Near-real-time Satellite Cloud Products For Icing Detection And Aviation Weather Over The USA

Patrick Minnis, William L. Smith, Jr., Louis Nguyen
Atmospheric Sciences
NASA Langley Research Center, Hampton, VA

Patrick Heck & Mandy Khaiyer
AS&M, Inc., Hampton, VA
Acknowledgements

• John Murray, ASAP/AVSP NASA LaRC

• Tom Ratvasky and NASA Glenn Twin Otter Icing Team
OBJECTIVES

• Develop a satellite-based icing detection methodology that can be applied operationally with results provided in a timely manner as part of an integrated icing product for the aviation community

• Use satellite data to provide near-real time cloud-top & base altitudes for aviation weather applications
OUTLINE

• DESCRIPTION OF METHODOLOGY AND CLOUD PRODUCTS
  (Minnis)

• RELATING AIRCRAFT ICING TO SATELLITE CLOUD PARAMETERS
  (Smith)

• DEMONSTRATION OF PROTOTYPE PRODUCT
  (Minnis)
APPROACH

• Use cloud properties currently being derived from satellite data at various time and space scales and relate them to aircraft icing

- Developed & applied algorithms to various satellite (GOES, AVHRR, etc.) data for field programs for climate research

- Currently deriving global cloud and radiation parameters from EOS sensors for global change studies as part of the Clouds and Earth’s Radiant Energy System (CERES) Experiment post processing

- Applying similar algorithms to 4-km GOES data to derive cloud and radiation parameters for DOE ARM program over SGP, for NASA CRYSTAL(FL), Icing (Midwest) running experimentally in R/T
# PIXEL-LEVEL CLOUD PROPERTIES

<table>
<thead>
<tr>
<th>Property</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective Radiating Temp</td>
<td>$T_c$</td>
</tr>
<tr>
<td>Effective Height, Pressure</td>
<td>$Z_c, P_c$</td>
</tr>
<tr>
<td>Top Pressure, Height</td>
<td>$p_t, z_t$</td>
</tr>
<tr>
<td>Thickness</td>
<td>$h$</td>
</tr>
<tr>
<td>Emissivity</td>
<td>$\varepsilon$</td>
</tr>
<tr>
<td>Phase (water or ice; 1 or 2)</td>
<td>$P$</td>
</tr>
<tr>
<td>Water Droplet Effective Radius</td>
<td>$r_e$</td>
</tr>
<tr>
<td>Optical Depth</td>
<td>$\bar{r}$</td>
</tr>
<tr>
<td>Liquid Water Path</td>
<td>LWP</td>
</tr>
<tr>
<td>Ice Effective Diameter</td>
<td>$D_e$</td>
</tr>
<tr>
<td>Ice Water Path</td>
<td>IWP</td>
</tr>
</tbody>
</table>

Blue indicates utility for icing
ICING

ICING CONDITIONS ARE DETERMINED BY CLOUD
- liquid water content, $LWC$ positive w/ intensity
- temperature, $T(z)$ negative w/ intensity
- droplet size distribution, $N(r)$ $r$ positive w/ intensity

SATELLITE REMOTE SENSING CAN DETERMINE CLOUD
- optical depth, $[]$
- effective droplet size, $re$
- liquid water path, $LWP$
- cloud top temperature, $Tc$
- thickness, $h$

IN CERTAIN CIRCUMSTANCES
CLOUD PRODUCTS VS. ICING PARAMETERS

- \( LWP = LWC \times h \)

- \( re = f[N(r)] \)

- \( Tc \& h \) can yield depth of freezing layer

- \( z_t \) is top of icing layer

- ceiling = \( z_t - h \)

IN MANY CASES, SATELLITE REMOTE SENSING SHOULD PROVIDE ICING INFORMATION
DATA

- GOES-8 IMAGER (4KM RESOLUTION) 75° W
  - Visible (0.63 µm; ch.1)
  - Solar Infrared (3.9 µm; ch.2)
  - IR Window (10.8 µm; ch.4)
  - Split Window (12.0 µm; ch.5) (G-12: 13.3 µm)

  Visible Channel Calibrated Following Minnis et al. 2002

- Rapid Update Cycle (RUC) 20 km x 20 km hourly analyses
  - surface air temperature => skin temperature
  - temperature & moisture profiles => absorption correction, heights

- CERES clear-sky albedo, surface emissivity (10', 1°)
  clear-sky reflectance, brightness temperature => cloud detection/retrieval

- Theoretical cloud reflectance & emittance models
  describes angular variation for range of re and => cloud detection/retrieval
METHODOLOGY FOR EACH IMAGE TIME

- Clear-sky albedo map
- Surface type map
- Surface emissivity map
- RUC Analysis

Process each image as a sequence of pixel groups (tiles)

- Compute clear reflectance
- Compute clear temperatures
- Compute atmos corrections

- Mask: cloudy? or clear

- GOES Radiance Pixel Tile
- GOES clear/cloud Pixel Tile

- VISST/SIRS Retrieve cloud properties
- cloudy pixels
- clear data
- No
- Clear values update

lat, lon

NASA Langley Research Center / Atmospheric Sciences
FAA In-flight Icing/Ground De-icing International Conference, Chicago, IL, June 16-20, 2003
CLOUD MASK

- To detect clouds, the radiances for cloud-free (clear) scene must be known

- Determine clear-sky albedos and surface emissivities after initial processing of data
  - start with CERES values and update

- Use RUC surface temperatures & profiles to estimate clear-sky brightness temperatures

- Must account for angular dependence: bidirectional reflectance models to estimate clear-sky reflectance for each pixel

