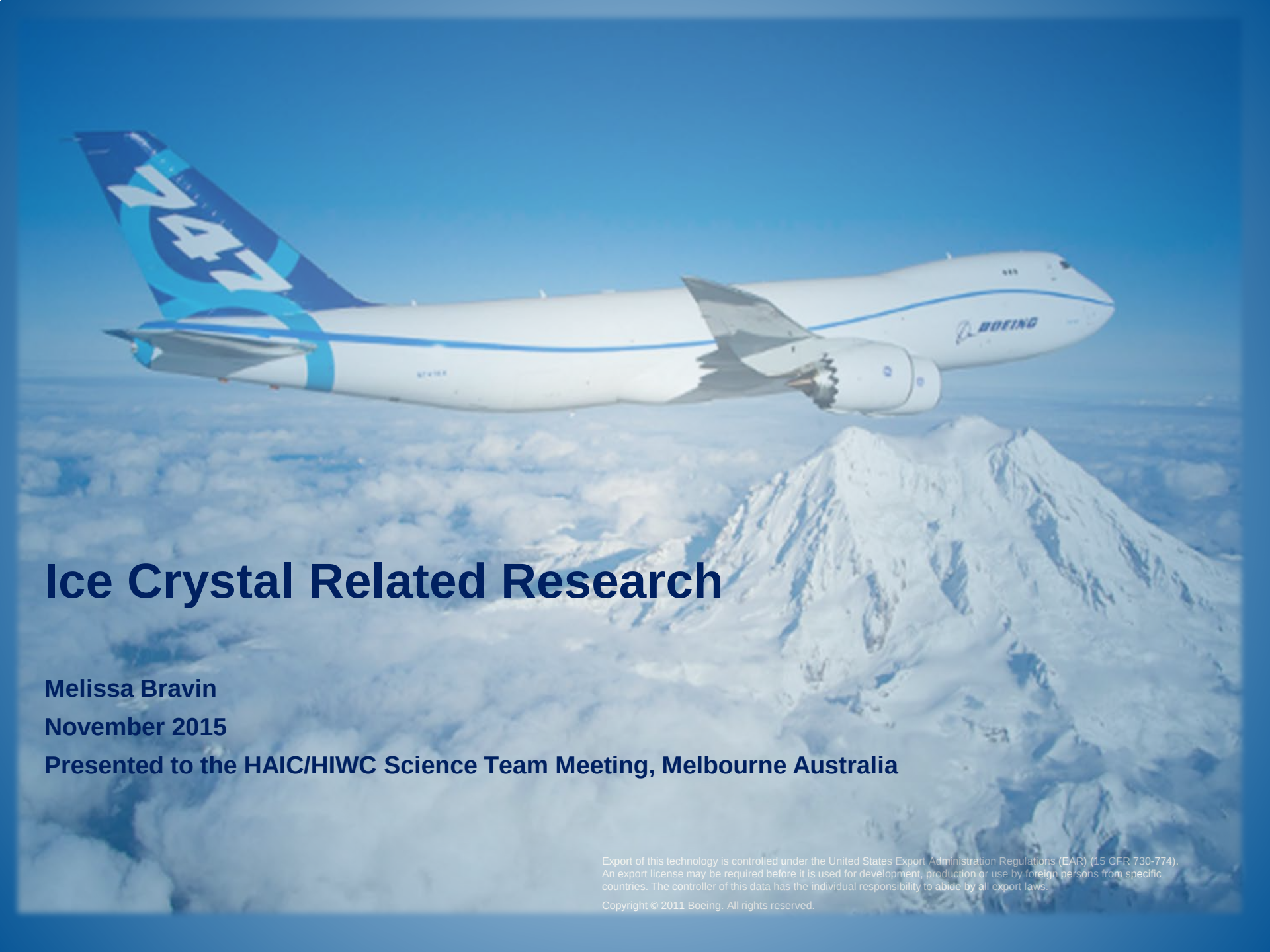


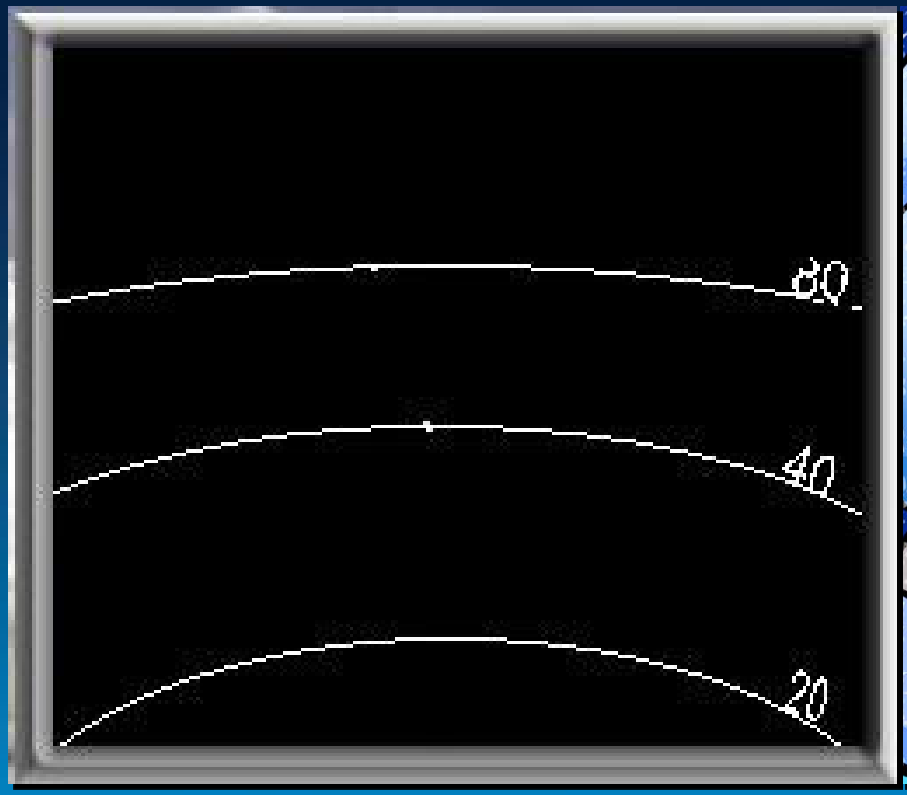
Ice Crystal Related Research

Melissa Bravin

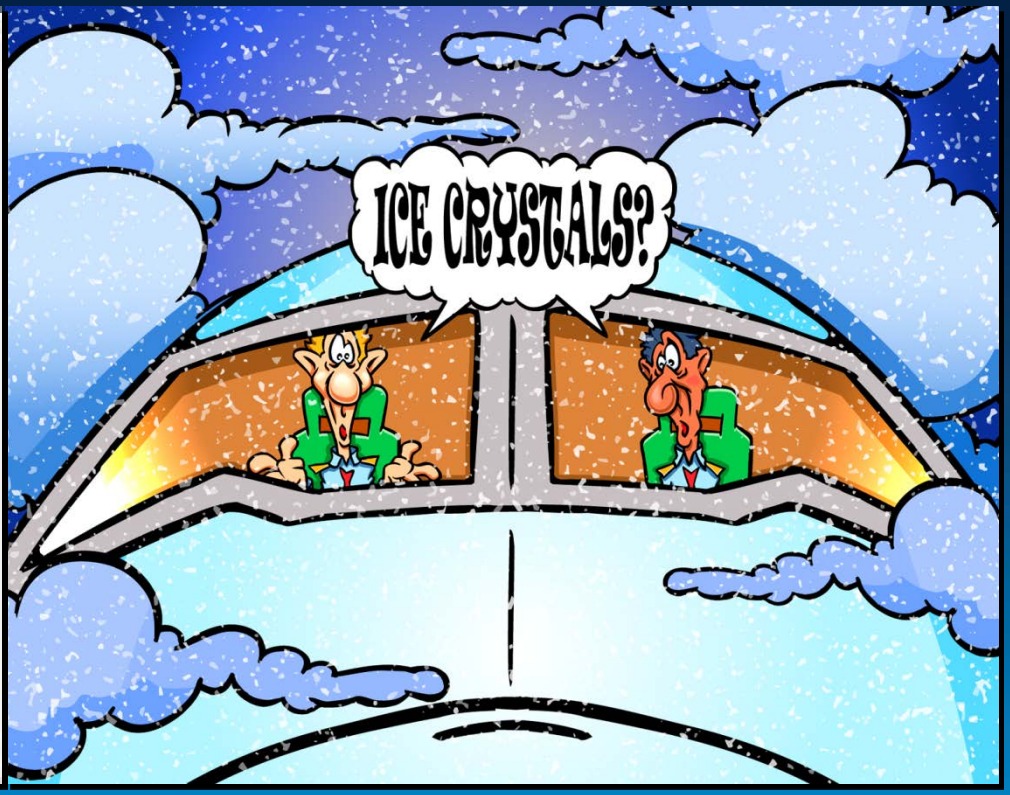
November 2015

Presented to the HAIC/HIWC Science Team Meeting, Melbourne Australia

Ice Crystal Icing – View From the Flight Deck



Weather radar



"I did not fly through a Mesoscale Convective System"

