Comparisons of Cloud In-Situ Microphysical Properties of Deep Convective Clouds to Appendix D/P, using Data from the HAIC-HIWC and HIWC RADAR I Flight Campaigns.

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Assessment of Appendix D/P (the "Appendix")

- Appendix D resulted from discussions within the Engine Harmonization Working Group (EHWG) 2004-2006
  - FAA App. D (rule 2014) and EASA App. P (rule 2015) envelopes are the same ("Appendix")
  - Developed as an interim Appendix
    - Total Water Content (TWC) estimates[1] based on theory scaled to measurements from 1950s (untraceable), particle median mass diameter (MMD) measurements based on sparse information, etc.
  - EHWG recommended collecting new modern, dedicated high IWC cloud dataset,
    - to support later assessment of the Appendix (now on-going), and
    - to provide information for general ICI projects

- Parts 1 and 2 of EHWG Technical Plan

  (1) Evaluate and develop of instrumentation for the measurement of high ice water content (IWC) conditions
  - EHWG concluded instrumentation accuracy and reliability in 2006 inadequate for high IWC, → Isokinetic evaporator (IKP) development for TWC, numerous PSD improvements

  (2) Perform flight test research for characterization of high IWC environments

[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

Flight Campaigns Providing Data for Appendix D/P Assessment

1. Darwin-2014 **HAIC-HIWC**[2,3] flight campaign (Australia)
   - French Falcon-20 research aircraft

2. Cayenne-2015 **HAIC-HIWC** flight campaign (French Guiana)
   - French Falcon-20 research aircraft
   - Canadian NRC Convair-580 aircraft

3. Florida-2015 NASA/FAA **HIWC RADAR I**[4] flight campaign (USA and Caribbean)
   - NASA DC-8

[2] High Altitude Ice Crystals (HAIC) project (Europe)
[3] High Ice Water Content (HIWC) project (North America)
[4] Ratvasky et al. 2019, this conference

French SAFIRE Falcon-20 aircraft

Canadian NRC Convair-580 aircraft

NASA DC-8 aircraft

- Used common instrumentation and common processing techniques for all three campaign datasets
  - IKP2 for TWC (processed by Met Analytics and Environment and Climate Change Canada)
  - 2D-S + PIP optical array spectrometers for PSDs and MMDs (processed by CNRS)

Primary Flight Campaign Partners/ Funders

- Federal Aviation Administration (FAA)
- European Aviation Safety Agency (EASA)
- National Aeronautics and Space Administration (NASA)
- Centre National de la Recherche Scientifique (CNRS)
- Service des Avions Français Instrumentés pour la Recherche en Environnement (SAFIRE)
- National Research Council of Canada (NRC)
- Environment and Climate Change Canada (ECCC)
- Australian Bureau of Meteorology (BoM)
- National Center for Atmospheric Research (NCAR)
- Meteo France (MF)
- Centro Italiano Ricerche Aerospaziali (CIRA)
- Ice Crystal Consortium

- Airbus
- Boeing
- Science Engineering Assoc. (SEA)

- U. Illinois
- U. Utah

Basis of this Presentation

- Based on FAA Technical Report[5] provided to an “Ice Crystal Icing (ICI)” Aviation Rulemaking Advisory Committee (ARAC).
  - Detailed final summary of 3-campaign dataset
    - adds HIWC RADAR I results (incl. high priority -50 C)
  - Compares campaign to Appendix, but does not make recommendations.
- ICI ARAC will assess whether flight campaigns warrant changes to Appendix D .
- Other reports have been provided to EASA by European partners.
  - Some differences to FAA report due to partner datasets, focus, interests,
  - overall effort to provide consistent results.
- This presentation provides only a very high level and basic summary

[5]Strapp, J. W., Schwarzenboeck, A., Bedka, K. , Bond, T. , Calmels, A. , Delanoë, J. , Dezitter, F. , Grzych, M. , Harrah, S. , Korolev, A. , Leroy, D. , Lilie, L. , Mason, J. , Potts, R. , Protat, A. , Ratvasky, T. , Riley, J. , and Wolde, M., 2018. “An Assessment of Cloud Total Water Content and Particle Size from Flight Test Campaign Measurements in High Ice Water Content, Mixed Phase/Ice Crystal Icing Conditions: Primary In-Situ Measurements”, FAA Tech. Rep. DOT/FAA/TC-18/1, in publication process.