- Estimate thresholds based on uncertainties in models & spatial/temporal variability of the clear radiances
CLEAR-SKY RADIANCE CHARACTERIZATION

• Predict radiance a given satellite sensor would measure for each channel if no clouds are present

• Estimate uncertainty based on spatial & temporal variability & angular model errors

• Develop set of spectral thresholds for each channel
  - Solar, uses reflectance, \( \bar{\text{\( r \)}} \)
  - IR, use temperature, \( T \)

  brightness temperature difference, \( \text{BTD} = T_{\text{\( l \)}} - T_{\text{\( l \)}} \)

  typically, \( \text{BTD}(3.7-11) \) or \( \text{BTD}(11-12) \)
CLEAR-SKY REFLECTANCE, SOLAR

• Estimate overhead-sun albedo, \( \bar{a}_o = \bar{a}(\mu_o = 1) \)

  derived empirically with initial runs using CERES VIRS data, then updated for each month using GOES

• Estimate albedo at given local time, \( a(\mu_o) = \bar{a}_o \bar{a}(\mu_o) \)

  directional reflectance model \( \bar{a}(\mu_o) \) derived for each IGBP type using VIRS

• Estimate reflectance for given viewing angles, \( r(\mu_o, \mu, f) = \bar{a}(\mu_o) \bar{c}(\mu_o, \mu, f) \)

  bidirectional reflectance (BRDF) model \( \bar{c} \) selected for each surface type

  from Kriebel (1978), Minnis & Harrison (1984), Suttles et al. (1988)

• Add uncertainty to set reflectance threshold, \( r_T(\mu_o, \mu, f) = \bar{r} + Dr(\mu_o, \mu, f) \)
PREDICTED CLEAR-SKY & OBSERVED VIS REFLECTANCE & CLOUD MASK
1700 UTC, 12/21/00
CLEAR-SKY TEMPERATURE, INFRARED

- **Estimate surface emissivity**, $\varepsilon_b(x,y)$
  
  derived empirically with using ISCCP AVHRR DX, VIRS, then Terra MODIS; water & snow theoretical models

- **Estimate radiance leaving the surface**, $L_s = \varepsilon_b B(T_{\text{skin}}) + (1-\varepsilon_b)L_{\text{ad}}$
  
  $L_{\text{ad}} = \text{downwelling atmo radiation}$, $T_{\text{skin}} = \text{skin temperature from model / obs}$

- **Estimate TOA brightness temperature**, $B(T_{\text{cs}}) = (1-\varepsilon_a)L_s + \varepsilon_a L_{\text{au}}$
  
  $L_{\text{au}} = \text{upwelling atmo radiation}$, $\varepsilon_a = \text{effective emissivity of atmo layer absorption emission computed using T/RH profile, correlated k-dist}$

- **Add uncertainty to set T or BTD thresholds**, $T_T(\mu) = T_{\text{cs}}(\mu) + \Delta T(\mu)$
  
  - reflected solar component included in 3.7-4.0 $\mu$m estimate
PREDICTED CLEAR-SKY & OBSERVED IR TEMPERATURE
1700 UTC, 12/21/00
PREDICTED CLEAR-SKY & OBSERVED BTD (3.7 - 11)
1700 UTC, 12/21/00
CERES CLOUD MASK 1700 UTC, 12/21/00
STANDARD NIGHTTIME MASK ALGORITHM

Top Level Nighttime Flow Chart

"A" Test
Simple IR (11μ) Threshold

Colder

Good Cloud

Warmer

"D1" Test
11μ clear-sky threshold

VIRS run statistics

"D2" Test
3.75-11μ clear-sky threshold (high)

"D3" Test
3.75-11μ clear-sky threshold (low)

∑

If = 0,
Good Clear

If (1 or 2)
Apply "E" Tests

Cannot = 3,
D2 and D3 cannot be equal to 1 at the same time
DAYTIME CLOUD RETRIEVALS

• VISST (Visible, infrared, solar-infrared, split-window technique)
  - physically based method using 0.65, 3.7, 11, & 12 μm
  - for cloudy pixels, match radiances to model values

• Yields more accurate cloud temperatures than simpler methods
  - adjusts temperature (altitude) of thin clouds

• Provides basis for determining phase
  - in most cases, ice & water models are distinct
Daytime Cloud Property Retrievals

- Derive cloud properties by matching observed radiances to model calculations for water droplets ($2 < r_e < 32 \text{ mm}$) and ice crystals ($6 < D_e < 135 \text{ mm}$) through reflectance and emittance parameterizations.

- 3.9 mm (GOES Channel 2) used for particle size retrieval.

- Particle phase determined by:
  - (1) Best available model solution
  - (2) $T_{10.8} - T_{12.0}$ Difference
  - (3) Visible/IR Layer Retrieval
  - (4) Retrieved Cloud Temperature

Cloud Tau, phase, $r_e (D_e)$, LWP (IWP), $Z_{cld}$, $T_{cld}$
Cloud properties from GOES-8
1815 UTC
March 3, 2000
Cloud mask & optical depths from GOES-8

1815 UTC

March 3, 2000
Cloud droplet radius & LWP from GOES-8
1815 UTC
March 3, 2000
Cloud-top temperature & height from GOES-8

1815 UTC

March 3, 2000
ARM-Sponsored Comparisons (March 2000)

Comparison of Surface, GOES and Aircraft Results (~10 hours)

- Effective radius (GOES/Aircraft)
- LWP (GOES/Aircraft)
- Optical depth (GOES/Aircraft)

Surface=7.6
GOES=9.7
Aircraft=7.9

Surface=194
GOES=192
Aircraft=196

Surface=35.4
GOES=31.2
Aircraft=32.7