An Upcoming Aircraft Investigation of High Ice Water Content Regions of Deep Tropical Convection (Darwin, 2011)

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Jet Engine Icing – a Safety and Business Problem

- Since 1990, over 100 reports of jet engine powerloss events on regional jets and wide-bodied passenger-carrying aircraft (e.g. 747) have been attributed to flight in and around areas of deep convection

- *Lawson, R.P., Angus, J.J., and Heymsfield, A.J., 1998: Cloud Particle Measurements in Thunderstorm Anvils and Possible Threat to Aviation, J. Aircraft, Vol. 35, No.1, 113-121.*
- *Mason, J.G., J.W. Strapp, and P. Chow, 2006: The Ice Particle Threat to Engines in Flight, 44th AIAA Aerospace Sciences Meeting and Exhibit, Reno, NV, Jan 9-12, 2006, AIAA 2006-206.*
- *Pasztor, A.,2008: Airlines Grapple with Engine Shutdown Peril, Wall Street Journal, 7 April 2008.*

- Hypothesis: Engine events are caused by flight into high Ice Water Content (IWC) regions caused by deep lift associated with convective cloud; supercooled LWC is not required

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Engine Powerloss

- **Stall:** jet engine experiences uncommanded slowing, spooling back to idle or sub-idle – no response to throttle control - may not be noticed by pilots – may require a manual restart
- **Surge:** instantaneous flow reversal in engine that sometimes occurs during a stall – loud noise, and possibly flame out the front of the engine – (like a backfire)
- **Flameout:** loss of fuel burn in combustor – this results in an auto-relight in most engines

Above are momentary events - all are thought to be due to the effect of shed ice passing through the combustor – all are recoverable at altitude – some automatic, some manual

- **Rollback** : uncommanded spoolback of engine – thought to be due to ice buildup on rotor blades choking the airflow – aircraft must descend to warmer air to clear – seen on smaller jet engines

ALL THE ABOVE RESULT IN INSIGNIFICANT THRUST FROM THE AFFECTED ENGINE

THERE HAVE BEEN MULTIPLE EVENTS WHERE ALL ENGINES WERE AFFECTED SIMULTANEOUSLY (I.E. NO THRUST)

Damage

- Ice buildup in the engine that is released during engine powerloss events can cause costly damage to the engine (~$100K) and take the aircraft temporarily out of service (more $K)

- this is a strong motivating factor for industry to try to solve the problem

Safety

- There has not been a single accident attributed to a powerloss event linked to this kind of engine icing ….. however
- In one commuter aircraft event, all four engines rolled back (no thrust) and engines were finally started at 1500’ above the ocean
- In a recent event, a Beechcraft-400 made a landing with no engine power in Florida after a powerloss event that occurred in a thunderstorm anvil
- The FAA Icing Specialist has stated that these powerloss events are “**precursors to a catastrophic accident**”

Engine Harmonization Working Group Technical Plan

- Task 1. Evaluate/Modify/Develop Instrumentation for the high ice water content environment
- Task 2. Perform Flight test research to characterize the high ice water content environments.
- Task 3. Perform experimental testing in support of ice accretion model development and validation for high ice water content environments.
- Task 4. Develop Test Facilities Requirements for demonstrating engine compliance with Appendix-D

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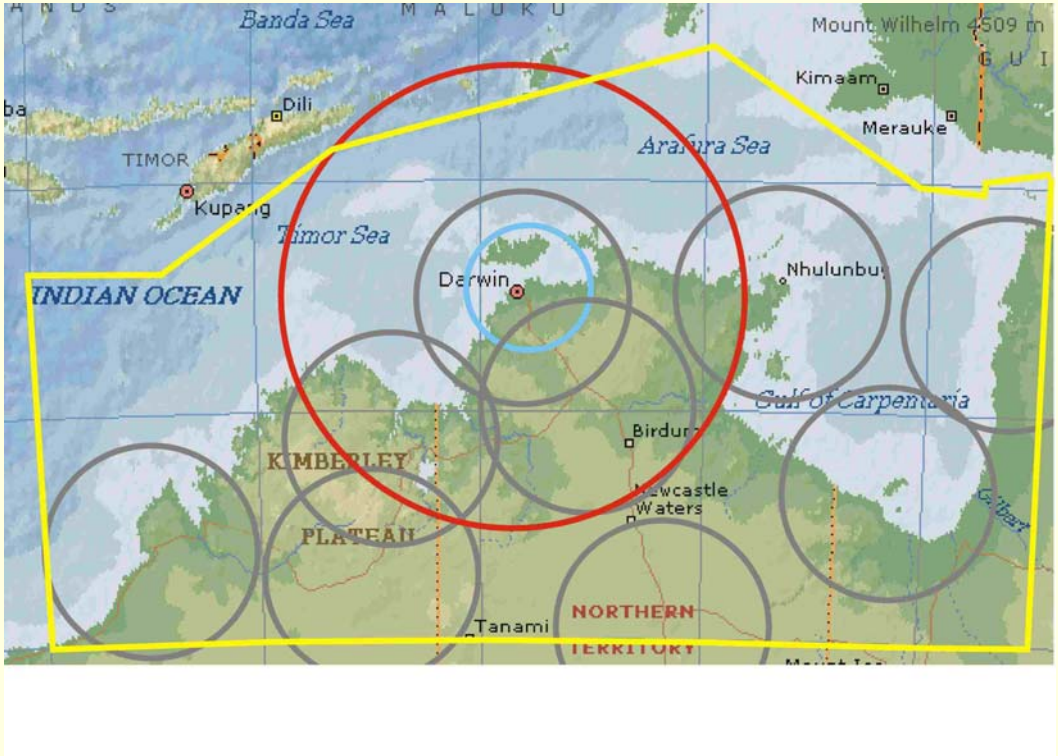
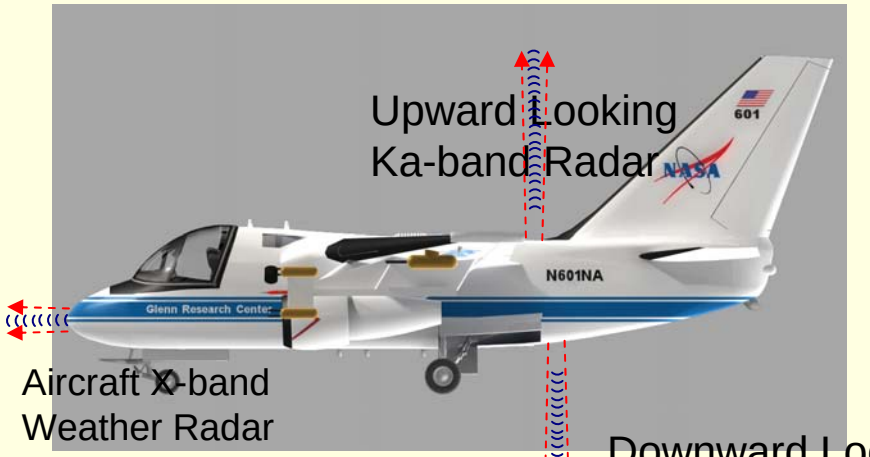
A Dedicated Flight Program for Characterization of Deep Convection

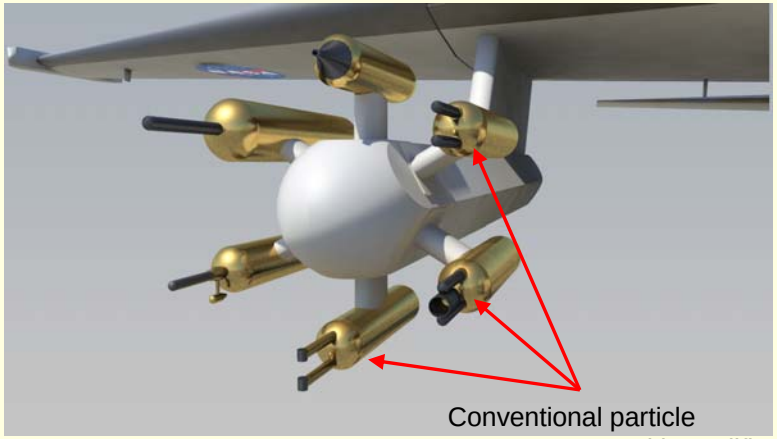
- instrument NASA S3 aircraft for high altitude cloud sampling
- test instrumentation and methodologies in one trial campaigns out of Puerto Rico (summer 2010)
- perform a characterization program of continental and oceanic tropical convection (Darwin, Jan.-Feb. 2011)



