New Methods to Infer Aircraft Icing Conditions from Satellite Cloud Retrievals

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Aircraft Icing

- Aircraft structures act as ice nuclei in super-cooled clouds
- Icing was the primary cause of 80 accidents (263 fatalities) worldwide in the last 10 years, and was a contributing factor in many more events (EASA).
- General aviation most susceptible, but impact to commercial operations also significant
- Pilots and aviation managers need to know where and when icing can occur

  - PIREPS are first order over USA: but *relatively sparse, aircraft dependent, location uncertain, very few over Europe*

  - Numerical analyses and forecasts: *freezing levels, cloud expectations*

    (clouds resolved explicitly in NWP only capture about 40% of icing PIREPS)

- Improved icing diagnoses/forecasts a high priority for NWS and FAA

Satellite cloud retrievals can improve resolution of icing conditions

Aircraft Icing

In-flight aircraft icing depends on:

- Meteorological factors
  - Presence of super-cooled liquid water, SLW
  - Liquid water content, LWC
  - Droplet size distribution, N(r)
  - Temperature, T(z)
- Airframe and flight parameters (not accounted for)

Ice accretion on wing leading edge

(a) while in cloud

(b) after ascending above cloud

Photo credits: NASA Glenn Research Center

Satellites observe icing conditions

- Low (liquid) cloud retrievals
  - Cloud Top Temperature, Phase, SLW
  - Liquid Water Path: LWP = f(LWC)
  - Effective Droplet Size: $r_e = f(N(r))$
- Ice over water clouds
  - Exploit multilayer techniques
  - For deep ice over water clouds, need to infer embedded icing. Vertical structure important. Satellite retrievals could be used to constrain the problem.

NASA LaRC Icing Algorithms

Goals: Likelihood for SLW, potential icing intensity, expected altitude range

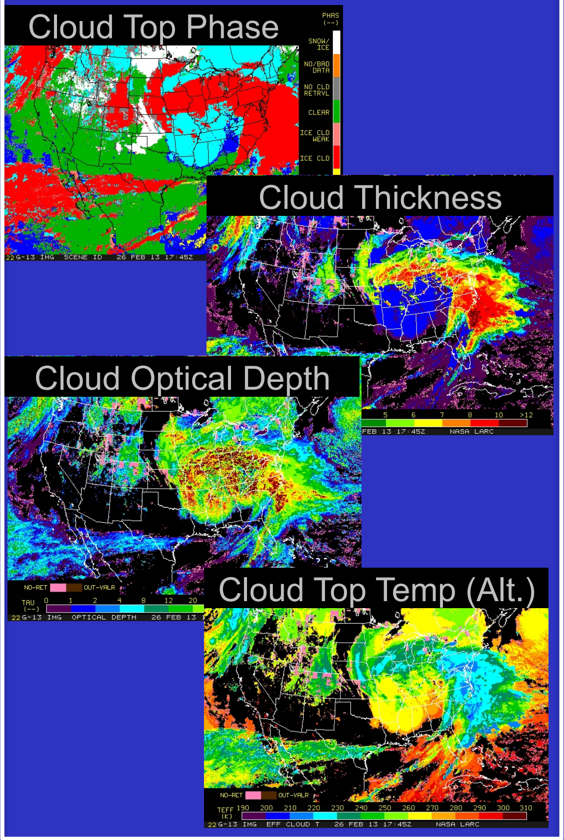
Satellite cloud retrievals are the primary inputs

Solutions for all clouds

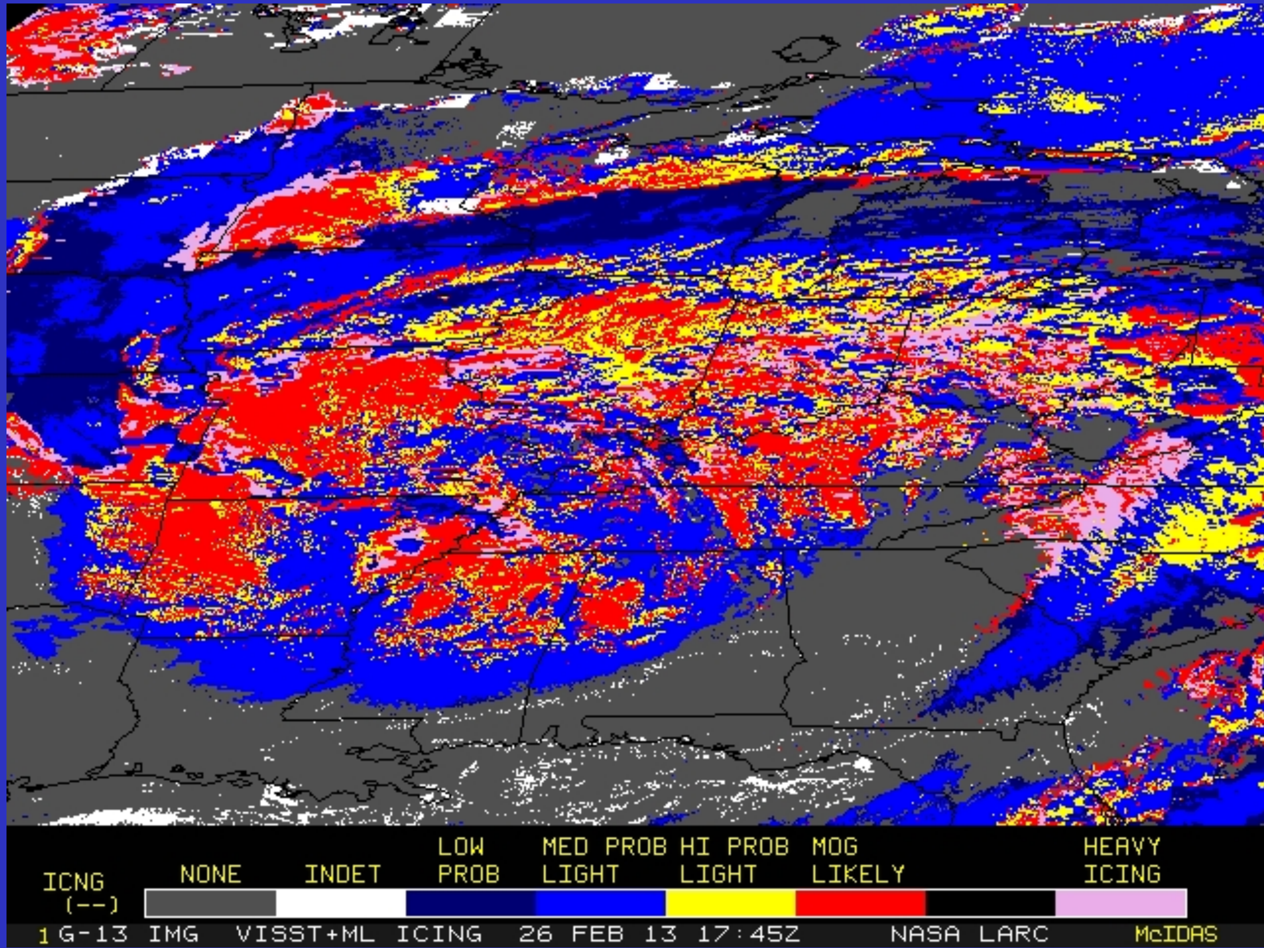
1. Low cloud algorithm (Low, liquid topped clouds)
2. Multi-layer algorithm (cirrus over stratus)
3. Optically thick ice cloud algorithm (Deep, ice over water clouds)

