Detection of Aircraft Icing Conditions Using an Enhanced Cloud Retrieval Method Applied to Geostationary Satellite Data

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Aircraft Icing

- Aircraft structures act as ice nuclei in supercooled clouds
  - ice collects, weight increases, plane falls
- Pilots need to know where and when icing can occur
  - PIREPS are first order
    - sparse, aircraft dependent, location uncertain
  - weather forecasts
    - freezing levels, cloud expectations
  - radar => precipitation
- All combined in NCAR/FAA/NOAA/NASA program to provide Current Icing Potential (CIP) & Future Icing Potential (FIP) products to pilots
  - some inadequacies remain
    - NWP uncertainties, intensity, altitude of icing, etc.

Remote Sensing of Icing Conditions

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, **τ**
- effective droplet size, *re*
- liquid water path, *LWP*
- cloud top temperature, *Tc*
- thickness, *h*

IN CERTAIN CIRCUMSTANCES

Radiative Transfer for Operational Remote Sensing

- For operational satellites (e.g., GOES or AVHRR), need means to represent multi-spectral radiance field for full range of expected conditions (surface, atmosphere, cloud)

    - three (four) wavelengths: 0.65, 3.8, 11.0, 12.0 µm

- LaRC approach (based on adding-doubling RTM)

    - compute 0.65 & 3.8 cloud reflectances in black vacuum, create LUTs for range of r_e and D_e, τ over all SZA, VZA, RAA

    - parameterize effective emissivity of clouds at 3.8, 11.0, 12.0 µm

    - create LUT of Rayleigh scattering at 0.65 µm

    - parameterize AD code using LUTs and surface reflectance => **TOA reflectances, R_i**

    - apply simple layer RT for 3.8, 11.0, 12.0 µm using gaseous absorption/emissivity based on correlated k-dist computed using NWP soundings => **TOA brightness temperatures, T_i**

- Find closest match between $R_i(r_e/D_e,\tau,p)$ & $R_i(obs)$; $T_i((r_e/D_e,\tau,p)$ & $T_i(obs)$

Products Derived from Geostationary & Polar-Orbiting Satellites

Current Products

0.65 µm Reflectance	3.7 µm Temperature	6.7 µm Temperature
10.8 µm Temperature	12 or 13.3-µm Temp	1.6 µm Reflectance
Skin Temperature	Optical Depth	Eff Radius/Diameter
Liq/Ice Water Path	Cloud Eff Temp	Cloud Top Pressure
Cloud Eff Pressure	Cloud Top Height	Cloud Eff Height
Cloud Phase	Cloud Bot Height	Cloud Mask
Cloud Bot Pressure	Icing Potential	Broadband SW Albedo
Broadband LW Flux	Infrared Emittance	

New products:

Surface Flux (Gridded)

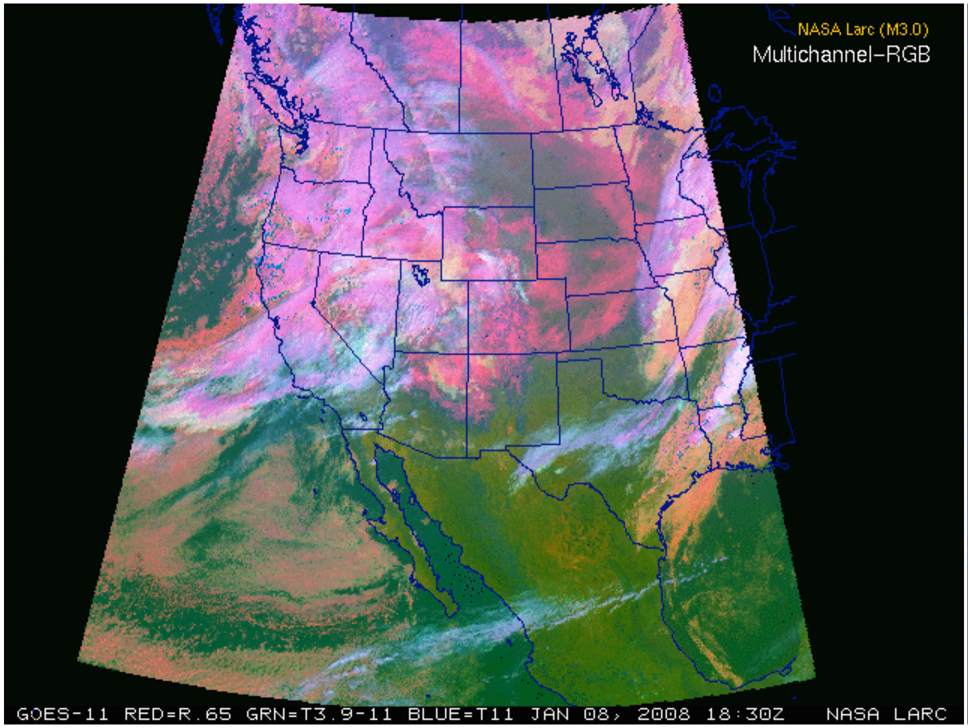
Multi Layer Cloud Mask & Layer Retrievals

