Summary of the High Ice Water Content (HIWC) RADAR Flight Campaigns

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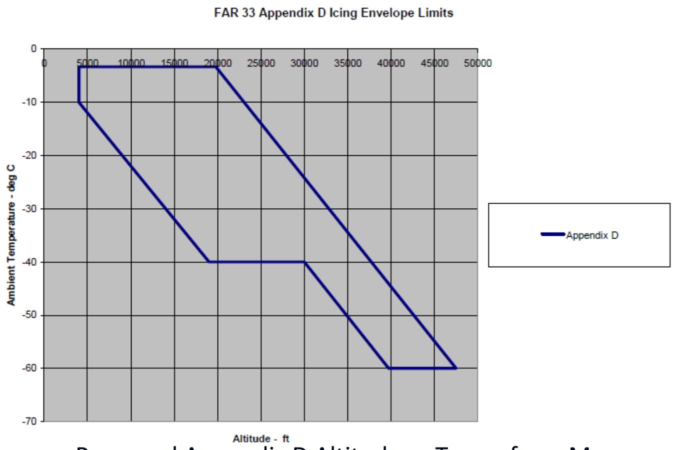
Background

- In 2003-05 timeframe, an ARAC Engine Harmonization Working Group (EHWG) reviewed numerous jet-engine powerloss events that occurred near deep convective storms. The effort resulted in a proposed Part 33 Appendix D and a Mixed-Phase/Glaciated Icing Technology Plan to guide future ice crystal icing research.
  - Tasks 1-2 were to improve cloud instruments for HIWC conditions and conduct flight research to characterize HIWC environments
- Mason, et al. (2006), described engine powerloss events and identified some common pilot observations,
  - No significant radar echoes (<30dBz) at flight altitude where engine event occurred
- In 2006, the High Ice Water Content (HIWC) Study was initiated in North America/Australia and developed the HIWC Science Plan[1] to define the aviation and science objectives, including:
  - Investigate use of onboard weather radar to detect HIWC conditions to enable pilots to avoid the HIWC environment



Proposed Appendix D Altitude vs Temp, from Mazzawy et al *Appendix D - An Interim Icing Envelope", SAE 2007-01-3311*

Locations of Powerloss Events, recreated from Mason et al *"The Ice Particle Threat to Engines", AIAA 2006-0206*

1 Strapp, et al., "The High Ice Water Content (HIWC) Study of Deep Convective Clouds: Science and Technical Plan," DOT/FAA/TC-14/31

Background

- In 2014 and 2015, the European-led High Altitude Ice Crystal (HAIC) project and HIWC team collaborated to conduct two HAIC-HIWC flight campaigns to acquire data to characterize the deep convective cloud environment and address other aviation and science objectives
  - 34 research flights of the SAFIRE Falcon 20 equipped with icing probes were conducted from Darwin, Australia (2014) and Cayenne, French Guiana (2015)
    - » The data set from these campaigns was substantial and unique, but:
      - ○ Insufficient amount of data at -50C flight level and
      - ○ No fundamental pilot radar data acquired along with in-situ cloud measurements to develop long-range identification technologies to enable avoidance

Background

- Post-Darwin, NASA and FAA initiated a collaborative effort to conduct another flight campaign
  - primary objective to quantify pilot weather radar measurements with in-situ measurements of HIWC in deep convective storms.
  - HIWC RADAR I (2015): NASA DC-8, Ft. Lauderdale, FL
  - HIWC RADAR II (2018): NASA DC-8, Ft. Lauderdale, FL/Palmdale, CA/Kona, HI

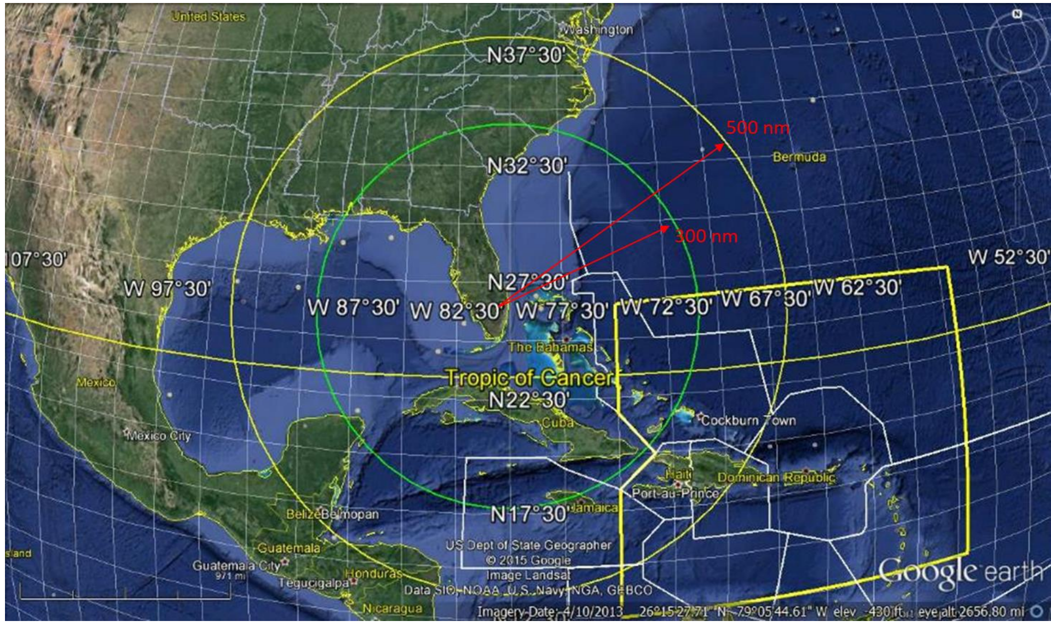
- Purpose of paper: Summarize how the campaigns were conducted and highlight key results

HIWC RADAR I (2015) Flight Campaign Overview:

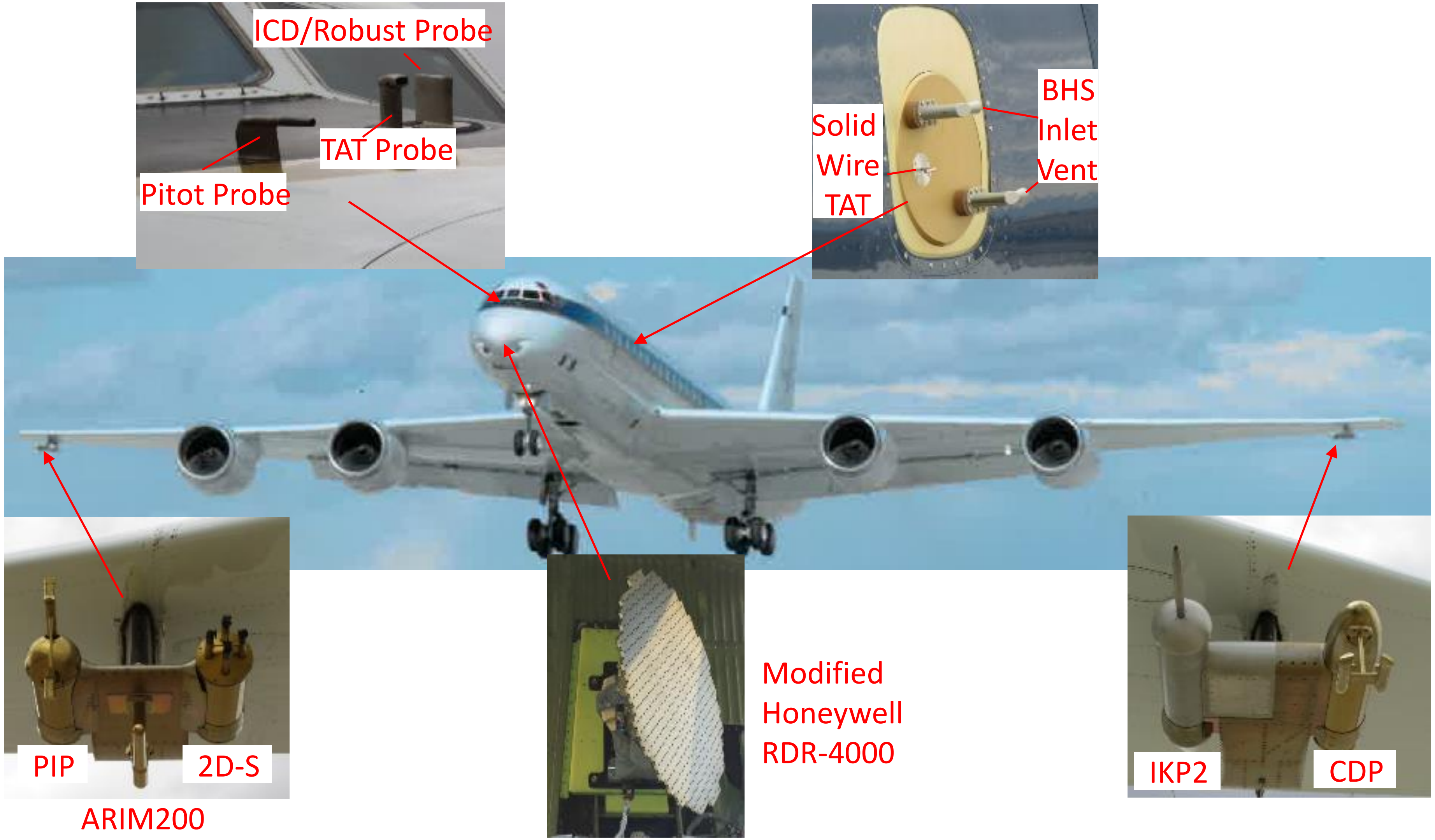
- 3 week campaign, 80 flt-hrs based from Ft Lauderdale, FL, Aug 10-31, 2015