Example of Icing Potential Index

GOES
Cloud Retrievals



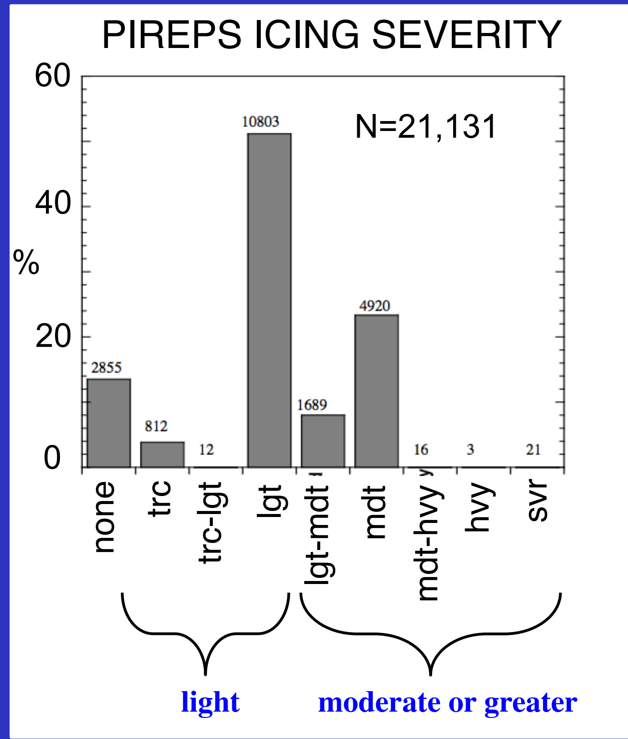
Flight Icing Threat from GOES

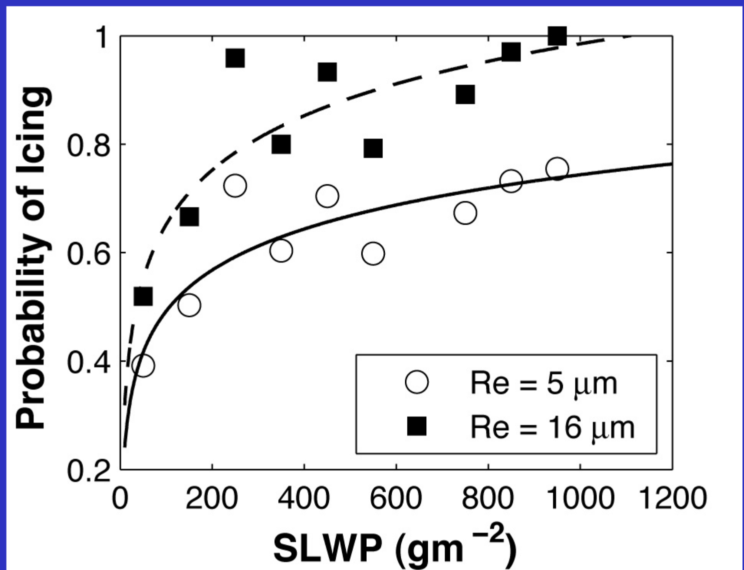


NASA LaRC Icing Algorithms

(1) Low cloud algorithm (SLW clouds)

- Cloud top phase, temperature identify SLW directly
- Icing probability (IP) and intensity inferred from retrieved LWP and CER. LWP scaled to layer above freezing level (SLWP)





PIREPS match-ups:
IP increases with increasing SLWP & CER

SLWP Thresholds developed to separate light from MOG intensities

SURFACE	*SLWP (g/m²)*
All	405
Snow	475
No Snow	379

Heavy: CER > 14 µm

NASA LaRC Icing Algorithms

(2) Multi-layer algorithm (cirrus over stratus)

- Derive lower level Tcld, LWP (see F.-L. Chang poster) and apply low cloud icing algorithm

(3) Optically thick ice cloud algorithm (deep, ice over water clouds)

More elaborate approach needed to infer embedded icing potential:

- Use imager cloud retrievals (cloud boundaries, T_t, COT, and IWP) to constrain climatological cloud vertical structure information derived as a function of cloud type from ARM data, CloudSat/CALIPSO, and cloud models

➔ goal to estimate icing probability and intensity profile, altitude boundaries and use to infer the icing threat for the layer

Thick Ice Over Water Cloud Algorithm

Quick overview of primary elements:

(1) Need TWP for thick clouds (IWP ≠ TWP for these clouds?)