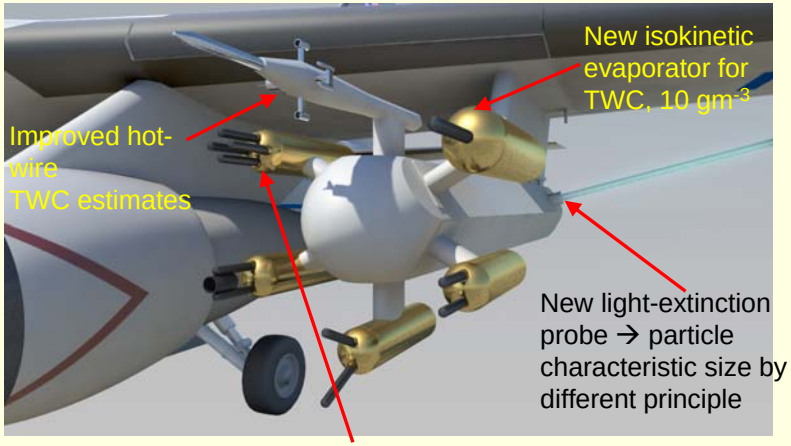
Instrumentation for high IWC



Downward Looking
Ka-band Radar



Conventional particle
Spectrometers with modifications
for high IWC environment



Latest tech for small ice particle
imaging and spectra (CPI, 2DS,CIP)

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Darwin Campaign

Propose:

- ~2 month field project
- January-February 2011
- based at RAAF Darwin.
- 100+ research hrs (TBD),
- 60 transit hrs

Cloud Sampling Strategies

Proposal:

- ~75% oceanic (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
  - sample vigorous clouds only in anvil away from direct core – work from outside in
  - Work dissipating stage

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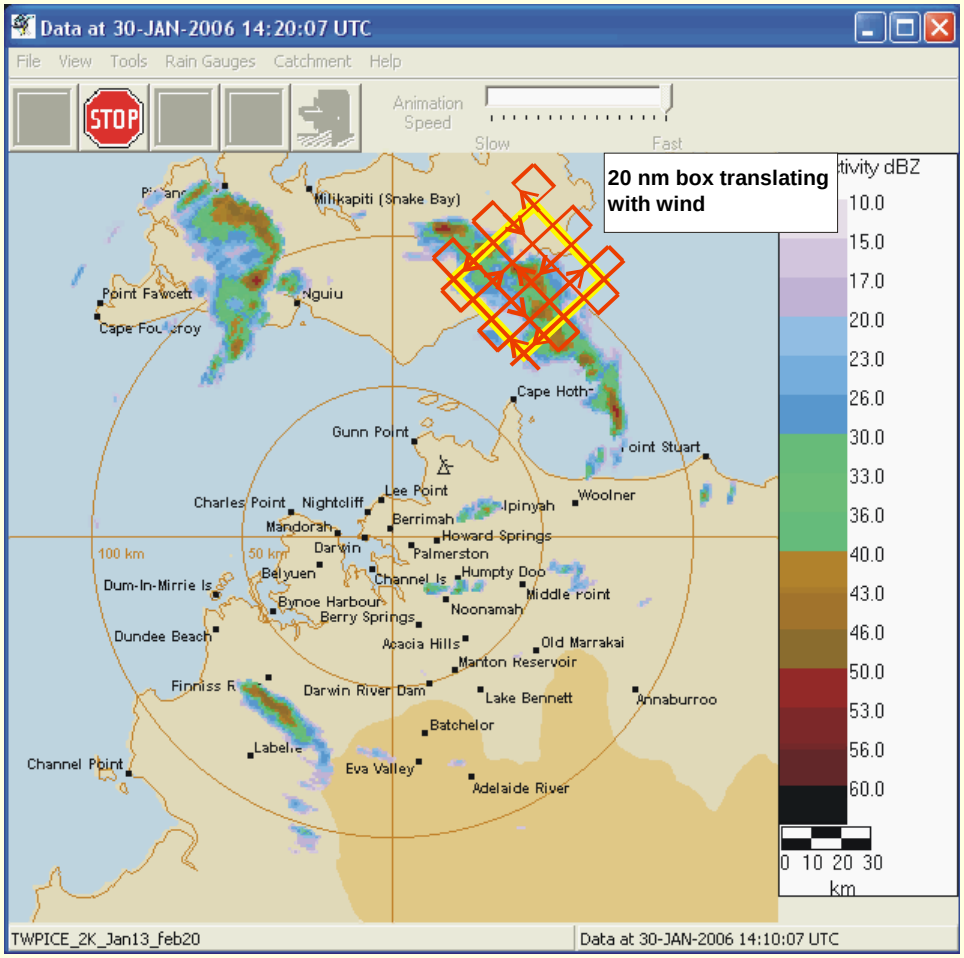
Oceanic Convection Example

- 20 nmile sided box oriented with one side down axis of expected updrafts
- box drifts with echo
- Collect repeated runs to build up statistics of 20 nmile average TWC (an lower)
- Concentrate on three temperature levels: -10 C, -20 C, -40 C



Science and Technical Team

NASA Glenn Research Center (Ratvasky):
•Engine performance monitoring, High IWC characterization for the EHWG

Environment Canada (Strapp, Korolev):
•High IWC characterization for the EHWG, cloud microphysics, instrumentation

Australian Bureau of Meteorology (May):
•Radar remote sensing algorithm development, cloud microphysics

NASA Goddard (Ackerman, Fridlind):
•Model performance and evaluation

NASA Langley (Minnis):
•Satellite remote sensing of High IWC, algorithm evaluation

NCAR (Politovich):
•Nowcasting high IWC regions

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Main Funding Partners

- **NASA Glenn Research Center**
- **Federal Aviation Administration**
- **Transport Canada**
- **The Boeing Company**

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Program Status

- Field programs in Puerto Rico (2010) and Darwin (2011) are funded

- technical problems on S3 → waiting for technical review of instrumentation integration and commitment from NASA to meet target dates (answer Jan. 2009)

Potential ARM Community Interest ?

- several scientists involved in the program also involved in ARM science community (May, Ackerman, Fridlind)

- Opportunity to take advantage of heavily instrumented aircraft being in Darwin to fulfill some specific ARM objectives that may not be a focus of the High IWC project

    - remote sensing comparisons to insitu aircraft over the Darwin ARM site

- interest from the Cloud and Aerosol Working Group ?

- possible proposal to be written to AVP for flight hours over ARM site / CPOL

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End of Presentation

Thank You.

