An Investigation into Location and Convective Lifecycle Trends in an Ice Crystal Icing Engine Event Database

Melissa Bravin, Boeing Commercial Airplanes

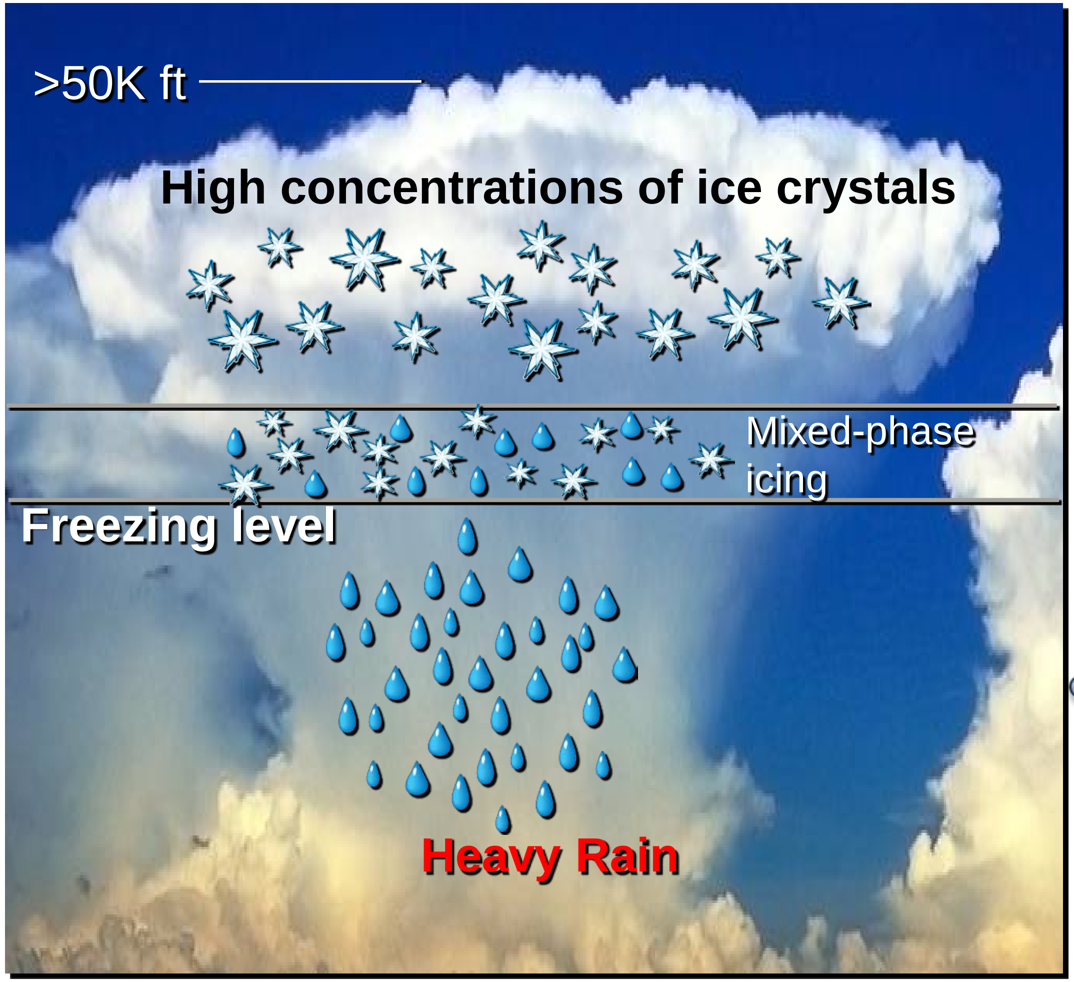
Walter Strapp, Met Analytics

Jeanne Mason, Boeing Commercial Airplanes

SAE 2015-01-2130

Motivation for Study

Are ice crystal icing events caused by long extents of moderate water content or short duration high water content?



What is the IWC which causes events?

Where in the cloud does the HIWC occur?

How close to the peak of convection does the event occur?

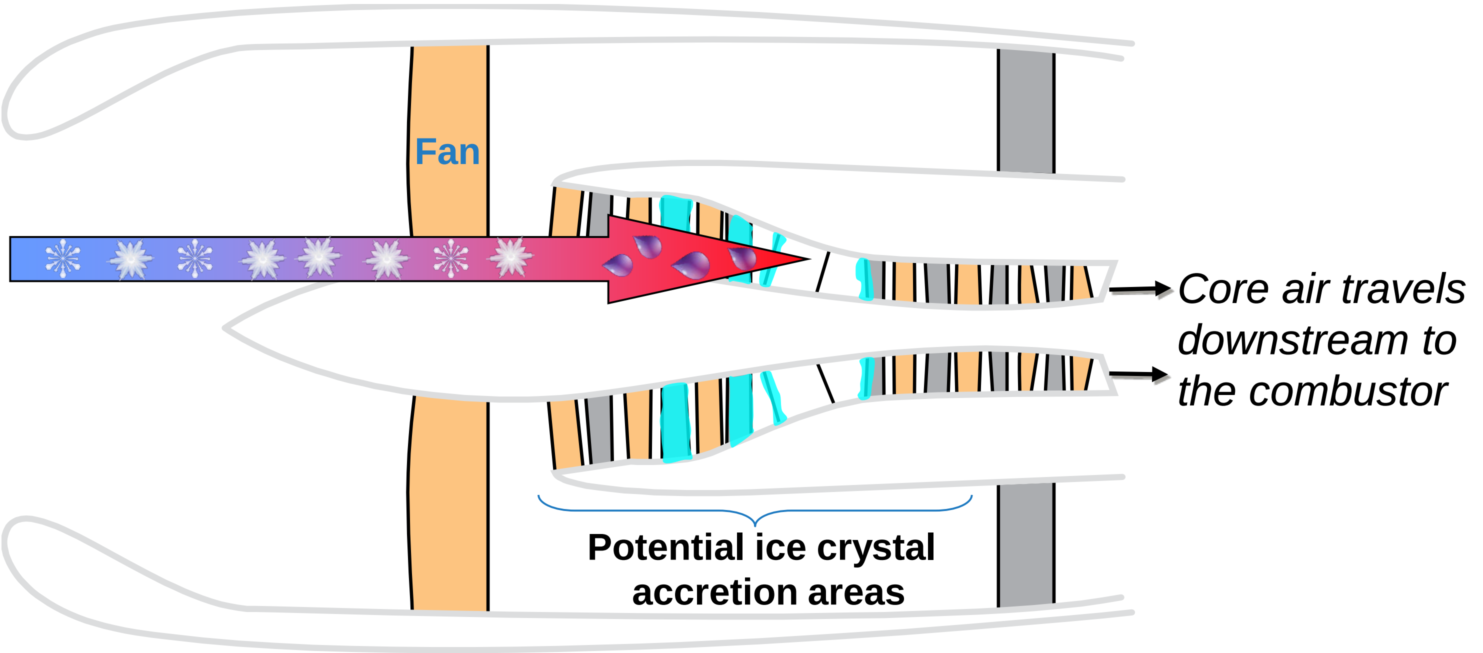
Agenda

- Introduction
- Database statistics
  - Update to 2006 engine event database
- Study of Japan / South China Sea
  - Event proximity to convective maximum
- Summary and Conclusions

