Preliminary Assessment of Appendix D/P Total Water Content from In-Situ Measurements of Deep Convective Clouds from the HAIC-HIWC Darwin-2014 Flight Campaign.

J. Walter Strapp[1,*], Alfons Schwarzenboeck[2], Julien Delanoë[3], Fabien Dezitter[4], Chris Dumont[5], Alice Grandin[4], Alexei Korolev[6], Lyle Lilie[7], Rodney Potts[8], Alain Protat[8], Thomas Ratvasky[9].

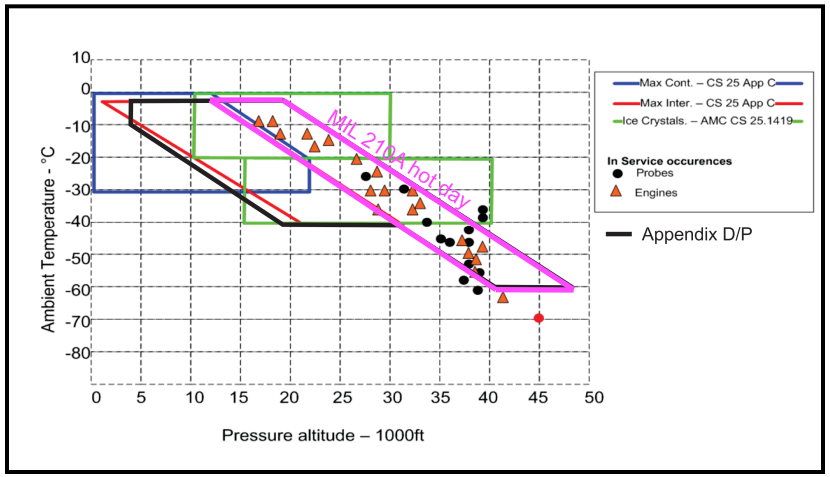
[1]Met Analytics Inc.
[2]CNRS-LaMP
[3]CNRS-LATMOS
[4]Airbus
[5]Federal Aviation Administration
[6]Environment Canada
[7]Science Engineering Assoc.
[8]Australian Bureau of Meteorology
[9]NASA Glenn Research Center

Presented at the HAIC-HIWC Science Forum, 9-Nov-15, Melbourne, Australia

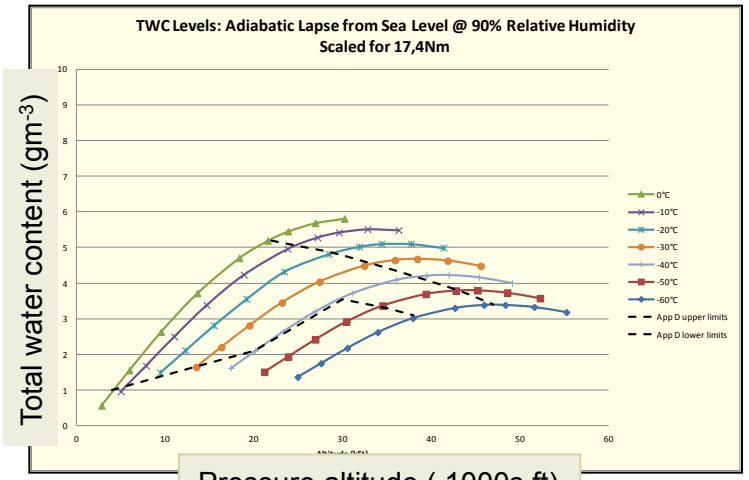
** Work funded by the FAA through as subcontractor to Science Engineering Associates*

New ice crystal envelope for aircraft certification

- New ice crystal envelopes resulted from discussions within the Engine Harmonization Working Group (EHWG) 2004-2006, resulting in…..
- FAA Appendix D [1] and EASA Appendix P, the same



APPENDIX D Temperature Envelope [1,2]



APPENDIX D Total Water Content [1]

- TWCs are theoretical maxima for air parcel deep-lift from low altitude , scaled down by factor 0.65 to 99th percentile 1950s RAE TWC data at 17.4 nm scale

[1] Mazzawy, Robert S., and J. Walter Strapp, 2007: Appendix D - An Interim Icing Envelope : High Ice Crystal Concentrations and Glaciated Conditions, *SAE Transactions, Journal of Aerospace*, 116, 634-642

[2] E. Duvivier, 2010, High Altitude Icing Environment. Intl. Air Safety and Climate Change Conf. 8-9 Sep. 2010, Cologne, Germany

Flights for In-Situ Appendix D/P Validation

- In-situ flight measurements in deep convective clouds recommended in EHWG Technical plan, to assess the new ice crystal regulatory envelope

- Target: collect 99th percentile TWC values on 17.4 nm distance scale, and its dependence on distance scale, in clouds similar to those that caused engine events, and with target TWC accuracy of 20%.
  - regulatory agencies and industry use 99th percentile values to test compliance, but under more extreme conditions (e.g. >>17.4 nm)

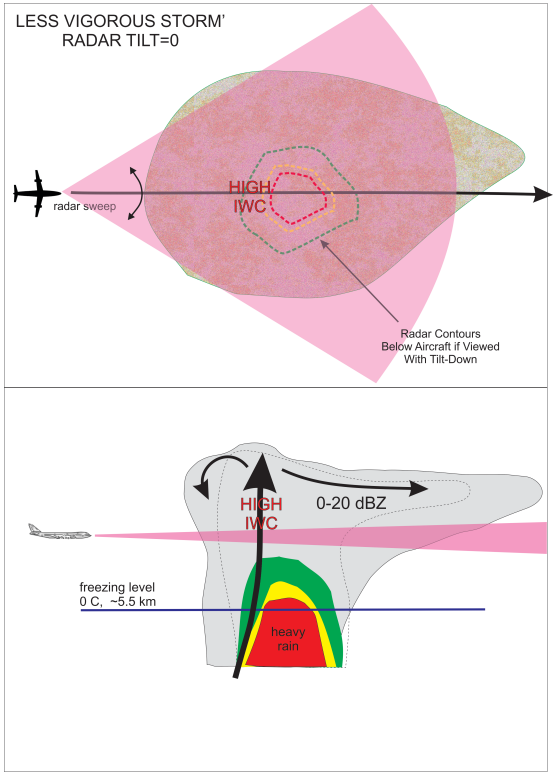
Isokinetic TWC Evaporator on Falcon-20, unique new instrument for high IWC measurement

- Necessary to develop and test a new instrument (IKP2) to measure TWC at high values and high airspeeds (NRC / Environment Canada / SEA / FAA / NASA / Met Analytics partnership): "IKP"→ "IKP-2"

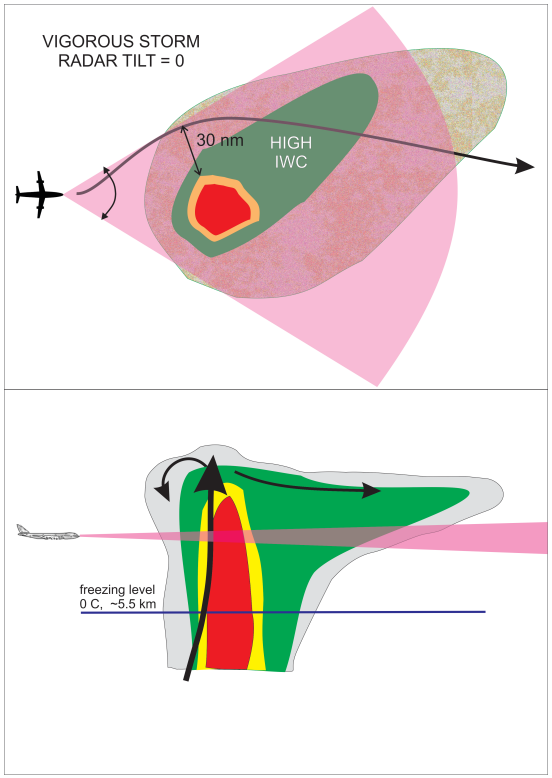
- Partnership High Altitude Ice Crystals (HAIC) and High Ice Water Content (HIWC) projects for collaborative measurements on French Falcon-20 aircraft (Darwin-2014 and Cayenne 2015); previous paper in this HAIC-HIWC Science Forum)