- Utilized NASA DC-8 Airborne Science Laboratory
  - Excellent platform for HIWC research:
    - » Flight performance: Range (5,400 Nm), Ceiling (41,000 ft), Endurance (12 hr)
    - » Instrumentation sites on wing pylons and fuselage

- Operating Area: Caribbean and Gulf of Mexico
  - Climatological analyses supported August timeframe
  - Areas defined to facilitate discussions with ATC and country clearances



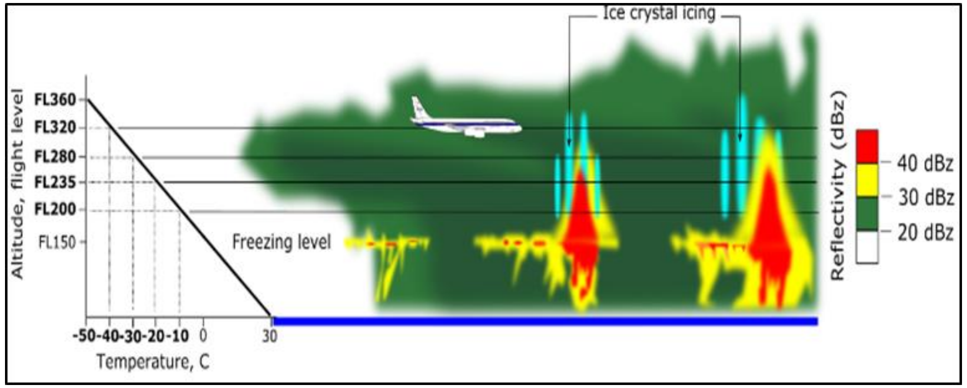
HIWC RADAR I Instrumentation:



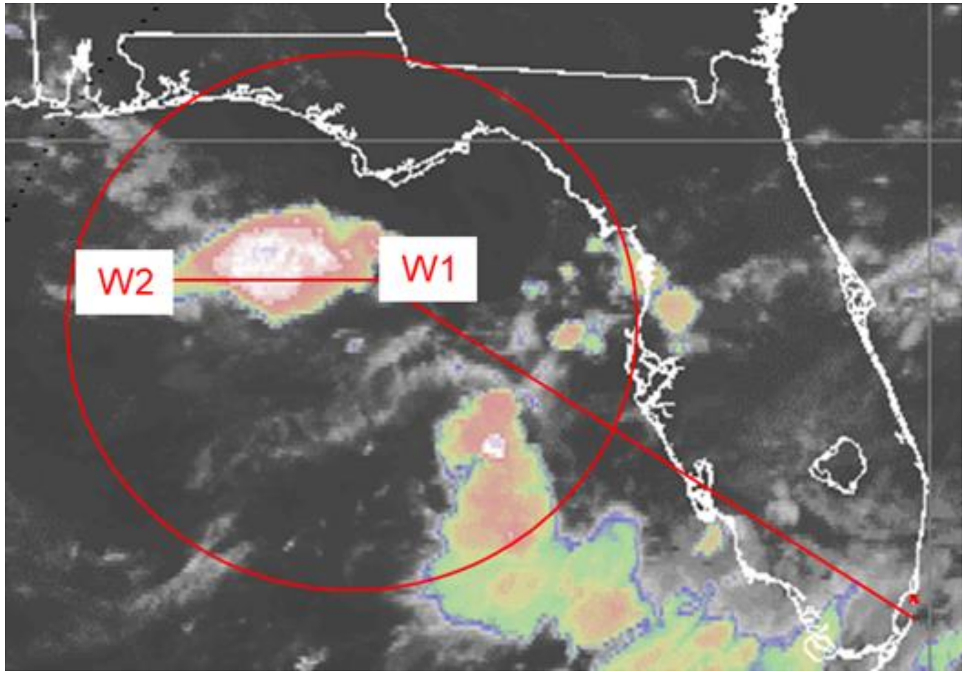
- Radar I&Q / Reflectivity
  - Honeywell RDR-4000
- Water Content
  - IKP2 (freestream)
  - SEA Robust/ICD (fuselage)
- Particle Spectra
  - DMT CDP2 (2-50 um)
  - SPEC 2D-S (10-1280 um)
  - DMT PIP (100-6400 um)
- Additional fuselage mounted instruments for background humidity, temperature, water content
- DC-8 systems: pitot-static for airspeed/altitude, TAT, GPS, etc.