The Ice Crystal Weather Threat to Engines

Initial Investigations of Engine Events

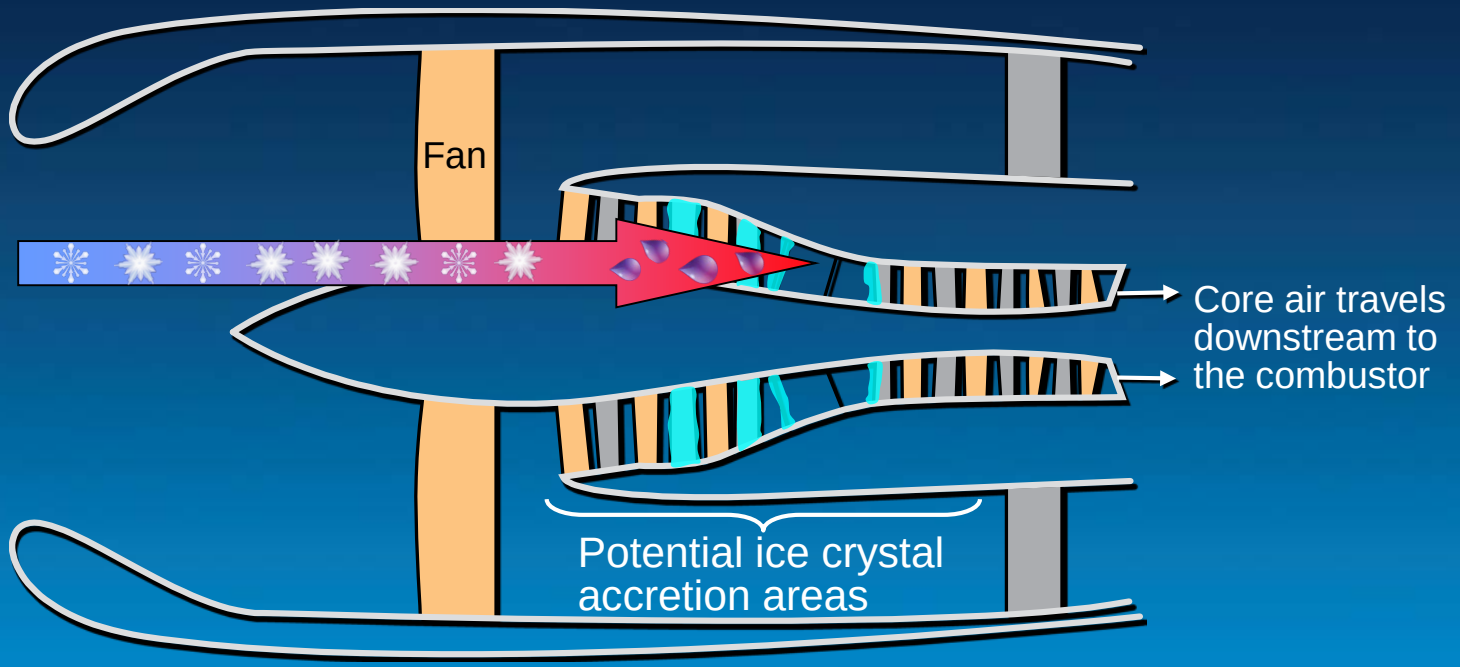
A wide range of pilot reports required detailed correlation:

- 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 the time colder than -40°C, where supercooled liquid water is not possible
- A mechanism for ice-particle ice accretion not understood

What Is Ice Crystal Icing?