Flight Plans[3]

Less vigorous, typically oceanic



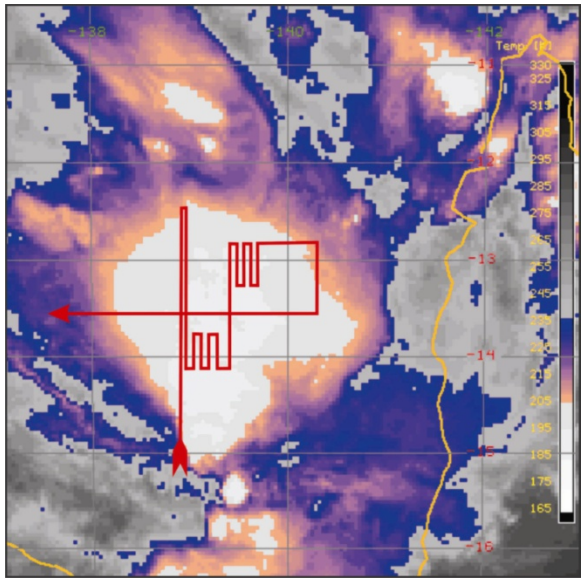
More vigorous, typically continental

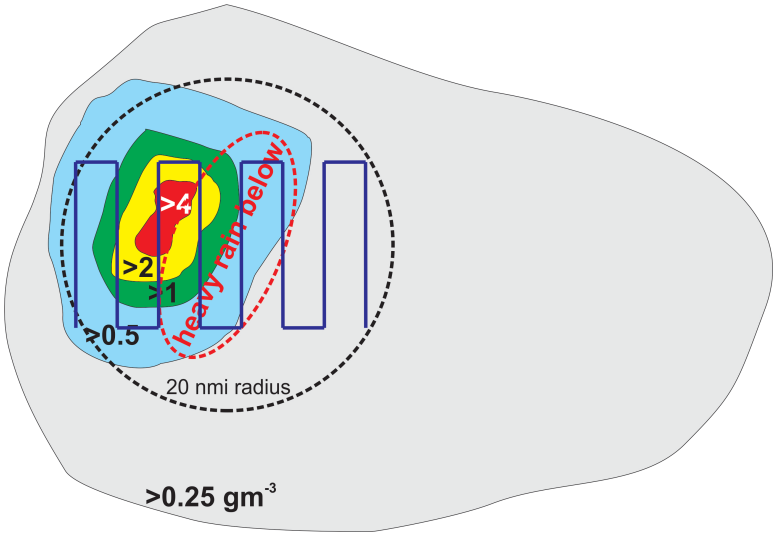


[3] *Strapp, J. W., A. Korolev, T. Ratvasky , R. Potts, A. Protat, at al., 2015: The High Ice Water Content (HIWC) Study of Deep Convective Clouds: Science and Technical Plan, FAA report DOT/FAA/TC 14/31, in press.*

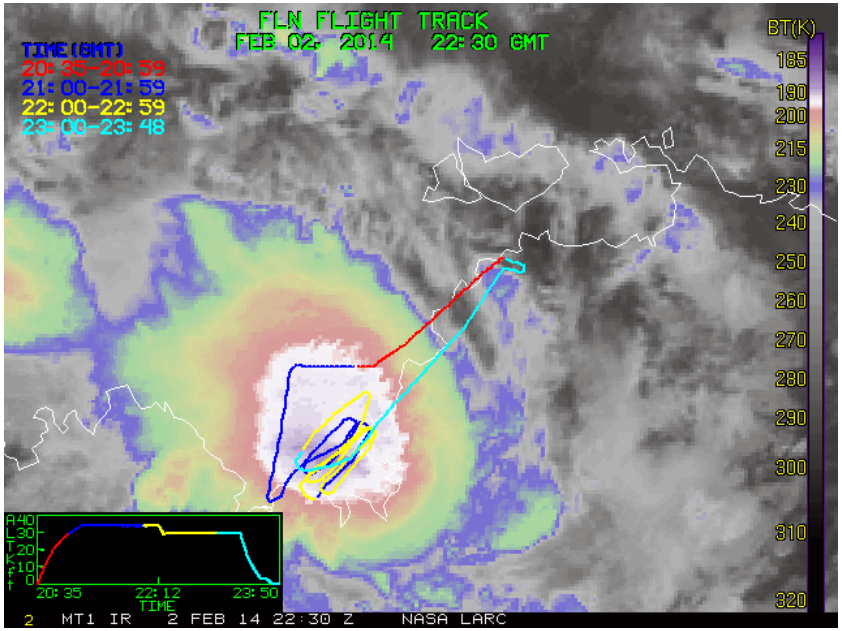
Flight Plans[3]

- To be consistent with the Boeing engine event data base, target large Mesoscale Convective Systems (MCSs) with anvil diameter > 100 nm
- Collect cloud in-situ data in a survey pattern near or in active cells, including some long runs to survey across entire anvil
- Collect data a temperature levels -50 C, -30 C, -10 C, in order of priority
- Target at least 100 17,4 nm data points at each altitude
- Attempt to stay within 20 nm of heavy precipitation below the aircraft (one way to provide context to statistics we collect)



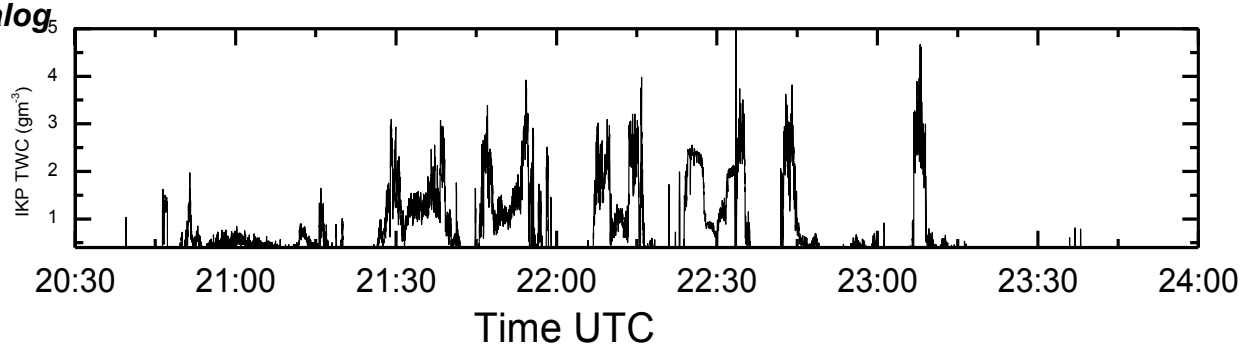


Flight Plans: Actual Darwin Flight Example



- Actual flight track example shown here
- Infrared imagery to left shows cloud top effective temperature, as in previous slide
- White threshold here is -78 C
- Coldest cloud tops here reached about -95 C.
- Cloud was sampled at -36 C and -26 C