EHWG Specification of Flight Campaigns

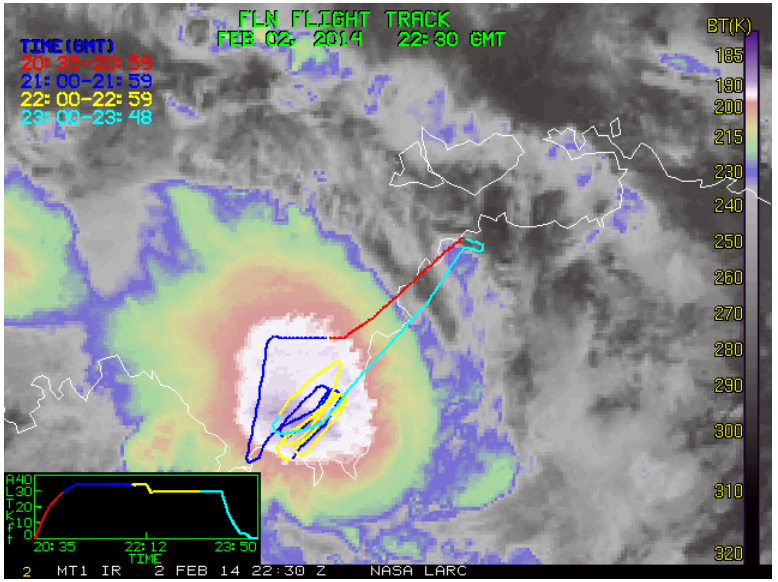
- Target Mesoscale Convective Systems (MCSs) ≥100 Nm characteristic size.
  - 85% MCS of oceanic origin, 15% afternoon continental convection.
  - obtain 99th percentile TWC (**"TWC_{99}"**) with 20% accuracy in each of the following temperature intervals:
    - -50, -40, -30, -10 (all ± 5C), in order of priority;
    - Up to 17.4 Nm distance scale and longer if possible.
  - Provide distance factor for TWC_{99} .
  - Characterize PSDs and MMDs in high IWC conditions.
  - Determine mixed phase characteristics of such clouds.

- Why TWC_{99} and why 17.4 Nm reference scale?
  - Consistent with Appendix C (uses 17.4 Nm and 99th percentile LWC)
  - Early EHWG investigation of TAT anomalies suggested 17.4 Nm as appropriate onset length for engines effects (more recent studies suggest maybe longer).
  - TWC_{99} at 17.4 Nm possible with available funding

- But 99th percentile is not an extreme value measurement (~1 in 100).
  - Regulatory agencies and industry: determine how to apply to means of compliance.

General Information on HAIC-HIWC Darwin-14 + Cayenne-15 + HIWC RADAR I Dataset (hereafter “the DATASET”)

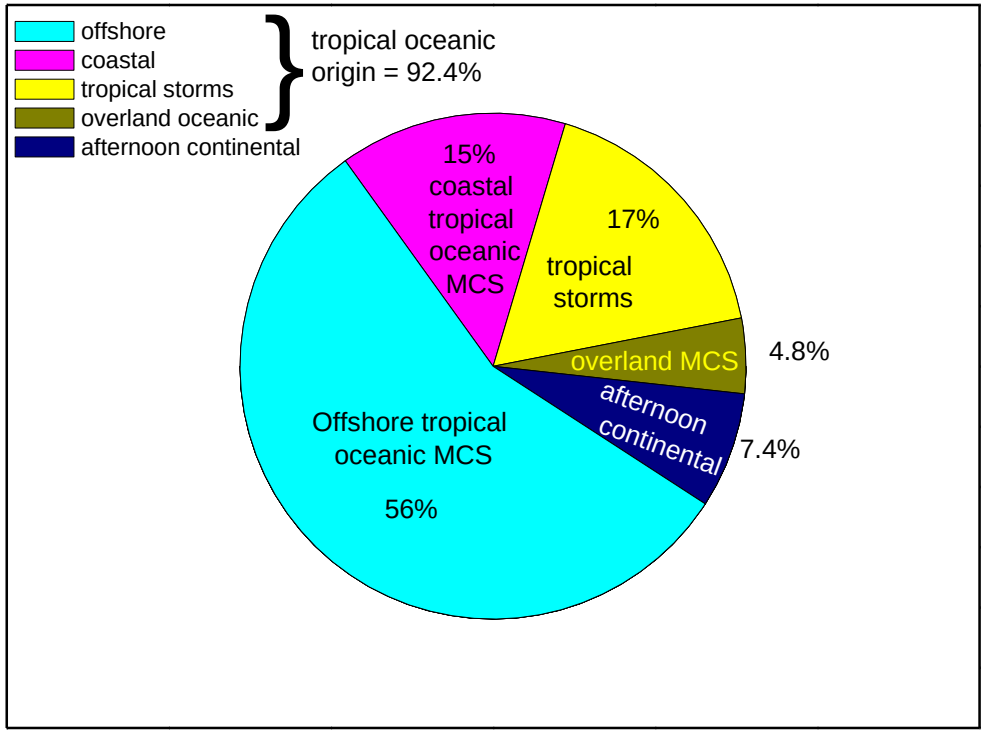
Number of geographical locations	3
Number of Research Flights	54
Number of Clouds	115
Number of Cloud Runs	471
Range of Altitude (feet)	17,000-39,000’
Range of Temperature	-5.8 to -52.5 C
Measurement distance in cloud	~29,600 Nm