http://www-angler.larc.nasa.gov/satimage/products.html

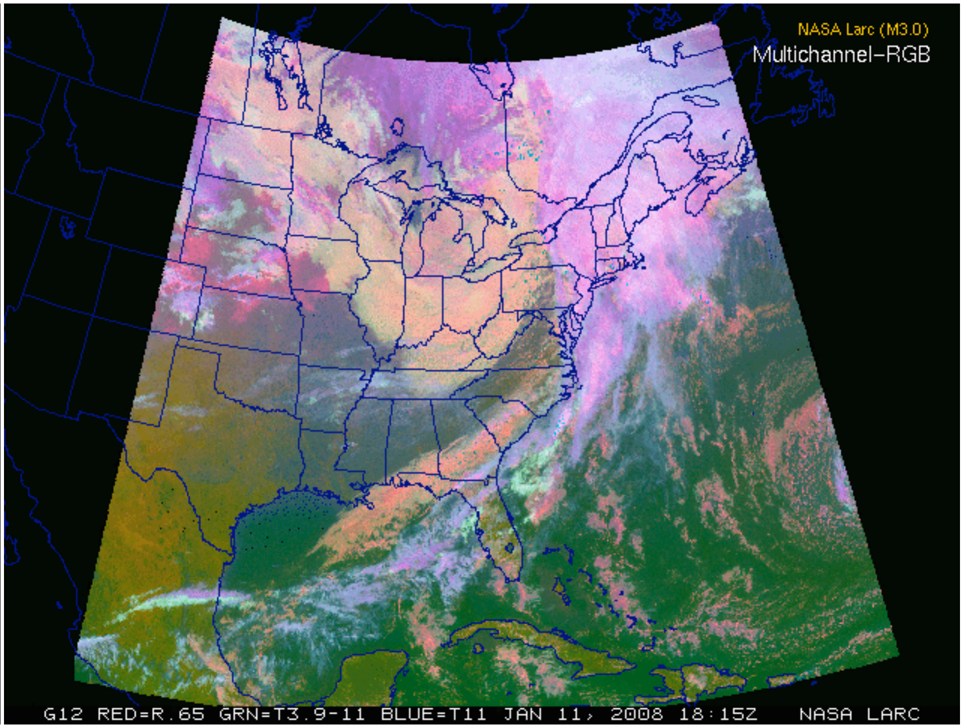
Analysis Applied to Two Satellites to Cover USA