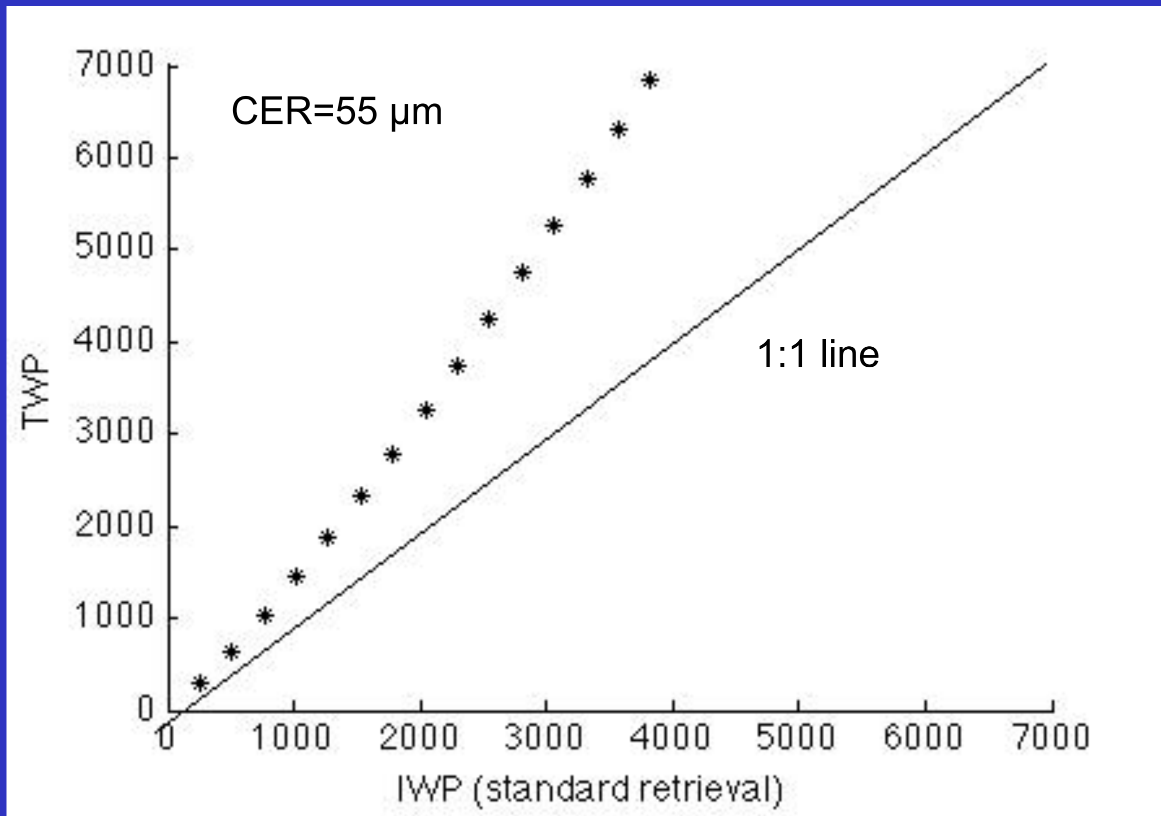
- IWP retrieval assumptions violated (not all ice, not VH)
- Reflectance saturation problem

(2) Want to distribute TWP in vertical (i.e. derive CWC(z)) and estimate the potential for liquid and SLWC(z)

Thick Ice Over Water Cloud Algorithm

TWP parameterization:

- Based on correlations between GOES cloud retrievals and ARM Microbase product (Radar/MWR retrievals) at SGP

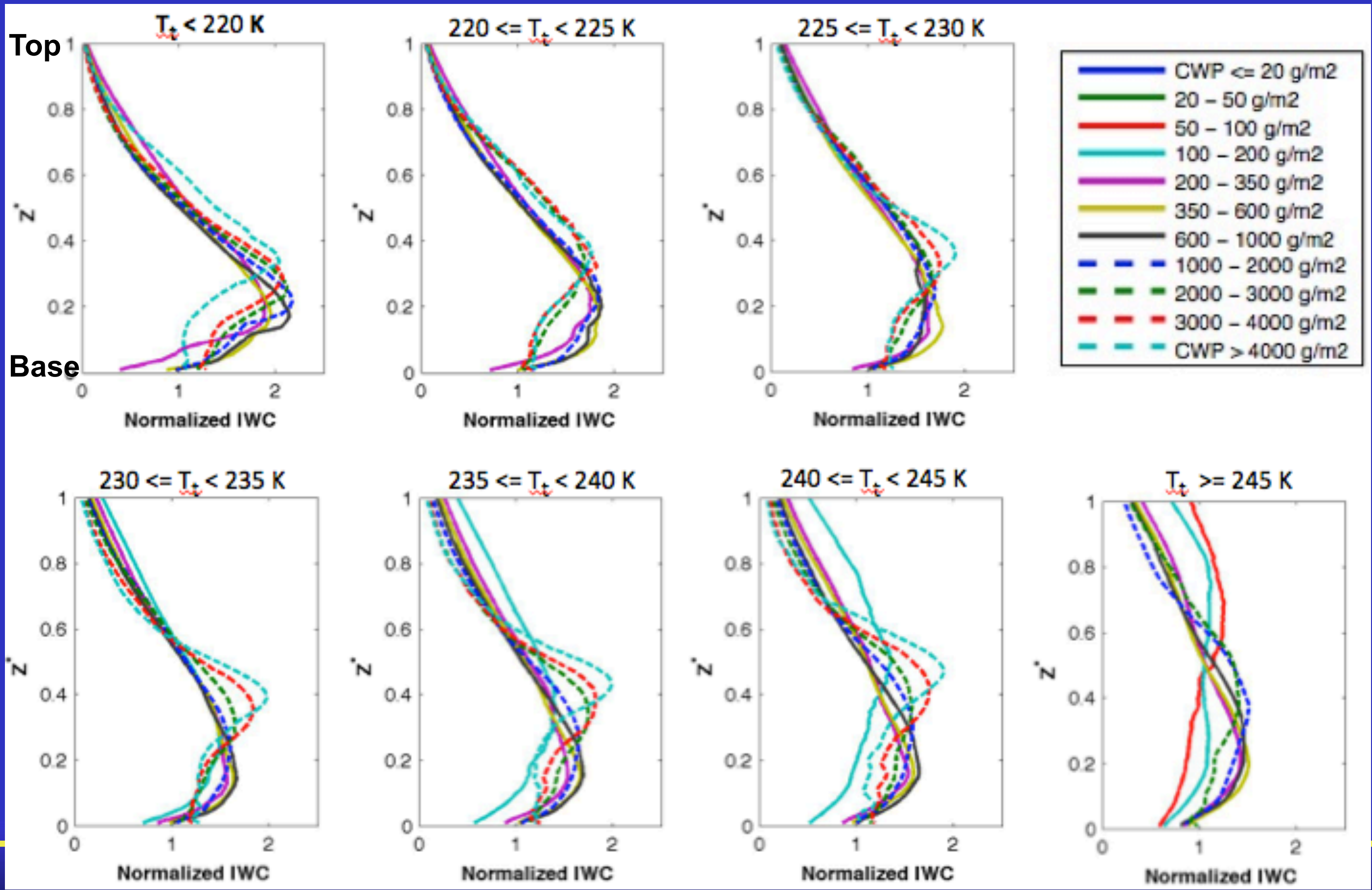


Thick Ice Over Water Cloud Algorithm

Normalized CWC Profiles, Hybrid (NWP + CloudSat/CALIPSO)