Dia. of white area ~90 Nm

General Information on the DATASET (cntd)

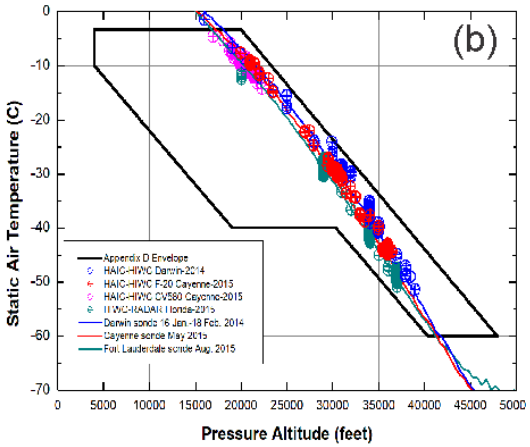
In-cloud distance percentages for various cloud types sampled



As intended, dataset is dominated by oceanic MCS

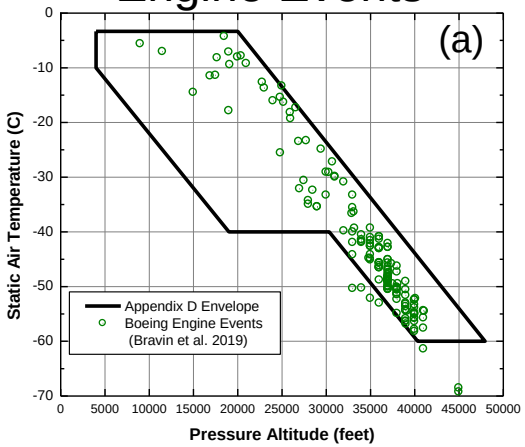
DATASET Results:
Temperature-Altitude Envelope

Flight Campaigns



- Run-averages of SAT vs. ALT for the DATASET
- Color-coded as per aircraft
- Average radiosonde values for each project also shown (solid lines, same colors)
  - Points typically lie around respective radiosonde curves
- Contained in Appendix, to -53 C

Engine Events



- Most recently published engine event data from Bravin et al. (2019)[6], this conference
- Note a few points outside of envelope, including close to -70 C.
- Engine events more diverse (year-round) than campaign (summer only), but nevertheless quite similar

[6]Bravin, M, J.W. Strapp, M. Grzych, and M. Clarkson. "A Continuing Investigation of Diurnal and Location Trends in an Ice Crystal Icing Engine Event Data Base". *Intl. Conf. on Icing of Aircraft, Engines, and Structures, 17-21 June, 2019,* SAE Technical Paper, 2019.

DATASET Results:
Characterization of Mixed Phase

DATASET Mixed-Phase Results

- Mixed phase was RARE in the DATASET.
- Spatial fraction was small, and decreased with altitude (<~5% at -10 C, <~1% at -30 C)
- LWC was low (< 0.32 gm^{-3}) distance scales were short (< 6.2 Nm)
- Significantly less severe than the Appendix for 0 to -20 C (see right)
- Mixed phase exists in DATASET to colder temperatures than the Appendix. Whereas Appendix currently identifies zero LWC for < -20 C, DATASET has to -35 C, albeit sparingly.

