

The Ice Particle Threat to Jet Engines in Flight, and a New High IWC Cloud Characterization Study

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Background

- ARMP experience in cloud microphysics measurements since mid-1970s – international reputation
- ARMP active in Aircraft Icing Projects since late 1980s – international reputation
- ARMP active in study widening aircraft certification envelopes since mid 1990s – IPHWG
- This presentation results from our activities in another form of aircraft icing research – jet-engine icing

Jet-engine icing

- Since early 1990s, passenger-carrying jets (all sizes) have been suffering engine powerloss events while flying near thunderstorms
- Engine events can range from momentary interruptions in power, to full engine shutdowns that require a manual restart - Multiple engine losses have occurred
- Thought to be related due to ingestion of high concentrations of ice particles (ARMP and other analyses) – unconventional form of icing – melting and refreezing in the engine
- ARMP worked with BAe Systems in the mid-1990s on BAe-146 jet engine icing problem – now known to be industry wide

Cost and Safety

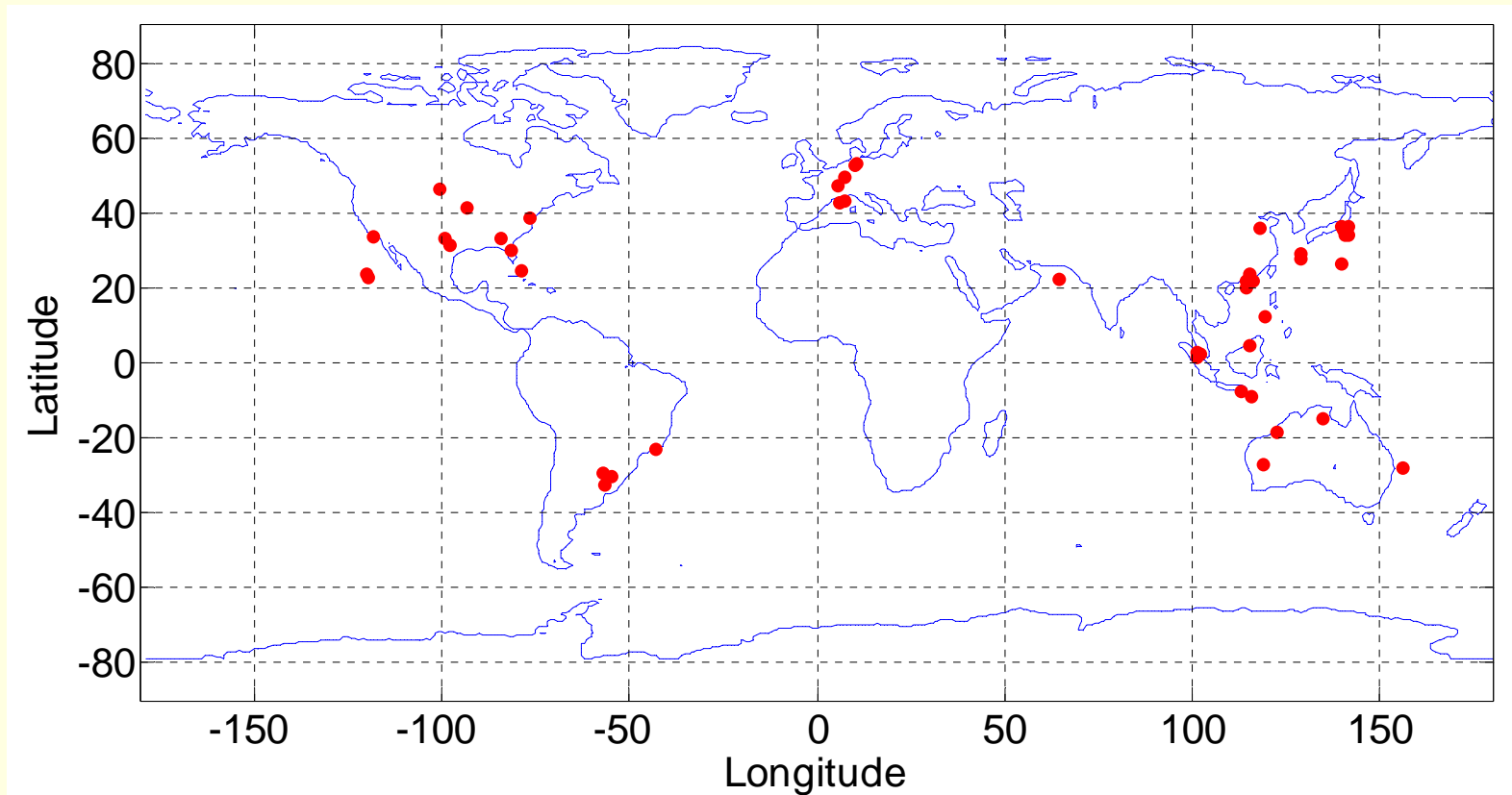
- Issue has caught the attention of Industry and Regulators – committee (Engine Harmonization Working Group) formed to make recommendations
- Damage to engines > \$100K
- One 4-engine complete powerloss – engines turned back on 1500' above the ocean
- One recent complete engine powerloss resulted in landing without engine power in Florida
- FAA Icing Specialist has stated that they consider these events to be the “precursor to a catastrophic accident”

Engine Harmonization Working Group

- International Group to recommend to the Ice Protection Harmonization Working Group a plan to remedy engine icing
- Environment Canada
- NASA
- FAA
- Transport Canada
- National Research Council of Canada
- SMECMA
- The Boeing Co.
- Airbus Ind.
- Pratt and Whitney Engines
- Honeywell Engines
- General Electric Engines
- Rolls Royce Engines