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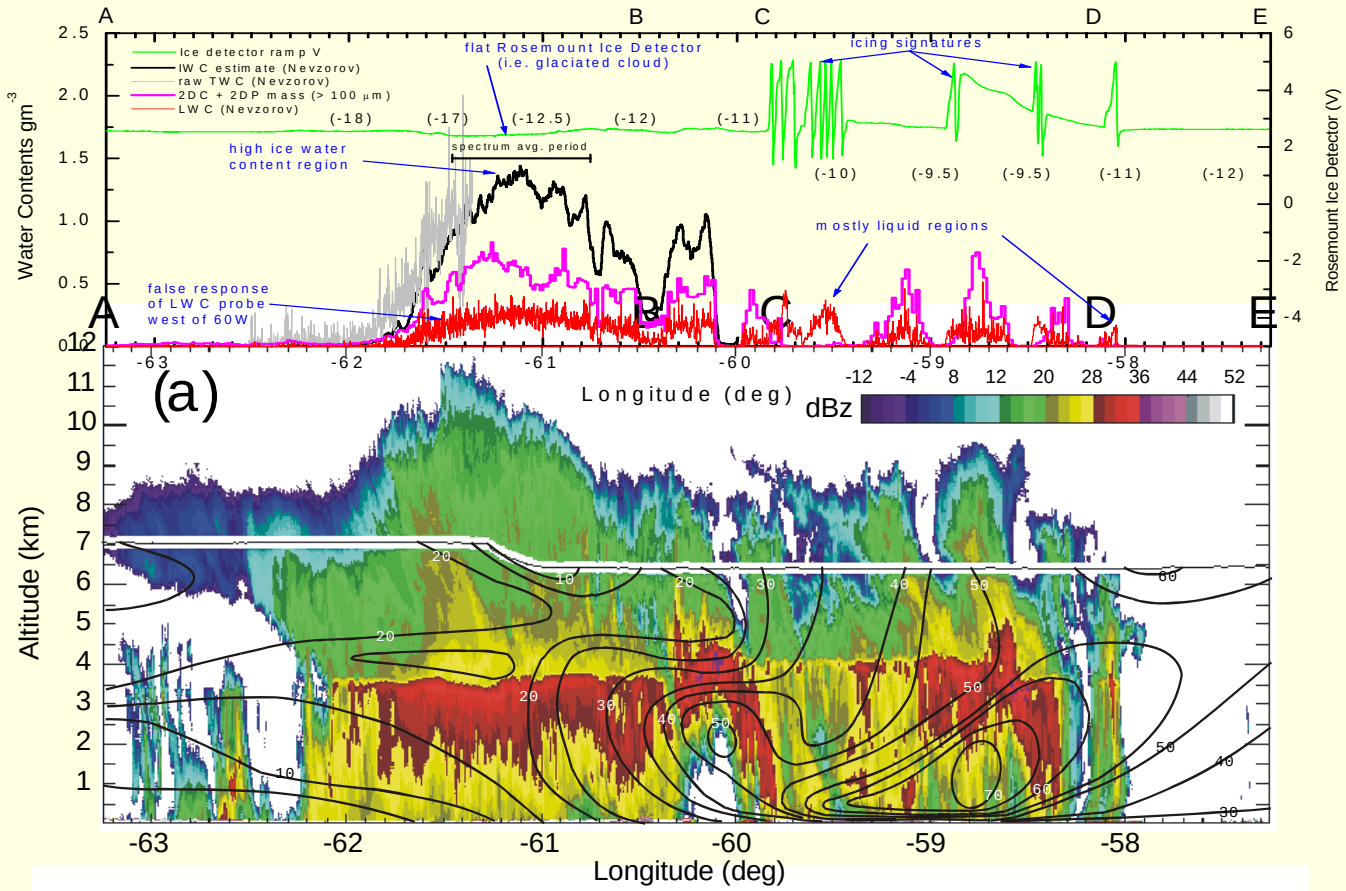
Example: Hurricane Michael (Oct. 19, 2000 (Convair-580) ;

radar and dropsonde wind speed cross-section



Surface pressure	987.5	985.2	985.3	982.8	982.8	n/a	975.9	978.4	985.6	989.1
Dropsonde #	1	2	3	4	5	6	7	8	9	10

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Instrumentation Table (page 1 of 2)

Atmospheric State Parameter Instrumentation:

TAT probe (standard probe sensitive to TAT freezing)
TAT probe (insensitive to TAT freezing)
Radiometric temperature (TBD)
LICOR water vapour mixing ratio probe
Chilled mirror dewpoint sensors (Edge-Tech and CR-2)
Tunable diode laser hygrometer system
Standard static pressure and airspeed sensors
Wind and gust measurement system (AIMMS-20)[5]
GPS position

Bulk Microphysics Probes for LWC, TWC, and IWC:

PMS King LWC hot-wire probe
Science Engineering LWC hot-wire probe (standard 2 mm solid wire[1,7])
Nevzorov LWC/TWC hot-wire probe (unmanned, standard sensor heads[2,7])
Science Engineering TWC hot-wire probe (modified solid wire[3,7])
SEA multi-wire TWC/LWC hot-wire system (multiple solid wires[6])
Counterflow Virtual Impactor for TWC/IWC (new[4,7?])
Isokinetic evaporator for TWC (new[4])

Instrumentation Table (page 2 of 2)

Cloud Spectrometers

PMS FSSP probes (5-95 um), normally for liquid cloud spectra[5]
PMS FSSP probe, modified as Fast FSSP[5]
DMT CDP forward scattering spectrometer (new[4,6])
PMS 2D2-C probe (35-1120 um), imaging at 35 um res. [5]
PMS 2D-P probe (200 – 6400 μm), imaging at 200 μm res. [5]
SPEC 2DS probe (10 – 1280 μm), imaging at 10 μm res. (new [4,6])
DMT CIP probe (25- 71600 μm), imaging at 25 um res., (new[6])
SPEC CPI probe (2.3- ?? μm) [6]

Others Important Microphysics Instruments:

EC extinction probe
Rosemount Ice detector

Remote Sensing Measurements:

Ka band radar: downward, upward (possibly scanning side to side)
Recording of pilot's forward scanning radar.
Stormscope for measurement of lightning sferics (recording TBD)

[1]More robust sensor design than King for harsh Appendix D environment
[2]possibly more robust sensor design for harsh Appendix D environment
[3]new sensor designs for efficient trapping of ice particles, best choice from Cox and Co. testing
[4]New purchase for Appendix D measurement
[5] modified to incorporate optical windows and canister dry air
[6]already suitable for harsh environment of Appendix D
[7]modified so as not to saturate in Appendix D high IWC

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Source 1:
Flight Data Recorder and Pilot Reports

- High altitude, cold temperature
- Aircraft in the vicinity of convective clouds/thunderstorms
- Significantly warmer than standard atmosphere
- Visible moisture
- Light to moderate turbulence
- Aircraft total air temperature (TAT) anomoly
- Lack of observations of significant airframe icing – no ice detector response if installed
- No reports of strong pilot weather radar returns at altitude and location
- Precipitation on heated windscreen – often reported as ‘rain’

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Flight Data Recorder and Pilot Reports – conclusions and suggestions

- conclude that average event is typically in a warm moist atmosphere, near deep convection, in cloud with no strong signs of LWC and probably mostly ice crystals (IWC) – possibly glaciated.
- suggests that IWC probably must be high, since deep convection has potential for high IWC, and engine events are not observed in low IWC non-convective winter clouds
- conclude that LWC in the atmosphere is not required, since some events are colder than -40C,
- 'rain' on the windscreen at nearly impossibly cold temperatures, in absence of airframe icing – thought to be rapid melting of high concentrations of small ice crystals on the heated windscreen – hint that ice particles might be small
- Other pilots reports of visible and audible features of precipitation, lack of airframe icing, and lack of radar echo also support ice particles rather than rain