What Is Ice Crystal Icing?

Physics:

- Crystals can form ice on engine surfaces warmer than freezing
- These warm engine surfaces are in the compressor (aft of the fan)



Ice shed from compressor surfaces can cause engine instability such as surge, flameout, or engine damage

SAE 2015-01-2130

Support for Appendix D/P Evaluation and Design of Flight Program

- FAA and EASA have established new rules for icing certification including a new ice crystal envelope
  - FAA: Appendix D to CFR Part 33
  - EASA: Appendix P to CS 25
- The new standard was built from a conservative evaluation of flights from the 1950s and the adiabatic maximum
- More information is needed about Total Water Content (TWC), particle size, and exposure distance for compliance
- FAA and EASA will assess the Appendices based on data from in-situ cloud measurements currently underway (HAIC-HIWC Project)
- Boeing database was instrumental in design of flight strategies to collect data

FIGURE D1 — Convective Cloud Ice Crystal Envelope

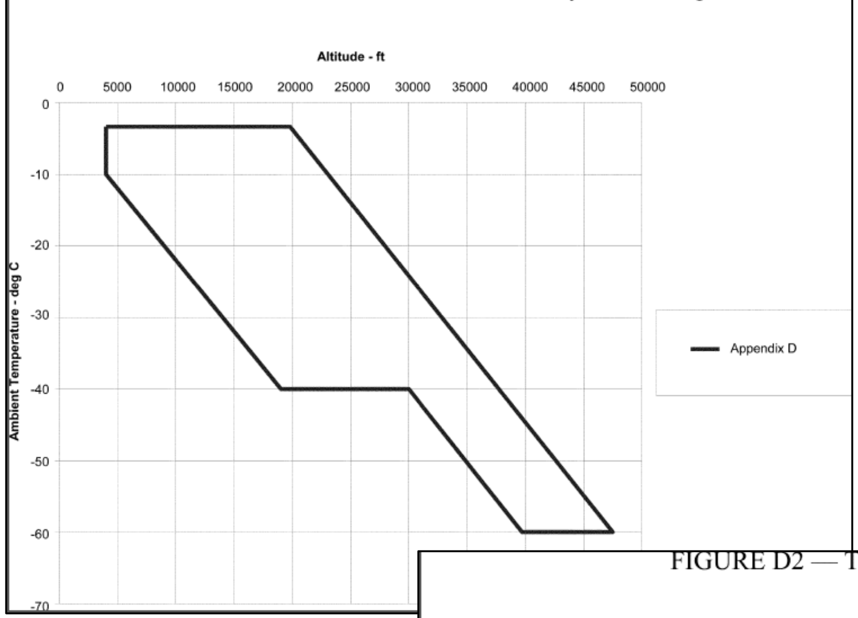
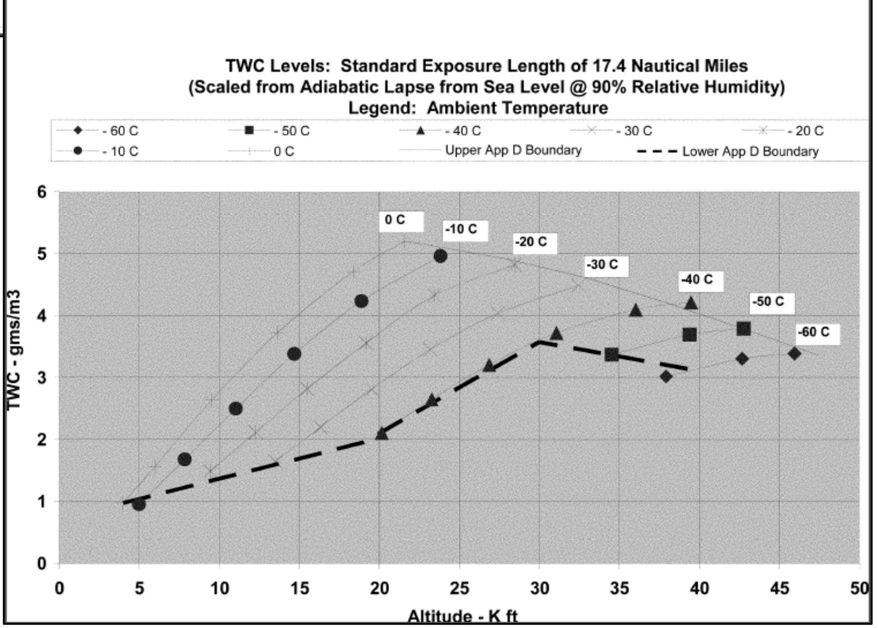


