Empirical Methods to Improve Cloud Water Budget Estimates From Passive Satellite Measurements

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Weather and climate applications require accurate characterizations of the vertical distribution of clouds

- Climate: needed for accurate radiative fluxes, to understand cloud effects (CERES), validate climate models
  - CERES SARB (Kato et al.) combining MODIS/imager cloud properties with CloudSat/CALIPSO
- Weather: 3-d cloud information also needed for accurate forecasting
  - Clouds wreak havoc on temperature forecasts
  - Needed by the energy and transportation sectors
  - Associated with hazardous weather (e.g. severe weather, fog, aircraft icing, etc)
  - NWP clouds not in the right place at the right time – only useful on synoptic scales, problems with mass, phase
  - Active sensor coverage insufficient

Satellite imagers observe clouds on time/space scales required
Pioneering work by CERES Cloud Team for Weather Applications

Cloud retrieval algorithm adapted for application to weather satellite data
- Started in late ‘90’s for ARM program
- Expanded for global application to GEOsats (R. Palikonda talk on Tuesday)
- Products available for operational use at NCEP and elsewhere
- Assimilated in NWP by NOAA and NASA (GMAO)
- GEO cloud products fed back to CERES for TISA

Innovative cloud retrieval development (led by P. Minnis)
- State of the art advances for ice clouds
- Accurate geometric cloud boundaries: physical tops, lapse rate approach for BL clouds, cloud thickness provides 3D potential (needed for weather)
- ML technique to ID overlapping clouds and improve retrievals

Next step, cloud impacts (how to make use of COT, IWP/LWP, $R_e$)
- Some model assimilation work using integral parameters in progress (NSSL, GMAO)
- Profiling technique (4-D clouds) and application for nowcasting aircraft icing conditions
GOES-13 Rapid Scan July 19, 2010

Smith et al (A-train mtg 2010)

GOES-13 Cloud Water Content

19-Jul-2010 (1515 UTC)

West

Location

East

CWC (g/m³)
Objectives

Describe recent progress in developing a profiling technique designed to improve the instantaneous vertical resolution of clouds from satellite imager cloud retrievals

- Exploit climatological information on cloud vertical structure derived from active sensor data and cloud models (need both to get the best answer)

- Focus on optically thick ice over water cloud systems (challenging for inferring accurate cloud properties and icing conditions)

- Demonstrate the accuracy and utility with comparisons to coincident active sensor retrievals and validation with icing PIREPS
Aircraft Icing

• Icing can overwhelm aircraft ice protection systems (if they exist)
• Icing 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 (NTSB)
• 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 (synoptic scale guidance)
  - Clouds resolved explicitly in NWP only capture about 40% of icing PIREPS
• Improved resolution of icing conditions a high priority for NWS and FAA
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)
  - One size fits all approach difficult

Ice accretion on wing leading edge

(a) while in cloud

(b) after ascending above cloud

Photo credits: NASA Glenn Research Center
Aircraft Icing

Information contained in satellite cloud retrievals

- Low (liquid) cloud retrievals (SLW observed directly)
  - Cloud Top Temperature, Phase, SLW
  - Liquid Water Path: $\text{LWP} = f(\text{LWC})$
  - Effective Droplet Size: $r_e = f(N(r))$

- Ice over water clouds (need to infer SLW properties)
  - Exploit multilayer techniques for Ci over St
  - For deep ice over water clouds, the situation is more complex. Need information on cloud vertical structure and phase partitioning (unobserved). Satellite cloud retrievals can be used to constrain the problem.