HIWC RADAR I Sampling Strategies & Concept of Operations

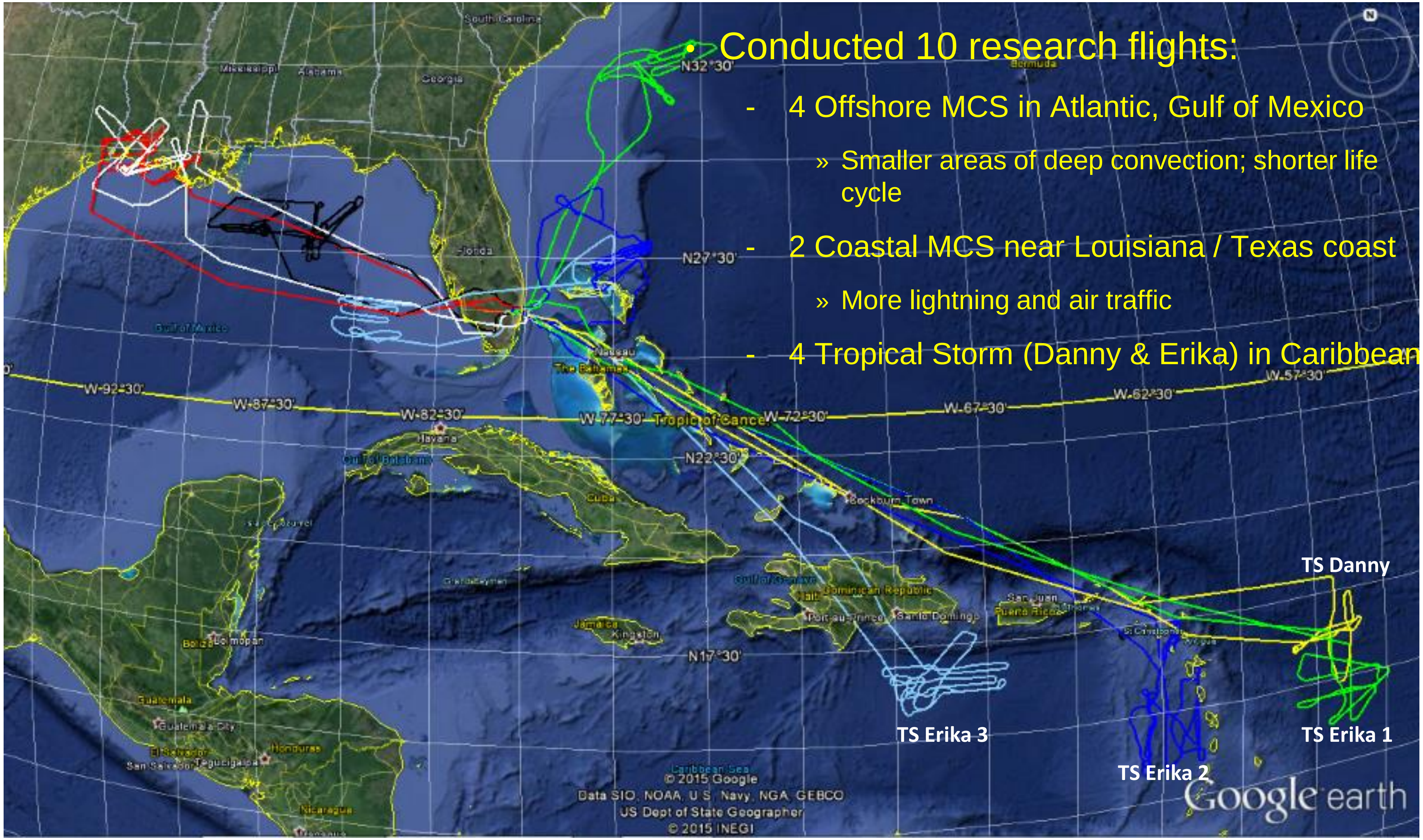
- Sampling Strategies: (consistent with HIWC Science Plan)
  - Oceanic MCSs (diam >100 Nm) with cloud top reaching tropopause; Tropical Storms highly desired
  - Level transects at altitudes associated with -50C, -40C, -30C, -10C± 5C



- Concept of operations
  - Climatology indicated peak convection in late morning
  - Anticipated life cycles: MCSs ~3 hours; TS ~days
  - Daily morning Wx briefings – identify region of interest, initial way point
  - After takeoff, ground guidance team provide way points, altitude for initial run.
  - Subsequent runs defined during flight. Parallel, offset tracks; or repeat tracks at different altitude

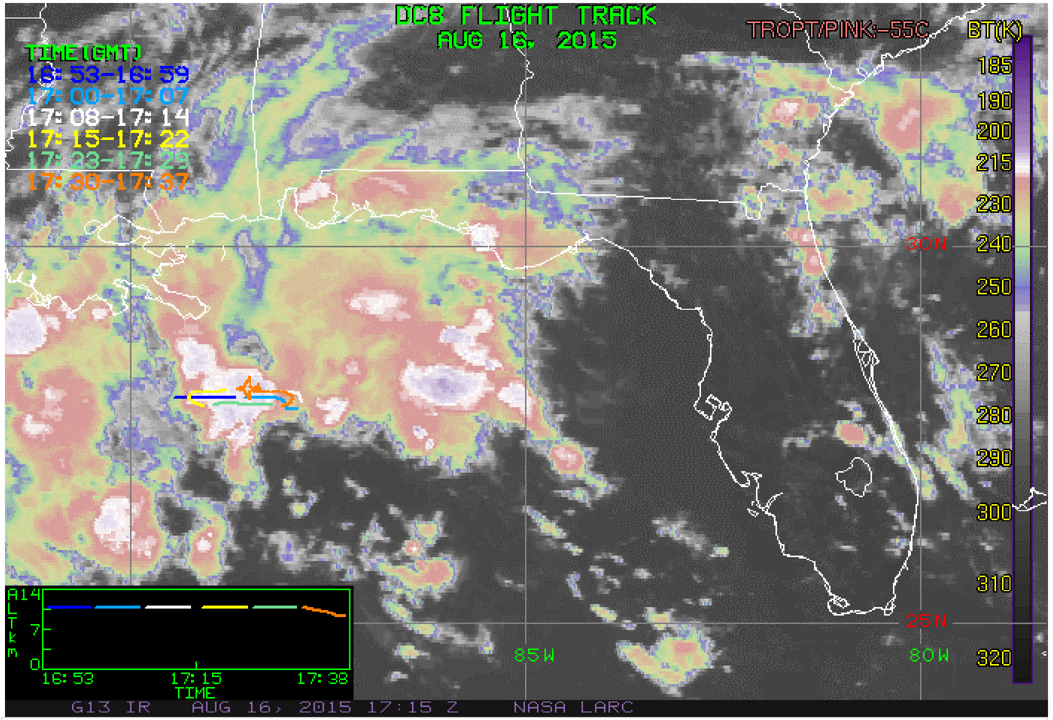


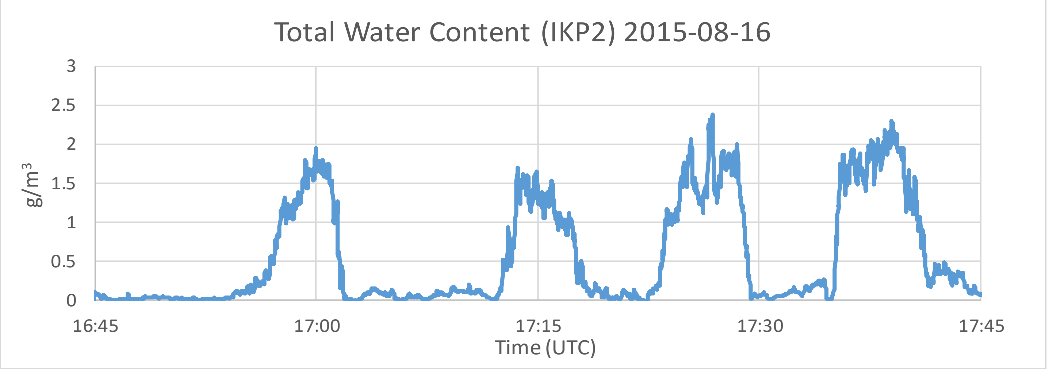
HIWC RADAR I Flight Campaign Outcomes:



- Conducted 10 research flights:
  - 4 Offshore MCS in Atlantic, Gulf of Mexico
    - » Smaller areas of deep convection; shorter life cycle
  - 2 Coastal MCS near Louisiana / Texas coast
    - » More lightning and air traffic
  - 4 Tropical Storm (Danny & Erika) in Caribbean

HIWC RADAR I Flight Campaign Outcomes:

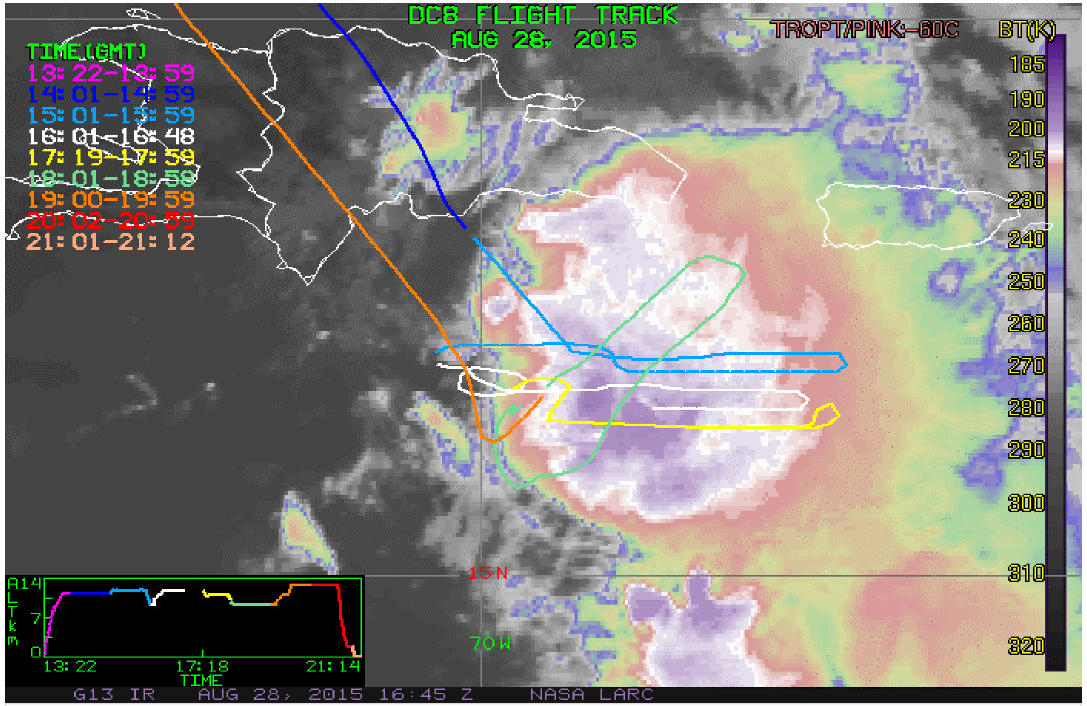


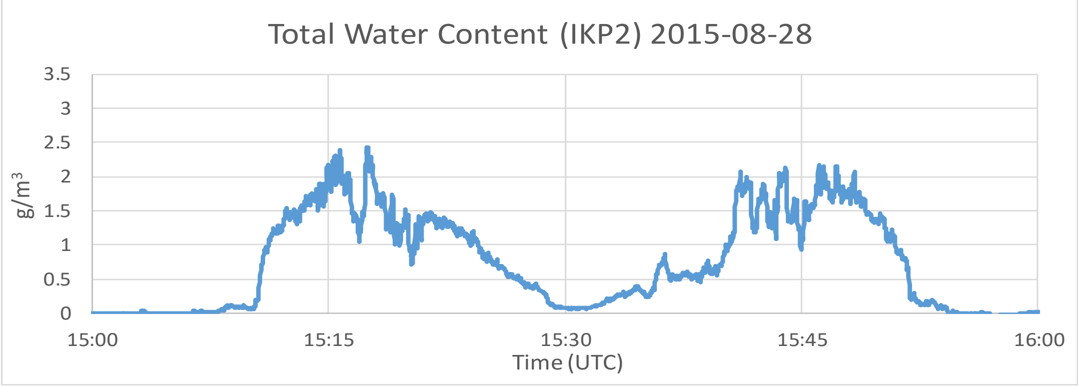


Alt=34Kft, Ts=-41C

- Offshore MCS (Flight 4) example:
  - Flight tracks of 4 parallel runs with 5 Nm offset
  - TWC variations across parallel runs are consistent
    - » IWC generally peaks about 2 g/m3
    - » Cloud extent for IWC>0.1 about 40 Nm

HIWC RADAR I Flight Campaign Outcomes:

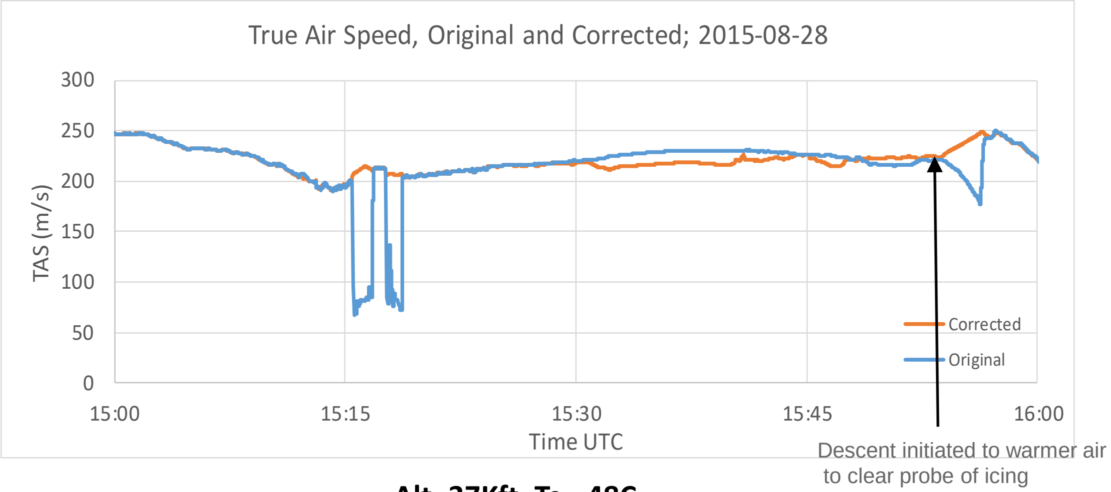




Alt=37Kft, Ts=-48C

- Tropical Storm (Flight 10) example:
  - Flight tracks of 2 parallel runs (cyan color) with 10 Nm offset
  - TWC variations across parallel runs are consistent
    - » IWC generally peaks about 2 g/m3
    - » Cloud extent for IWC>0.1 about 130 Nm
- General comparison of TS to MCS
  - TS provide deeper (colder) and longer data runs
  - TS are have longer life-cycle, predictable path and overall easier for flight planning

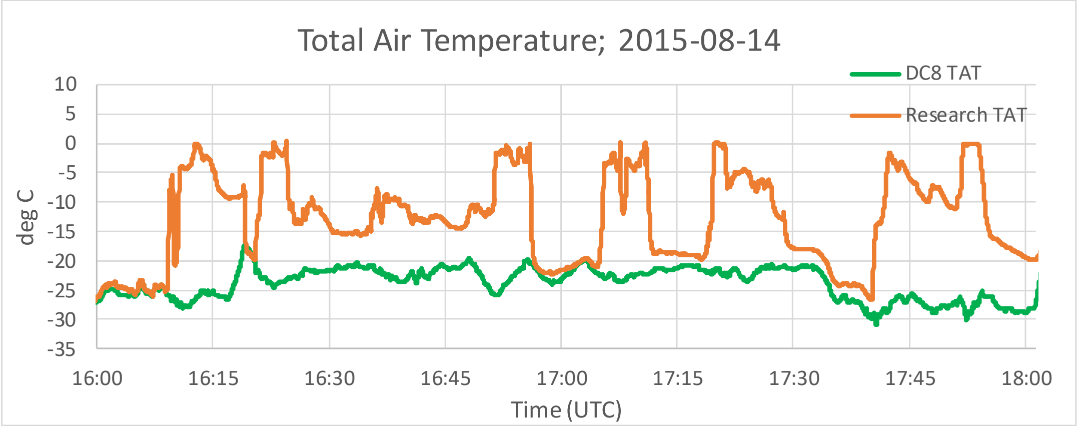
HIWC RADAR I Flight Campaign Outcomes: Pitot Probe Anomalies



Alt=37Kft, Ts=-48C

- Pitot probe icing has occurred in-service events during HIWC encounters
- During HIWC RADAR I, pitot probe icing occurred in 6 of ten flights.
- Airspeed anomalies were sometime abrupt (120 m/s drop) and other times subtle.
- Flight crew followed pre-planned mission rules and procedures when airspeed anomalies occurred
- Airspeed corrections were developed post flight and applied to SAT, TWC, PSD/MSD calculations