Caveats:

- LWC was possibly present where we did not fly (e.g. high reflectivity cores, high lightning areas)
- Analysis may have missed some mixed-phase (e.g. Goodrich Ice Detector erosion in high IWC)
- **N.B.** Results may not be applicable to smaller and/or warmer topped convection (very large and deep clouds sampled, tops < -60 C, with ubiquitous ice)

Current Appendix D/P

"The TWC can be treated as completely glaciated (ice crystals) except as noted in Table 1 of this Appendix (see below)"

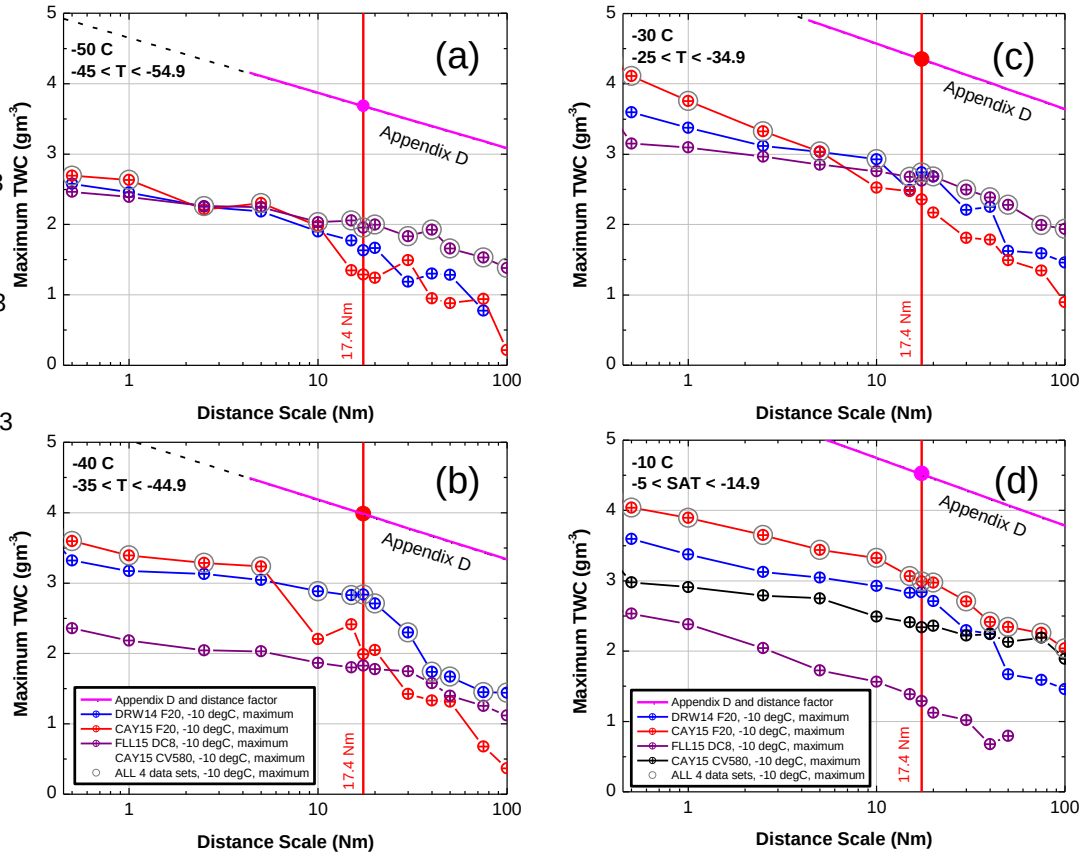
TABLE 1—SUPERCOOLED LIQUID PORTION OF TWC

Temperature range—deg C	Horizontal cloud length—nautical miles	LWC—g/m³
0 to –20	≤50	≤1.0
0 to –20	Indefinite	≤0.5
< –20		0

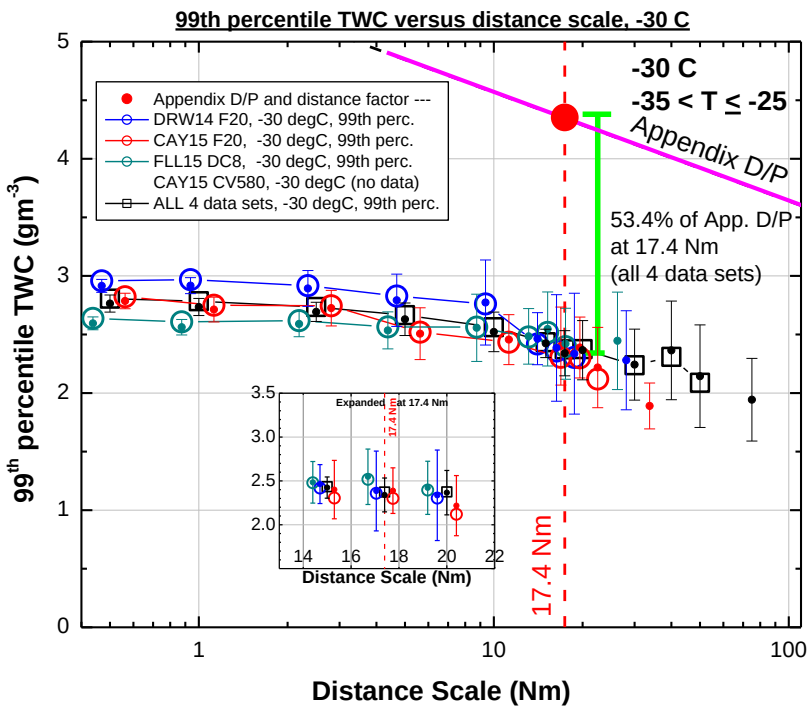
DATASET Results:
TWC characterization – TWC maxima