FIGURE D2 — Total Water Content



SAE 2015-01-2130

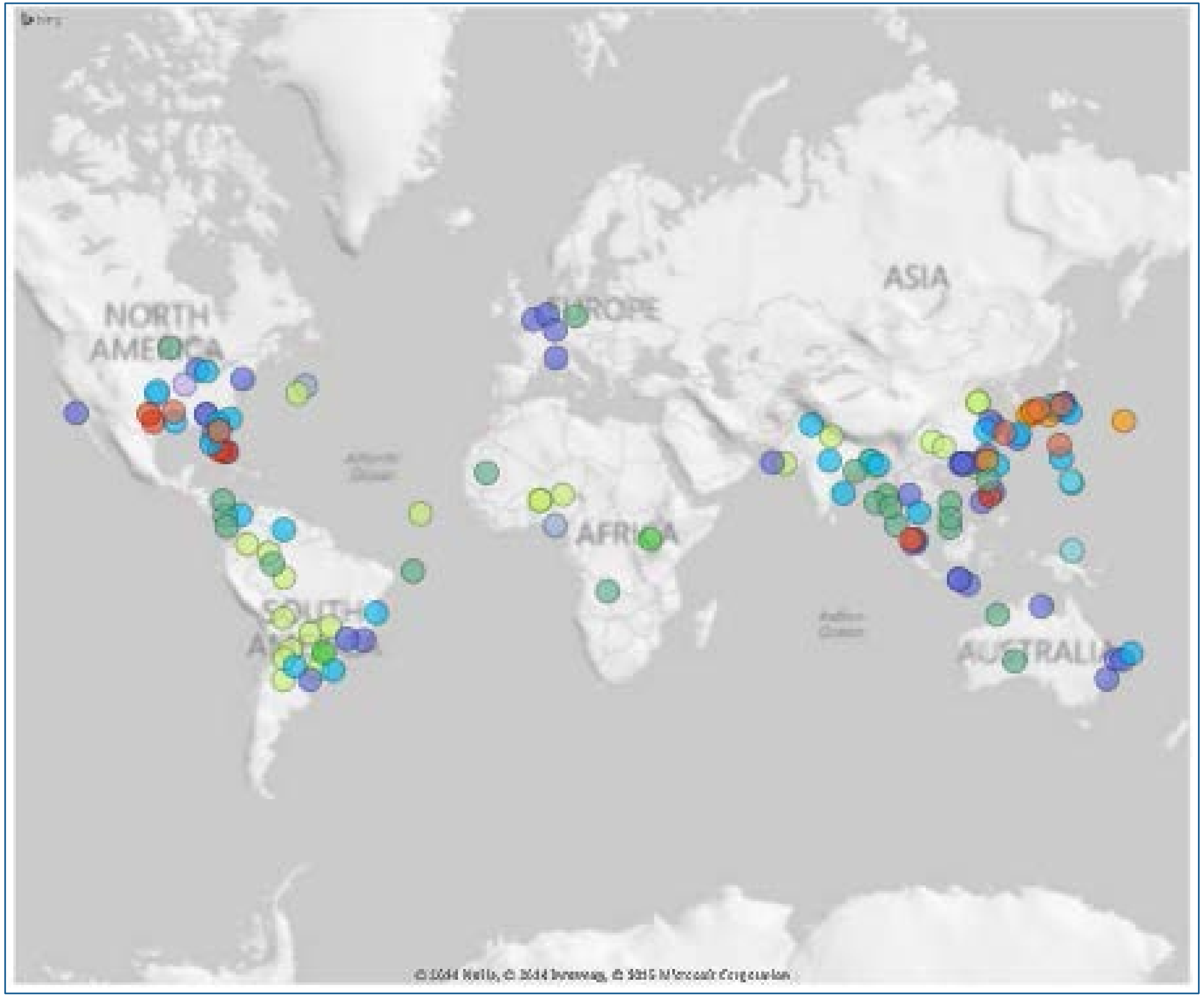
Figures D1 & D2 are from
FAA Rule, Document # 2014-25789

General Statistics From Current Database

- Latitude 32°S - 52°N, with 92% contained within the tropical and subtropical latitude band
- Generally warmer than the FAR Part 25 Appendix C temperature-altitude envelope
- Update from 46 to 162 cases

Year	SAT	Altitude
2006	-55°C to -10°C, median -21°C	FL115-FL390, median FL258
2015	-58°C to -3°C, median -36°C	FL110-FL450, median FL350

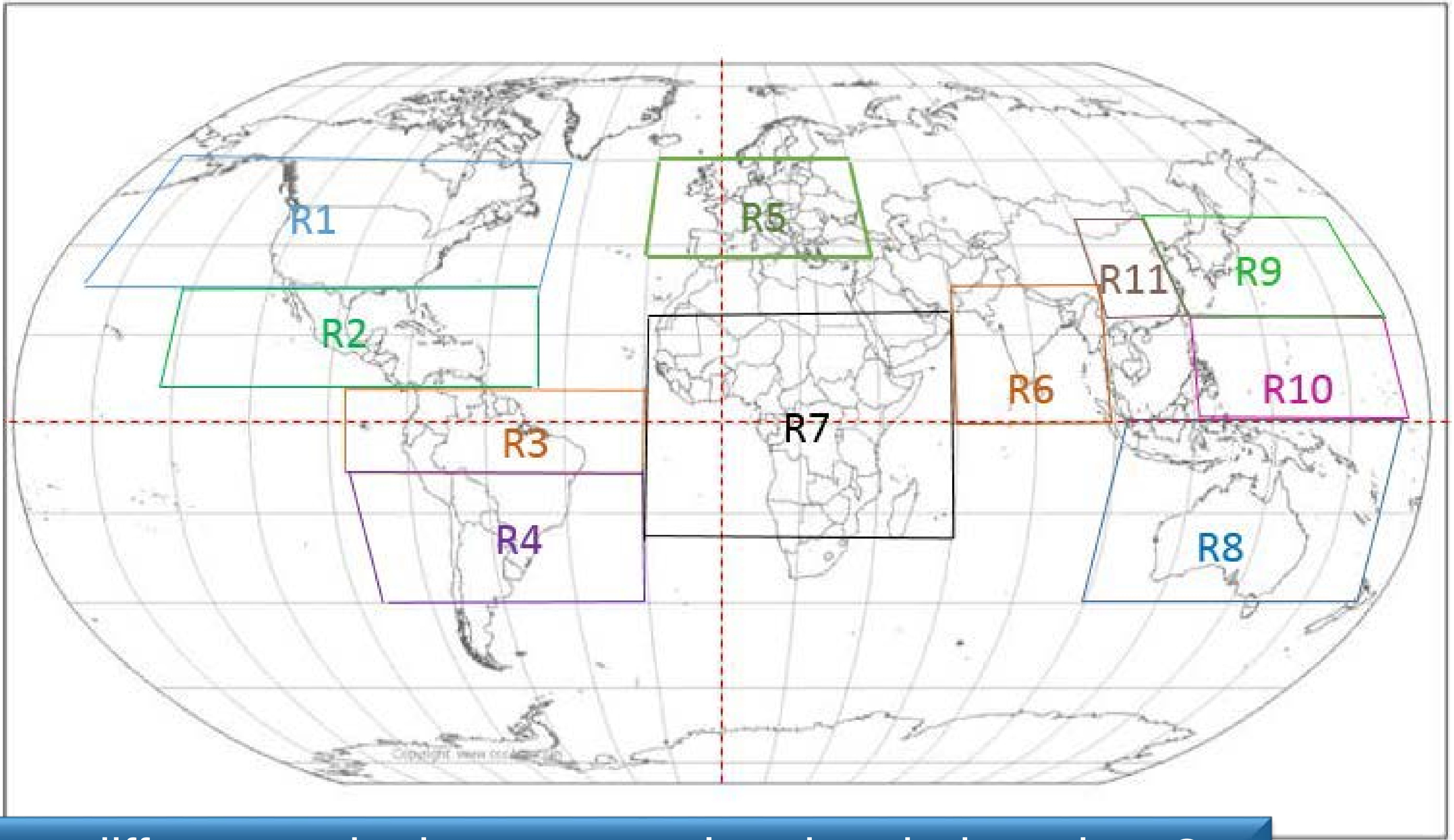
- High occurrence of events associated with tropical oceanic airmasses (‘oceanic convection’)