50+ cloud types defined by CWP, T_t ;   Ice-topped clouds with COT > 10

Multiply by retrieved CWP / ΔZ to estimate CWC(z)



Thick Ice Over Water Cloud Algorithm

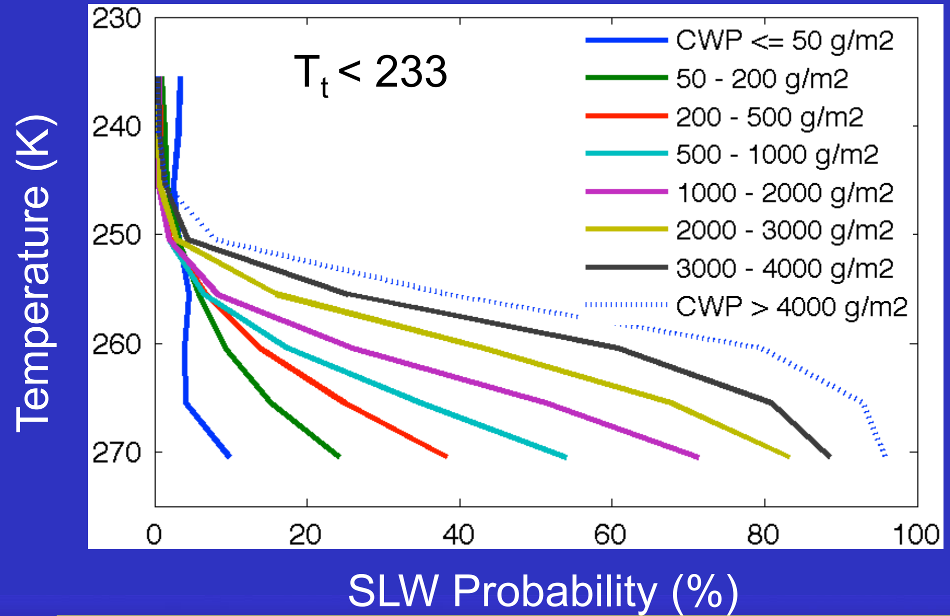
- Have CWC(z), need SLWC(z) for icing

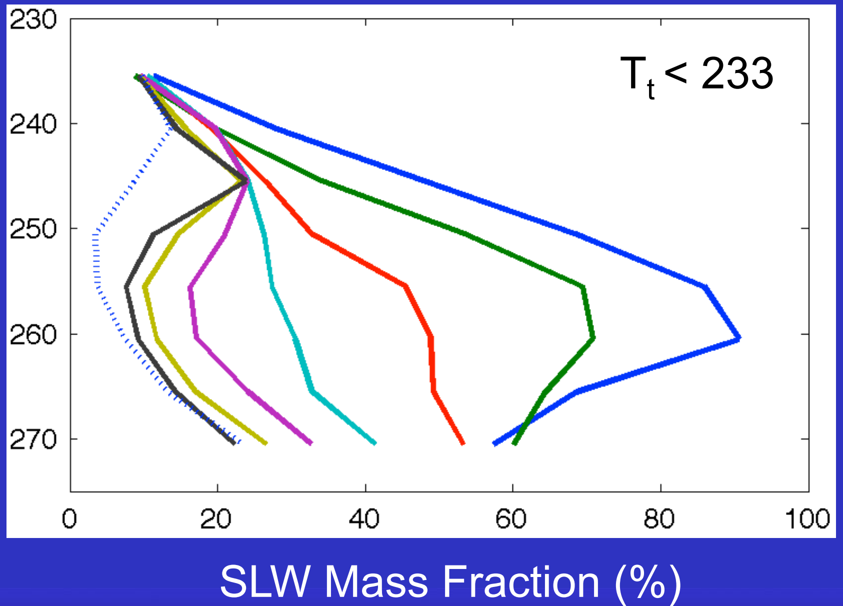
Thompson/NCAR Cloud Microphysics
liquid: $q_{liq} + q_{rain}$
ice: $q_{ice} + q_{snow} + q_{graupel}$

- NWP cloud analyses (e.g. NOAA RUC/RAP) have what we want, are SLW friendly but we can't use directly (cloud not in right place/time)

SLW probability and mass fraction

Climatological approach as a function of T for lots of cloud types





How do we pull this all together to estimate the Flight Icing Threat embedded in deep ice over water clouds

- Cloud water content, cloud probabilty, SLW probability and SLW mass fraction VDF's stored in lookup tables
- Derive standard cloud retrievals from favorite imager and estimate TWP
- For each cloudy pixel, determine the cloud type based on the retrieved T_{top}, Tau, IWP, and ΔZ
- For that cloud type extract the appropriate VDF's and apply to the appropriate satellite derived cloud products to determine:
  1. The probability for cloud as a function of altitude
  2. The probability for SLW as a function of altitude
  3. The S-LWC profile
- Combine (1) and (2) to estimate probability for icing
- Map (3) to the potential intensity (airfoil model) →

Icing Intensity Mapping

LWC (gm^{-3})	Icing category
<0.01	No icing
0.01 to 0.017	Trace
0.017 to 0.03	Trace-light
0.03 to 0.066	Light
0.066 to 0.12	Light-moderate
0.12 to 0.2	Moderate
0.2 to 0.37	Moderate-heavy
>0.37	Heavy

From Politovitch (2003)

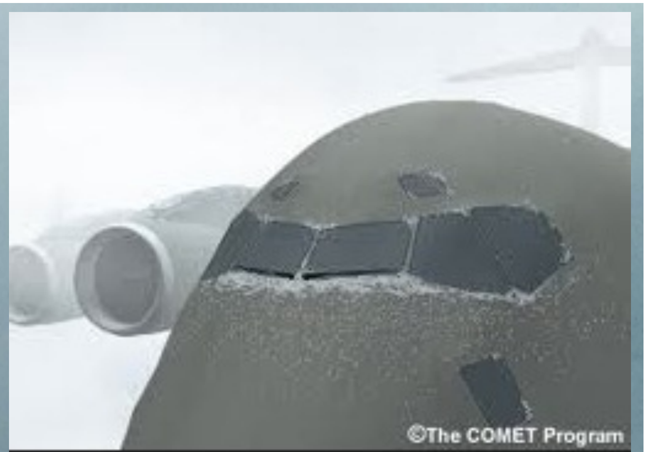
Consolidate for users:

- Define icing threat for layer (max Picing, intensity)
- Determine icing altitude boundaries

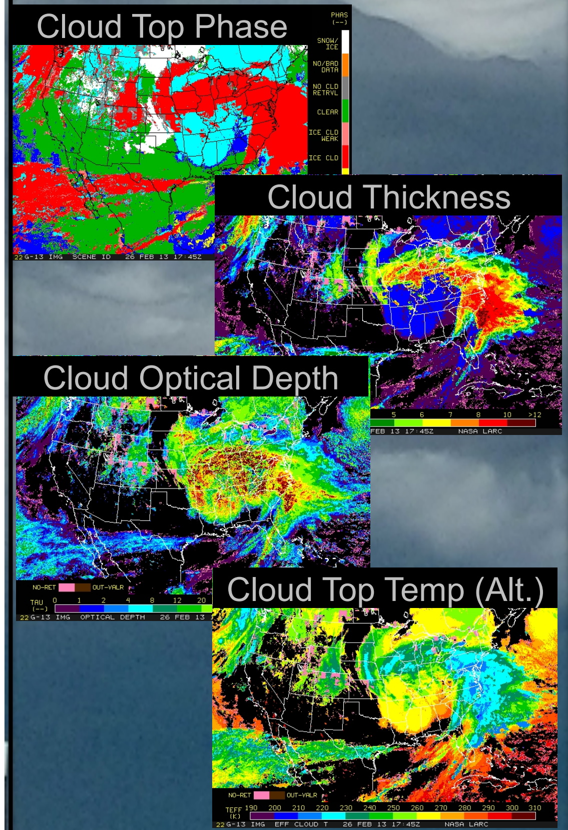
  - Variable PSLW threshold used to estimate top
  - Icing base determined from retrieved Z_{base}, and Z_{273k}

Aircraft Icing

Satellite cloud retrievals can resolve aircraft icing conditions and improve forecasts



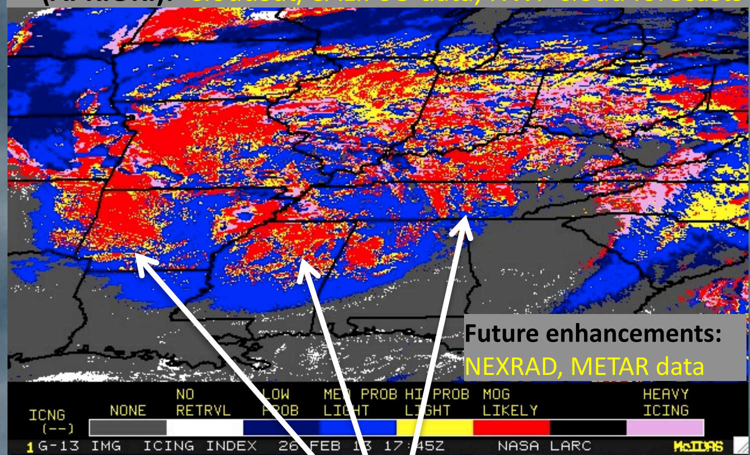
GOES Cloud Properties

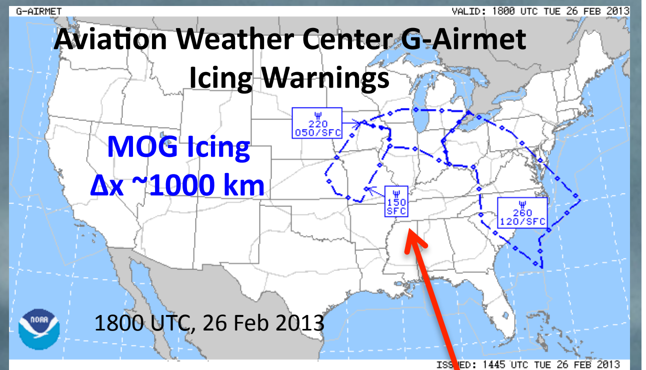


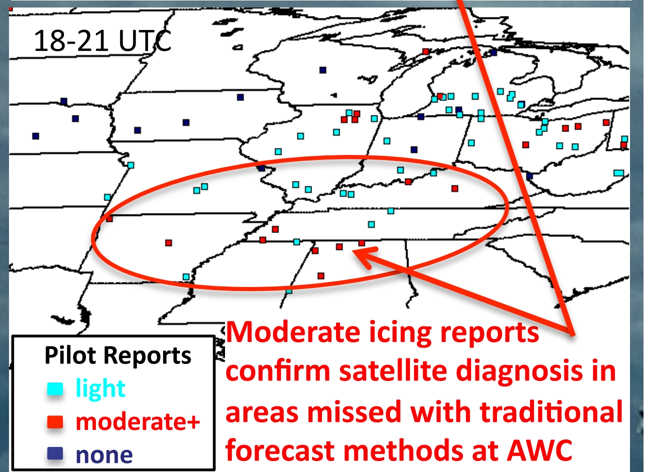
Satellite Flight Icing Threat

INPUTS (R/T): **GOES cloud properties**; NWP T(z), RH(z)

(APRIORI): CloudSat/CALIPSO data; NWP cloud forecasts





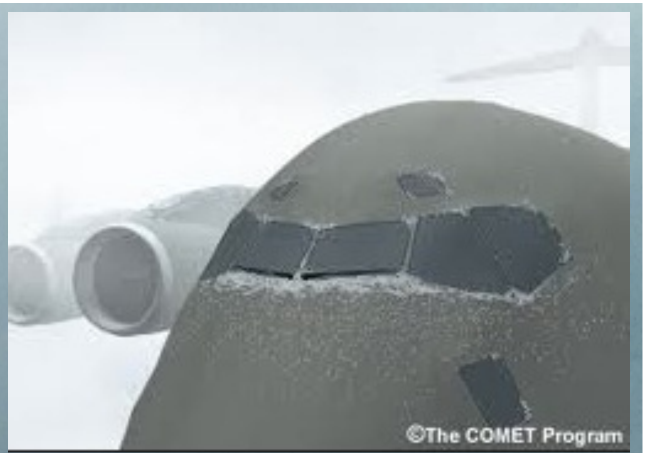


Moderate icing reports confirm satellite diagnosis in areas missed with traditional forecast methods at AWC