Location of engine events

- high frequency of events in southeast Asia

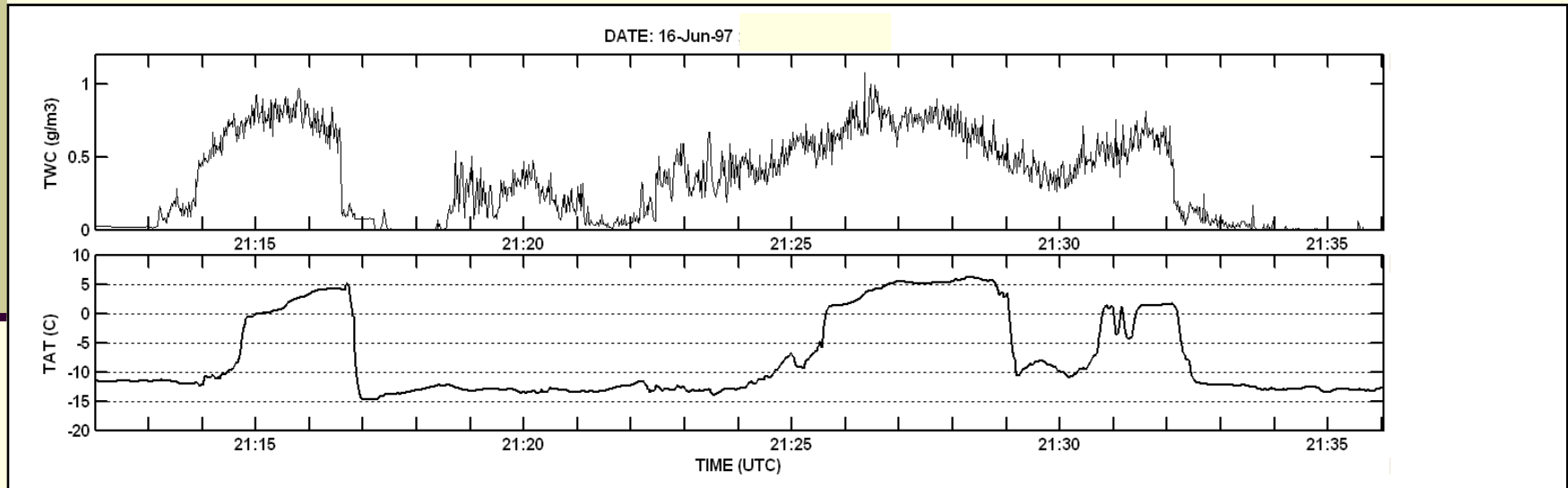


Observations about meteorology

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

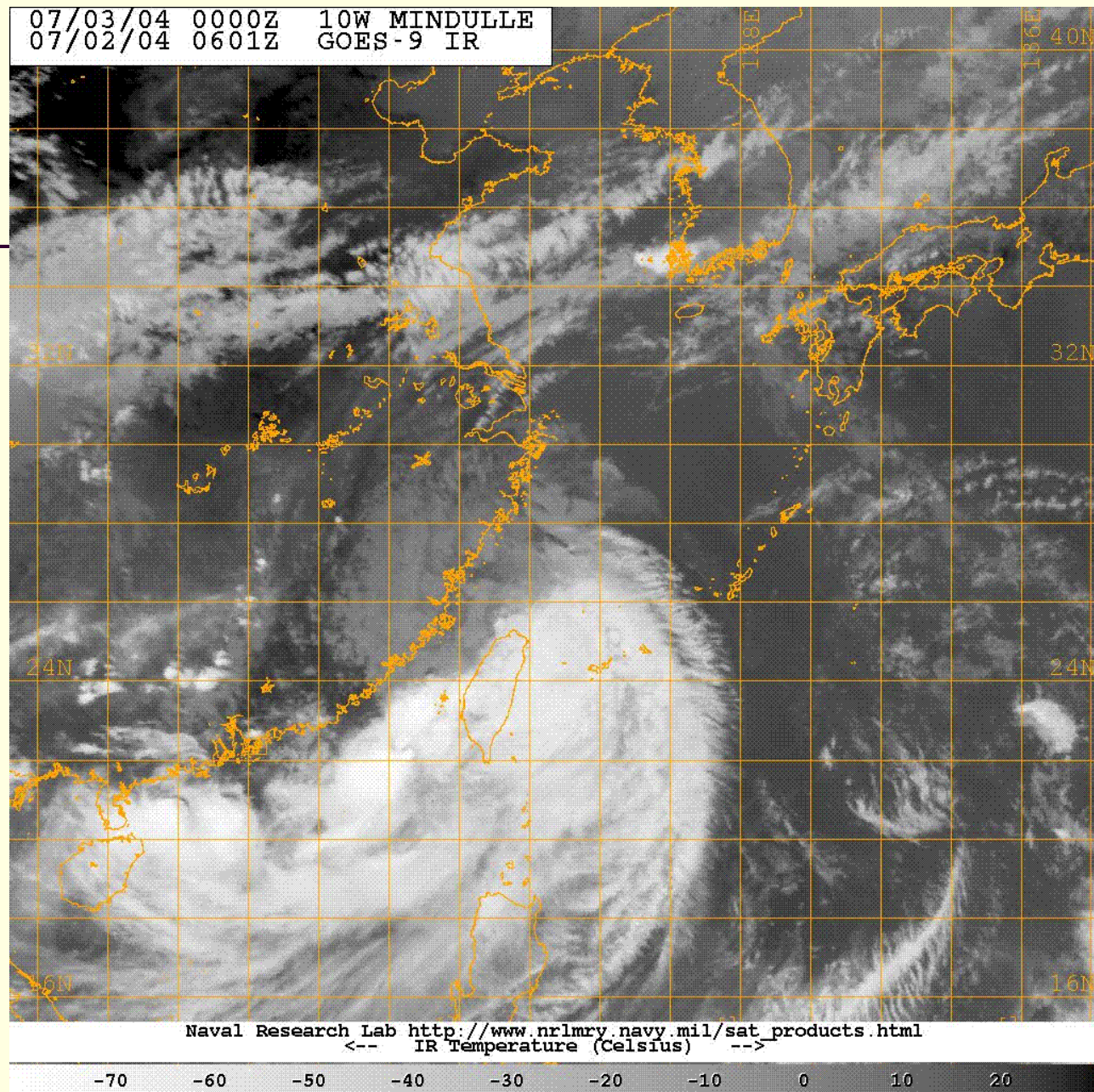
TAT anomaly

- Error in TAT measurement thought to be caused by ice particle collecting and blocking the airflow through the probe
- In commuter event below (glaciated cloud -26 C), occurs within 60 s of IWC exceeding 0.5 gm^{-3} , and clears within 30 s of IWC falling below 0.5 gm^{-3}