SAE 2015-01-2130

Regions Visually Chosen For Comparison Based on Clustering

- Events occur in clusters related to numerous factors, such as:
  - Air traffic density and air traffic control
  - Probability of suitable cloud (deep convection)
- Region 7 events are new since Mason 2006



Are there any differences in the events related to their regions?

SAE 2015-01-2130

Regional Comparisons by Season

Events by Season, by Region				
Northern Hemisphere	**Jan-Mar**	**Apr-Jun**	**Jul-Sep**	**Oct-Dec**
1 - North America North	4	3	11	2
2 - North America South	2	4	0	1
3- South America NH	2	3	2	0
5 - Europe	0	0	2	2
6 - India/Thailand	0	7	7	0
7 - Africa	0	1	6	0
9 - Japan	0	9	11	2
10 - South East Asia/South China	1	12	9	6
11 - Continental China	0	2	3	0
Northern Hemisphere Subtotals	**7.9%**	**36.0%**	**44.7%**	**11.4%**

Events by Season, by Region				
Southern Hemisphere	**Jan-Mar**	**Apr-Jun**	**Jul-Sep**	**Oct-Dec**
3 - South America North SH	3	1	0	0
4 - South America South	6	0	0	8
8 - Australia/Indonesia	5	2	0	3
7- Africa SH	1	0	0	0
Southern Hemisphere Subtotals	**50.0%**	**10.7%**	**0.0%**	**39.3%**

Summer
Winter

Events tend to maximize in local summer months

SAE 2015-01-2130

Regional Comparisons by Time of Day

- Regions analyzed by local solar time in 6-hour groupings
- Too few points per region to establish clear trend, except:
  - Region 4 - 9/12 events between 06:01 – 12:00 (no meteorological influence)
  - Region 7 - 8/9 events at night (18:01 – 06:00)

Events per Time of Day, by Region				
Region	**18:01-24:00**	**00:01-06:00**	**06:01-12:00**	**12:01-18:00**
1 - North America North	8	3	5	4
2 - North America South	2	2	1	2
3 - South America North	2	5	3	1
4 - South America South	2	0	9	1
5 - Europe	1	1	1	1
6 - India/Thailand	1	3	5	3
7 - Africa	4	4	1	0
8 - Australia/Indonesia	1	2	3	2
9 - Japan	4	6	7	4
10 - South East Asia/South China	7	5	4	9
11 - Continental China	1	2	0	2