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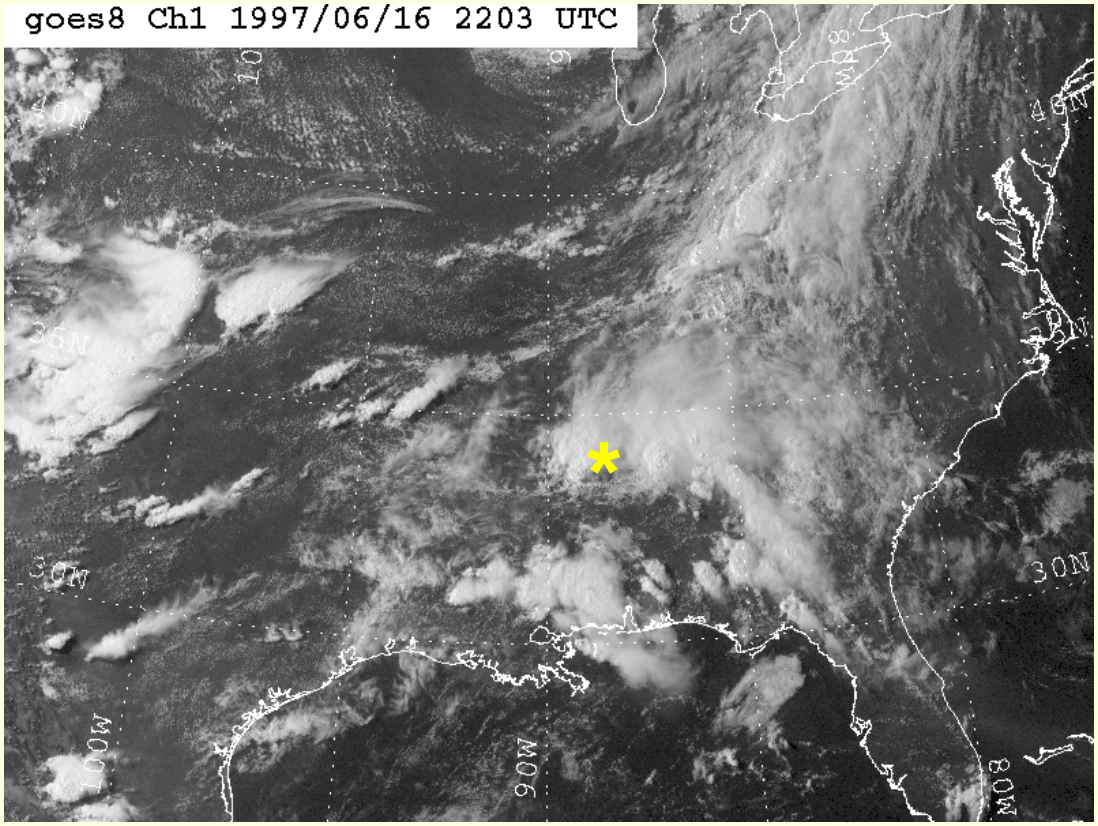
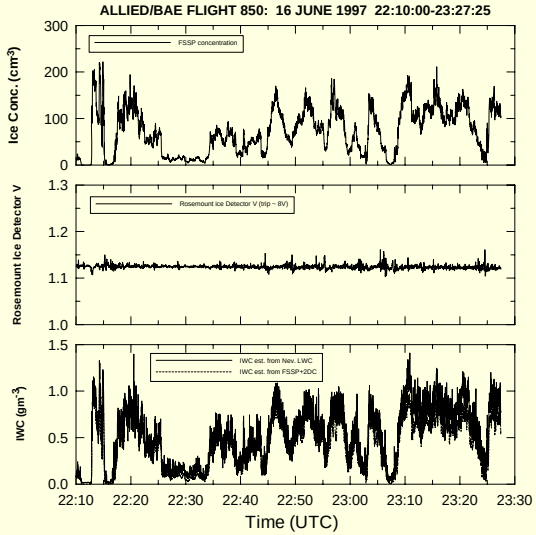
Source 2:
BAe-146 flight test program data

- BAE-146 instrumented for cloud measurements, and with a modified engine, to study engine rollback in deep convection anvils
- able to induce an engine rollback by orbiting in a thunderstorm anvil near Memphis

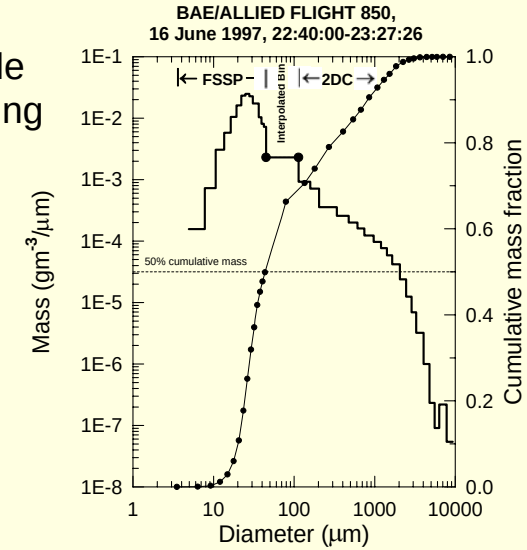


BAe-146 flight test program data (ref. 3)

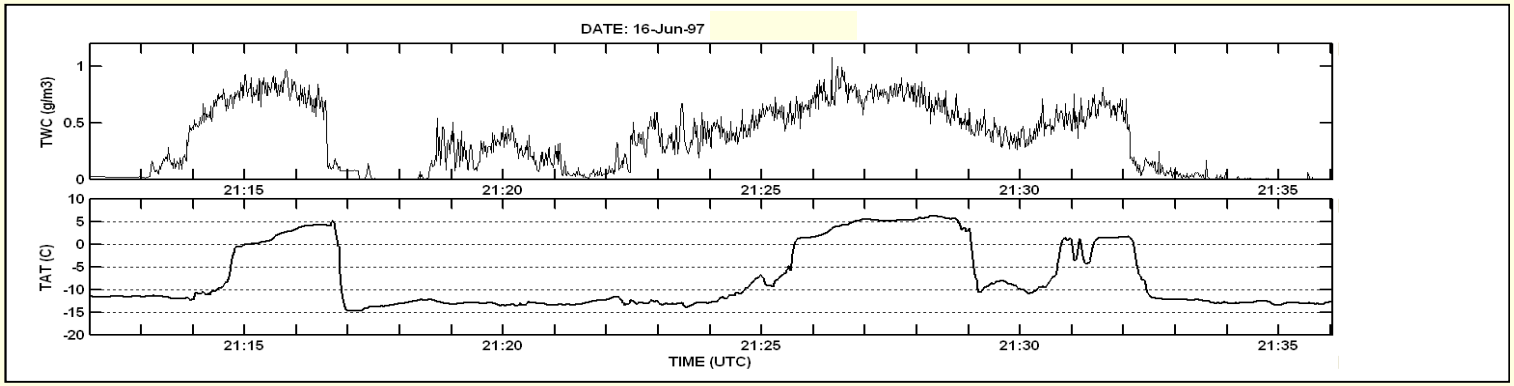
(a) TWC and icing during rollback



(a) Particle sizes during rollback



(c) TAT anomaly



[3] Strapp, J.W., P. Chow, M. Maltby, A.D. Bezer, A. Korolev, I. Stomberg, and J. Hallett, "Cloud Microphysical Measurements in Thunderstorm Outflow Regions during Allied/BAe 1997 Flight Trials," *37th AIAA Aerospace Sciences Meeting and Exhibit , Reno, NV.* , Jan. 11-14, 1999, AIAA 99-0498

BAe-146 flight test program data – conclusions and suggestions

(1) Conclude: Engine rollback could occur in deep convective cloud with insignificant amounts of atmospheric LWC

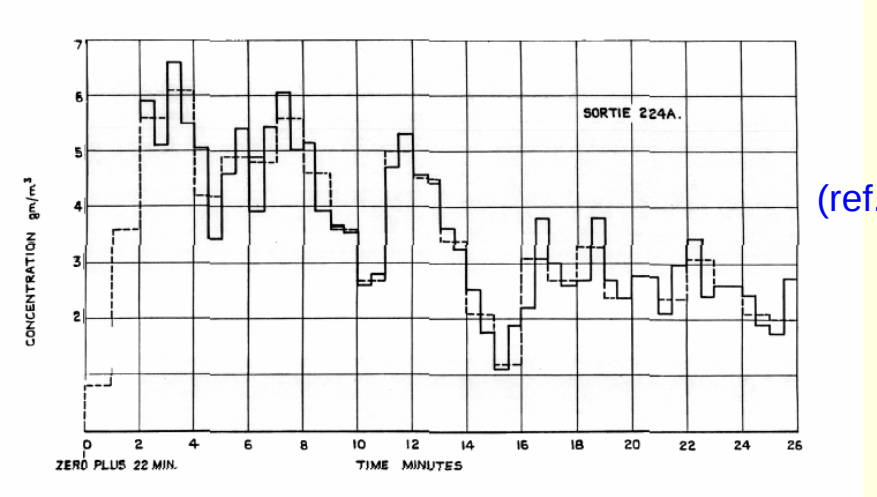
(2) Conclude: Relatively high IWC required to cause engine event