- Good cue for flight in high IWC



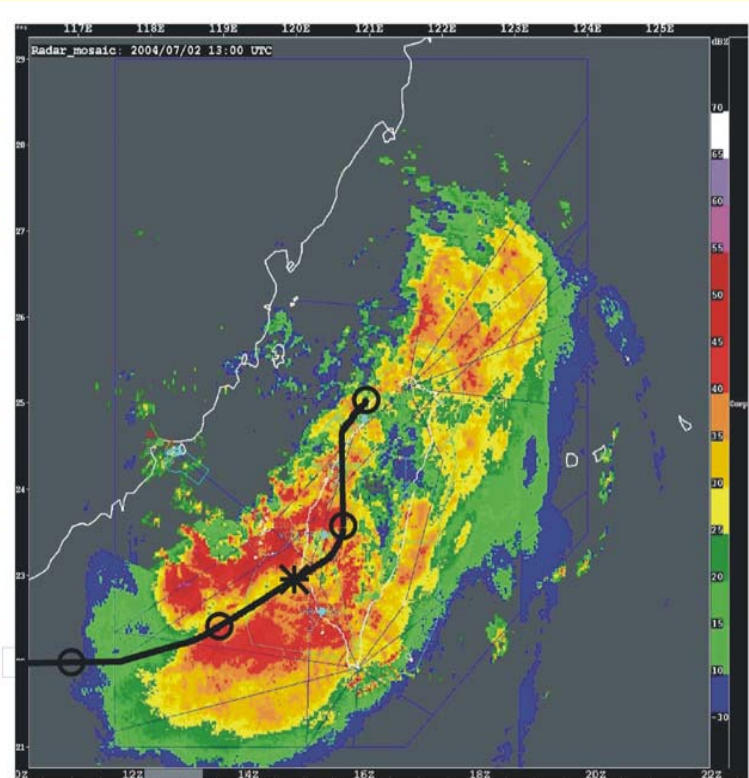
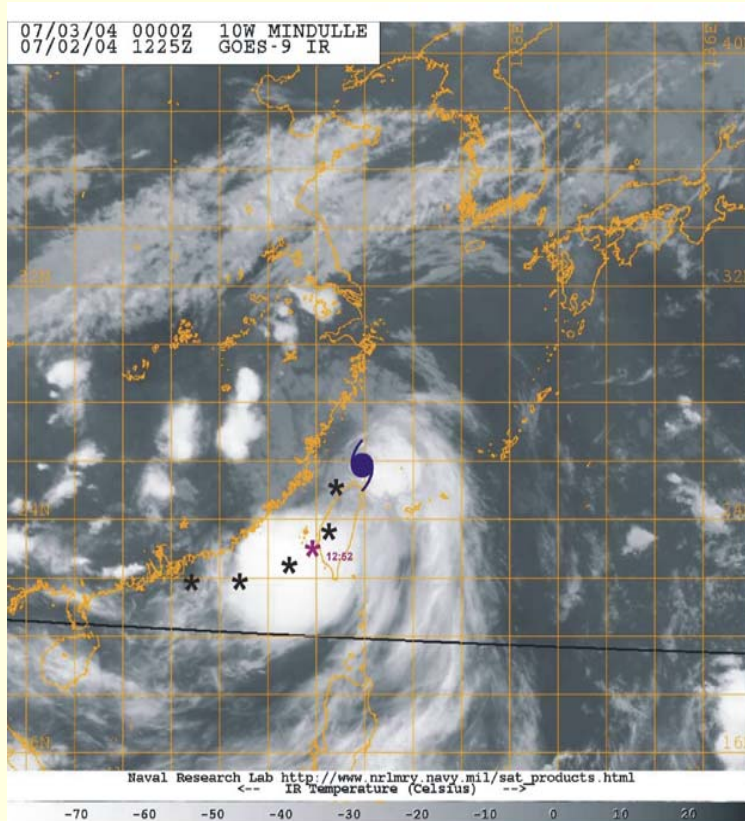
Engine event case study

- Satellite Infrared sequence starting 5.5 hrs before incident
- note convective elements southwest of Taiwan grow and merge into massive convective complex
- growth of bright cloud tops in this region indicate potential for dense ice crystal zones at high altitude