Daytime
Nighttime

Overall, no preferred time-of-day for events

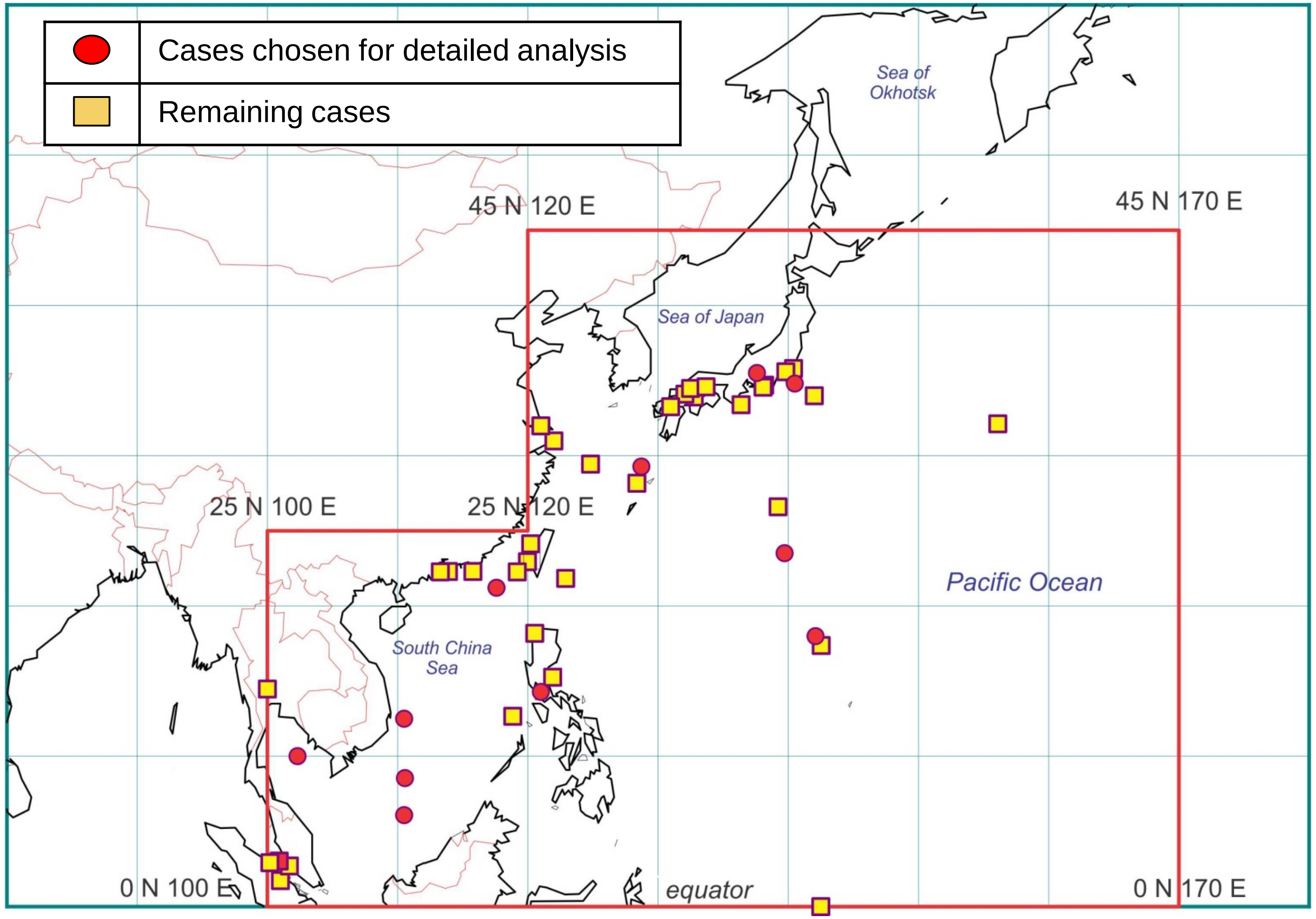
Convective Maximum

- Are engine events occurring near the time and location of peak convective activity?
  - Such regions are hypothesized to be associated with local maximum in ice water content
  - Some convective clouds peak in intensity overnight, diminishing during daytime hours
  - Commercial aircraft fly during all hours of the day
    - Flight crews have more challenges / fewer cues to identify weather at night, since ice crystals are poor reflectors of radar energy
  - Flight test measurements will be taken only in day-time hours for safety reasons

Is it important to gather data for the engineering standard near the peak of convective activity?

Detailed Investigation of Japan and South China Sea Regions

- 50 cases in these two regions
  - 11 cases have been chosen for detailed meteorological analysis
- General Properties of 11 cases analyzed
  - From April to November (monsoon and tropical storm season)
  - All oceanic MCS
  - 9 in cruise, 2 in descent
  - -56°C to -7°C SAT, median -43°C
  - Evenly distributed across solar-time
  - FL 185-400, median FL 370