HIWC RADAR I Flight Campaign Outcomes: TAT Probe Anomalies

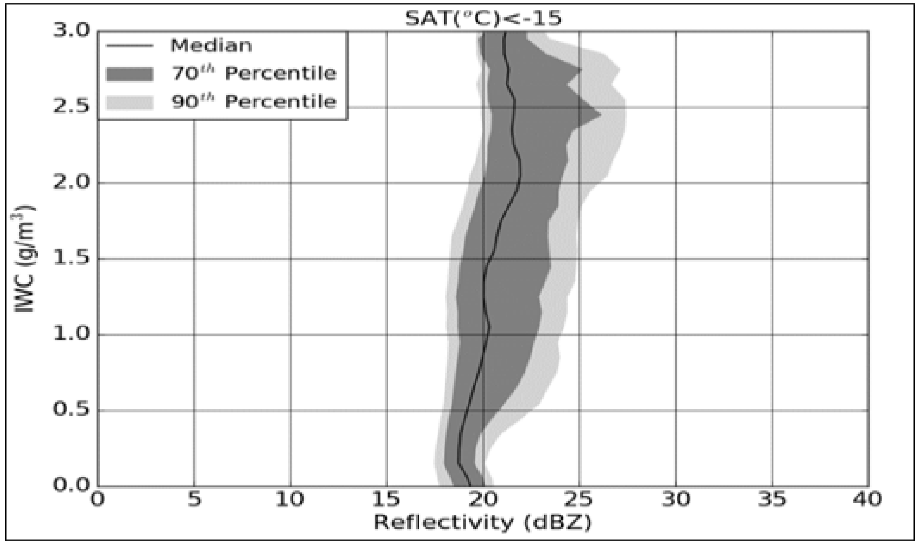


Alt=37-34Kft, Ts=-49 to -42C

- TAT probe icing has occurred in-service events during HIWC encounters
- During HIWC RADAR, a TAT probe with in-service events was mounted on the nose near SEA TWC probe. TAT anomalies occurred under when IWC and SAT thresholds were reached.
- TAT anomalies were abrupt. After initial event, recoveries were sometimes incomplete.
- TAT probe location important factor. Other similar TAT probe designs on DC-8 had no TAT anomalies

HIWC RADAR I Flight Campaign Key Findings:

- Correlation of radar reflectivity to IWC [1]
  - Conclude reflectivity alone insufficient for IWC detection
- Augmented TWC and PSD/MSD at -50C data set (68%) for Part 33 Appendix D assessment [2]
- Confirmed common observations from in-service events and previous campaigns
  - High IWC in low radar reflectivity
  - Pitot and TAT probe anomalies
  - Water streaming on windscreen in high IWC
  - Linkage of research data to in-service events

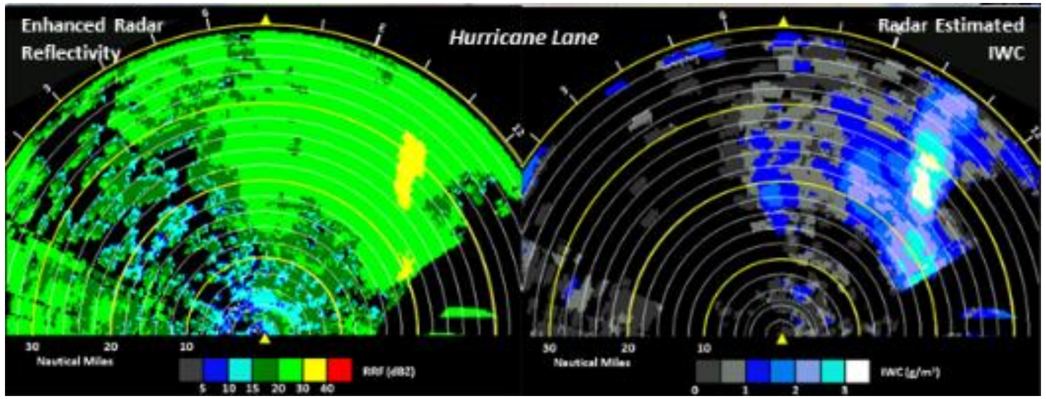


- Lessons Learned
  - Tropical storms were good targets for HIWC research flights
  - DC-8 performance excellent; no issues with engine operation in HIWC
  - Need for instrumentation improvements for airspeed, background humidity, winds

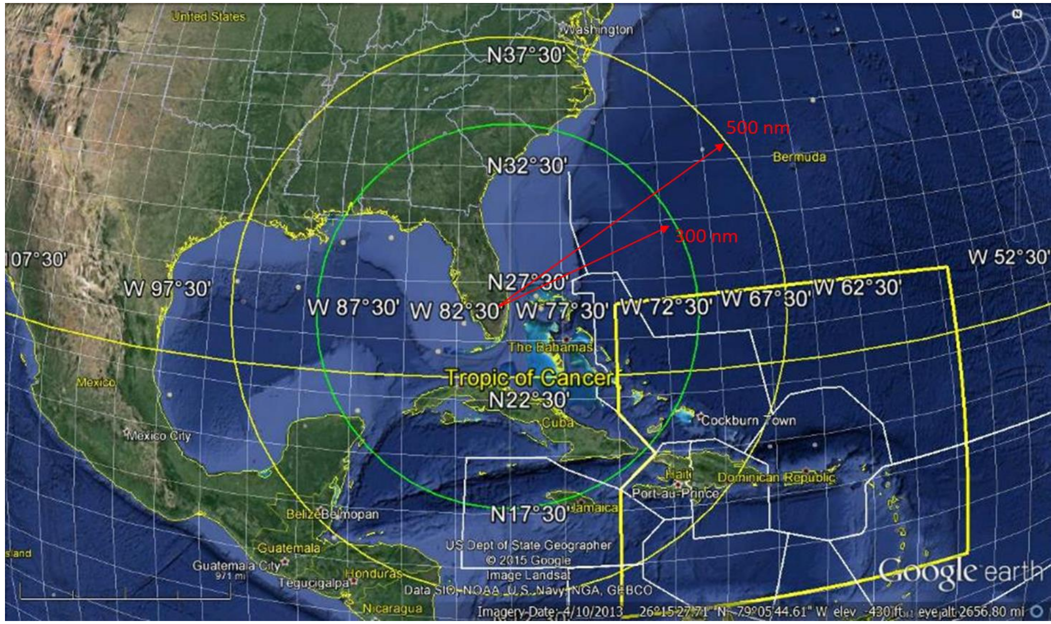
[1] Harrah, et al., this conference
[2] Strapp, et al., this conference

HIWC RADAR II (2018) Flight Campaign Overview:

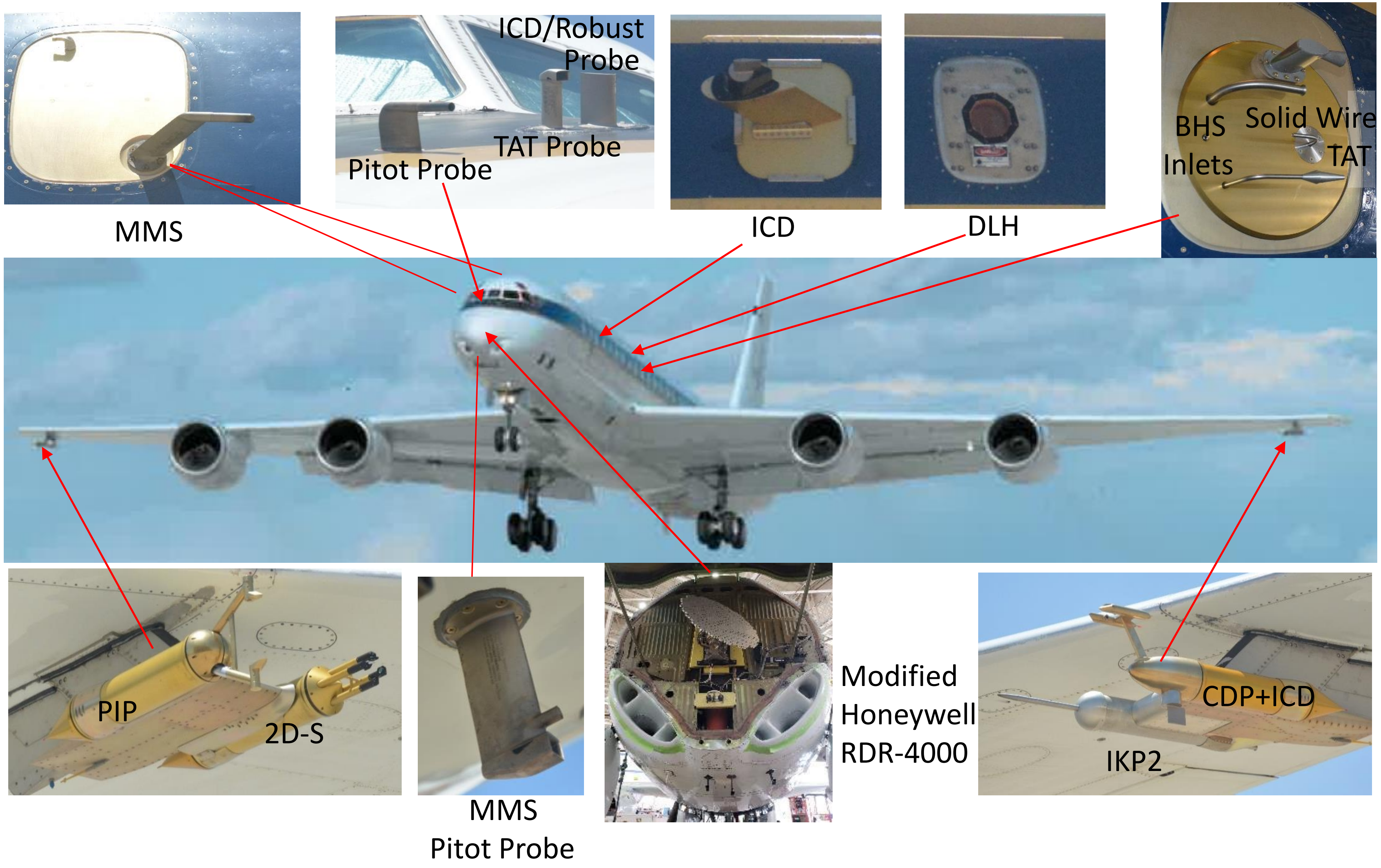
- As a result of insufficient correlation of RRF to IWC, NASA Langley radar researchers identified other promising radar-based candidates for long-range HIWC detection
  - Dual-polarimetric radar (Wolde, et al.)
  - Swerling (new process relating RRF Index of Dispersion to IWC (Harrah, et al.)



- Second flight campaign to evaluate the new methods
  - 3 week campaign, 50 flt-hrs based from Ft Lauderdale, FL, July 30-Aug19, 2018
  - Utilized NASA DC-8 Airborne Science Laboratory
  - Operating Area: Caribbean and Gulf of Mexico
  - Same sampling strategy, but add -20C flight level
  - Dual-pol not tested due to hardware delivery issue



HIWC RADAR II Instrumentation:



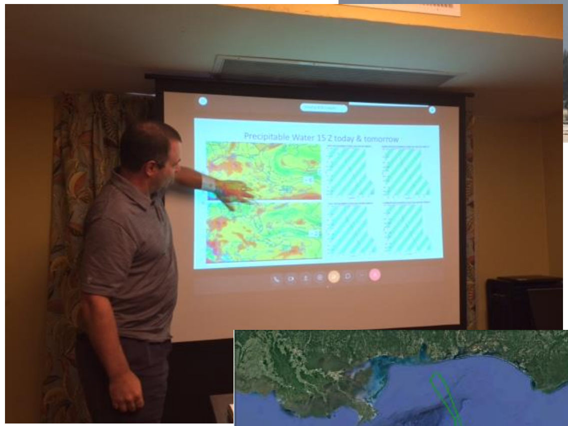
- Same instrumentation suite as 2015 plus:
- Auxiliary research pitot-static for airspeed/altitude
- Meteorological Measurement System (MMS) for winds and gusts
- Diode Laser Hygrometer (DLH) for background humidity
- Improved inlets for background humidity system
- N_2 purge for particle probes
- Hotwire TWC on wing canister and on window mount
- Collins Aerospace Optical Ice Detector (OID) [3]

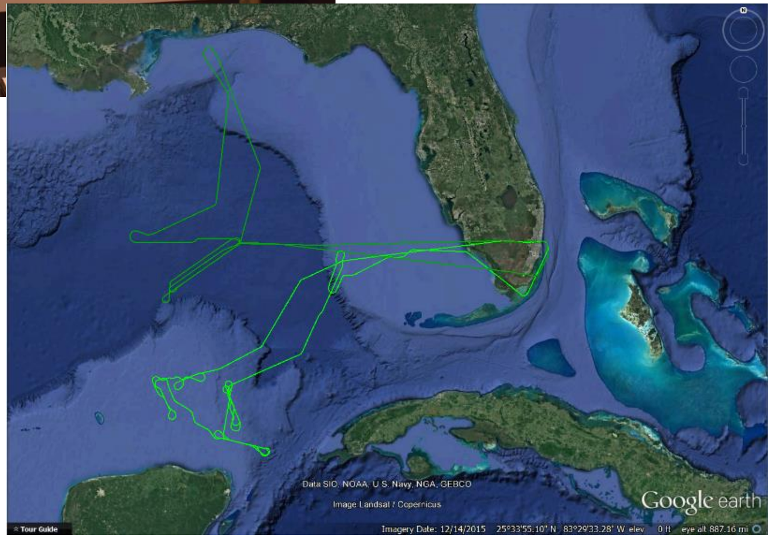
[3] **Anderson, et al., this conference**

HIWC RADAR II Flight Campaign Outcomes: 7 Research Flights

- Initial flights from Ft. Lauderdale, FL into Offshore MCS in Gulf of Mexico
  - Smaller scale storms
  - 2 flights in 8 days
  - Dry air/dust off Africa and cooler ocean temps in Caribbean suppressing deep convection
    - » Forecasts indicated much the same for duration
  - Meanwhile, multiple MCS and tropical storms/hurricanes developing in eastern Pacific

- Decision Time
  - During post flight debrief (Aug-06), team discussed option to re-deploy back to AFRC and sample storms in Pacific
  - By end of meeting, decided to return to AFRC
  - Ferry flight back on Aug-08