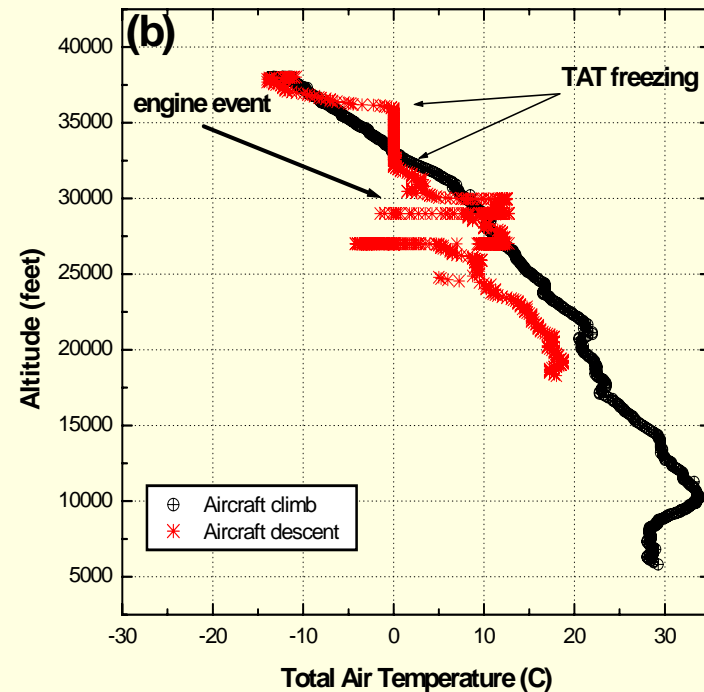
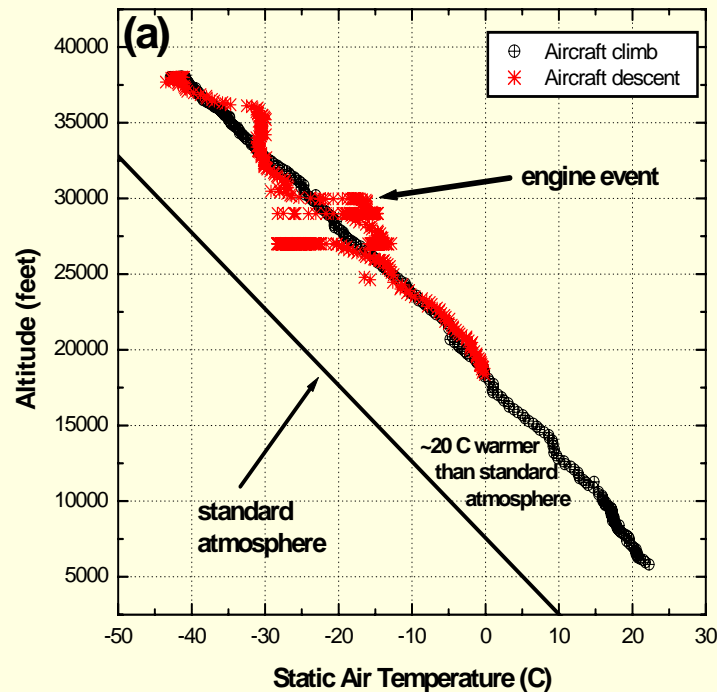


Engine event case study (cntd)

Figure shows heavy precipitation below aircraft altitude, obvious convection of fully developed typhoon

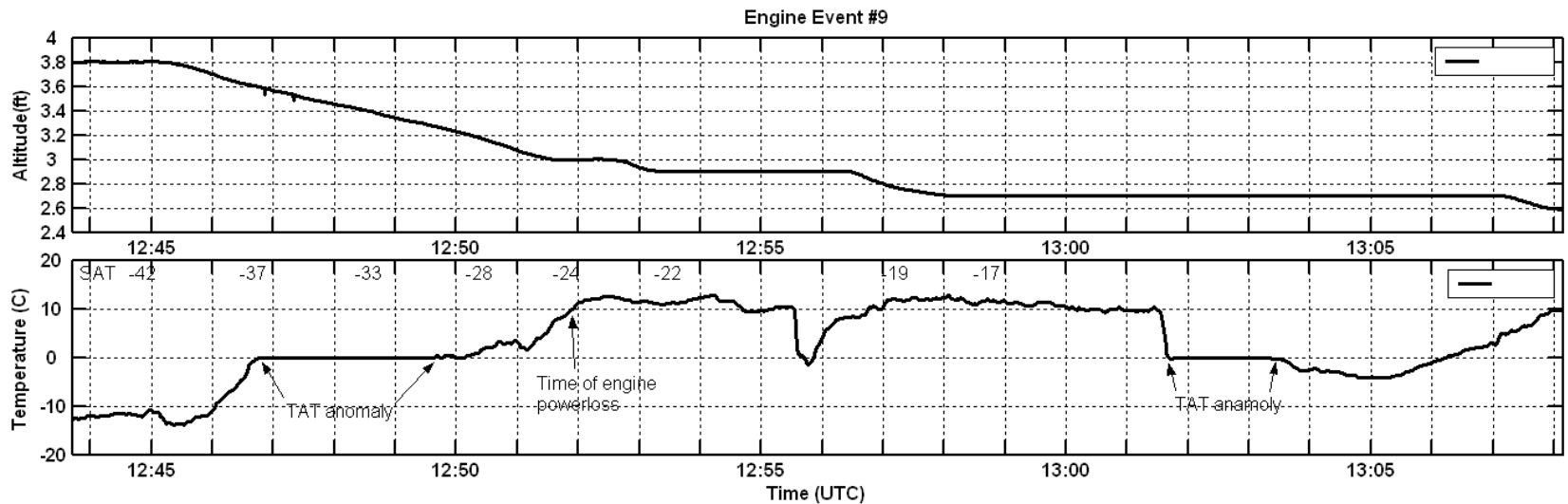


The TAT anomaly from FDR data



Static Air Temperature (a) and Total Air Temperature (b) measured during climb from Hong Kong (black symbols) and during descent towards Taipei (red symbols), illustrating the TAT anomaly observed before the engine event