The physics:

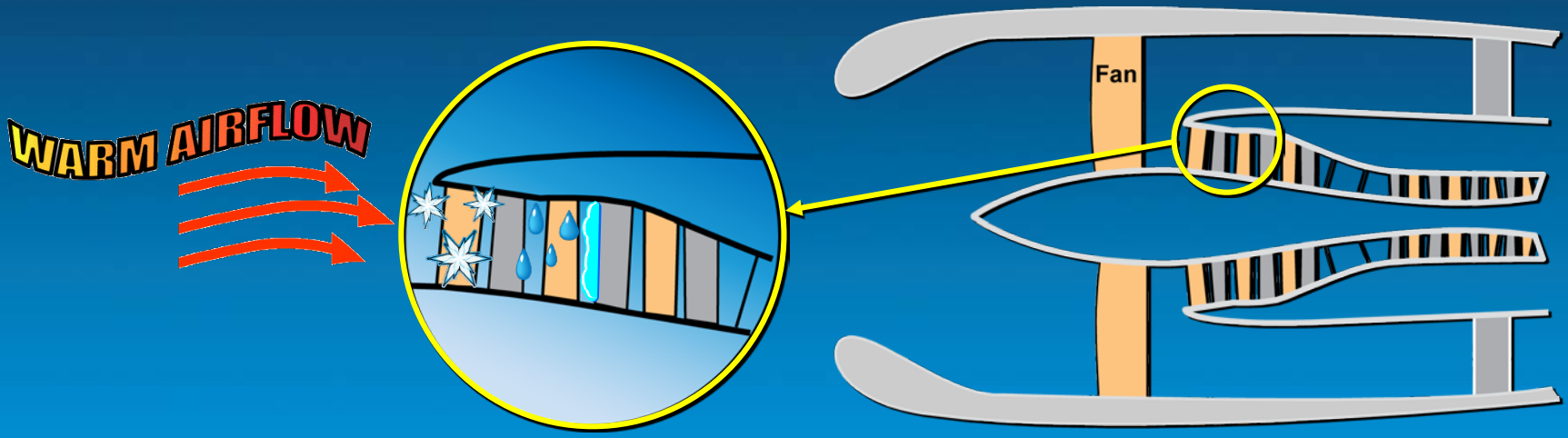
- Crystals can form ice on engine surfaces warmer than freezing
- These warm engine surfaces are in the compressor aft of the fan



Ice shed from compressor surfaces can cause engine instability

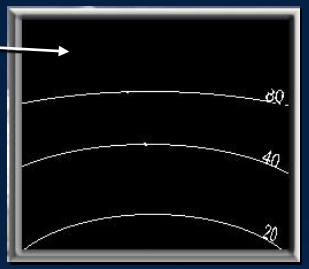
What is Ice Crystal Icing? (continued)

- Frozen ice crystals impinging on a warm surface in the engine
- Some crystals melt, wetting the surface
- Crystals impinging on wetted surface stick, cool the surface to 0°C
- Ice begins to form
- At high altitude, ice can form deep in the engine core