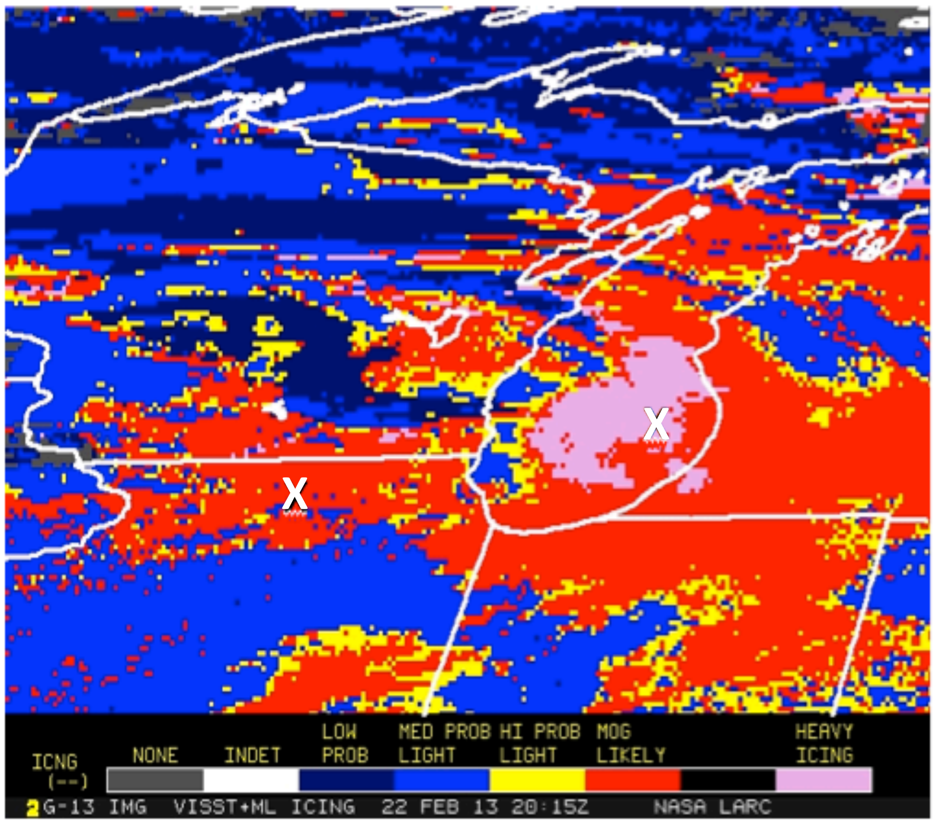
"Satellite method can provide early warning and improved resolution of icing threat not captured in current forecasting techniques, and reduces over-warning."

Aircraft Icing

Satellite retrievals can resolve heavy to severe icing conditions



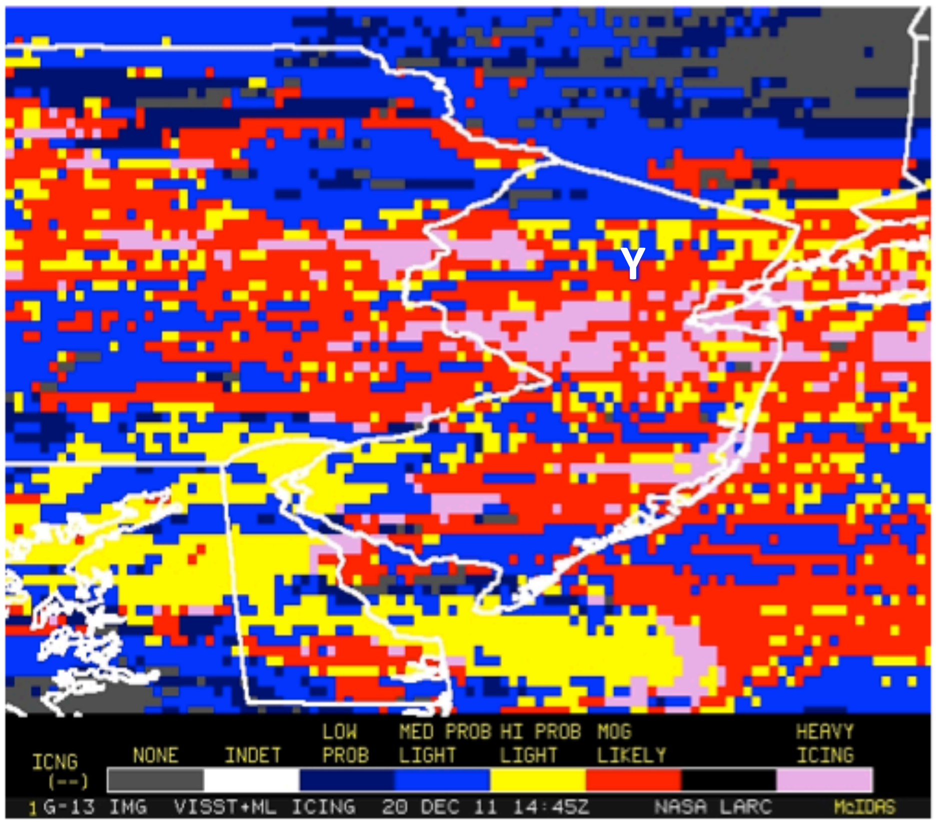
22 Feb 2013 (2015 UTC)



X – denotes severe icing PIREPs

AWC issued SIGMET 2-3 hours later

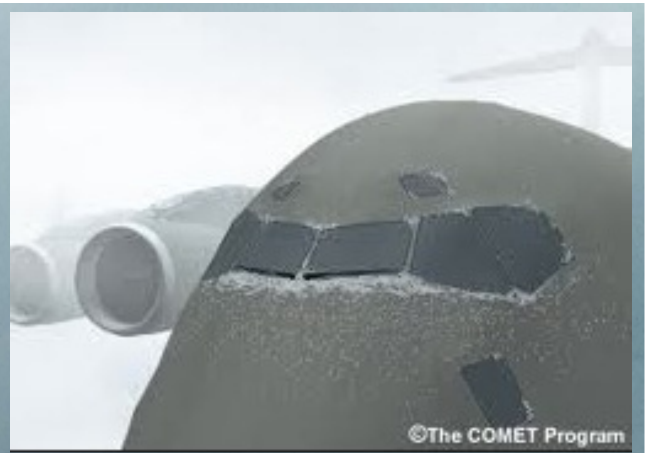
20 Dec 2011 (2015 UTC)