1815 UTC, 8 Jan 2008

GOES-11 RGB



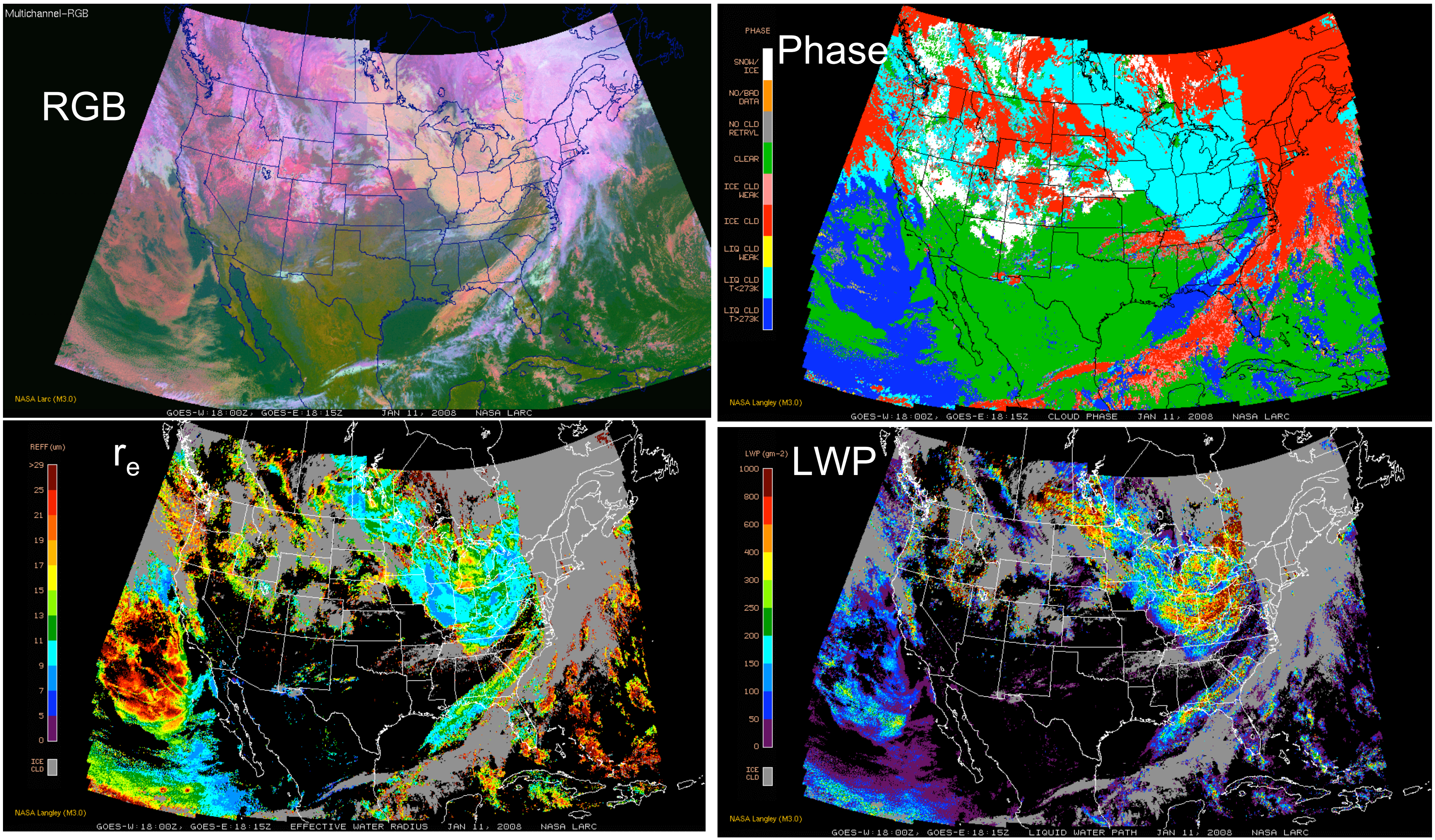
GOES-12 RGB



Each image is analyzed and the results are combined

Combined GOES-11/12 Retrievals, 1815 UTC, 8 Jan 2008