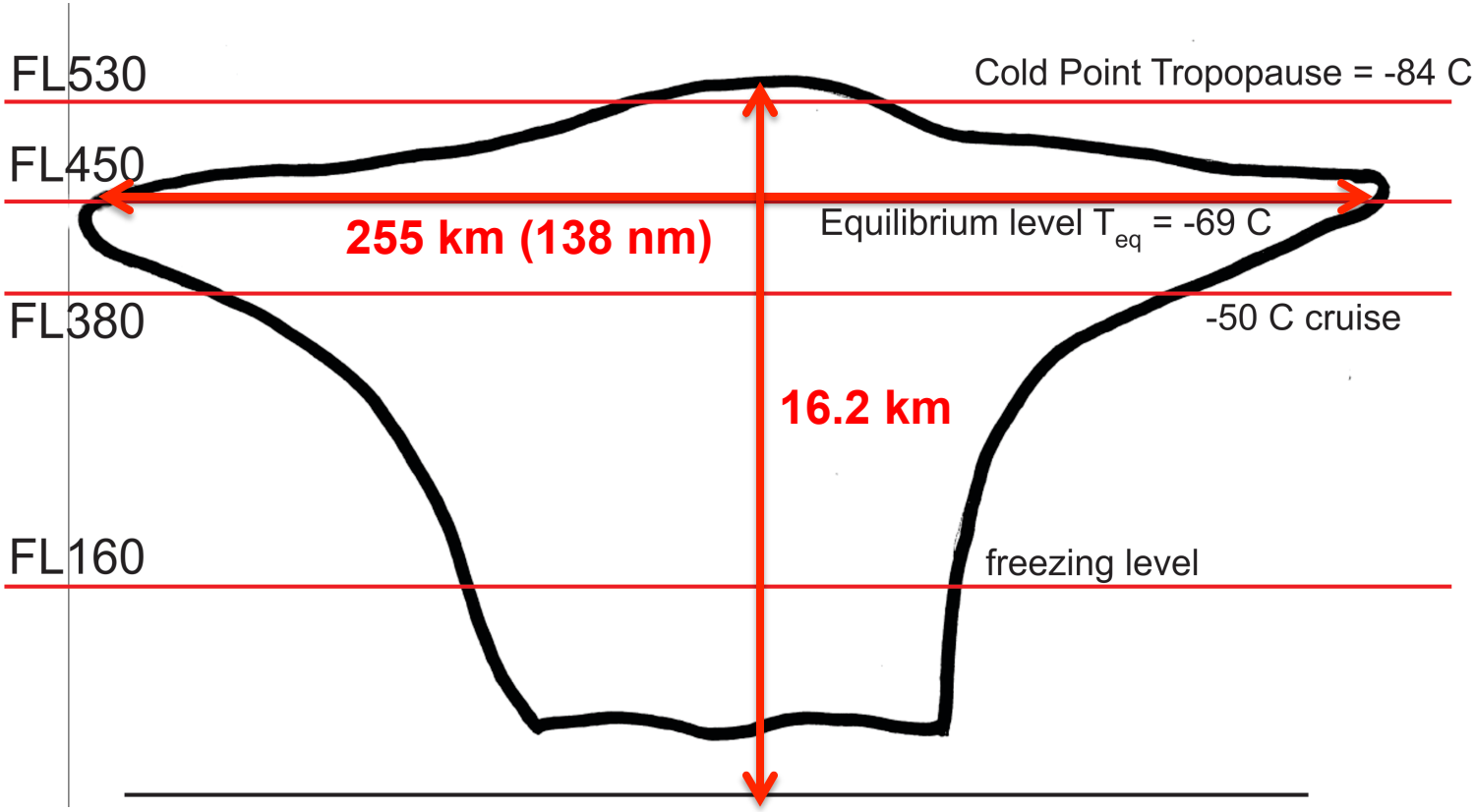
Courtesy of NCAR field catalog



Darwin-14 General Statistics

Number of Flights:	23
Number of flights with Appendix D/P cloud measurements:	16
Number of Oceanic MCS flights:	14 (88%)
Number Continental MCS flights:	2 (22%)
Number Isolated Cumulonimbus:	0
Number of Segments:	157
Total Distance in Segments (nm):	7648
Avg. length of Segment (nm):	36.5

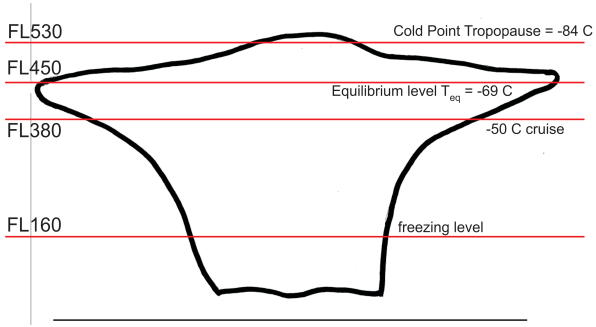
Simplified cartoon: Medians of properties of Darwin clouds sampled

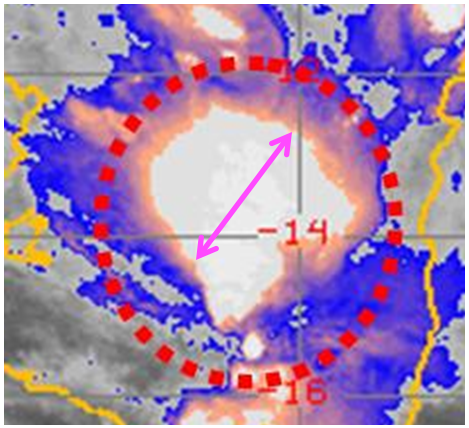


Aspect ratio = 15.7

Darwin Clouds: Comparison to Engine Event Clouds

	Engine Event Clouds		Darwin Clouds
	Grzych & Mason (2010)	**Bravin et al. (2015)***	**this study****
Precipitable Water median (mm)	58.4***	63.8	64.6
Min Cloud Top Temp. at event time (ET) median (C)	n/a	-84	-83.5
Equilibrium level temp. median (C)	n/a	-67	-69
Scale of cloud at -70 C level (~ELT) median (km)	~185 ****	231	255

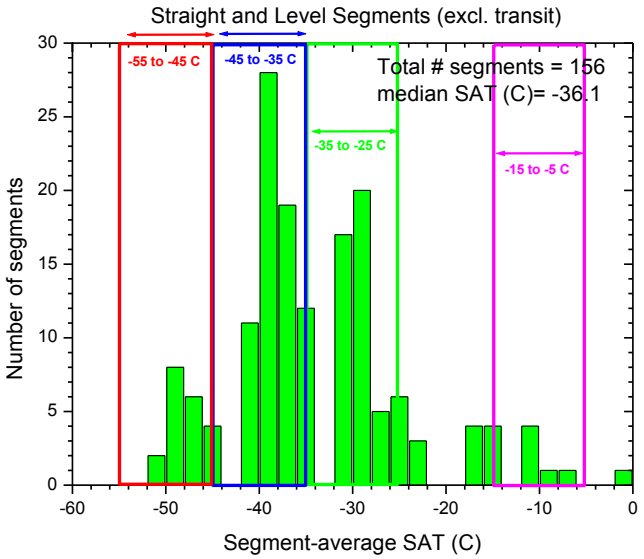




* 11 detailed case studies in Japan/Southeast Asia
** 16 flights in Darwin
*** 49 soundings analyzed (global)
**** at tropopause or Teq level – not specifically -70 level