- At 0.5 Nm:……TWC_{max} ~4.1 gm^{-3} (Cayenne, -30 C)
- At 17.4 Nm:…….TWC_{max} ~3.0 gm^{-3} (Cayenne, -10 C)
- At -50 C, 17.4 Nm:..TWC_{max} ~2.0 gm^{-3} (Florida)
- At 100 Nm:……TWC_{max} ~ 2.0 gm^{-3} (Cayenne, -10 C)
- Some significant differences between projects, discussed in FAA report.

Maximum TWCs versus distance scale



DATASET Results:
TWC characterization 99th Percentiles



- Color code in this and all subsequent plots:
  - Open circular symbols:
    - Darwin-14,
    - Cayenne-15 Falcon-20,
    - Cayenne-15 Convair-580,
    - Florida-15 DC-8
  - Open black square symbols:
    - All above combined

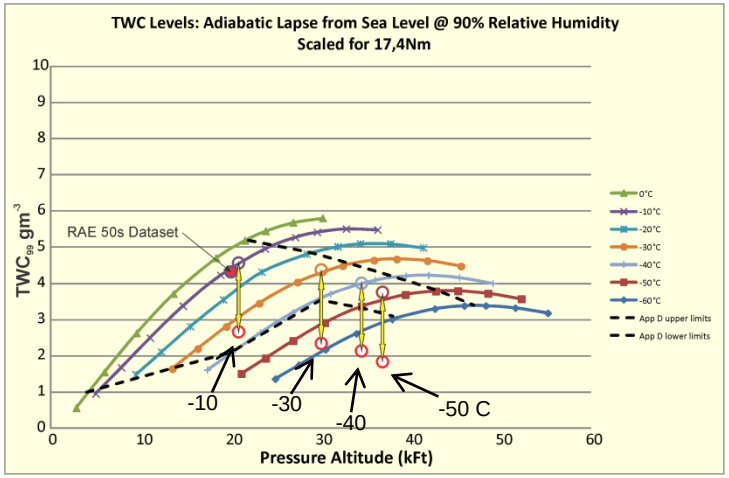
DATASET Results: TWC characterization
99th Percentile TWC (TWC_{99}) at 17.4 Nm

Temp. Interval (±5 C)	No. of 17.4 Nm Points	Flight Campaign TWC_{99} (gm^{-3})	±2σ sampling uncert. (gm^{-3})	App. D/P TWC_{99} (gm^{-3})	Flight Campaign % of App. D/P
-10	273	2.66	0.27	4.57	59.4
-30	449	2.34	0.19	4.38	54.5
-40	435	2.13	0.25	4.00	53.0
-50	263	1.84	0.14	3.76	49.1