(3) Conclude: TAT anomaly very highly correlated to passage through high-IWC regions – TAT anomaly in FDR data a good indicator of presence of high IWC

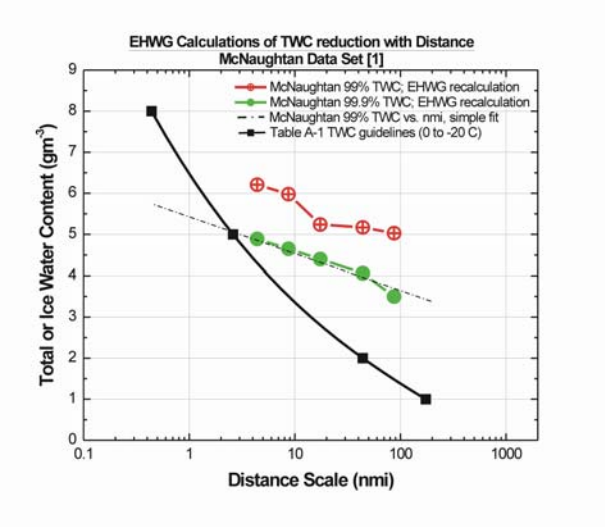
(4) Suggestion: median mass diameter of ice particles unexpectedly low (contentious measurement issue)

Source 3: Royal Aircraft Establishment (RAE) Cloud Survey (1955-1957)

- collected by RAE to characterize the levels of TWC (IWC+LWC) in deep convective clouds and thick layer clouds in the inter-tropical convergence zone
- addressing issues of engine inlet, pitot tube and other instrument icing in turbine engine aircraft
- extensive set of flights: 101 cloud measurement flights with 44.5 hours of in cloud data "McNaughtan data set"



(ref.4)



(ref.5)

[4] McNaughtan, I.I.,"The Analysis of Measurements of Free Ice and Ice/Water Concentrations in the Atmosphere of the Equatorial Zone," *Royal Aircraft Establishment (Farnborough) Technical Note No. : Mech. Eng. 283,* 1959.

[5] Mazzawy, R.S. and J.W. Strapp, 2007: Appendix D - An Interim Icing Envelope, 2007 SAE Aircraft and Engine Icing International Conference, Seville, Spain, 24-28 Sep., 2007, 2007-01-3311

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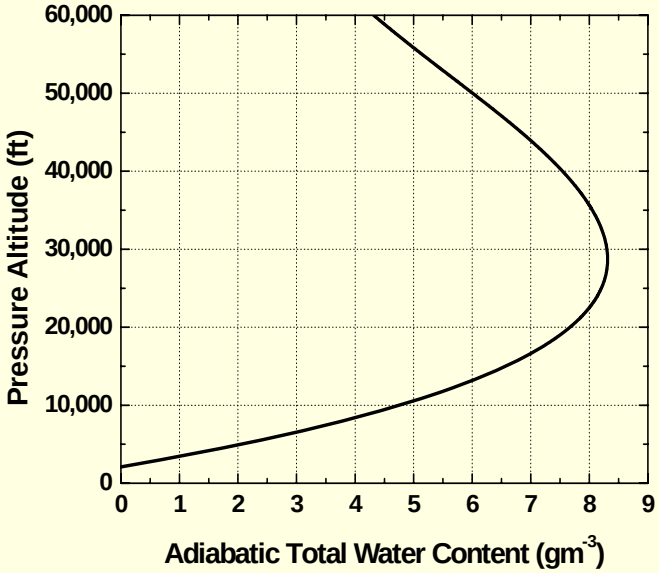
Zero-order estimate of maximum IWC

- Simple calculations of adiabatic parcel lift and condensation provide first approximation of maximum IWC – shown at right approaches 9 gm^{-3}
- More complicated processes at play – entrainment dilution, redistribution by precipitation, etc.



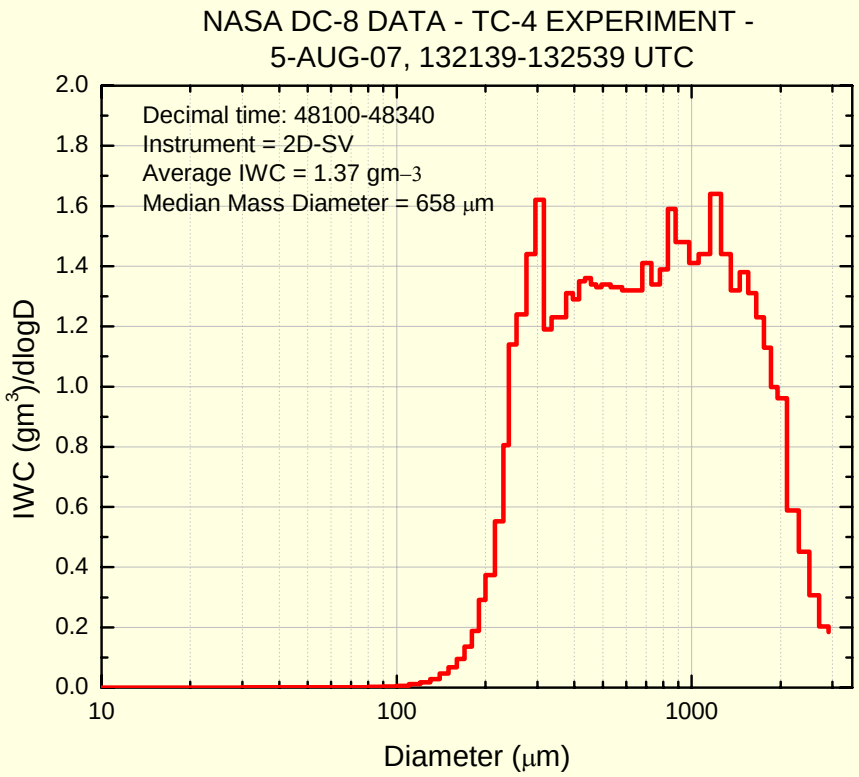
RAE Cloud Survey (1955-1957) EHWG conclusions and suggestions

- conclude: only study to provide extensive data set on levels of TWC to be expected – can be very high in tropical convection (up to 8 gm^{-3}, similar to adiabatic maximum estimates)
- suggested: most of TWC was due to ice crystals
- conclude: accuracy of RAE measurements no longer traceable – insufficient for long-term guidelines

Source 4: Cloud Data from the Atmospheric Science Research Community

- abundant information on the structure of deep convection from radar, satellite, models
- abundant cloud microphysical data on summer and winter clouds, including some data in deep convection, however….
  - limited data on high-TWC regions in deep convection – most measurements are in the trailing anvil regions well away from the cores where the highest TWC is expected
- common observation of rarity of LWC at high altitude in deep convection, especially at temperatures colder than -10 C.
- Some further data on high-IWC in deep convection associated with Atlantic Hurricanes – also some data showing relatively low MMDs of ice particles, ~200 μm
- improvements in instrumentation → better MMD estimates ….. Piggyback opportunities

NASA DC-8 TC4 Data: Anvil mass spectrum well away from convective core



- piggyback opportunities on AR community convective cloud experiments
- MVD in anvil well away from core (left) ~650 μm
- another case (not shown) closer to the core ~250 μm

Cloud Data from the AR Research Community Conclusions and Suggestions:

- Conclude: extensive in-situ measurements of high IWC regions of deep tropical convection have not been done by the AR community
- Conclude: some general results support other data sources (e.g. dominance of ice mass over liquid, and case studies that high IWC encounters > 3 gm^{-3} probably exist)
- Conclude: AR community data will continue to be valuable in understanding some of the detailed microphysical questions, and recent data uses more modern instrumentation
- continue to be accuracy issues IWC measurement at high values, and small ice particle measurement improving but not yet resolved (MMD accuracy)