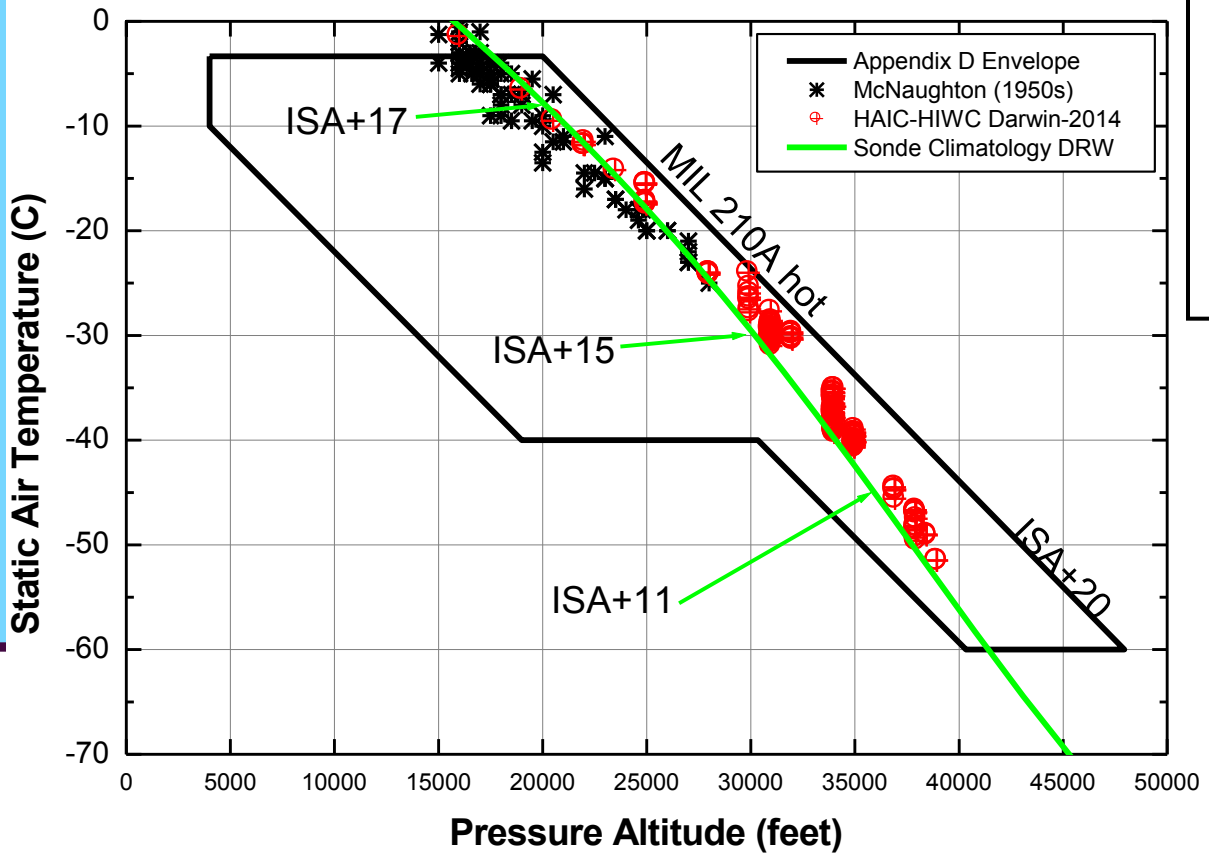
Temperature intervals as per discussions with Engine Icing Working Group

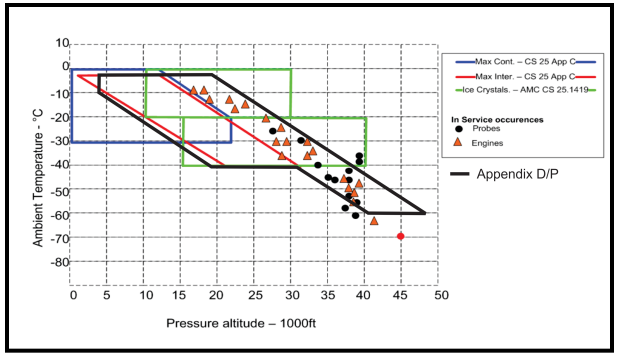
Temp.	Planned 17.4 nm pts.	Collected 17.4 nm pts.	No. of segments
-10 ± 5 ºC	100	12	6
-30 ± 5 ºC	100	145	42
-40 ± 5 ºC	100	171	64
-50 ± 5 ºC	100	33	6



- -10 C and -50 C under-sampled in Darwin, emphasis for Cayenne-2015 project

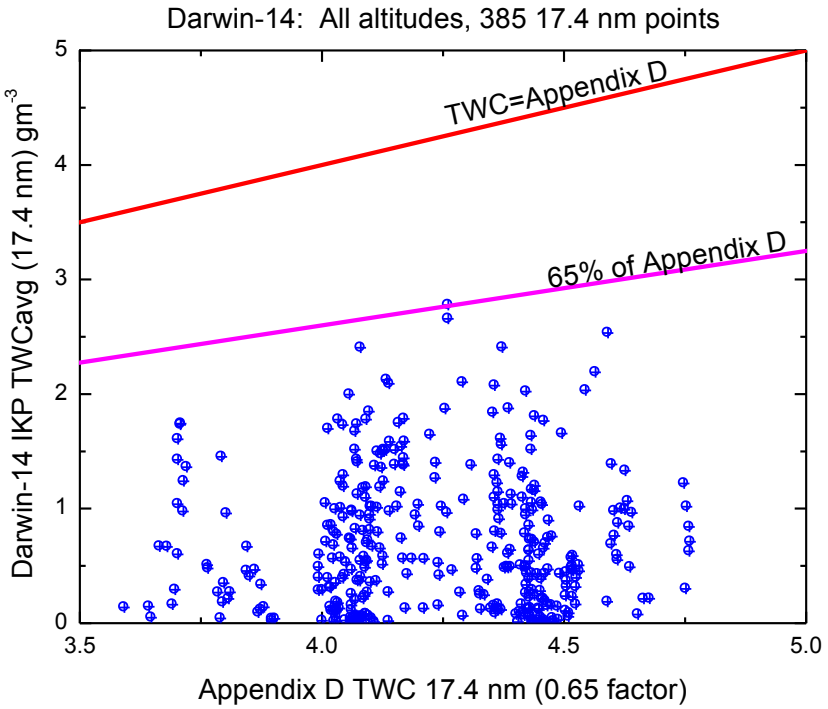
Appendix D Altitude-Temperature Envelope