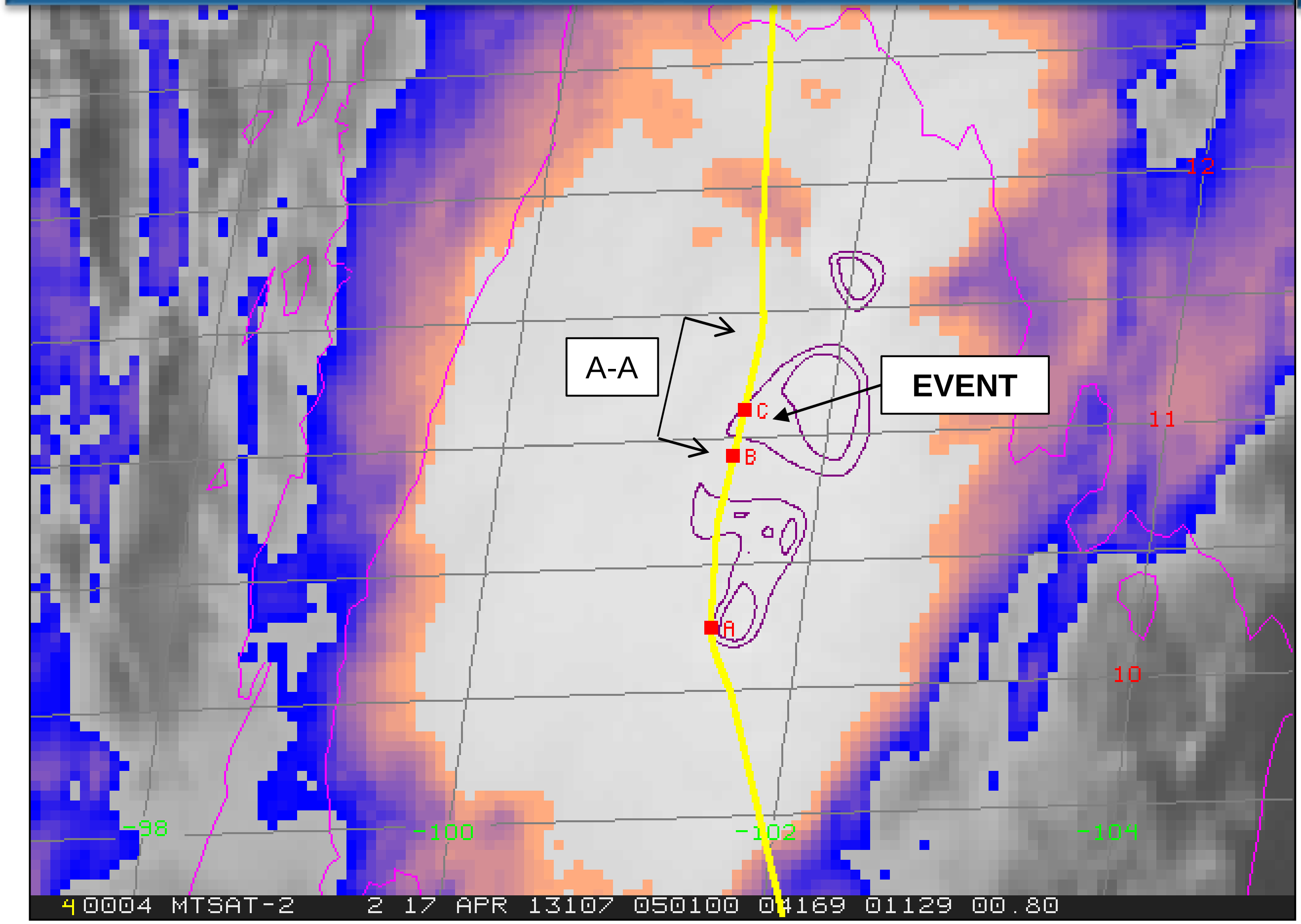


SAE 2015-01-2130

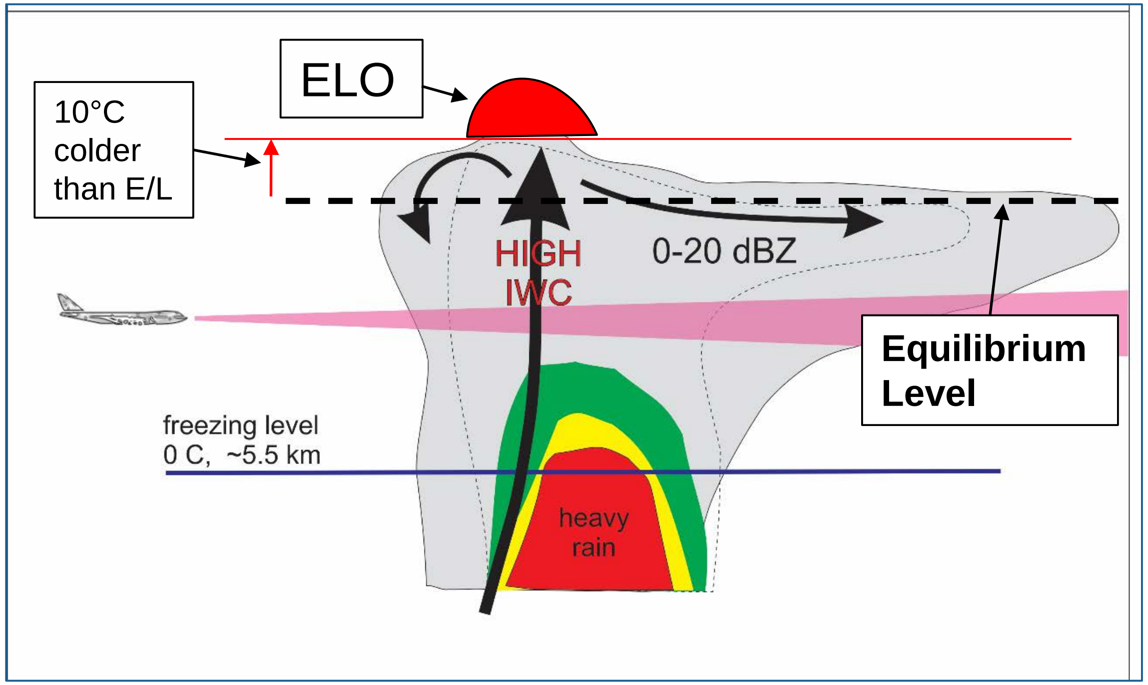
High Ice Water Content (HIWC)

- **Satellite Imagery**

Top View: Example “enhanced color” infrared image of ICI event

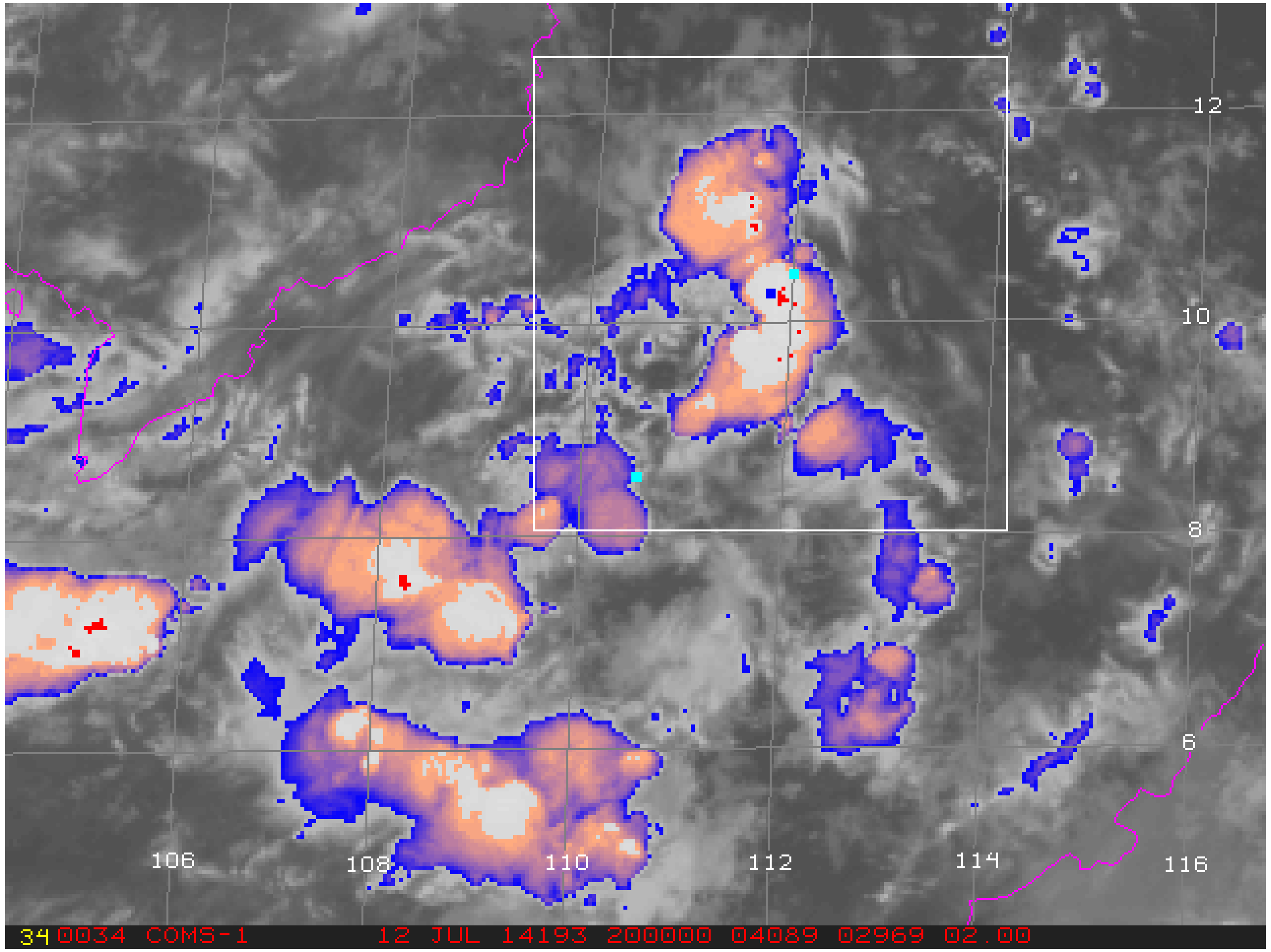


View A-A: Side view of example of a cell of an MCS showing location of HIWC*



* **Side view is adapted from:** Strapp, J.W., Korolev A., Ratvasky T., Potts R., Protat A., May P., Ackerman A., Fridlind A., Minnis P., Haggerty J., Riley J. T., Grzych M., and Isaac G.A.. 2015. “The High Ice Water Content (HIWC) Study of Deep Convective Clouds. Science and Technical Plan.” *FAA report DOT/FAA/TC-14/31*