All more than factor 2 greater than 100 points requested

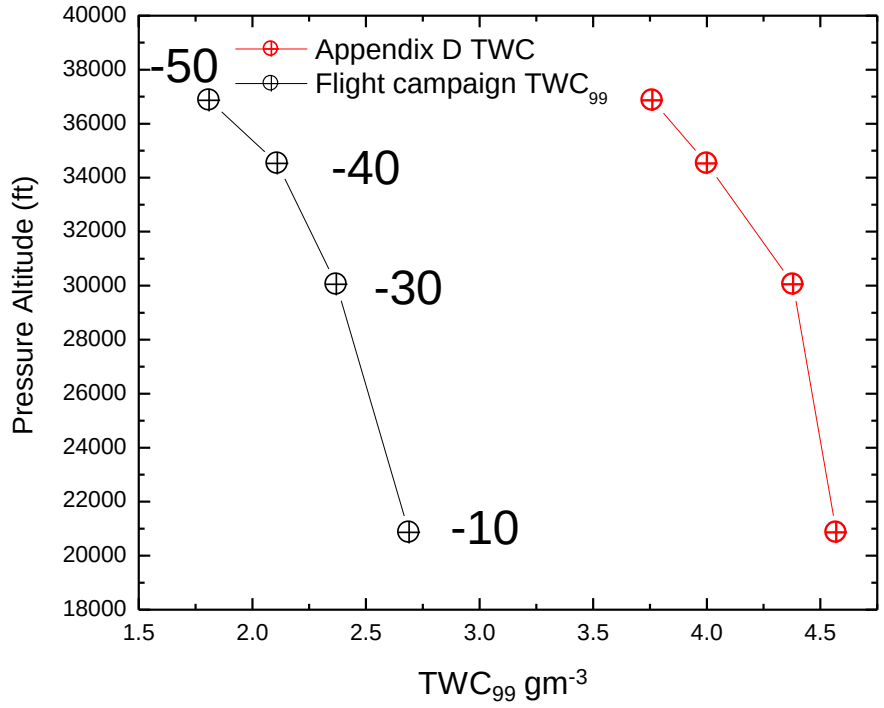
~8-12% of TWC_{99}

Flight Campaign TWC99 ~50% of Appendix



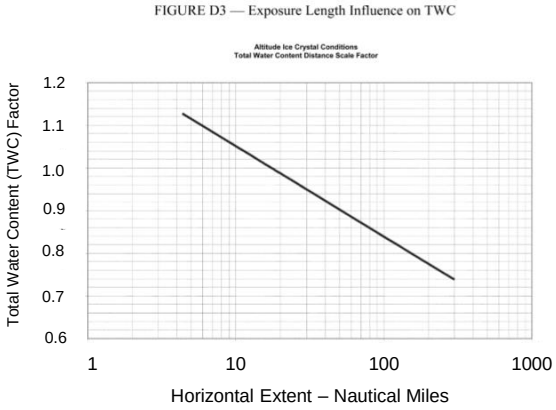
Same results on App. D/P TWC_{99} envelope

DATASET Results:
99th Percentile TWC (TWC_{99}) vs. Altitude (@17.4 Nm)

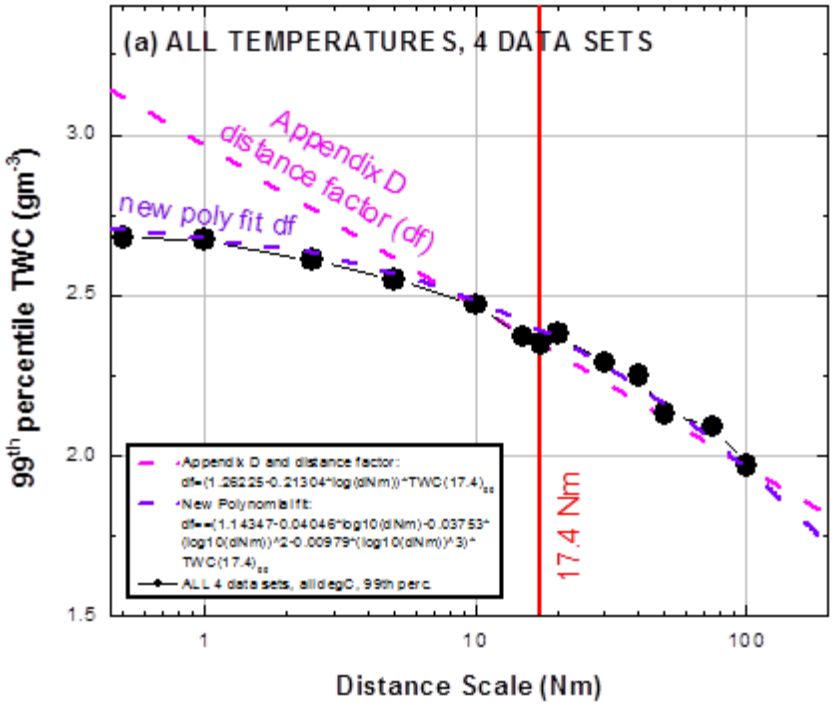


- Campaign and TWC_{99} Appendix TWC_{99} both decrease with altitude, well correlated
- Provides support for the underlying basis of Appendix D/P
- One way to adjust Appendix D/P, is just to change scale factor
- 0.65 → 0.35

DATASET Results:
TWC_{99} Distance Factor



FLIGHT CAMPAIGN DATA



- Existing Appendix distance factor (**magenta dashed line**):
  - good from 5-100 Nm
  - Increasingly overestimates TWC for distance scales < 5 Nm
- New polynomial fit, proposal to ARAC shown in **purple dashed line**, valid to 100 Nm.
- New df is improvement over the old in all temperature intervals (not shown)

DATASET Results: Particle Size Distribution (PSD) and Median Mass Diameter (MMD) characterization

- Led by U. Blaise Pascal, CNRS (France) for the 3 campaigns

- Complex image analysis of cloud probe 2D particle imagery to obtain PSDs and MSDs
  - Used state-of-the-art technique summarized by Leroy et al. (2017)[7],
  - see also Coutris et al.[8] (this conference) for a new technique and a discussion on on MMD uncertainty.