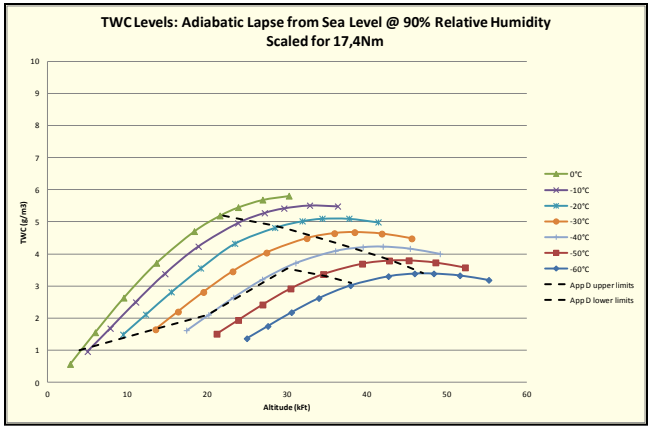


Appendix D comparison – TWCs average over 17.4 nm

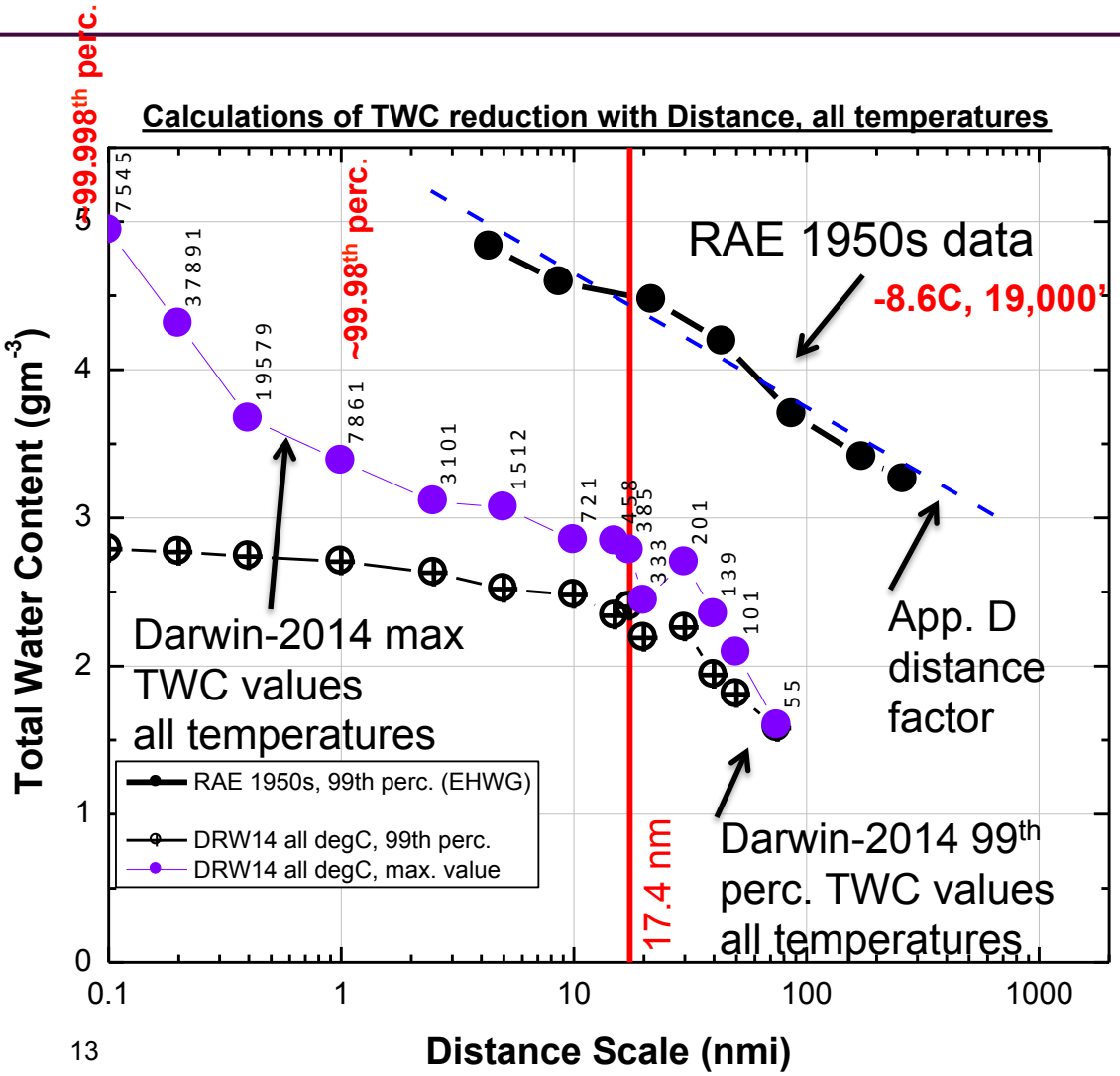
- Very little LWC was observed in Darwin-2014. Data are highly dominated by ice crystals.
- Maximum IKP TWC values averaged over 17.4 nm are falling below about 65% of Appendix D



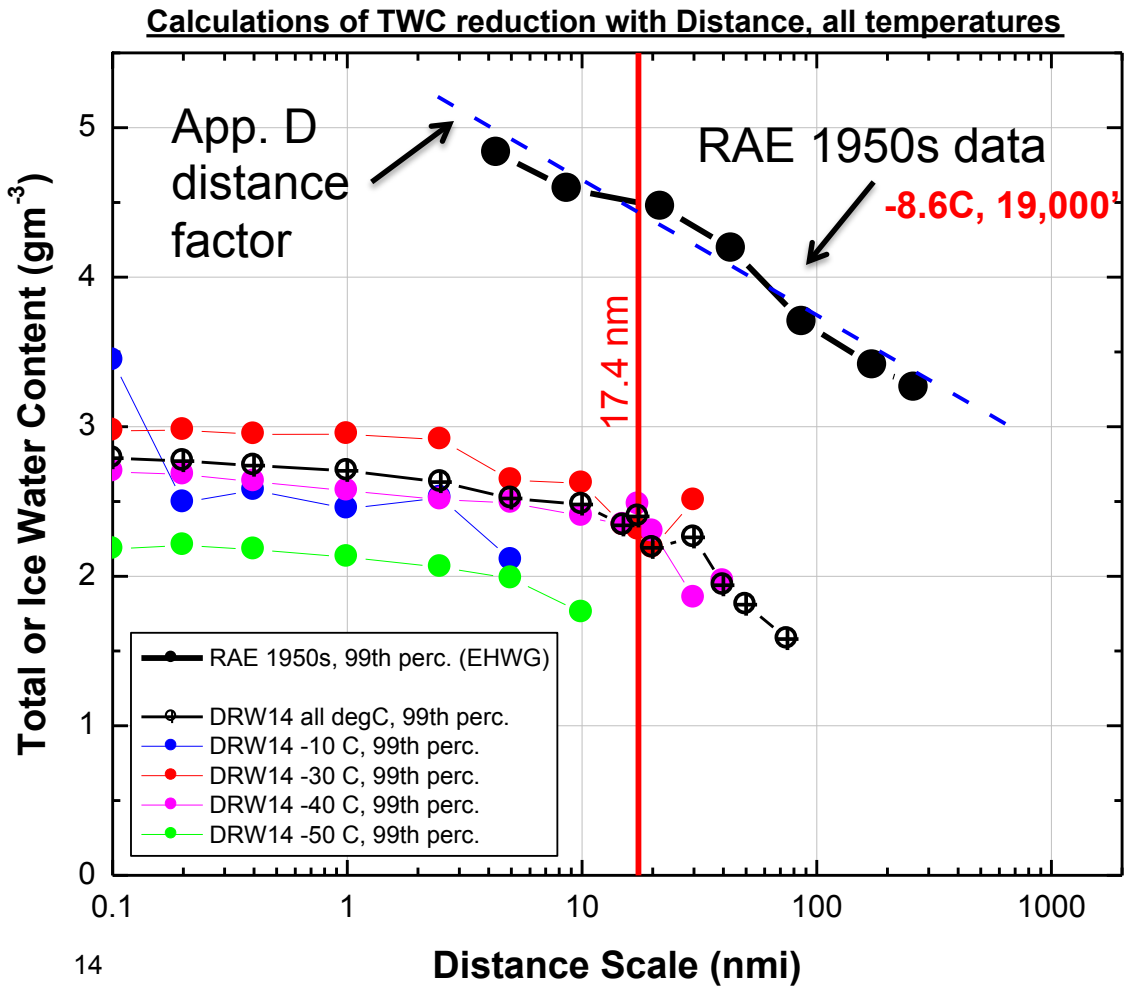
99th percentile TWC for all points above is 2.5 gm-3