Light Blue - Supercooled

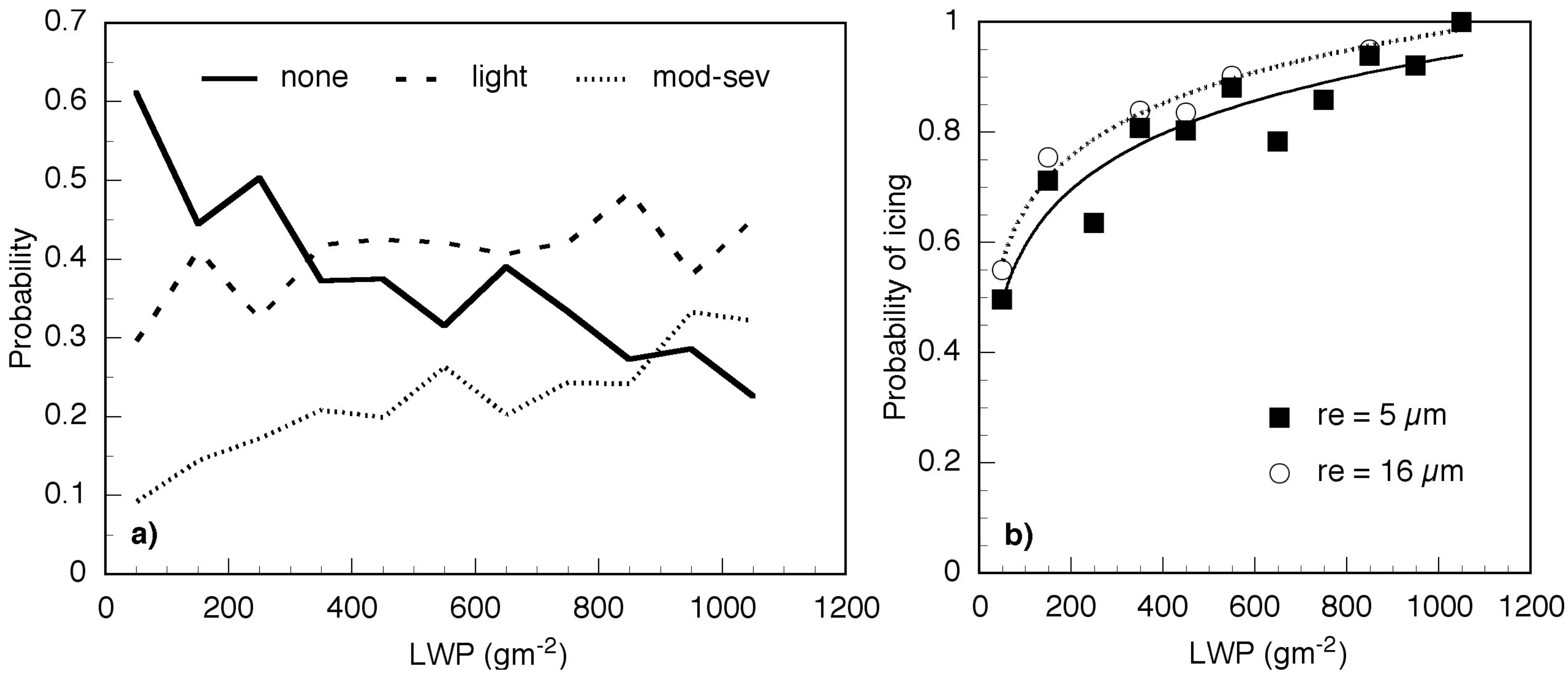


CLOUD PRODUCTS VS. ICING PARAMETERS

- $LWP = LWC * h$
- $re = f[N(r)]$
- 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