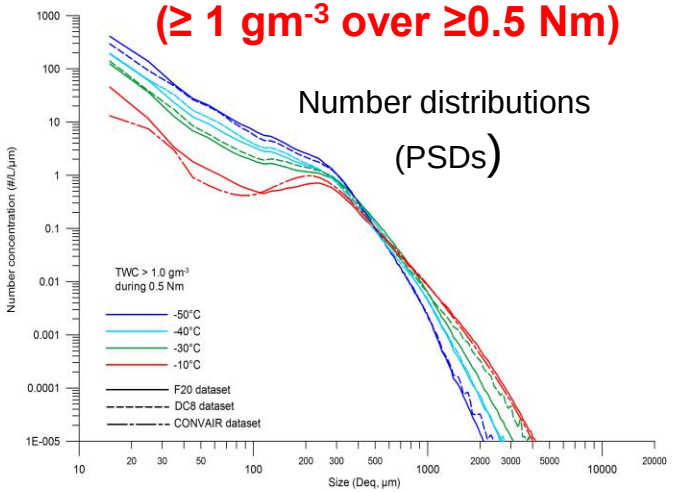
- To support TWC_{99} data, different statistic is desired for MMDs than 99th percentiles.
  - Objective to characterize MMDs in high IWC regions only, not generally
  - Filtered to accept only TWC ≥ 1 gm^{-3} over ≥ 0.5 Nm
    - within a reasonable range of above thresholds, MMD sensitivity was low
  - Excluded the relatively small number of mixed phase regions, to produce ice spectra

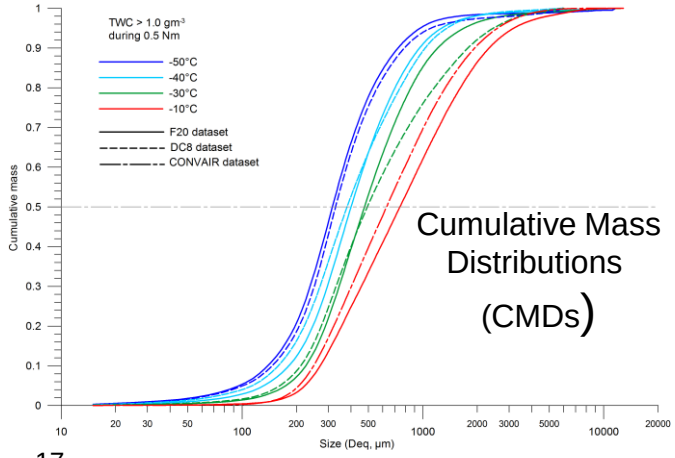
[7]**Leroy, D.,** Fontaine, E., Schwarzenboeck, A., Strapp, J. W., Korolev, A., McFarquhar, G., Dupuy, R., Gourbeyre, C., Lilie, L., Protat, A., Delanoe, J., Dezitter, F., and Grandin, A.: Ice Crystal Sizes in High Ice Water Content Clouds, Part II: Statistics of Mass Diameter Percentiles in Tropical Convection Observed during the HAIC/HIWC Project, J. Atmos. Ocean. Technol., 34, 117–136, https://doi.org/10.1175/JTECH-D-15-0246.1, 2017

[8]**Coutris, P.,** Schwarzenboeck, Leroy, D., Grandin, A., Dezitter, F., Strapp, J.W., "Uncertainty of the ice particles Median Mass Diameters retrieved from the HAIC-HIWC dataset: a study of the influence of the mass retrieval method". *Intl. Conf. on Icing of Aircraft, Engines, and Structures, 17-21 June, 2019,*SAE Technical Paper, 2019

DATASET Results:
PSD and MMD characterization (cntd)

Composite high IWC Spectra
(≥ 1 gm^{-3} over ≥0.5 Nm)