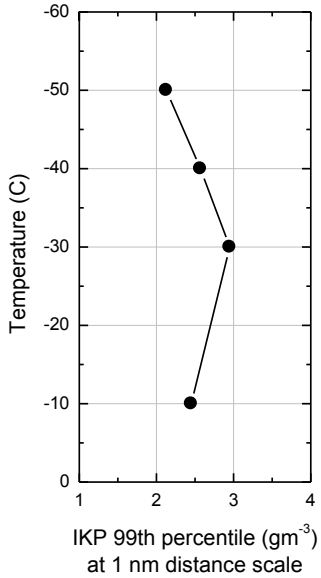
Appendix D TWC Darwin-2014 : TWC roll-off with distance scale– all temperatures



Appendix D TWC Darwin-2014 : TWC roll-off with distance scale – by temperature



Vertical Profile of 99th perc. TWC at 1 nm



Note reverse-y temperature scale

Conclusions

- An excellent data set was collected for Appendix D/P assessment during Darwin-2014
- Darwin clouds found to be very similar to engine event clouds, especially those in Japan/ Southeast Asia region
- Very little LWC observed, highly dominated by IWC …. but not a lot of data collected at -10 C .
- Need more data at -10 C and -50 C target temperatures.
- Preliminary assessment of the Darwin-2014 data yields statistics on TWC values:
  - Maximum 0.1 nm TWC ~ 4.9 gm^{-3}
  - TWC (all temperatures) averaged over 17.4 nm did not rise above about 65% of Appendix D value; 99^{th} percentile 17.4 nm TWC ~ 2.5 gm^{-3}
  - Max observed TWC versus deep-lift adiabatic: ~40% at 17.4 nm, ~70% at 0.1 nm
- Rolloff of TWC with increasing distance scale is nearly flat for short distance scales (< ~10 nm), and similar to Appendix D for distance scale > ~10 nm
- 99^{th} percentile TWCs vary with temperature, maximize at -30 C, minimize at -50 C (1 nm)

Thank you

walter.strapp@gmail.com

spare slides

Conclusions (cntd)

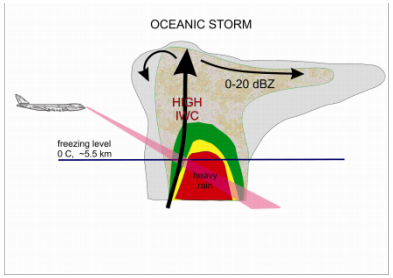
- Maximum TWCs observed in Darwin were surprisingly high (up to almost 5 gm^{-3} on short distance scales and frequently sustained above 2 gm^{-3}):
  - About a factor of 2 higher than speculated by senior cloud physics researchers from the atmospheric science community
  - The data set is a unique resource for the cloud research community

- Compared to the conventional supercooled LWC regulatory envelope (Appendix C), Appendix D has much higher TWCs at the longer distance scales, e.g.
  - Appendix C maximum 99^{th} percentile 0.8 gm^{-3} at 17.4 nm
  - Appendix D 4.5 gm^{-3} at 17.4 nm
  - Darwin-2014 99^{th} percentile TWC 2.5 gm^{-3} at 17.4 nm

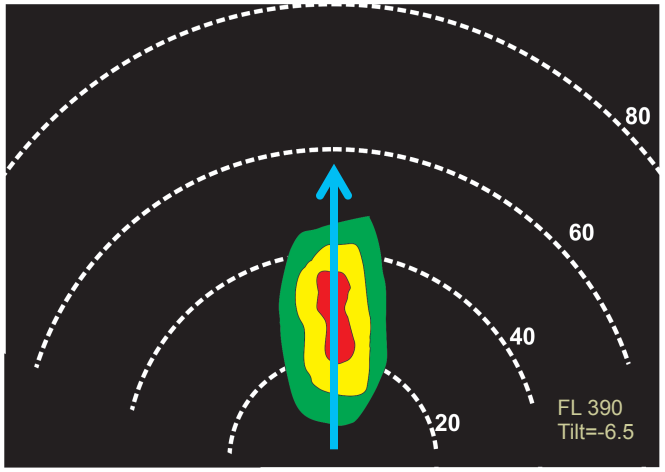
- Properties of ice particle size to be discussed by Alfons Schwarzenboeck, this meeting

Proposed solution to conduct Appendix D/P flight tracks (cntd)

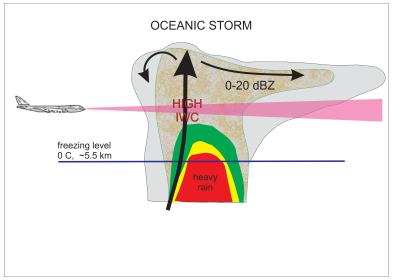
- **First approximation of run, tilting radar down on approach**



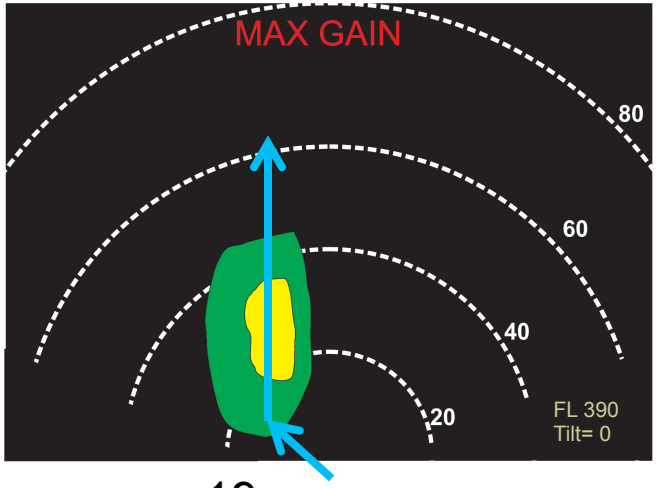
Tilt down, Normal gain



- **Tilting radar back up, and setting to max gain, fine-tune track if possible to go through area of maximum dbZ at flight altitude – otherwise use track in picture above**