Dependence of Icing on LWP and r_e

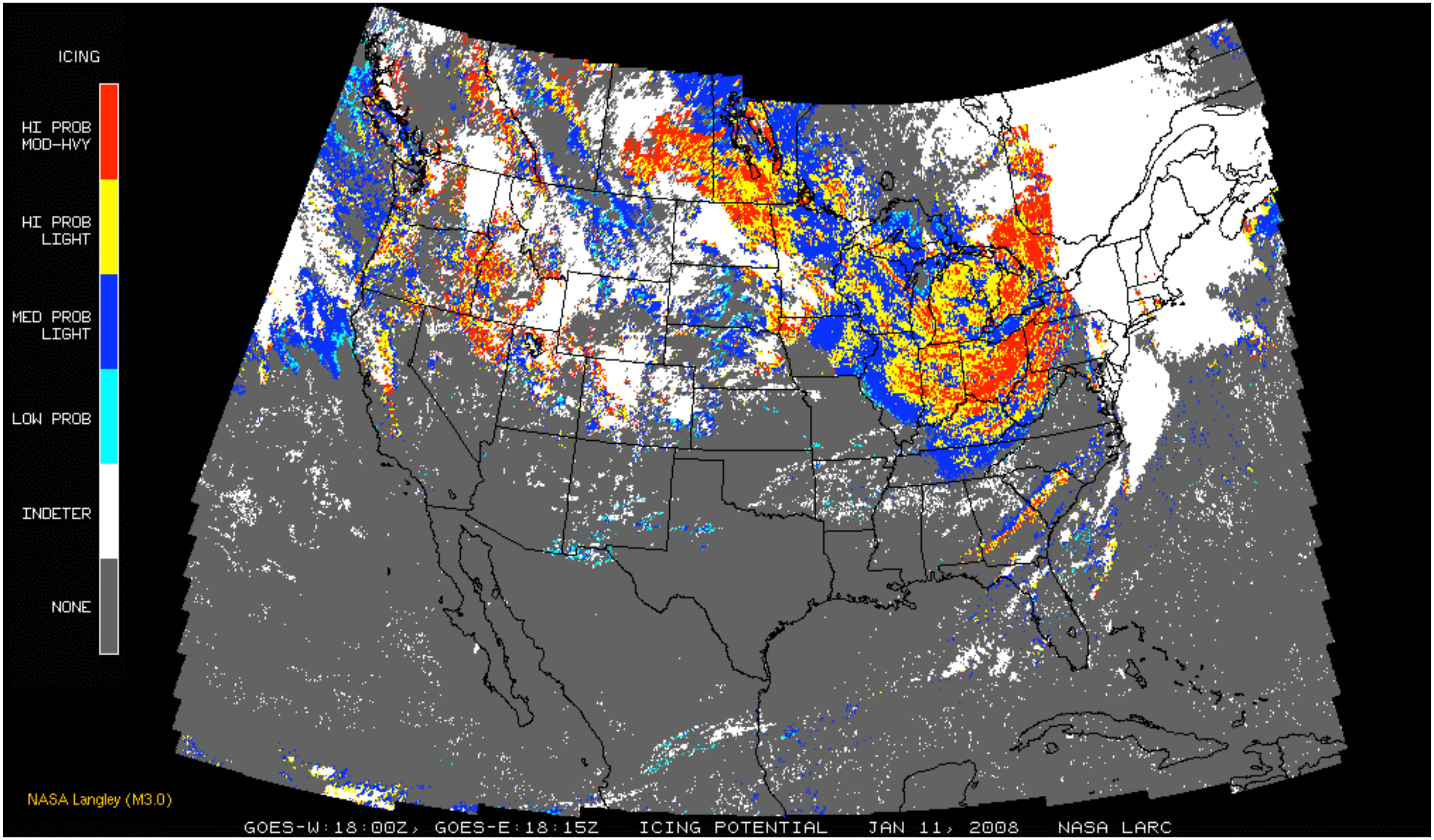


Major dependence on LWP, minor on r_e

Formulation developed for icing potential

Icing Potential from GOES Data Alone

1815 UTC, 8 Jan 2008



Many indeterminate areas (white)