Ice accretion on wing leading edge

(a) while in cloud

(b) after ascending above cloud

Photo credits: NASA Glenn Research Center
NASA LaRC Icing Algorithms

Satellite cloud retrievals are the primary inputs

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

1. Low cloud algorithm (SLW clouds)
   • Map LWP, $R_e$ to icing threat for SLW pixels

2. Multi-layer algorithm (cirrus over stratus)
   • Derive lower level $T_{cld}$, LWP (F.-L. Chang technique) and apply low cloud icing algorithm

3. Optically thick ice cloud algorithm (deep, ice over water clouds)
   • Use imager cloud retrievals (cloud boundaries, $T_i$, 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?)
   • Optically thick clouds matter for weather and climate (small % of clouds but significant fraction of total cloud water)
   • IWP retrieval assumptions violated (not all ice, not VH)
   • Reflectance saturation problem (max COT=150)

(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

![Graph showing TWP parameterization with a 1:1 line and CER=55 µm]
Cloud Water Content Profiling Technique

GOAL: Develop normalized climatological CWC profiles \( S(z) \) from observations and models and constrain with imager cloud properties to estimate profiles with high space/time resolution over wide areas

Cirrus clouds (COT < 10, \( T_{\text{base}} < -20 \text{C} \))
- Compute from CloudSat and CALIPSO (CC) IWC retrievals

All other clouds
- Combine explicit cloud analyses from models (better in lower trop) + CC (upper trop)

\[
S(z^*) = \frac{CWC(z^*)}{CWC} \\
where \quad \frac{CWC}{CWP} = \frac{CWP}{\Delta Z}
\]

Normalized vertical coordinate
\[
z^* = (z - z_b)/(z_t - z_b) \\
z^* = 1 \quad (z_t) \\
z^* = 0 \quad (z_b)
\]

(1) Develop \( S \) from CC and models
- 50 cloud types (\( T_{\text{top}}, \text{CWP} \))

(2) Retrieve \( CWC(z) \) by multiplying \( S \) by \( CWP/\Delta Z \) retrieved from imager data
Normalized CWC Profiles (Cirrus) Cloudsat 2C-ICE

(CONUS, Jan-Mar, 2007)

- $T_t < 220$ K
- $220 \leq T_t < 225$ K
- $225 \leq T_t < 230$ K
- $230 \leq T_t < 235$ K
- $235 \leq T_t < 240$ K
- $240 \leq T_t < 245$ K
- $T_t \geq 245$ K

Normalized IWC vs. $z^*$ for different temperature intervals.
Normalized CWC Profiles (Cirrus) Cloudsat RVOD

(CONUS, Jan-Mar, 2007)
Normalized CWC Profiles (All Clouds) Cloudsat RVOD

Normalized IWC Profiles, CloudSat RVOD (CONUS, Jan-Mar, 2007)

$T_t < 220 \text{ K}$

$220 \leq T_t < 225 \text{ K}$

$225 \leq T_t < 230 \text{ K}$

$230 \leq T_t < 235 \text{ K}$

$235 \leq T_t < 240 \text{ K}$

$240 \leq T_t < 245 \text{ K}$

Altitude of mass peak is too high for denser clouds

CPR Attenuating


245 ≤ T_t < 253 K

253 ≤ T_t < 263 K

263 ≤ T_t < 273 K

T_t ≥ 273 K

Warm Liquid Clouds

Normalized CWC Profiles (All Clouds) NWP + RVOD
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 / $\Delta Z$ to estimate CWC(z)

Top

Base

CWP <= 20 g/m²
20 - 50 g/m²
50 - 100 g/m²
100 - 200 g/m²
200 - 350 g/m²
350 - 600 g/m²
600 - 1000 g/m²
1000 - 2000 g/m²
2000 - 3000 g/m²
3000 - 4000 g/m²
CWP > 4000 g/m²
Cirrus IWC Profiles from MODIS: Validation

CALIPSO+CloudSat vs. CERES MODIS w/RVOD+RAP VDF’s

IOLAP=4

<table>
<thead>
<tr>
<th>COD Range</th>
<th>PDFc</th>
<th>PDFm</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 &lt; COD &lt;= 1</td>
<td>IWPcc=8, IWPm=6</td>
<td>IWPcc=22, IWPm=21</td>
</tr>
<tr>
<td>1 &lt; COD &lt;= 3</td>
<td>IWPcc=18, IWPm=21</td>
<td>IWPcc=58, IWPm=45</td>
</tr>
<tr>
<td>3 &lt; COD &lt;= 6</td>
<td>IWPcc=58, IWPm=45</td>
<td>IWPcc=58, IWPm=45</td>
</tr>
</tbody>
</table>