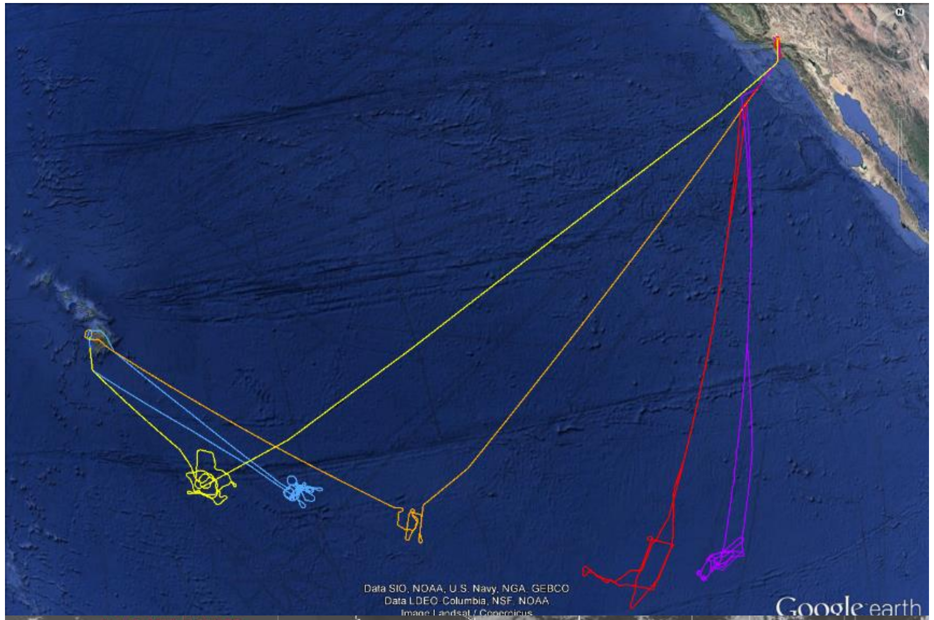


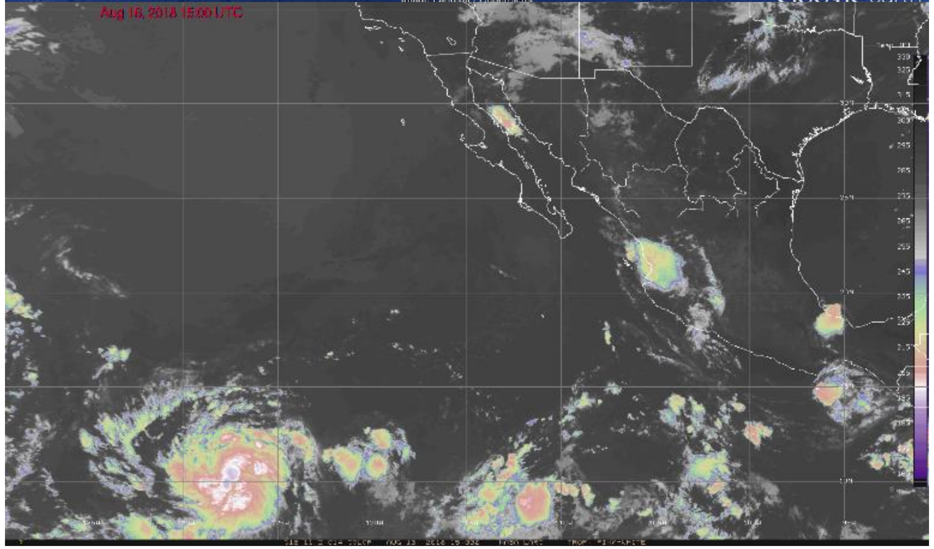


HIWC RADAR II Flight Campaign Outcomes: 7 Research Flights

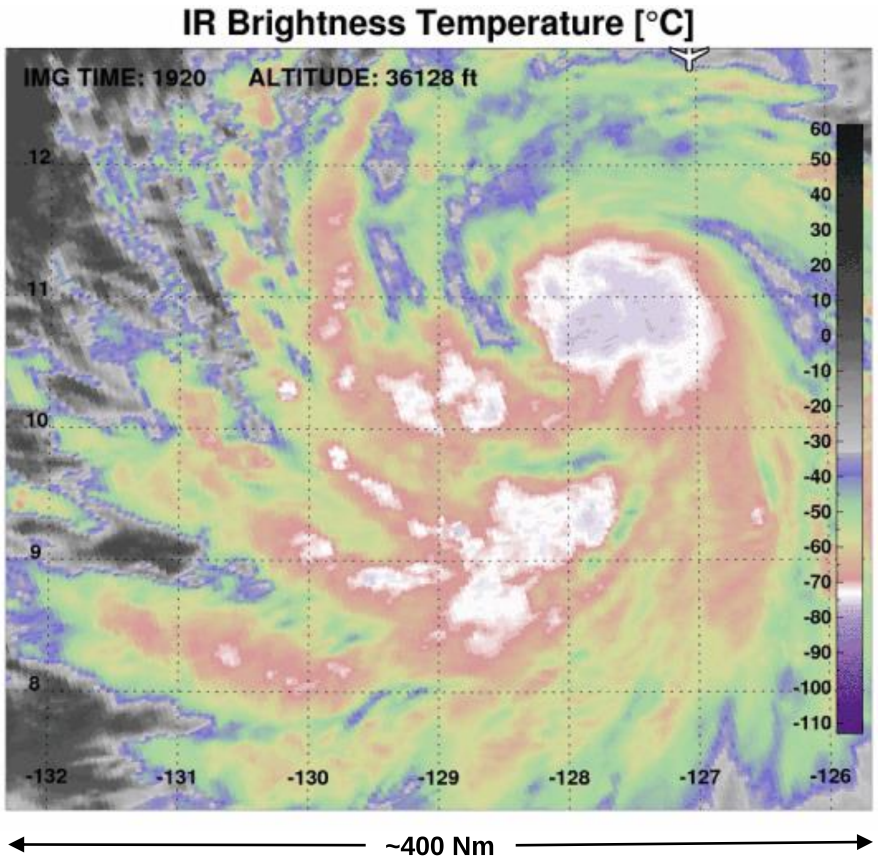
- After unplanned engine swap, 5 flights were made over the eastern Pacific
  - Aug-15: Tropical Storm Lane
  - Aug-16: Tropical Storm Lane
  - Aug-18: Hurricane Lane – Cat 4
  - Aug-19: Hurricane Lane – Cat 3
  - Aug-20: Hurricane Lane – Cat 4

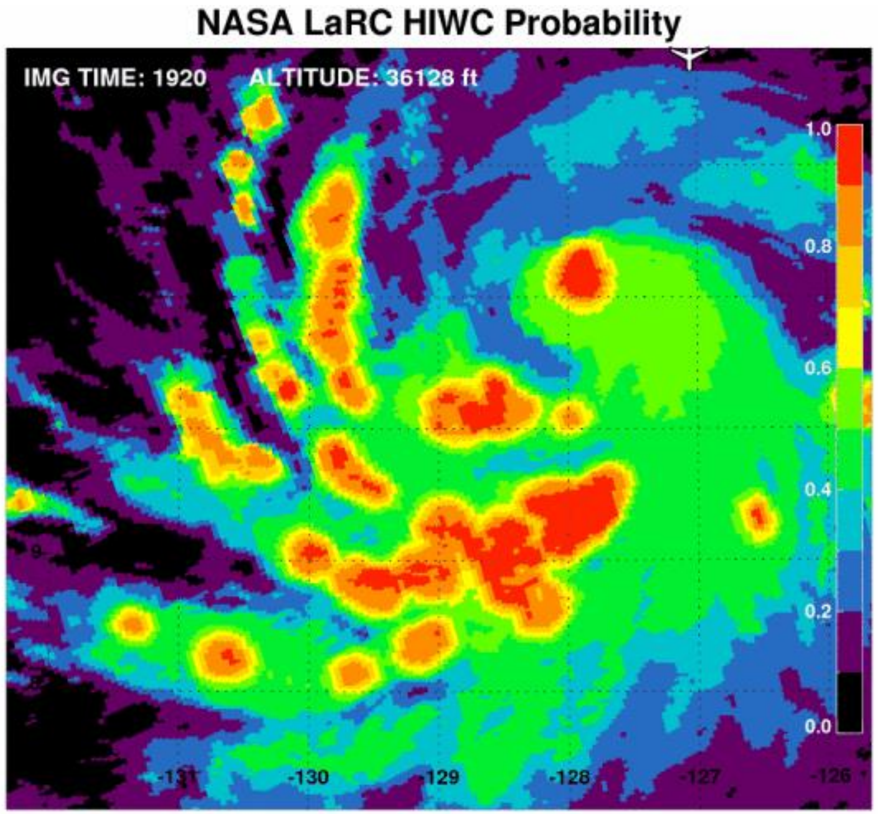
- Long transit flights (> 3 hr) from Palmdale; rebase from Kona, Hawaii for last 3 flights
- Large scale deep convection (~300 Nm diameter)