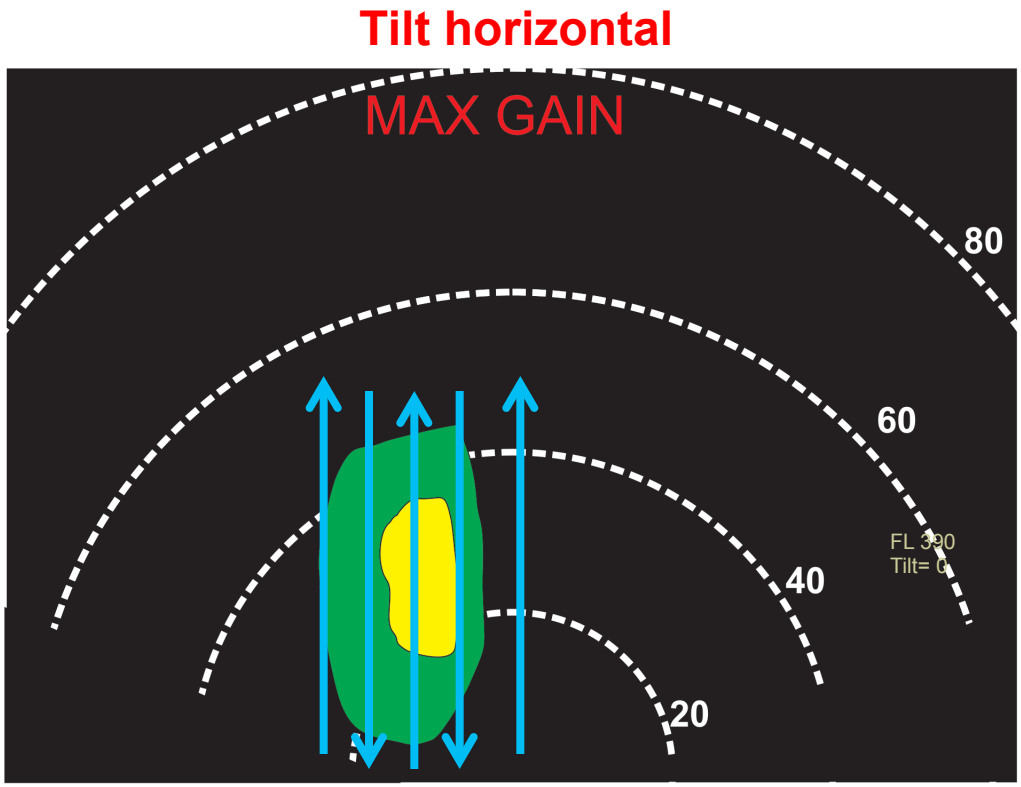


Tilt horizontal, Max gain



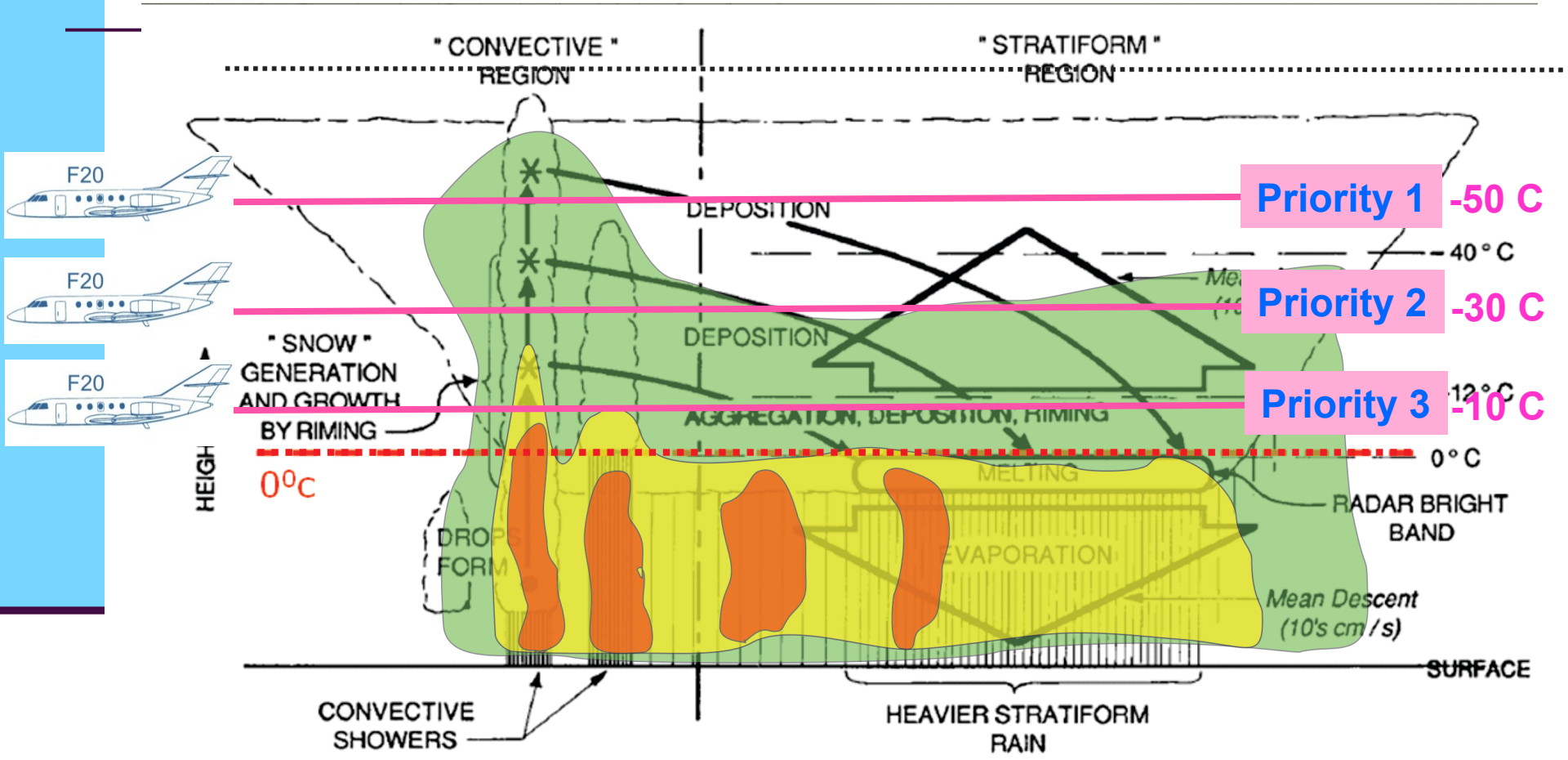
Proposed solution to conduct Appendix D/P flight tracks (cntd)

- **On-board IKP and RASTA operators monitor cloud on first run**
- **If conditions are good, pilots set up repeated runs with horizontal spacing of (nominally) 5 nm (have been using larger)**
- **On-board flight director provides pilots with feedback after each run, and any other recommendations from the back**
- **Pilot occasionally tilts radar down to ensure aircraft is ideally within 20 nm of rain area below.**



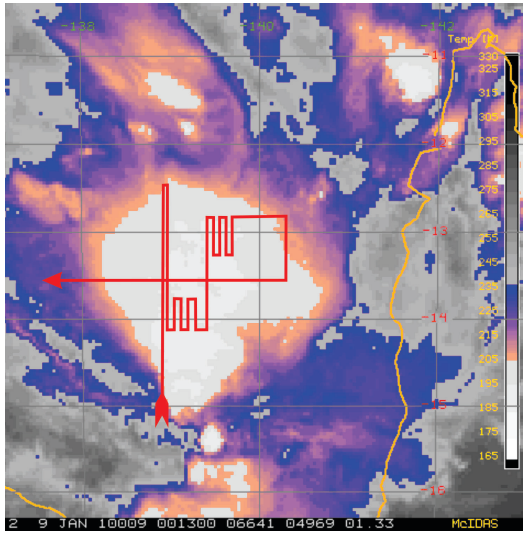
MCS Cross Section

**Monsoonal over water



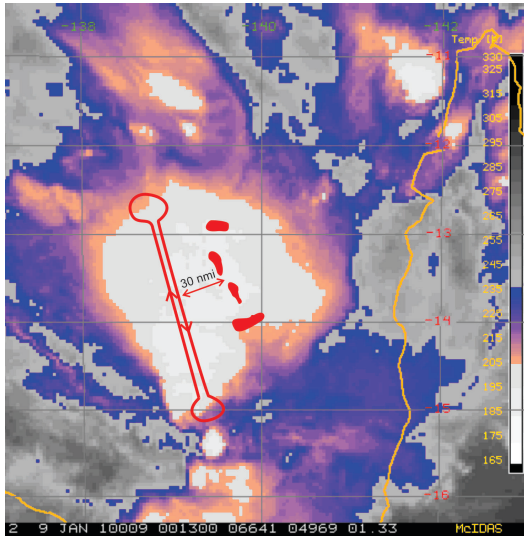
Review of Types of Cloud to Sample

Less vigorous Oceanic MCS



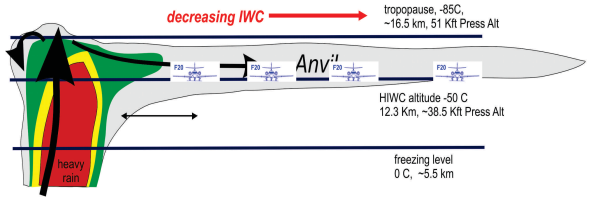
- 60% of flight hours
- Target MCS scale > 100 nm