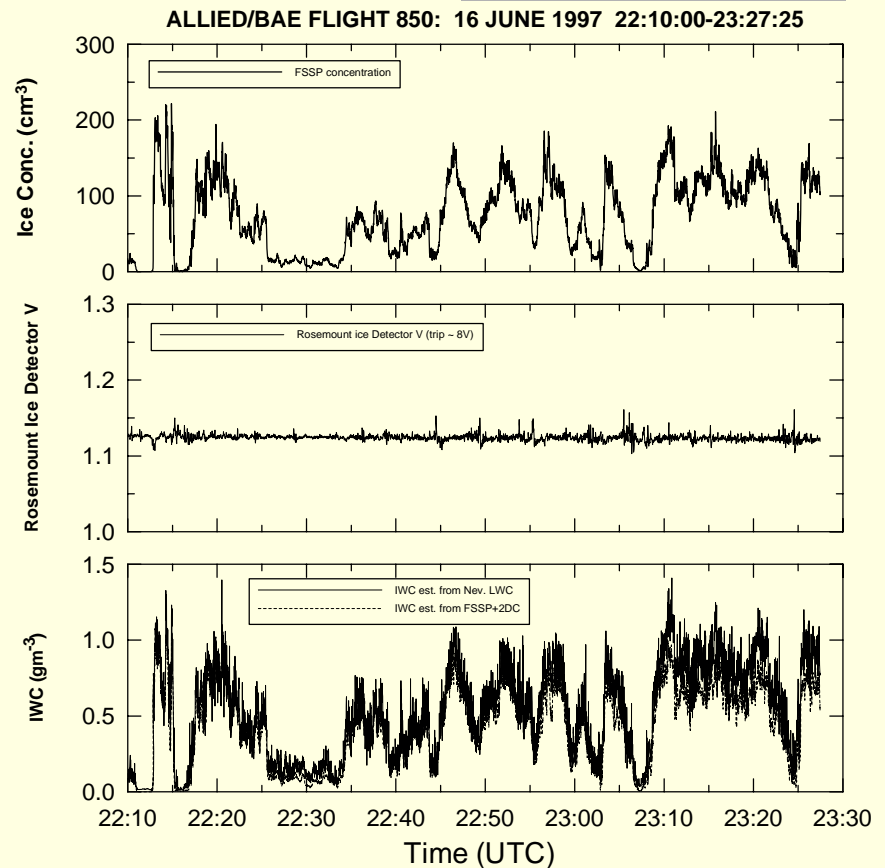
The time sequence of the engine event



Time history of altitude and Total Air Temperature (TAT), surrounding the time of the engine event at 12:52:58. The estimated Static Air Temperatures (SAT) are shown in text at the top of the lower panel for reference. Note the time of powerloss is identified in figure.

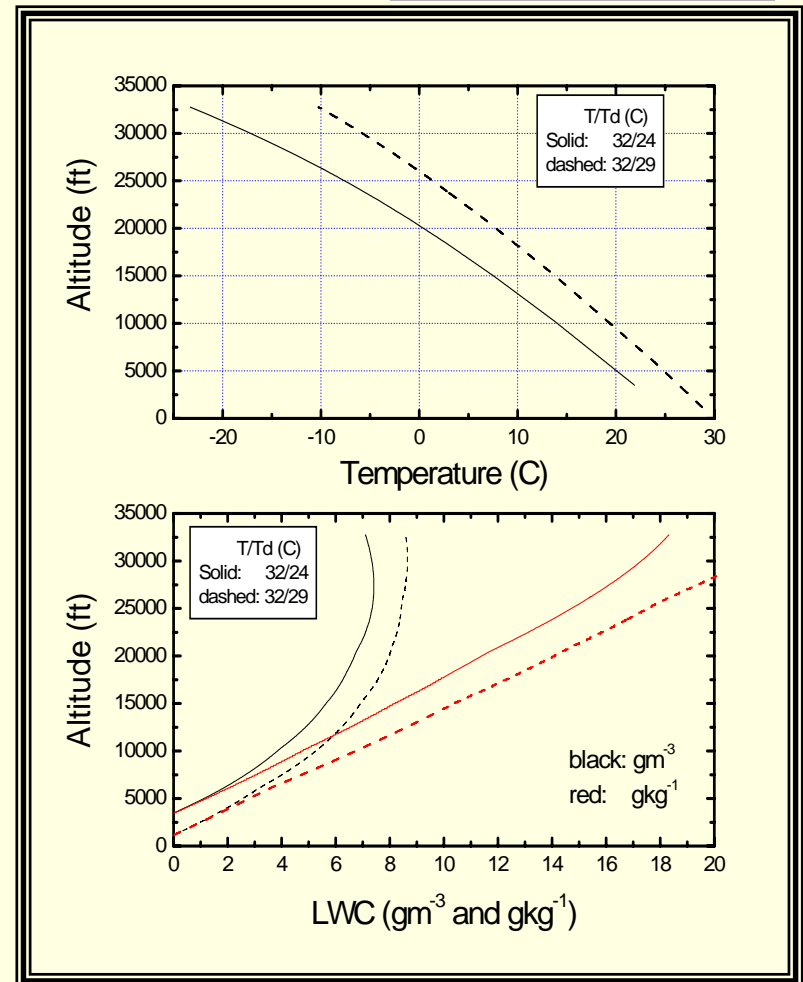
An industry measurement of an engine event