HIWC RADAR II Flight Campaign Outcomes: TS Lane Example





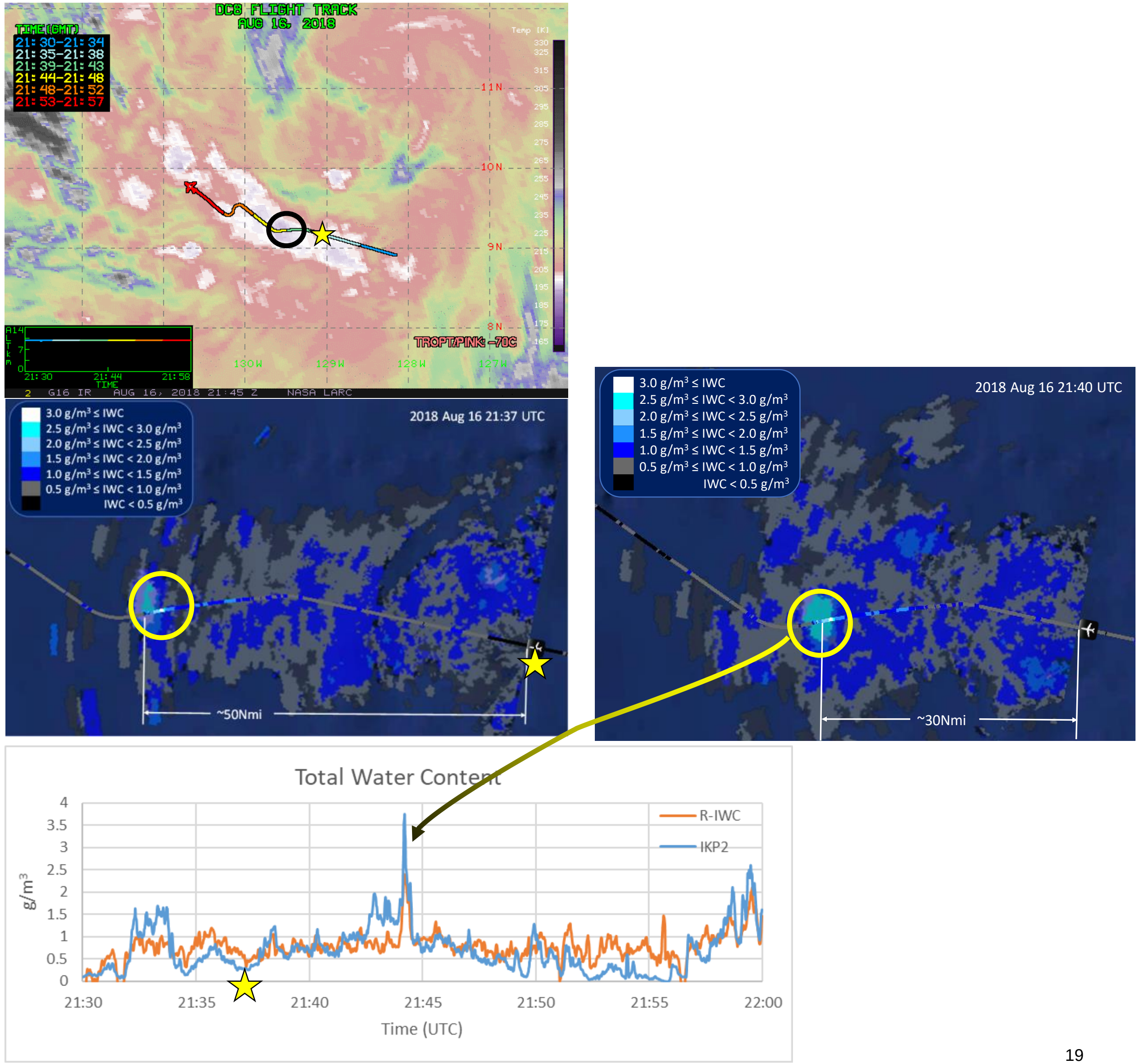
Satellite Products

- Strategic planning
  - » deep, cold cloud areas where high IWC anticipated
  - » Areas of overshooting tops
- Tactical planning
  - » As storm at left was ebbing, HIWC zones were shrinking
  - » Near end of flight, pilots flew to intercept “string of pearls” visible in feeder bands and based on Swerling R-IWC

http://clouds.larc.nasa.gov/prod/OT/GOES16_DC8overlay_IR-HIWCP_16AUG2018.gif

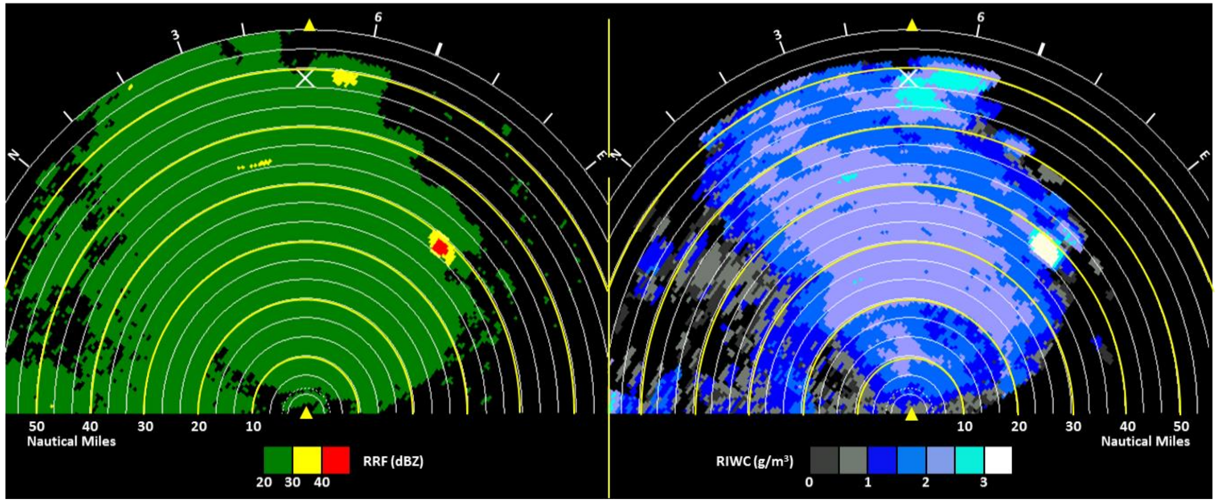
HIWC RADAR II Flight Campaign Outcomes: TS Lane Example

- Swerling R-IWC: real-time, onboard guidance
  - IWC thresholds, 0.5 g/m^3 steps
  - ~ 50 Nm range, initial detection of small region with IWC ~ 2.5-3 g/m^3
    - » Radar team notified crew and monitored
  - ~30 Nm range, the region of IWC ~ 2.5-3 g/m^3 increased about 5 Nm wide
    - » Radar team requested left turn to intercept
  - When DC-8 passed through the radar-identified region, the IKP recorded IWC 1.5-2.2 g/m^3 with peak of 3.6 g/m^3
    - » R-IWC generally lower, but within 1 g/m^3 of IKP
- These encounters increased confidence in Swerling R-IWC product and was used to guide flight tracks in remaining flights



HIWC RADAR II Flight Campaign Key Findings/Contributions:

- Swerling concept can identify HIWC conditions in low RRF about 60 Nm ahead of the aircraft[1]
- Data can be compared to HIWC characterization data from previous flights
- Satellite diagnostic products from NASA Langley were very useful for strategic and tactical guidance[4]



- Lessons Learned
  - Diode Laser Hygrometer solved a prior problem of measuring background humidity in HIWC conditions on the DC-8
  - DC-8 pitot anomalies occurred, but MMS provided accurate and reliable true airspeed
  - DC-8 performance capabilities were critical for this campaign

[1] Harrah, et al., this conference
[4] Bedka, et al., this conference

HIWC RADAR Flight Campaign Summary:

- Two flight campaigns (2015 and 2018) using NASA DC-8 successfully flew in deep convective storms to acquire high IWC data with pilot weather radar and in-situ instruments
  - Demonstrated radar-based technique to identify HIWC conditions at 60 Nm ahead of airplane
  - Acquired data at -50C altitude for Appendix D characterization
  - Provided validation data for HIWC diagnostic products
- Future Work:
  - Continued evaluation of Swerling technique and other data from the flight campaigns
  - Working groups in RTCA and ARAC