- -50 C blue, -40 C cyan, -30 C green, -10 C red
- PSDs shows tendency for lower temperatures (blue) to have more particles than warmer temperatures (red) at small sizes, and fewer particles at large sizes
- Cumulative mass distributions: mass shifts to larger sizes as temperature increase, and MMD increases with temperature
- Quite similar results from individual aircraft datasets. (solid, dash, dot-dashed lines)

DATASET Results:
PSD and MMD characterization (cntd)

High IWC Zone
Median Mass Diameters (μm)

Distance scale : 0.5 Nm *IKP-2 TWC : ≥1 gm^{-3}*	Temperature Interval			
	-50°C	-40°C	-30°C	-10°C
Falcon-20 dataset (Darwin+ Cayenne)	316	401	476	747
DC-8 dataset (Florida)	329	381	493	-
Convair-580 dataset (Cayenne)	-	-	-	630
Averages (number weighted)	**326**	**396**	**483**	**708**

Flight Campaigns

- MMD increases with increasing temperature
- Generally higher than current Appendix D/P, but still quite low, especially at colder temperatures

Current Appendix D/P

"*Ice crystal median mass dimension (MMD) range is 50-200 microns (equivalent spherical size) based on measurements near convective storms*"

- From very limited data available from modern instrumentation at the time.

Comments on Scope of DATASET

From HAIC-HIWC Science Team Meeting, December 2016

1. Tropical/subtropical *oceanic* clouds, for most part, are represented well by the DATASET (sizes, depths, intensities).

2. DATASET is lacking large vigorous *continental* MCS, which arguably could have different TWC and PSD characteristics
   - in 2019 (Bravin et al.[6], this conference) ~40% of events are over land (not a small fraction)

3. DATASET is mainly from *low-aerosol (low air pollution)* environments.
   - Hypothesis: high aerosol feeding updrafts delays precipitation → increase TWC aloft relative to low aerosol
   - Some supporting evidence in the literature from Brazil research flights.
   - Very high aerosol environment off the coast of China is a hot-spot for engine events (but heavy air traffic also).

4. DATASET is from *daytime flights only* (mostly because of safety concerns).
   - Satellite study: Unlikely an issue for Cayenne-2015 and Florida-2015.
   - Darwin-14 clouds sample on the average ~3 hours after suspected ideal time. (TWC length scales longer earlier, peak TWC ??).
   - Bravin et al. 2015, 2019: engine events do not preferentially occur near time of maximum activity, but rather convective surges throughout lifecycle
   - Difficult to draw conclusions about this Darwin delay

Summary

- Very little reliable information on the in-situ properties of deep convective clouds was available in 2006

- New flight campaigns (2014-2015) produced unique and high quality in-situ cloud dataset of tropical/subtropical oceanic Mesoscale Convective Systems for Appendix D/P assessment:
  - 3 distantly-separated locations, 29600 Nm of in-cloud data.

- Data collection used strategies and objectives prescribed by Engine Harmonization Working Group, guided by weather of Ice Crystal Icing engine events, and specifically for Appendix D/P assessment

Summary (cntd)

- **MIXED PHASE:**
  - Mixed phase was rare and LWCs were low when encountered.
  - LWC levels and distances were significantly less severe than the Appendix, although experienced to colder temperatures (sparsely)
  - **N.B.** Results may be specific to the very large and deep MCS sampled, unwise to generalize

- **Maximum TWC:**
  - At 0.5 Nm distance scale, TWC up to 4.1 gm^{-3}
  - At 100 Nm distance scale, TWC up to 2.0 gm^{-3}

- **99^{th} Percentile TWC (TWC_{99}) at 17.4 Nm distance scale:**
  - Correlated well with the Appendix values, but about a factor of 2 lower.
  - Good correlation provides support for the logic behind the Appendix TWC envelope.

Summary (cntd)

- **99th Percentile TWC Distance Factor:**
  - Current Appendix distance factor pretty good. New distance factor proposed to improve distance scales < 5 Nm.

- **Ice Particle MMDs:**
  - MMD found to increase with increasing temperature (~325 µm at -50 C, to ~708 µm at -10 C)
  - MMDs generally higher than current Appendix, but nevertheless fairly low.

- **Not represented in the DATASET** (HAIC-HIWC Science Team):
  - Large vigorous continental MCS, MCS in high aerosol environments, night time measurements

  - 99th percentile TWC is not a particularly extreme statistic. Industry and regulators must decide how to use for means of compliance.

Thank you

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Comparisons of Cloud In-Situ Microphysical Properties of Deep Convective Clouds to Appendix D/P using Data from the HAIC-HIWC and HIWC-RADAR Flight Campaigns.

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