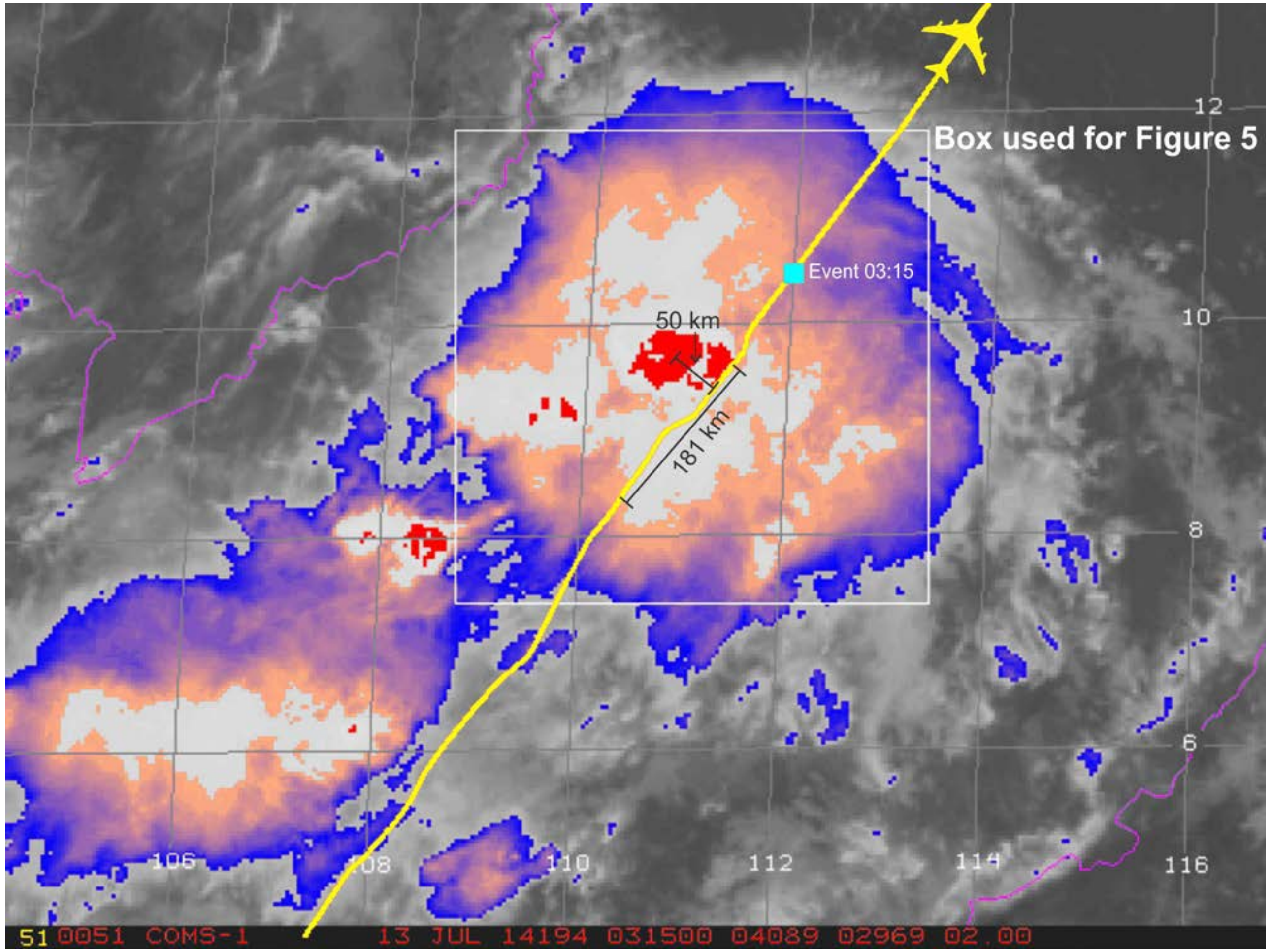
Analysis Method

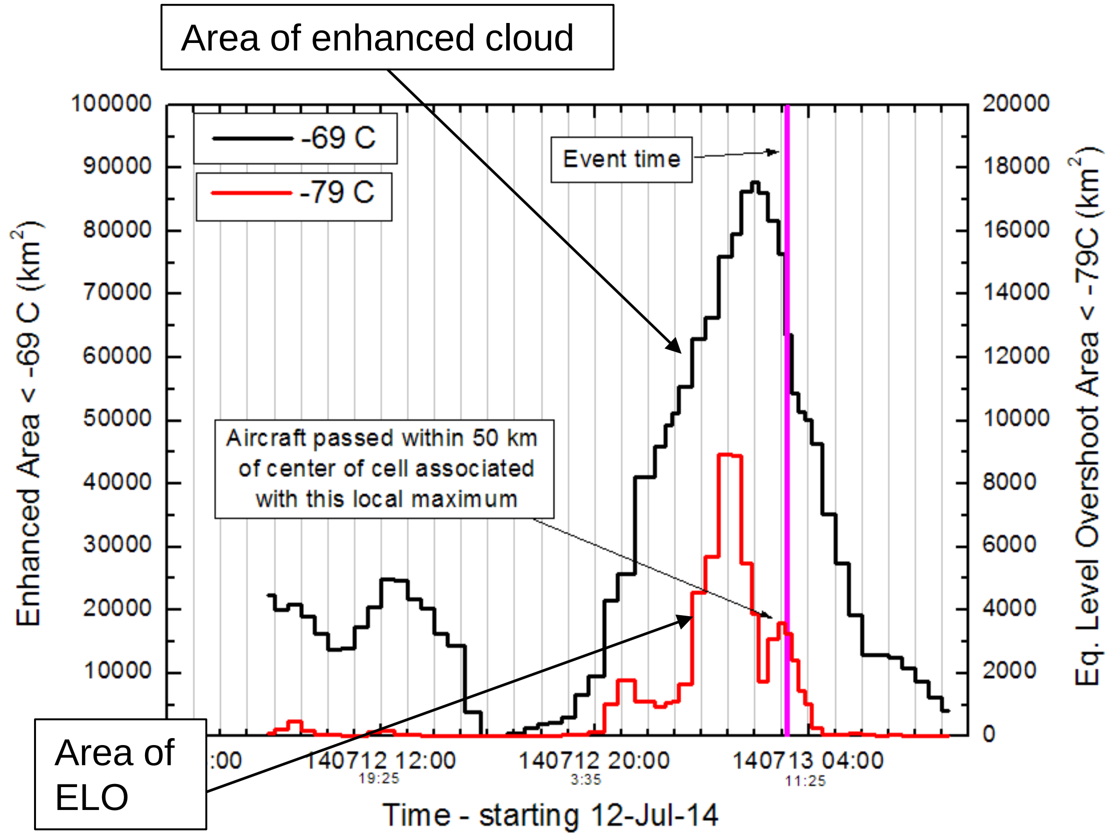


- Convective cloud in which event occurred was tracked from 24 hours before event to 6 hours after event
- MTSAT IR images used: approximate cloud top temperatures
- Moving box defined to encompass cloud – statistics inside box computed versus time
- Prime statistics:
  - Total area of cloud colder than equilibrium ‘enhanced’ level (top altitude a rising air parcel reaches before becoming negatively buoyant) – bright-white + red cloud at left
  - Total area of cloud 10°C colder; enhanced level overshoot (ELO) – red cloud at left
  - Red areas are indicators of center of updraft in cloud

SAE 2015-01-2130

Example of Analysis Results



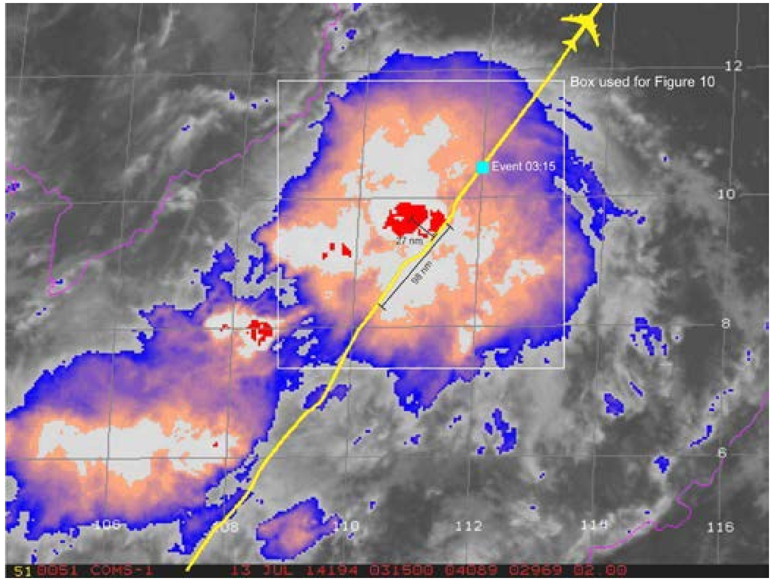


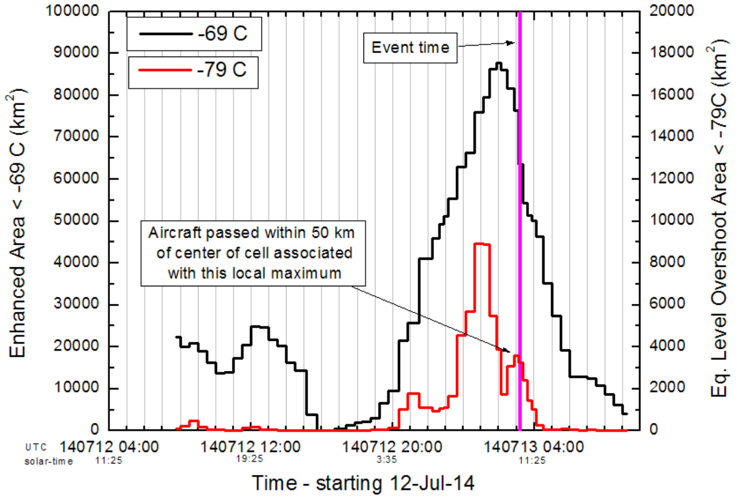
- Aircraft event just after maximum enhanced cloud area
- Event at approximate time of local overshoot
- Aircraft traversed 181 km of ‘enhanced’ cloud and came within 50 km of center of ELO

SAE 2015-01-2130

Results of 11 Cases

Parameter	Range	Average	Comment
Enhanced Distance Traversed	72-272 km	194 km	Similar to findings of Grzych and Mason (2010)
Event time – time of max enhanced (black line)	-1.2 to + 8.6 hrs.	2.1 hrs.	Events typically after peak in enhanced level area
Event time – time of max ELO (red line)	-0.8 to 3.5 hrs.	0.88 hrs.	Events closely aligned in time to peak in area of local ELO– average < 1 hour
Aircraft minimum distance to center of ELO	22-54 km	41 km	Aircraft always passed fairly close to center of an ELO, close to the time of its maximum area
Aircraft penetrated ELO (red) area?			8 of 11 cases (2 of 3 that did not were in descent)