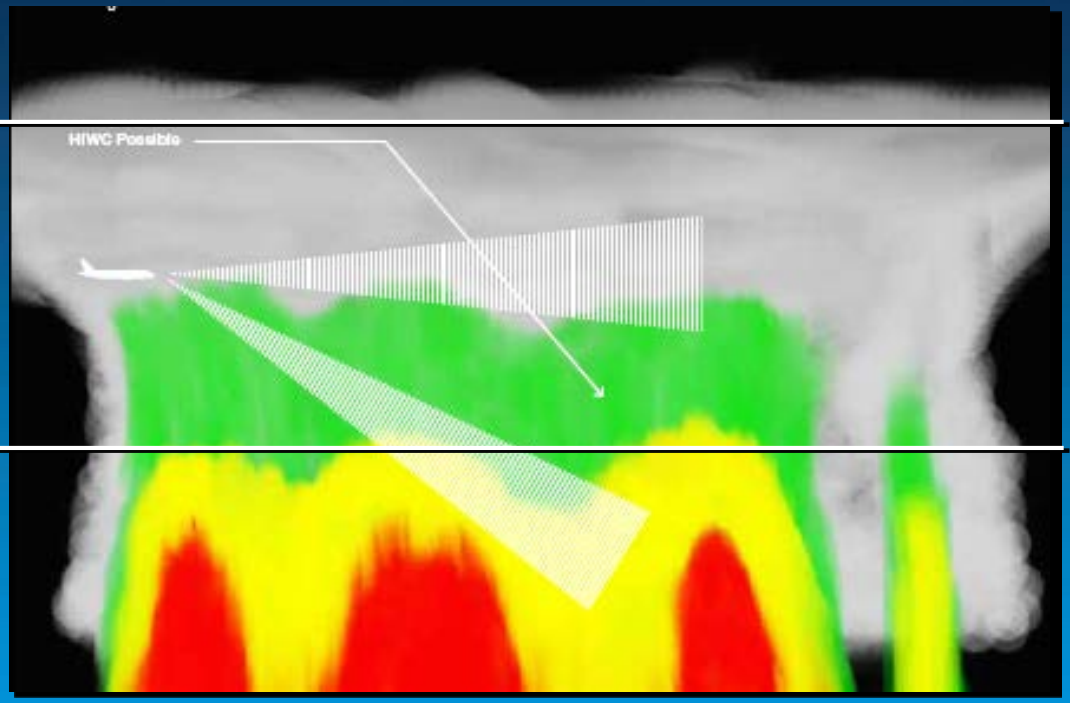
Ice Crystal Characteristics

- 80% of all events - little or no returns at flight level
- Amber and red returns below the aircraft
- Low updraft velocity, light to moderate turbulence
- Aircraft in deepest (tallest) part of the cloud
- Clouds can spread out hundreds of miles



Tropopause

Freezing level



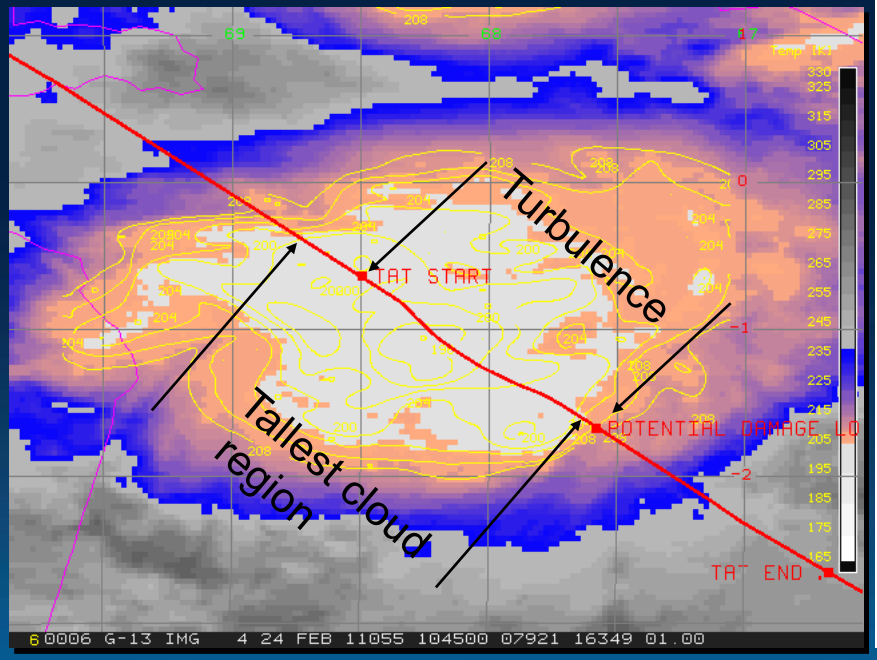
Many engine events occur ***without*** flight-level weather radar returns

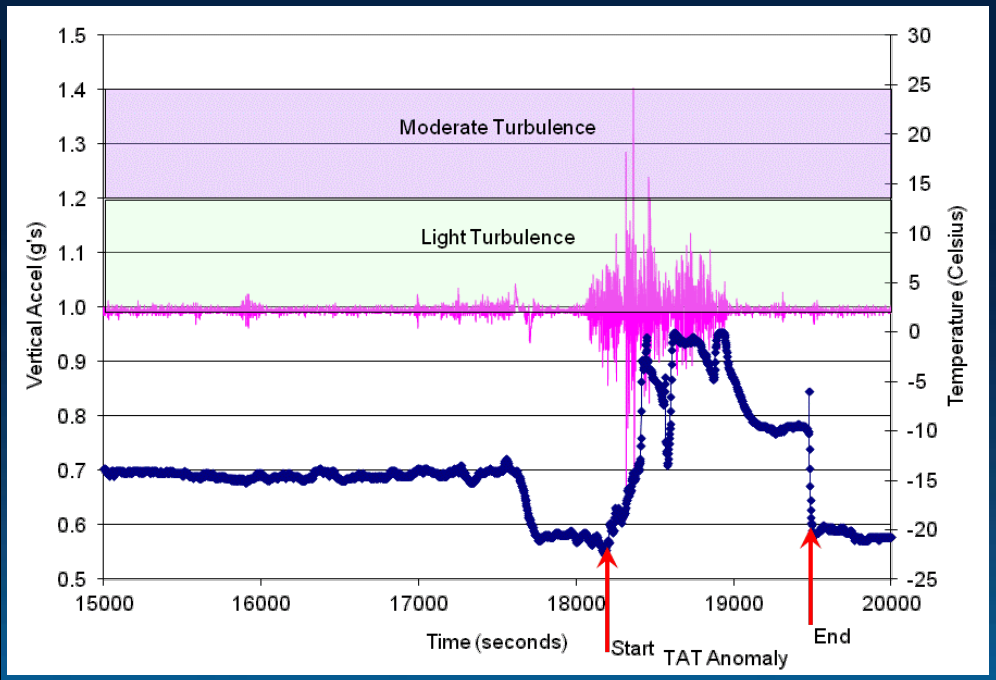
Ice Crystal Icing Reports from the Flight Deck