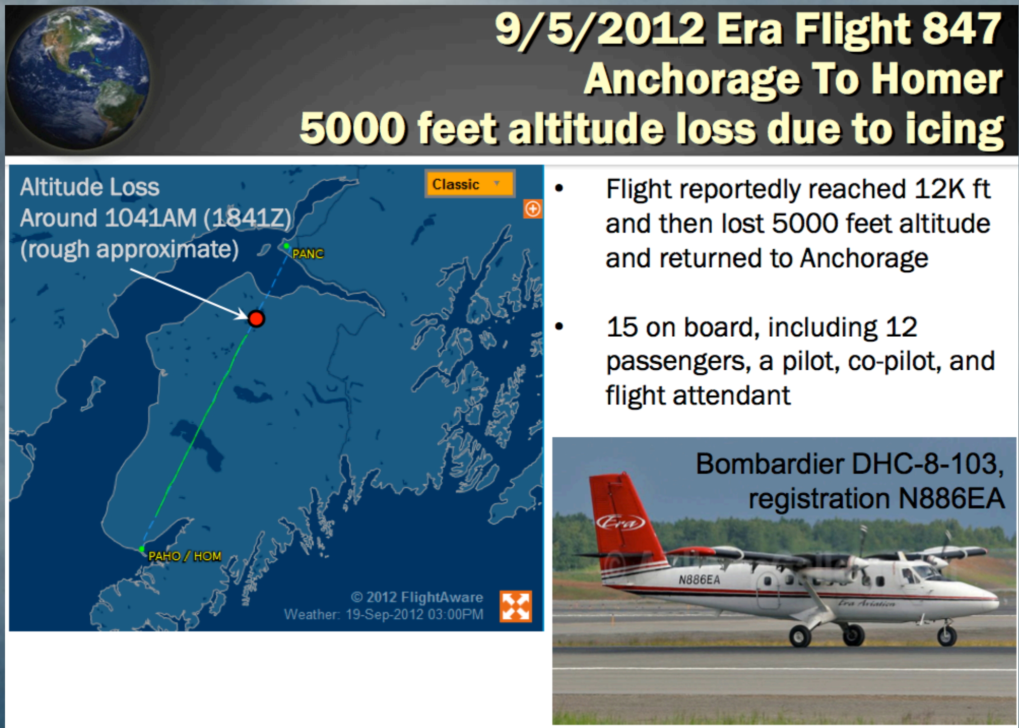


Y – denotes location of TBM-700 crash

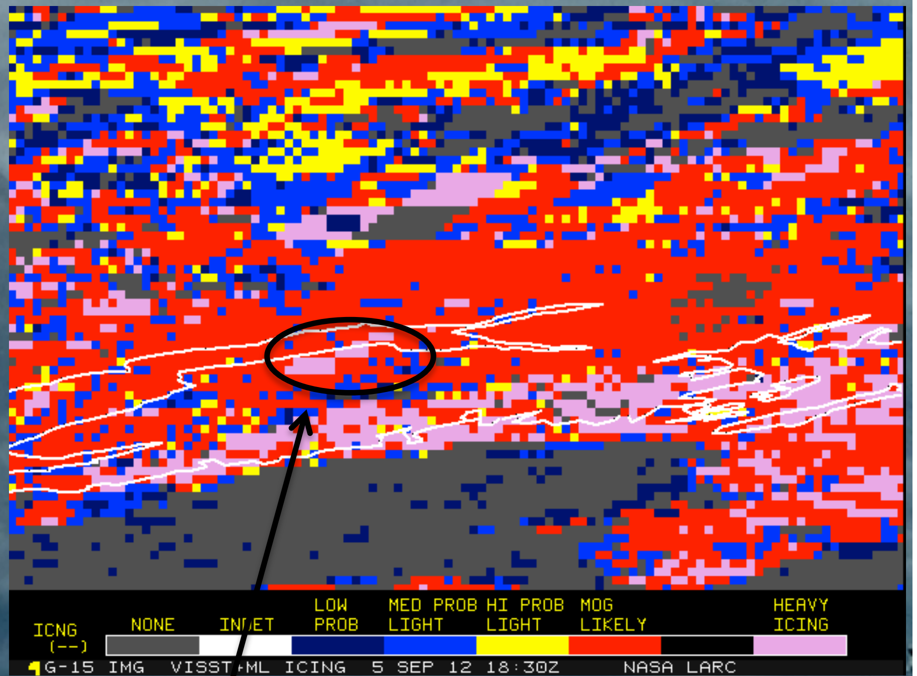
Aircraft Icing

Satellite retrievals can resolve heavy to severe icing conditions





GOES Flight Icing Threat
5 Sep 2012 (18:30 UTC)



Heavy icing detected from GOES in vicinity of aircraft incident

Verification: Icing Detection vs. PIREPS

Jan – Mar, 2013 (USA)

Satellite icing assessed in 20-km radius region at PIREP

Satellite Method	N	PODY	Accuracy
OVC Liquid Clouds	5201	99%	91%
OVC Ice Clouds	2408	99%	86%
All OVC Regions	11712	99%	90%

- Icing detection accuracy beneath ice clouds almost as accurate as that for unobscured liquid clouds
- False alarms difficult to quantify since icing PIREPS biased (few ‘no icing’ reports). PODN, POFD, TSS not meaningful

Verification: Icing Intensity vs. PIREPS

Icing intensity from satellite also has skill

Dominant intensity in 20-km satellite region

Source	N	PODL	PODM	Accuracy
Liquid Clouds	5013	60%	61%	60%
Ice Clouds	2236	61%	45%	57%

Dominant intensity (ambiguous satellite regions count as hit)

Source	N	PODL	PODM	Accuracy
Liquid Clouds	5013	76%	66%	73%
Ice Clouds	2236	80%	47%	72%

Ice cloud PODM low but fraction of MOG icing agrees with PIREPS (~25%)