Height (km)

log (IWC (g/m^3))
Cirrus IWC Profiles from MODIS: Validation
CALIPSO+CloudSat vs. CERES MODIS

**IWPcc** = 129
**IWPm** = 91

**IWPcc** = 24
**IWPm** = 21
Cirrus IWC Profiles from MODIS: Validation

CloudSat vs. CERES MODIS w/CloudSat Top and Base

IWPcc = 7
IWPm = 6

IWPcc = 20
IWPm = 21

IWPcc = 39
IWPm = 45
Cirrus IWC Profiles from MODIS: Validation

CloudSat vs. CERES MODIS w/CloudSat Top and Base

w/RVOD VDF's
(Thick) IWC Profiles from MODIS: Validation
CALIPSO+CloudSat vs. CERES MODIS w/RVOD+RAP VDF’s IOLAP=4

All Clouds; 10 < COD <= 20; PDF

All Clouds; 20 < COD <= 40; PDF

All Clouds; 40 < COD <= 80; PDFc

All Clouds; 10 < COD <= 20; PDF

All Clouds; 20 < COD <= 40; PDFr

All Clouds; 40 < COD <= 80; PDFm

IWPcc=182
IWPm=172

IWPcc=319
IWPm=309

IWPcc=654
IWPm=714
(Thick) IWC Profiles from MODIS: Validation
CALIPSO+CloudSat vs. CERES MODIS w/RVOD VDF’s
IOLAP=4

All Clouds; 80 < COD < 150; PDFr

- CC MODIS
  AVG = 0.300 0.400
  BIAS = +0.1027

- IWPcc=1224
  IWPm=1471

All Clouds; COD = 150; PDFm

- CC MODIS
  AVG = 0.567 0.610
  BIAS = +0.0727

- IWPcc=2518
  IWPm=2645

All Clouds 10 < COD <= 150; PDFc

- CC MODIS
  AVG = 0.068 0.102
  BIAS = +0.0099

- IWPcc=508
  IWPm=535
Thick Ice Over Water Cloud Algorithm

- Have CWC(z), need SLWC(z) for icing
- NWP cloud analyses (e.g. NOAA RUC/RAP) have what we want, are SLW friendly but we can’t use directly (clouds not in right place/time)

SLW probability and mass fraction
Climatological approach as a function of \( T \) for lots of cloud types

\[
\text{liquid: } q_{\text{liq}} + q_{\text{rain}} \\
\text{ice: } q_{\text{ice}} + q_{\text{snow}} + q_{\text{graupel}}
\]
How do we pull this all together to estimate the Flight Icing Threat embedded in deep ice over water clouds

- Cloud water content, cloud probability, 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 $T_{\text{top}}$, Tau, IWP, and $\Delta Z$
- 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)

Consolidate for users:
- Define icing threat for layer (max $P_{\text{icing}}$, intensity)
- Determine icing altitude boundaries
  - Variable PSLW threshold used to estimate top
  - Icing base determined from retrieved $Z_{\text{base}}$, and $Z_{273k}$

### Icing Intensity Mapping

<table>
<thead>
<tr>
<th>LWC (gm$^{-3}$)</th>
<th>Icing category</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;0.01</td>
<td>No icing</td>
</tr>
<tr>
<td>0.01 to 0.017</td>
<td>Trace</td>
</tr>
<tr>
<td>0.017 to 0.03</td>
<td>Trace-light</td>
</tr>
<tr>
<td>0.03 to 0.066</td>
<td>Light</td>
</tr>
<tr>
<td>0.066 to 0.12</td>
<td>Light-moderate</td>
</tr>
<tr>
<td>0.12 to 0.2</td>
<td>Moderate</td>
</tr>
<tr>
<td>0.2 to 0.37</td>
<td>Moderate-heavy</td>
</tr>
<tr>
<td>&gt;0.37</td>
<td>Heavy</td>
</tr>
</tbody>
</table>

From Politovitch (2003)
Satellite cloud retrievals can resolve aircraft icing conditions and improve forecasts.