More vigorous Continental MCS



- 25% of flight hours
- Target MCS scale > 100 nm

Isolated Continental Cumulonimbus



- 15% of flight hours

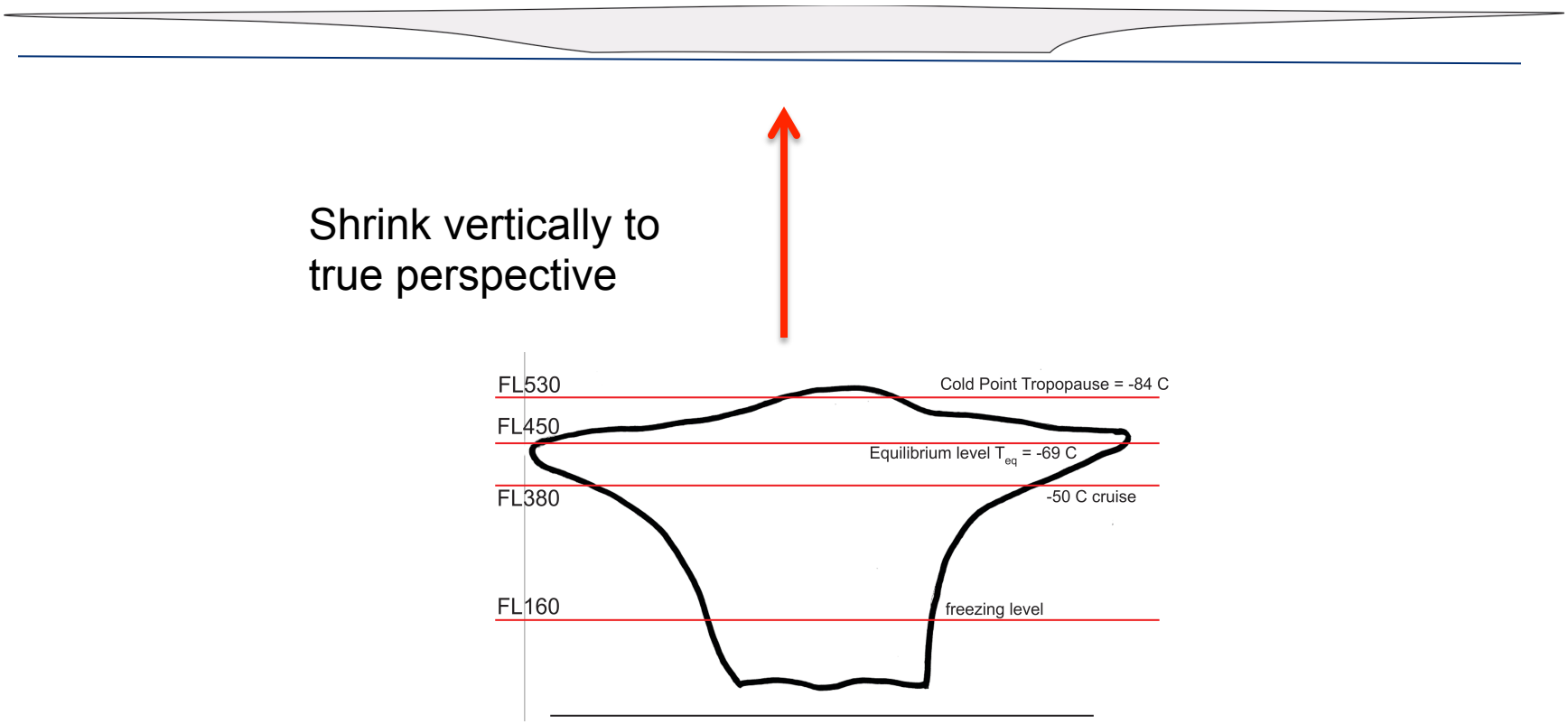
Review– altitudes/temperatures

In order of priority, 100 20 nm segments* at each of the following altitudes/temperatures:

- **-50 ±3 C,** 12.4 Km above ground, or approximately **38.5 Kft** pressure-altitude (ISA+6 °C).
- **-30 ±3 C,** 10.2 Km above ground, or approximately **31.4 Kft** pressure-altitude (ISA+21 °C).
- **-10 ±3 C** , 7 Km above ground, or approximately **21.8 Kft** pressure altitude (ISA+22 °C).

* Each segment ideally within 20 nm of a heavy rain area below, as per pilot's radar

Darwin Cloud Simplified Cartoon
True perspective (upper)

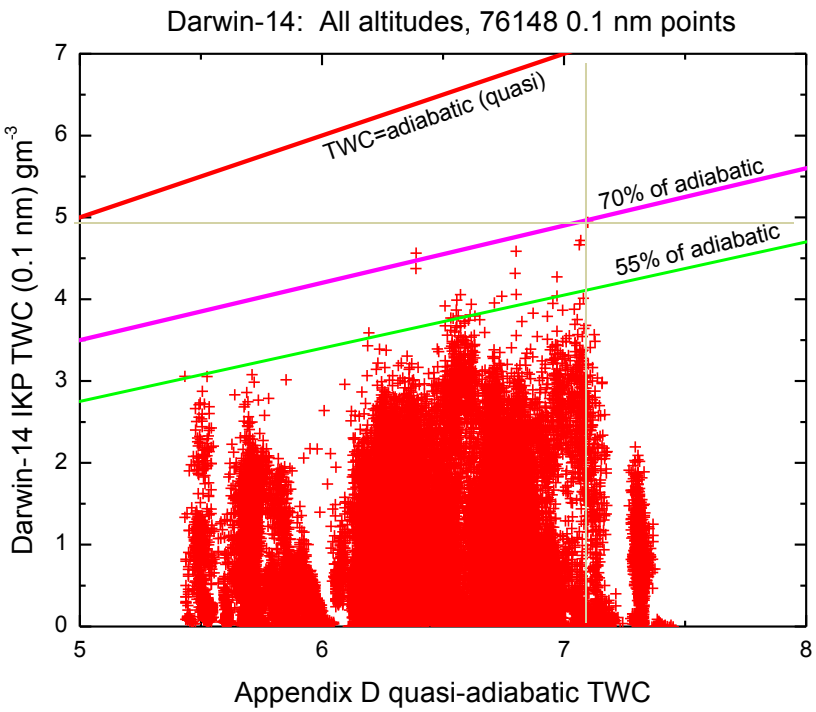


Work still to do by HAIC-HIWC group

- Integrate Cayenne-2015 flight program data (collecte May-2015) and determine whether there is sufficient data to complete Appendix D/P assessment for 4 target temperatures
- Further filter Darwin (and Cayenne) data to limit use of data in long traverses in stratiform areas > 20nm from active cells
- Incorporate other data sets if sufficiently accurate and appropriate to support Appendix D assessment
  - W-band airborne radar-derived IWCs from Darwin-2014 and Cayenne-2015
  - Robust probe data from A340 flight tests in Darwin 2010, Cayenne 2010, and Chile 2011
- Perform similar analysis for particle Median Mass Diameter as TWC

Short distance scale (0.1 nm) vs. adiabatic

- Full atmospheric column quasi-adiabatic value here, following saturated adiabat down to near surface (assuming 90% RH at surface; cloud base ~250 m MSL)
- Extreme 0.1 nm TWCs reach about 70% of adiabatic
- 55% of adiabatic may be better characterization of typical limit
- 99th percentile TWC for all points on this graph is about 2.8 gm^{-3}
- Max of 4.94 gm^{-3} represents ~99.999th percentile



Appendix D/P TWC Darwin-2014 : IKP roll-off with distance scale – all temperatures