- BAe-146 test aircraft instrumented for cloud microphysics
- successfully induced an engine powerloss event orbiting in an anvil downwind of a thunderstorm core
- no LWC measured, just moderately high IWC up to $\sim 2 \text{ gm}^{-3}$
- Very small median mass diameters
- Our working hypothesis on what to expect in deep convection (glaciated, high IWC, small particles)



How high can TWC get ?

- Extensive study in 1950s by Royal Aircraft Establishment to measure TWC levels in equatorial deep convection (Singapore, Darwin, Entebbe) – measured values up to $\sim 8 \text{ gm}^{-3}$
- Not much since – mainly just penetrations away from convective core in the trailing anvil region
- Calculations of adiabatic IWC predict maxima up to about 9 gm^{-3} in the most wet tropical atmosphere



What does the EHWG recommend?

- An interim “Appendix D” certification envelope based on the RAE data and adiabatic calculations of TWC
- A Technical Plan with the following Tasks:
 - **Task 1.** Instrumentation development and evaluation for high ice water content
 - **Task 2.** Flight test research for characterization of high ice water content environments.
 - **Task 3.** Experimental testing in support of ice accretion model development and validation for high ice water content environments.
 - **Task 4.** Test Facilities Requirements for demonstrating engine compliance with Appendix-D

TASK 1: Instrumentation development

ARMP is taking the lead in this activity

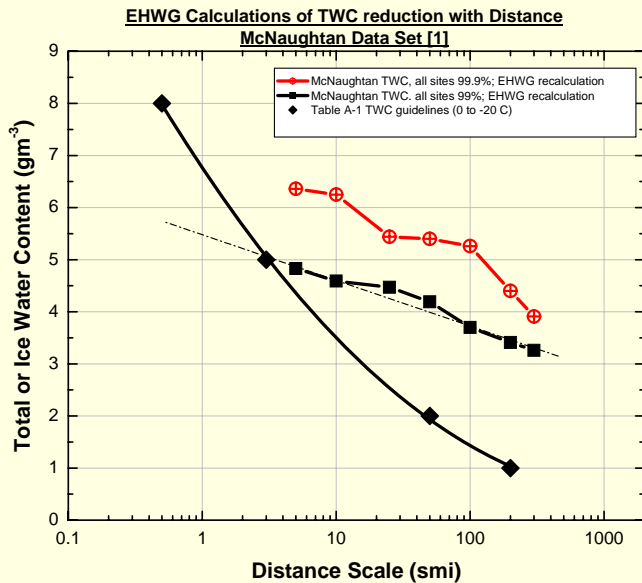
- Wind tunnel testing to identify best equipment for the hostile thunderstorm anvil environment (Cox and Co. tunnel, NYC ; NRC M7 icing tunnel Ottawa)
- Development of a new isokinetic device to measure TWC up to 10 gm^{-3} at 200 ms^{-1}
- Funding from FAA for this purpose

TASK 2: Characterization of the environment

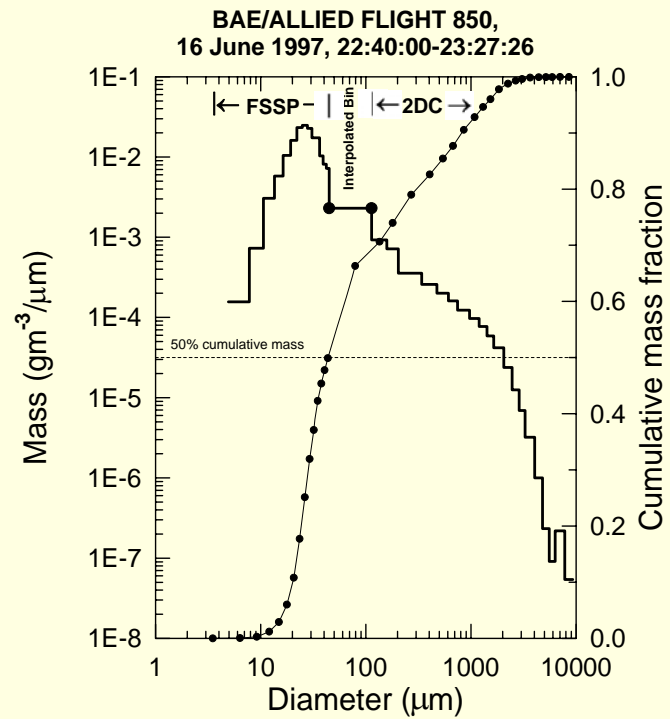
NASA is taking the lead in this activity, partnering with ARMP

- A newly acquired NASA S-3 aircraft will be instrumented for cloud measurements
- The S-3 aircraft will be flown in deep tropical convection to get statistics on the levels of Total Water Content and particle characteristic size