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General Hypothesis Based on 4 Sources

- Engine events result from direct encounters with high IWC regions in or near deep convective cloud – IWC values are likely in excess of 2 gm^{-3}, may reach up to 9 gm^{-3}
- No supercooled LWC is required
- Ice particle mean mass diameter is relatively low, likely less than 300 um and perhaps below 50 um in some cases (TBD)

Other notes:

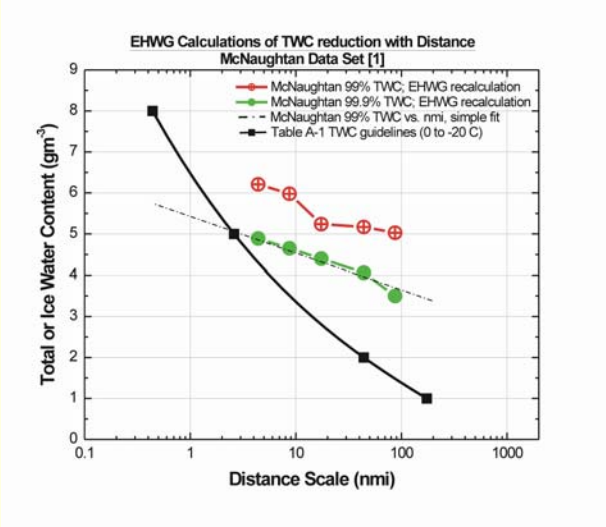
- High IWC regions with small median mass diameter are not strong radar scatterers. This may be the explanation as to why these regions are not visible on pilot's radar

The need for further measurements

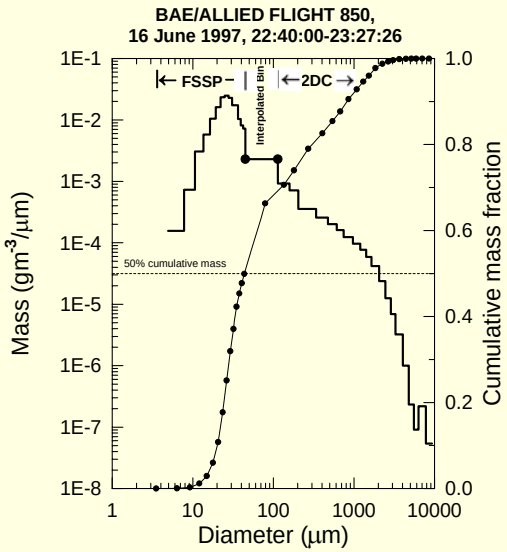
- EHWG concluded that accuracy of current cloud information adequate for interim guidance material for manufacturers and regulators (next paper), but further measurements are needed for long-term confidence
- EHWG Technical Plan calls for further work:
  - improvement of instrumentation for cloud measurements,
  - a future dedicated cloud characterization flight program

Measurements:

New statistics on TWC versus distance scale



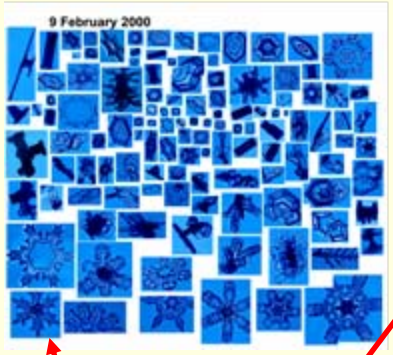
Particle distributions and median mass diameter



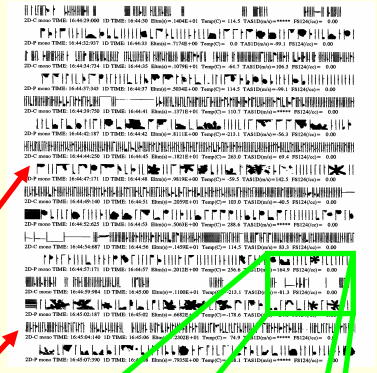
Instrumentation Work

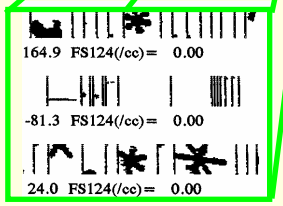
- Update current cloud measurement instrumentation to operate in the hostile high-altitude deep tropical convection environment
- develop a new isokinetic TWC instrument to target a maximum value of 10 gm^{-3} at 200 m/s
- calibrate an NRC tunnel with an ice cloud simulation (shaved ice) for absolute estimates of IWC

CPI Facetted Ice



Standard PMS 2D Imagery





CPI data courtesy of Alexei Korolev

Under-wing particle probes

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EHWG Conclusions and Recommendations on Characterization

Current guidance on the properties of deep convective clouds is not traceable, and not sufficiently accurate for long-term needs.

Instruments must be improved and developed to provide sufficient accuracy for this environment

New airborne measurements should be made to characterize deep convection

APPROACH :

- interim Appendix-D based on RAE data
- instrumentation work
- Flight Program to Characterize Deep Convection