Events tend to occur at or close to the peak in ELO area

SAE 2015-01-2130

Summary

- Boeing database has been updated from Mason et al. (2006) with 46 events to current 162 events
- Types of clouds, temperature levels, and length of cloud traversed similar to previous studies
- Regional influences hard to identify due to low frequencies in each region
- No evidence overall of a time-of-day bias in events, even though research literature reports time-of-day influences on deep convective cloud frequencies
- Most significant new finding is that events occur in MCS close to a local active cell near the time of its peak intensity, identified herein as an "Enhanced Level Overshoot" (ELO). Time of the event ELO may be quite different from the time of the MCS system overall peak intensity

Conclusions and Future Work

- Event timing and location results of this study provide important context for new flight test measurements for Appendix D/P validation
- Results imply that the link to a local ELO may be more important than overall MCS lifecycle and time-of-day
- High Ice Water Content (HIWC) Project Science Plan flight strategies, adopted for HAIC-HIWC Flight Test measurements, target updraft areas of deep convection, and are consistent with flights in vicinity of ELOs

Future Work

- Results need to be extended to more cases
  - Plan is to investigate automation of the process to evaluate as much as possible of the database. Only a small fraction has undergone the detailed lifecycle analysis, and in only one region.

Any Questions?

Author contact information:

- Melissa Bravin: melissa.m.bravin@boeing.com
- Walter Strapp: walter.strapp@gmail.com
- Jeanne Mason: jeanne.g.mason@boeing.com