TASK 2: Characterization of the environment – type of data required



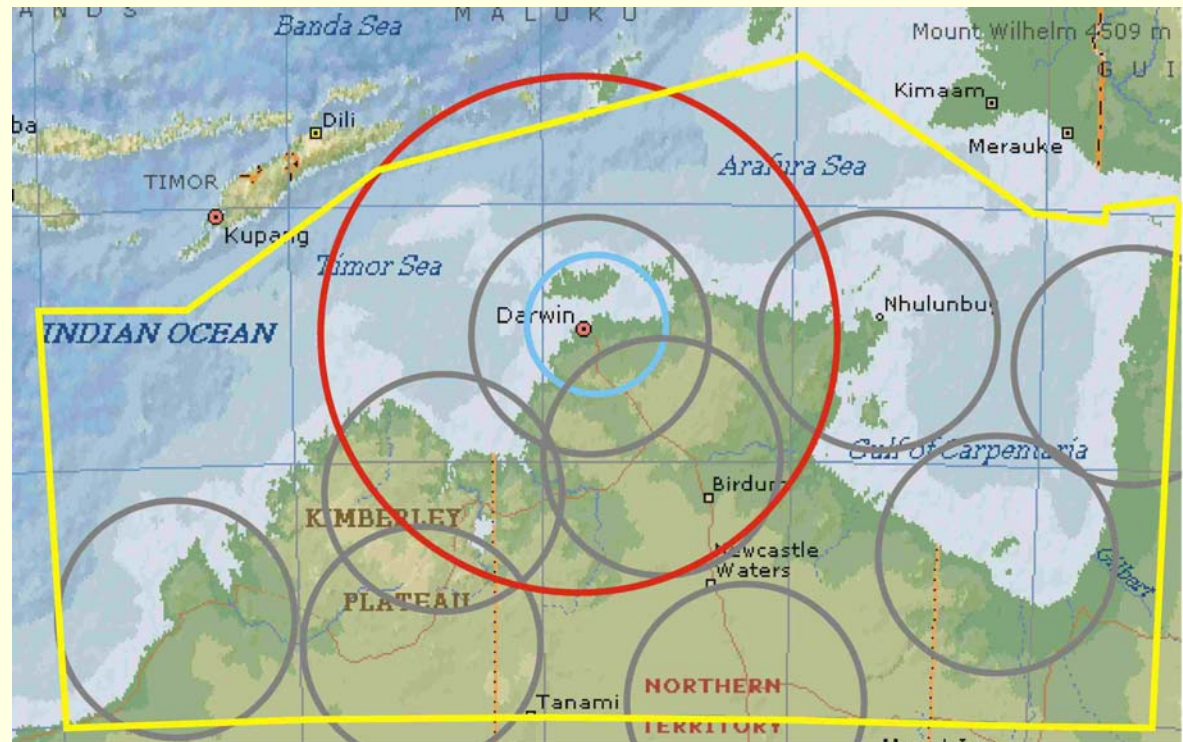
**STATISTICS ON TWC
 VERSUS DISTANCE**



**PARTICLE SPECTRA AND
 MEDIAN MASS DIAMETER IN
 HIGH TWC SITUATIONS**

Proposed airborne project

- out of Darwin, Australia in Jan-Mar 2010
- partner with NASA and Australian Bureau of Meteorology
- May entrain other international groups
- first modern airborne measurements of this type into cores of deep tropical convection



Cloud-Type Sampling Strategy

Proposal:

- ~75% oceanic convection (incl. ~2 tropical storms), ~25% continental
- Oceanic convection flights:
 - monsoon oceanic convection or tropical storms
 - Perform a major fraction within CPOL coverage and/or dual-doppler region (e.g. 75%), and the rest (e.g. 25%) more remote from coast.
- Continental convection flights:
 - do between monsoon periods,
 - may not get directly into cores due to safety

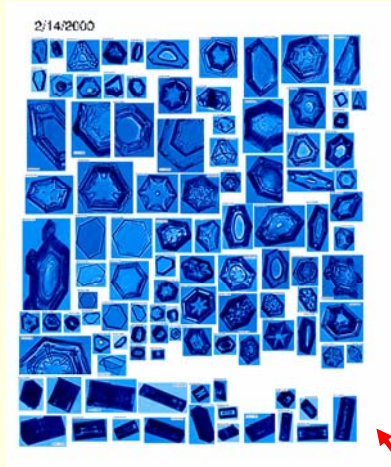
Concept of S-3 Instrumentation Layout



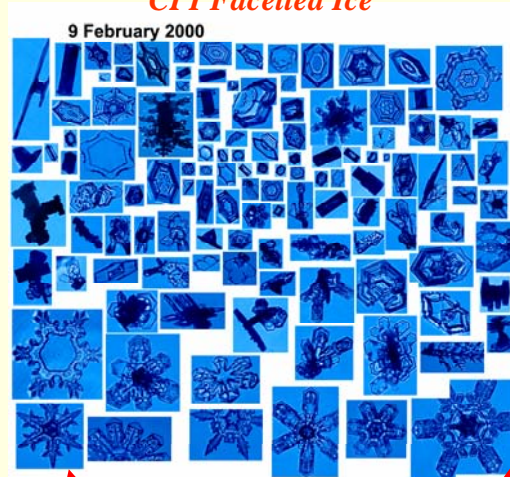
Cloud Particle Probes on NRC Convair-580