Conditions Reported

- Speckled green on weather radar
- Rain on the windscreen
- Small collection of ice particles on wiper post
- “Shhh” sound
- Erroneous TAT near zero
- Humid cockpit
- Ozone smell
- No engine changes

“Satellite” Weather Analysis: A Recent Event





- Traversed 195 km/ 105 mi through tallest cloud region
- Pilots reported no radar returns at flight level
- Moderate turbulence at onset of TAT anomaly
- Engine performance shift

Typically, clouds which cause events are about 100 nmi/185km in diameter

General Statistics From Current Database

- Latitude 32°S - 52°N, with 92% contained within the tropical and subtropical latitude band
- Generally warmer than the FAR Part 25 Appendix C temperature-altitude envelope
- Update from 46 to 162 cases
- High occurrence of events associated with tropical oceanic airmasses (‘oceanic convection’)

Year	SAT	Altitude
2006	-55°C to -10°C, median -21°C	FL115-FL390, median FL258
2015	-58°C to -3°C, median -36°C	FL110-FL450, median FL350

International Collaboration on Ice Crystal Icing Began in 2003

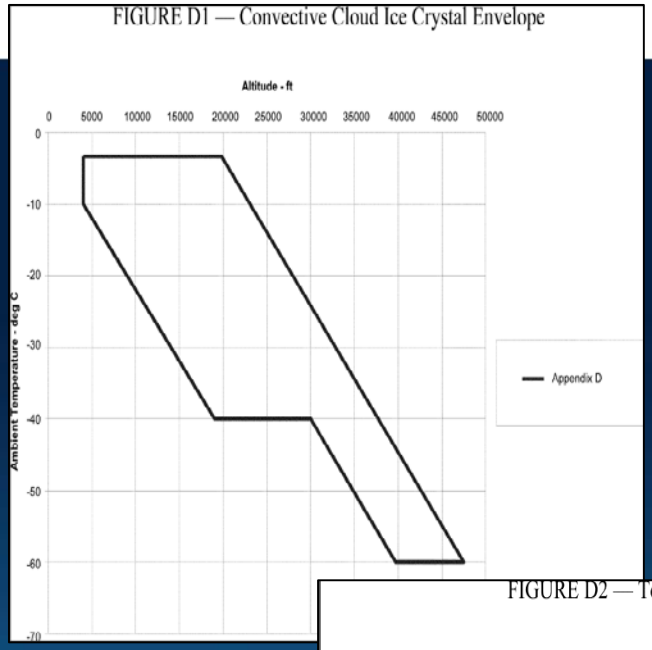
- Engine Harmonization Working Group was formed with engine manufacturers, airplane manufacturers, FAA, CAA and Transport Canada members
- Tasked by the NTSB to develop draft rules for SLD and Mixed Phase Icing
- Developed a database of 222 events related to engine (turbojets, turbofans, turboprops) icing for years 1989-2003
- Glaciated/Mixed phase events were determined to be the leading cause of icing-related engine powerloss
- Developed draft regulations and advisory material, as well as an environmental envelope defining the ice crystal threat – Appendix D to FAR 33