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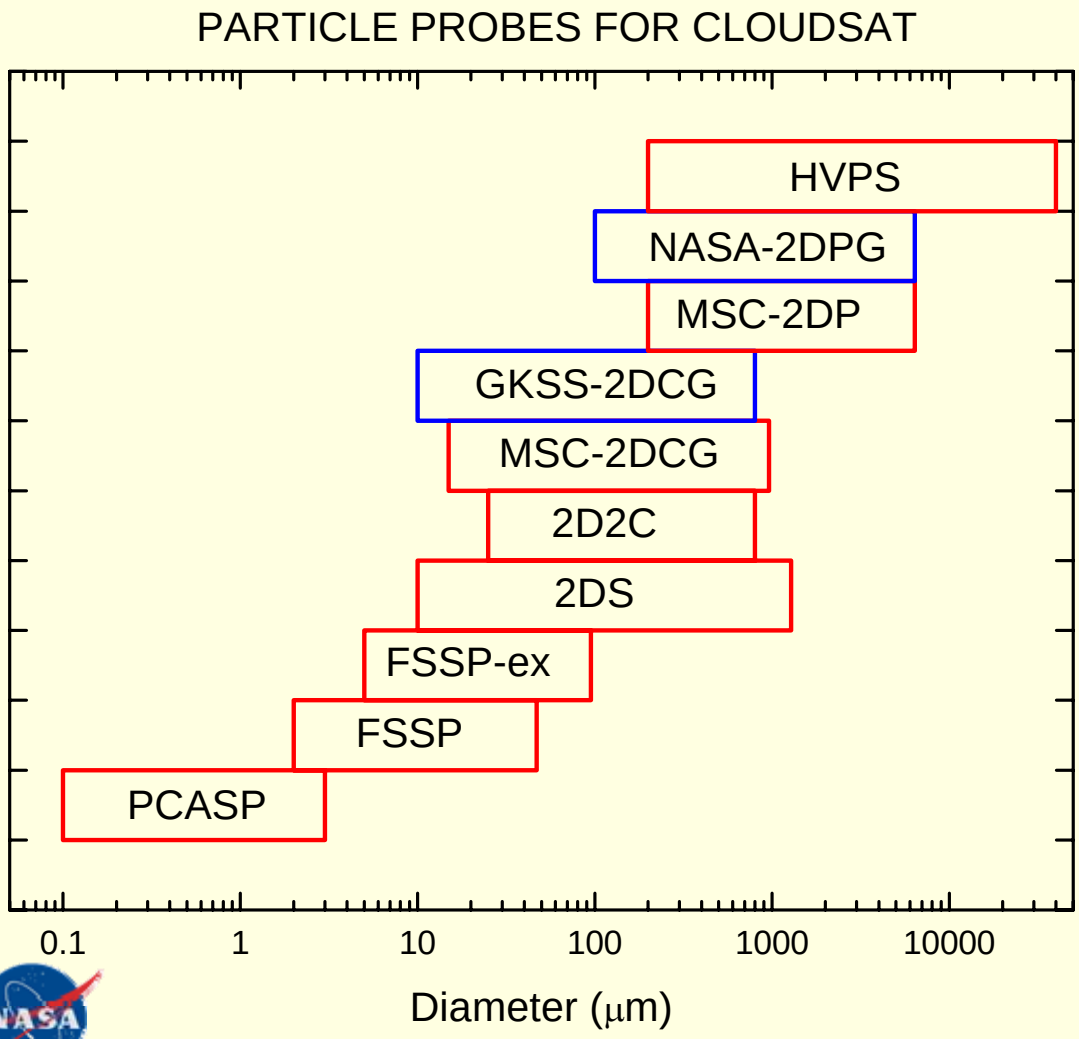
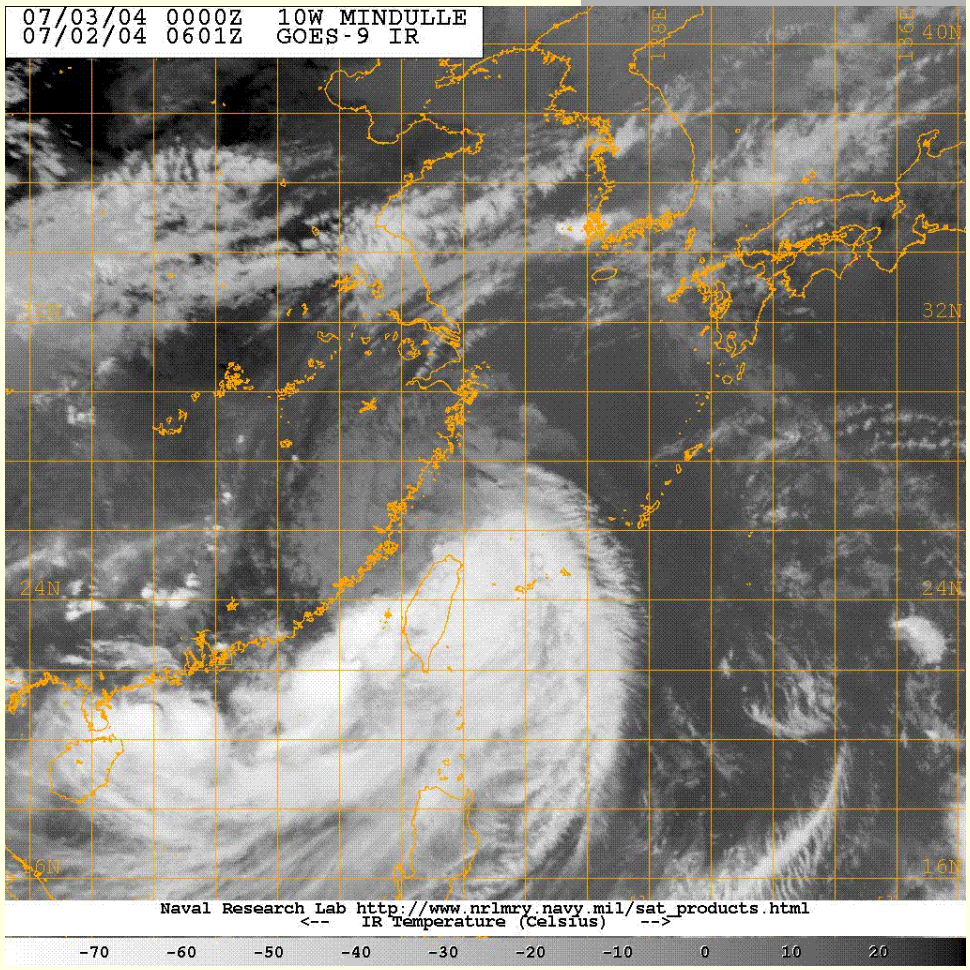
Particle Probe Ranges



Oceanic Deep Convection

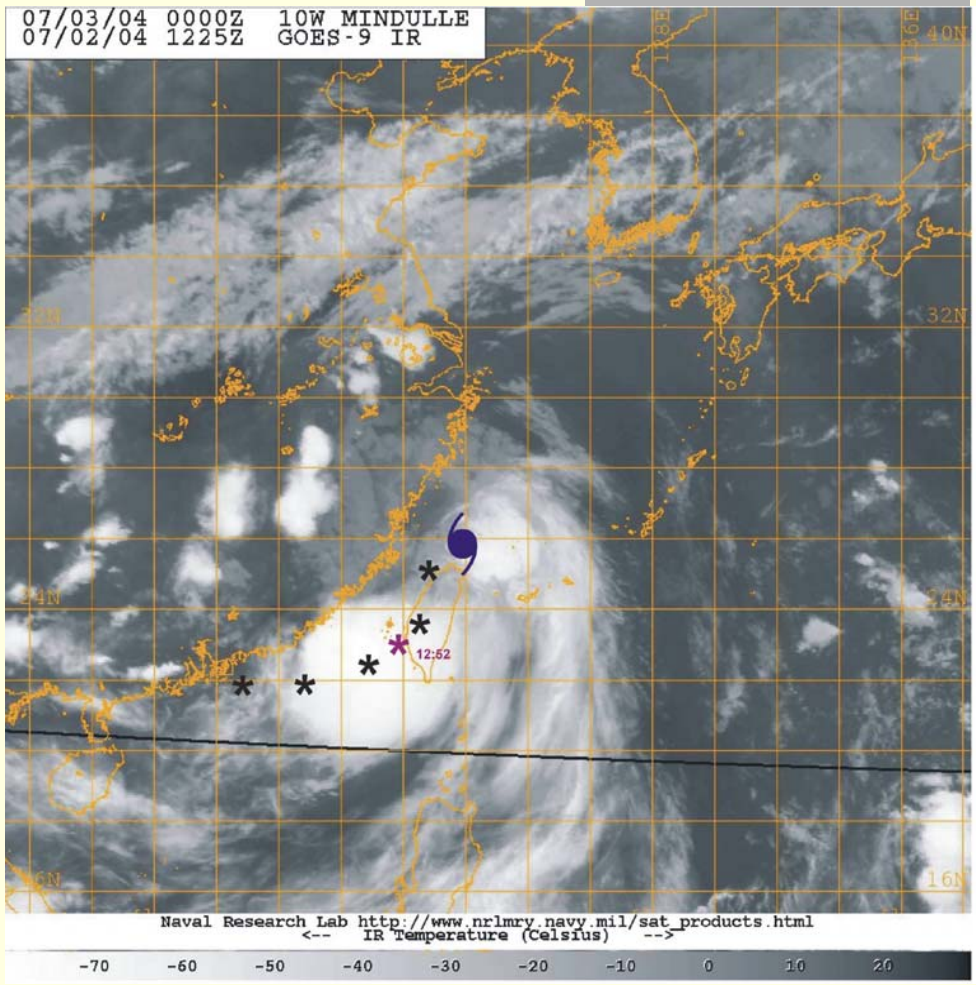
- note convective elements southwest of Taiwan grow and merge into massive convective complex
- growth of bright cloud tops in this region indicate potential for dense ice crystal zones at high altitude