Verification: Icing Intensity vs. PIREPS

Icing intensity from satellite also has skill

Dominant intensity in 20-km satellite region

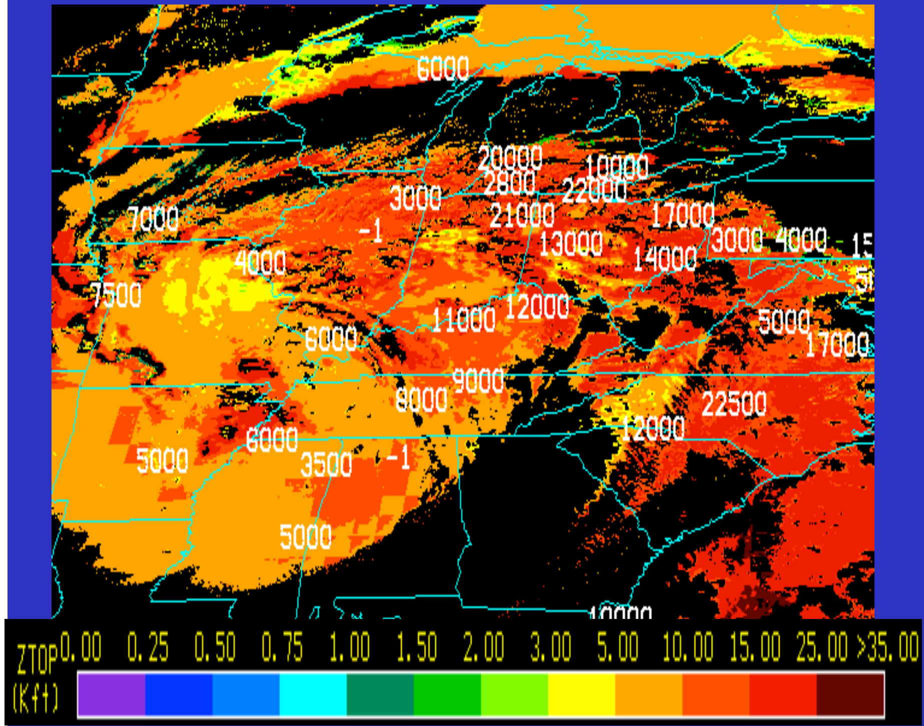
Source	N	PODL	PODM	Accuracy	Pirp	%MOG	Sat
Liquid Clouds	5013	60%	61%	60%	27		46
Ice Clouds	2234	71%	34%	64%	20		30

Dominant intensity (ambiguous satellite regions count as hit)

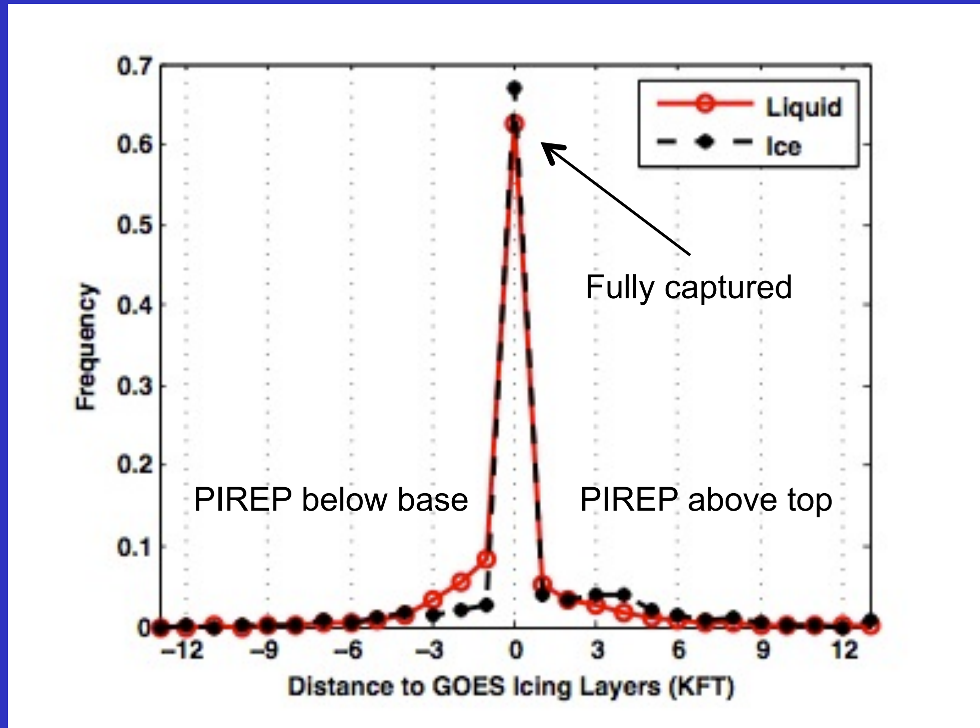
Source	N	PODL	PODM	Accuracy	Pirp	%MOG	Sat
Liquid Clouds	5013	76%	66%	73%	27		36
Ice Clouds	2236	88%	37%	78%	19		16

Verification: Icing Layer Top and Base Altitude

GOES Icing Layer Top Altitude



Frequency of icing PIREPS relative to satellite icing layer altitude boundaries



Derived icing altitude boundaries capture most icing PIREPS found in ice and liquid topped clouds

Summary

- Satellite cloud retrievals improve the spatial and temporal resolution of icing conditions compared to traditional forecasting methods

- Icing detection accuracy is ~ 90%. Icing severity ~60-80% (daytime only) – pretty good considering aircraft dependencies and uncertainties associated with verification data.

- 3.9 µm CER retrievals can identify dangerous icing conditions associated with SLD provided the layer is unobscured by thin water or ice clouds aloft. Other channels could also help (e.g. 1.6 and 2.2 µm)

- Quantifying false alarms is a significant challenge. Some are obvious (e.g. large water droplet retrievals in ice contaminated pixels along the edge of ice cloud systems). Filtering methods need to be developed to flag/eliminate these.

- Cloud profiling technique looks promising. SLWC inferred in thick ice over water clouds corresponds well with PIREPS, LWP agrees pretty well with MWR data, and IWC in upper troposphere agreeing well with CloudSat/CALIPSO over wide range of COT

- Less information is available at night (yes/no/unknown icing index).

- User feedback is needed. Lots of interest from Aviation weather community but just starting to get data to users.