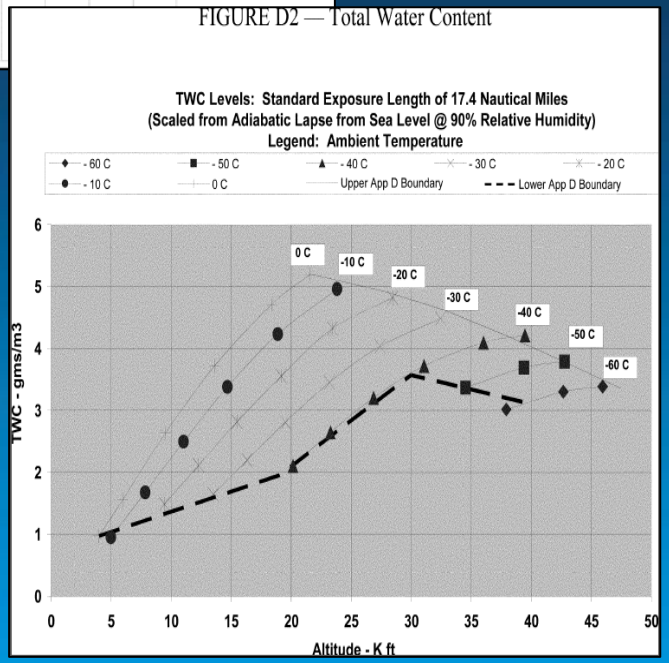
Industry Efforts to Address the ICI Technology Gap

- EIWG Developed a technology plan with four areas of research:
  - Improve instruments for measuring ice crystal icing in the atmosphere
  - Collect in-situ cloud data characterizing the ice crystal environment
  - Perform research on engine ice crystal accretion and shedding
  - Develop engine test facilities representative of flight environment

Appendix D/P Evaluation and Need for Additional Research

- FAA and EASA have established new rules for icing certification including a new ice crystal envelope
  - FAA: Appendix D to CFR Part 33
  - EASA: Appendix P to CS 25
- The new standard was built from a conservative evaluation of Total Water Content (TWC) from flights the 1950s and adiabatic TWC maxima
- More information is needed about TWC, particle size, and exposure distance for compliance
- FAA and EASA will assess the Appendices based on data from in-situ cloud measurements currently underway (HAIC-HIWC Project and potentially others)
- Boeing database was instrumental in design of flight strategies to collect data



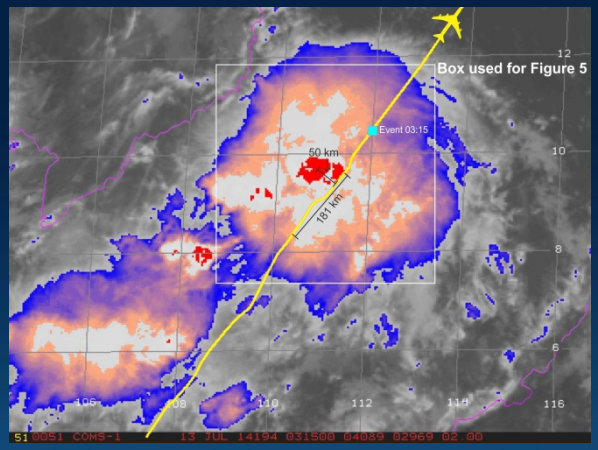


Figures D1 & D2 are from FAA Rule, Document # 2014-25789

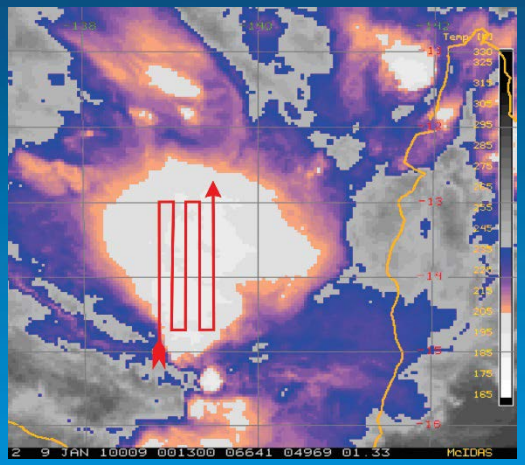
New Cloud In-Situ Measurements

- Several exploratory and primary-data-collection in-situ flight programs have now been completed by European, North American, and Australian partners (following presentation)
- Design of flight programs have been guided by Boeing engine event data base.
- Data will be used for evaluation of Appendix D, but also provides a rich data set for scientific research

HIGH IWC Flight Plans



Engine event case study, Bravin et al. 2015



Idealized measurement program flight plan , HIWC Science Plan

- Boeing engine event data base has described conditions that cause engine events (Mason et al. 2006, Grzych and Mason 2010, Mason and Grzych 2011, Bravin et al. 2015)
  - Long traverse through Large anvil reaching near tropopause (scale diameter ~ 100 nm)
  - High Precipitable Water
  - Flight over areas of heavy rain below
  - Proximity in time and location to peak of overshooting local cell