A Large Transport Aircraft Engine Event

- occurred while descending into tops of deep oceanic convection

  no significant echoes at altitude on pilot's radar

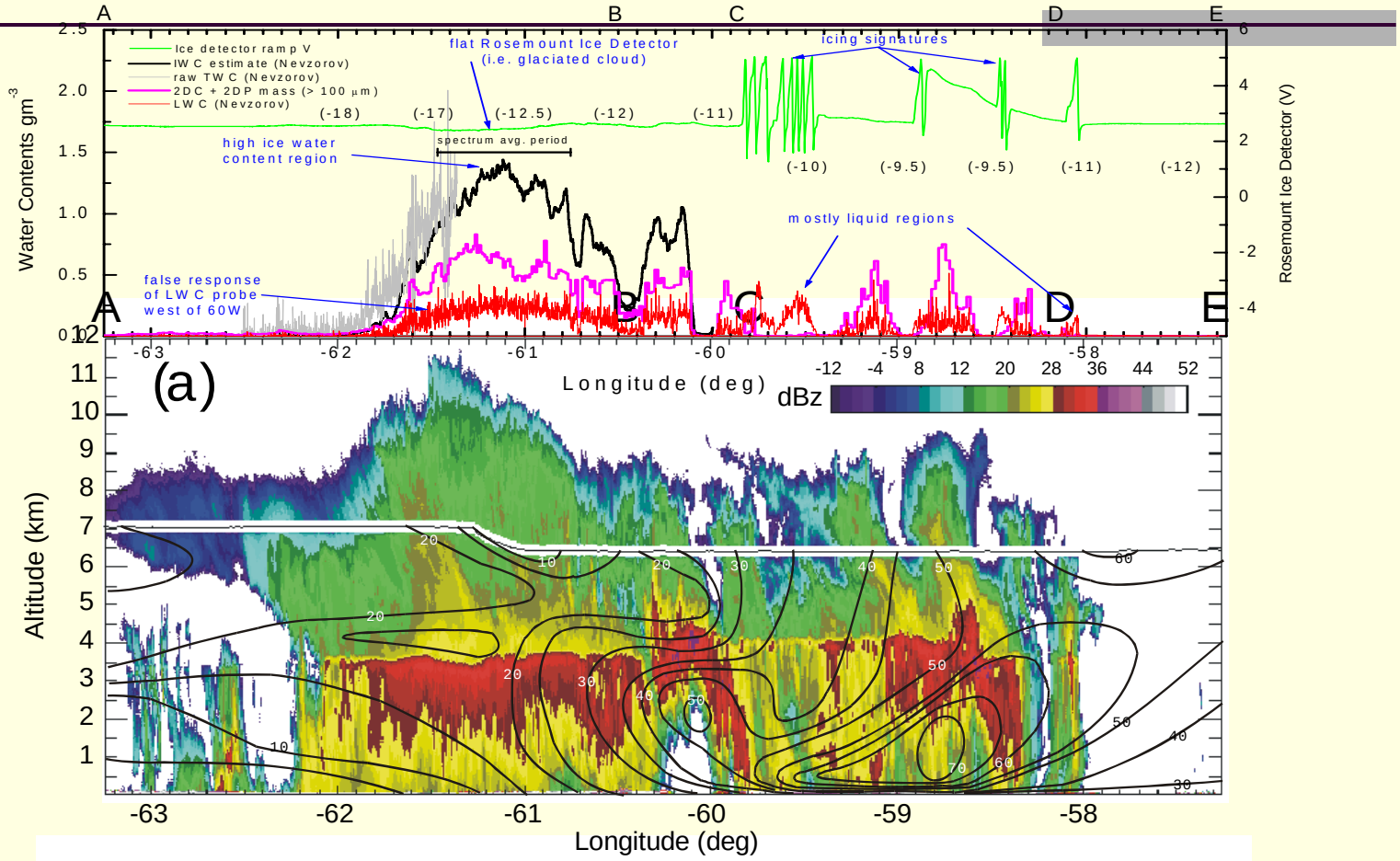


Oceanic versus Continental Convection

Attribute	Continental	Oceanic
depth	10-20 km	10-20 km
Updrafts	Strong (~20 m/s)	Weak-moderate (~5 m/s)
lightning	abundant	rare
hail	possible	no
Red echo at altitude	frequent	unlikely

- Continental convection much more likely to have dangerous core areas at high altitude
- Oceanic convection may have ‘radar-invisible’ cores at altitude, with little or no lightning
- Both types have the same potential for high IWC – same deep lift creating same potential condensed water and ice
- Engine events associated with both types

Hurricane Michael



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Dropsonde #	1	2	3	4	5	6	7	8	9	10

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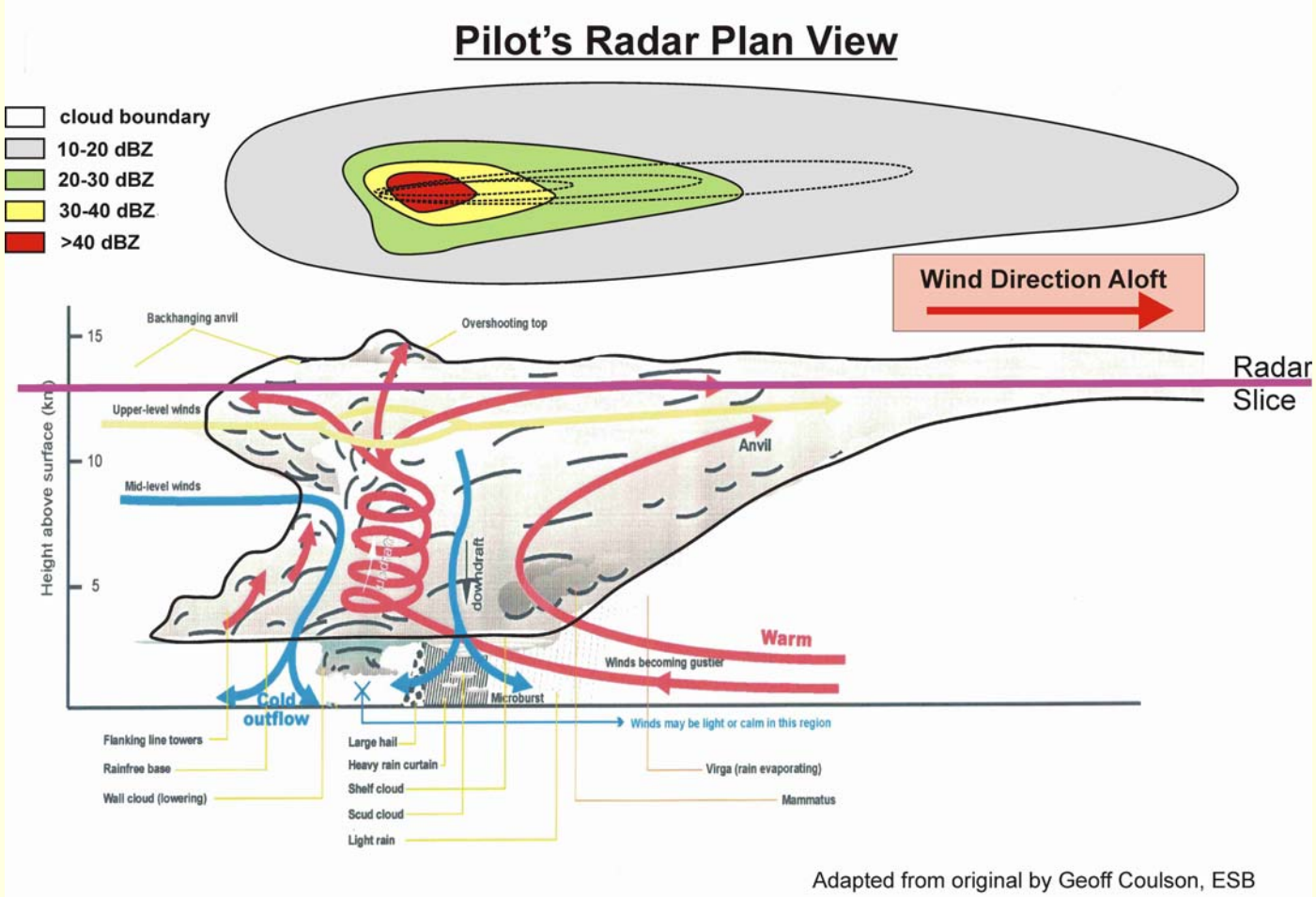
Cumulonimbus (CB) Cloud and associated features



Sources of Information Information on Microphysical Properties of Deep Convection

(1) Engine Event Data: Indirect information from the Flight Data Recorders and from pilot interviews for engine powerloss events

(2) BAe-146 industry flight test program in 1997

(3) Royal Aircraft Establishment 1956-1958 Flights in equatorial areas (mainly TWC)

(4) Atmospheric sciences research community: not much available on high IWC regions near convective cores, but some modern information in thick anvils