**Satellite Flight Icing Threat**

Future enhancements: NEXRAD, METAR data

```
none  indet  Low  Med  Hi  Hi  MOG  Heavy
```

**Satellite method can provide early warning and improved resolution of icing threat not captured in current forecasting techniques, and reduces over-warning.**
Satellite retrievals can resolve heavy to severe icing conditions

X – denotes severe icing PIREPs

AWC issued SIGMET 2-3 hours later

Y – denotes location of TBM-700 crash
Satellite retrievals can resolve heavy to severe icing conditions

9/5/2012 Era Flight 847
Anchorage To Homer
5000 feet altitude loss due to icing

- Flight reportedly reached 12K ft and then lost 5000 feet altitude and returned to Anchorage
- 15 on board, including 12 passengers, a pilot, co-pilot, and flight attendant

Bombardier DHC-8-103, registration N886EA

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

<table>
<thead>
<tr>
<th>Satellite Method</th>
<th>N</th>
<th>PODY</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>OVC Liquid Clouds</td>
<td>5201</td>
<td>99%</td>
<td>91%</td>
</tr>
<tr>
<td>OVC Ice Clouds</td>
<td>2408</td>
<td>99%</td>
<td>86%</td>
</tr>
<tr>
<td>All OVC Regions</td>
<td>11712</td>
<td>99%</td>
<td>90%</td>
</tr>
</tbody>
</table>

- 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

<table>
<thead>
<tr>
<th>Source</th>
<th>N</th>
<th>PODL</th>
<th>PODM</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid Clouds</td>
<td>5013</td>
<td>60%</td>
<td>61%</td>
<td>60%</td>
</tr>
<tr>
<td>Ice Clouds</td>
<td>2236</td>
<td>61%</td>
<td>45%</td>
<td>57%</td>
</tr>
</tbody>
</table>

Dominant intensity (ambiguous satellite regions count as hit)

<table>
<thead>
<tr>
<th>Source</th>
<th>N</th>
<th>PODL</th>
<th>PODM</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid Clouds</td>
<td>5013</td>
<td>76%</td>
<td>66%</td>
<td>73%</td>
</tr>
<tr>
<td>Ice Clouds</td>
<td>2236</td>
<td>80%</td>
<td>47%</td>
<td>72%</td>
</tr>
</tbody>
</table>

Satellite method produces the right fraction of MOG icing (~25%, agrees with PIREPS)
Derived icing altitude boundaries capture most icing PIREPS found in ice and liquid topped clouds
Summary

• Cloud water content profiling technique producing good results and the potential for more realistic global estimates of IWP/LWP, and atmospheric heating rates
  - SLWC inferred in thick ice over water clouds corresponds well with icing PIREPS
  - LWP also agrees reasonably well with MWR data
  - MODIS and CloudSat IWP in upper troposphere (< 253K) agree to 5% on average for all clouds
  - MODIS and Calipso+Cloudsat IWC agreement also about 5% for Cirrus clouds but MODIS IWC about 40% higher in deep ice over water clouds (attributed to MODIS IWP/DZ correlation)

• Future work includes global application to CERES MODIS and comparisons with CCCM profiles

• Satellite cloud retrievals improve the spatial and temporal resolution of icing conditions compared to traditional forecasting methods
  - Icing detection accuracy is ~ 90%.
  - Icing severity accuracy vs PIREPS ~60-75% (daytime only)
  - Icing altitude boundaries well captured

• 3.9 µm CER retrievals can identify dangerous icing conditions associated with SLD.

• Future work needed to reduce false alarms (difficult to assess). Some known problem areas (e.g. large SLW CER around ice cloud edges)
Satellite method provides early warning and improved resolution of icing threat not captured in current forecasting techniques (for low clouds). Model approach used at AWC captures the icing threat in deep ice over water clouds.