- HIWC flight plans (HIWC Science Plan) target clouds similar to those that cause engine events:
  - Large, deep tropical MCS as first priority, with scale diameter ~100 nm
  - Survey pattern around area of expected highest IWC (over heavy rain, near overshooting tops)

Science Opportunities

Unique Aspects of Flight Measurements:

- New bulk ice water content (IWC) probe developed for project
  - First time accurate measurements of IWC at high concentrations and high altitude
- Flight measurements in active cells of storms
  - previously very little in-situ information in such areas of clouds
- Measurements in high IWC conditions with relatively low radar reflectivity
  - A challenge to explain these conditions from current understanding of microphysical processes
  - Opportunity for discovery

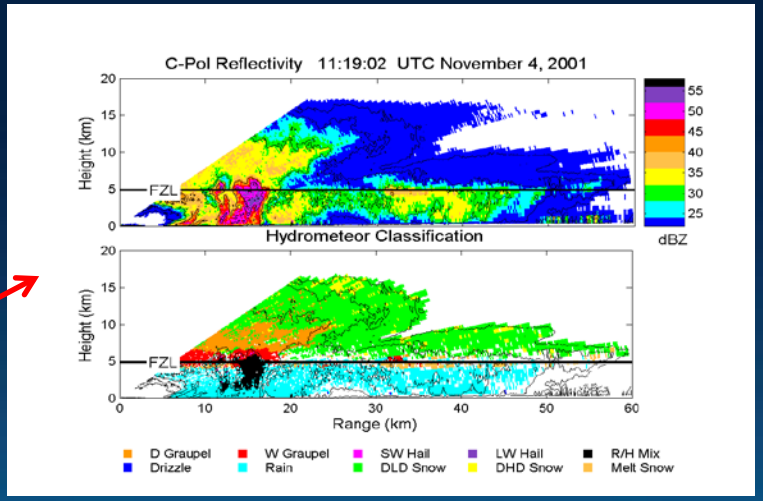
Exploiting HIWC Measurements for Science

HIWC Science Plan (est. 2007), overall topics:

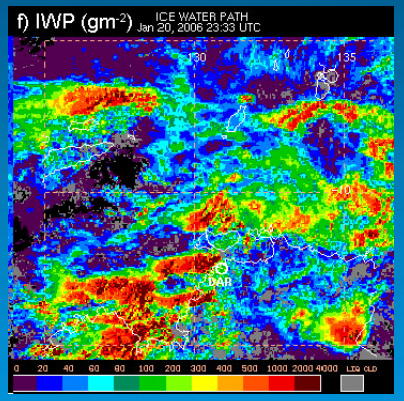
- Fundamental cloud physics processes
- Validation of remote sensing retrievals of cloud properties
- Development of HIWC nowcasting
- Improvement of numerical cloud model simulations

(e.g.)

Radar hydrometeor classification (BoM)



Satellite derived cloud products (NASA Langley)



Partnership of North American HIWC and European HAIC projects for Flight Measurements and Science

High Ice Water Content Project Major Partners:

- Federal Aviation Administration
- NASA Glenn Research Center
- NASA Langley Research Center
- NASA GISS
- Boeing
- Airbus
- Environment Canada
- Transport Canada
- National Research Council of Canada
- National Center for Atmospheric Research
- Australian Bureau of Meteorology
- Science Engineering Assoc.
- U. Illinois, U. Utah

High Altitude Ice Crystals (HAIC) Major Project Partners:

- Airbus
- Université Blaise Pascal
- Laboratoire Atmosphères, Milieux, Observations Spatiales (LATMOS)
- Service des Avions Français Instrumentés pour la Recherche en Environnement (SAFIRE)
- Meteo France
- Australian Bureau of Meteorology
- (HAIC has over **40 partners overall** in a broad program focused on ice crystal research for aviation)

Conclusions

- The discovery of an aviation-wide ice crystal icing issue has led to new icing certification regulations that have recently become law.
- A technical plan was adopted by an industry-government working group to address 4 primary issues related to ice crystal icing (instrumentation, cloud characterization, ice accretion physics, and development of ground simulation facilities)
- Regulatory agencies have requested new in-situ cloud characterization measurements to support new icing envelope.
- A multi-national multi-agency effort has been assembled to collect in-situ cloud data for this purpose. Several flight programs have been completed
- Science partnerships have been formed to exploit the unique flight data sets.

Thank you