Standard PMS 2D Imagery

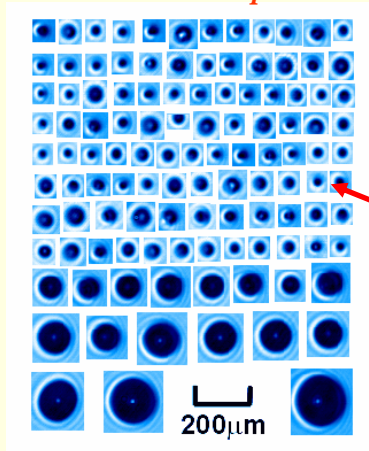
CPI Pristine Ice



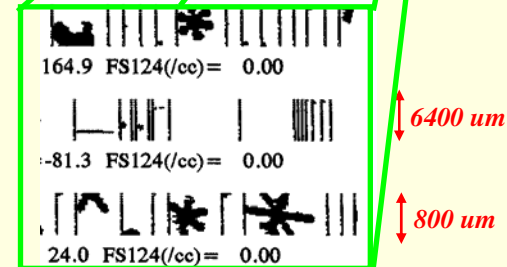
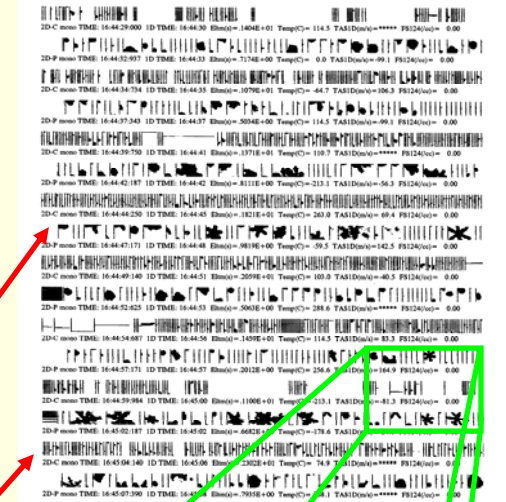
CPI Faceted Ice



CPI Small droplets

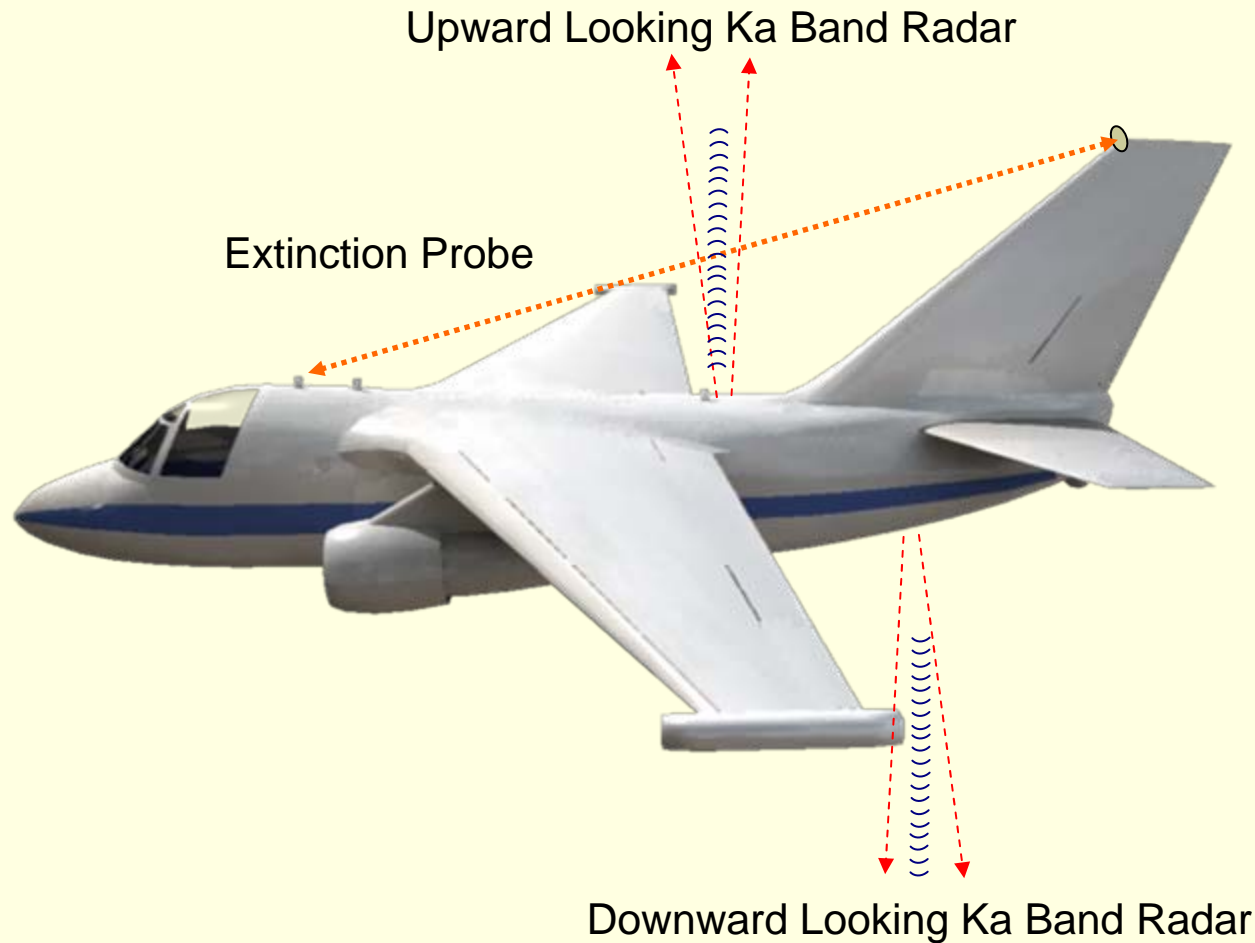


Under-wing particle probes



CPI data courtesy of Alexei Korolev

Concept of S-3 Instrumentation Layout (cntd)



End of Presentation

Thank You.