Single-Layer Cloud Reflectance Model

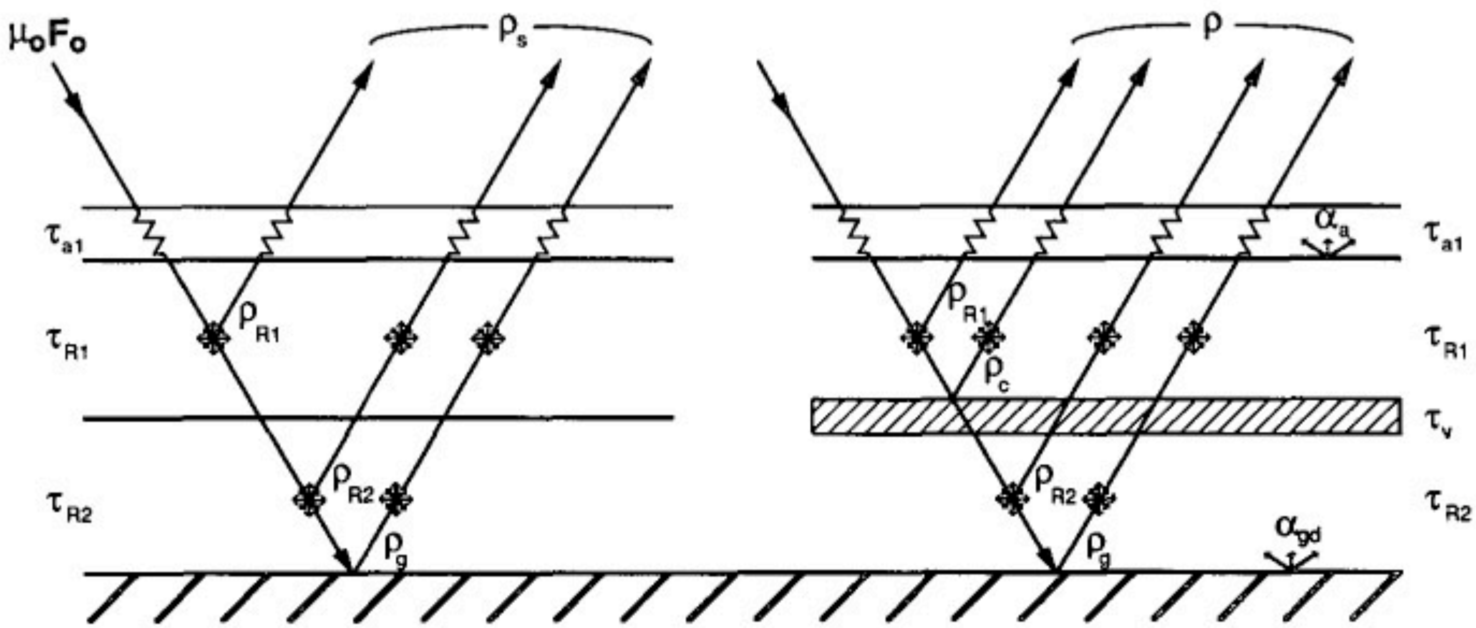


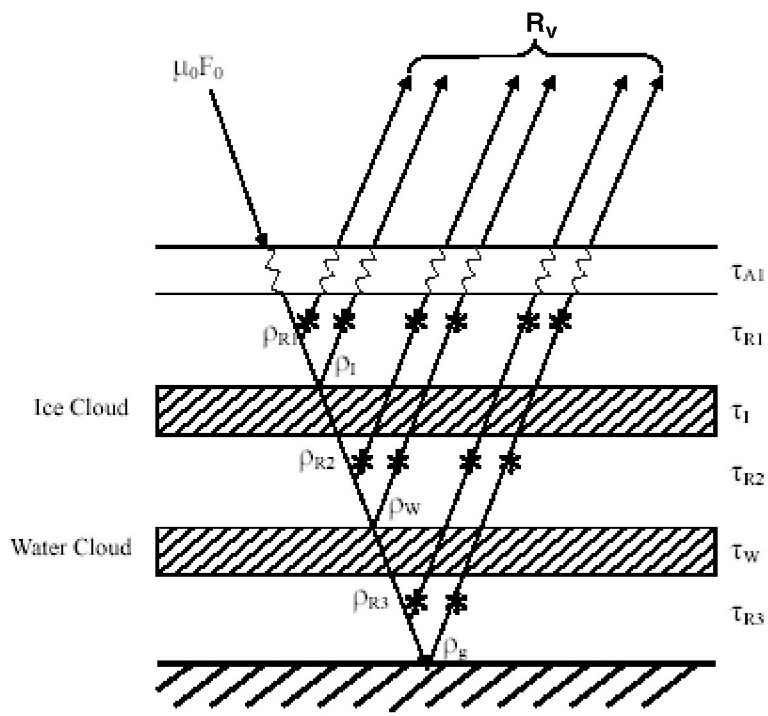
FIG. 3. Schematic diagram of scattering and absorption processes for a three-layer atmosphere with no clouds (left) and with one cloud layer (right).

Finding More Icing in Indeterminate Areas

Multilayer Cloud Detection & Retrieval

- Some indeterminate cloudy pixels are overlapped ice over water clouds
  - multilayered cloud detection needed to find those areas where icing is a problem
- Need a multilayered VISST to derive low cloud properties

Use AD model to develop LUTs for ice over water clouds



Minnis et al. JGR 2007

Multilayered Cloud Detection Using 11 & 13.3 µm Channels

- Use sounding to predict 11 & 13.3 BTs
- Use radiative transfer to obtain solution satisfying both channels by adjusting background temperature and upper layer cloud optical depth
    - OD(UL)
    - T(UL)
    - T(LL)
- Use UL cloud OD with 2-layer VISST to determine OD of LL
- If OD(LL) > 6 and T(LL) < 273 K => ML icing
- Only applies to GOES-12+ over CONUS

Determine the Upper-layer Cloud Temperature/Emissivity and Related Lower-layer Temperature Using 11-μm & 13.3-μm Radiances

- **Methodology - Determine $T_{11\text{-Upper}}$ and $\varepsilon_{11\text{-Upper}}$ using the measurements of R_{11} and R_{13} :**

$$R_{11} = \varepsilon_{11-\text{Upper}} B(T_{11-\text{Upper}}) + (1 - \varepsilon_{11-\text{Upper}}) B(T_{11-\text{Lower}})$$
$$R_{13} = \varepsilon_{13-\text{Upper}} B(T_{13-\text{Upper}}) + (1 - \varepsilon_{13-\text{Upper}}) B(T_{13-\text{Lower}})$$

- **The pairs of $T_{11\text{-Upper}}$ & $T_{13\text{-Upper}}$, $T_{11\text{-Lower}}$ & $T_{13\text{-Lower}}$, and $\varepsilon_{11\text{-Upper}}$ & $\varepsilon_{13\text{-Upper}}$, respectively, are related through radiative model calculations.**

- **$B(T_{11\text{-Lower}})$ is related to R_{11} , $T_{11\text{-Upper}}$, and $\varepsilon_{11\text{-Upper}}$.**

- **$B(T_{11\text{-Lower}})$ and $B(T_{13\text{-Lower}})$ are assumed blackbody calculations, which represent from a lower layer or the background surface.**

Determine Whether Is a Single-layer or a Multi-layer Cloud Pixel

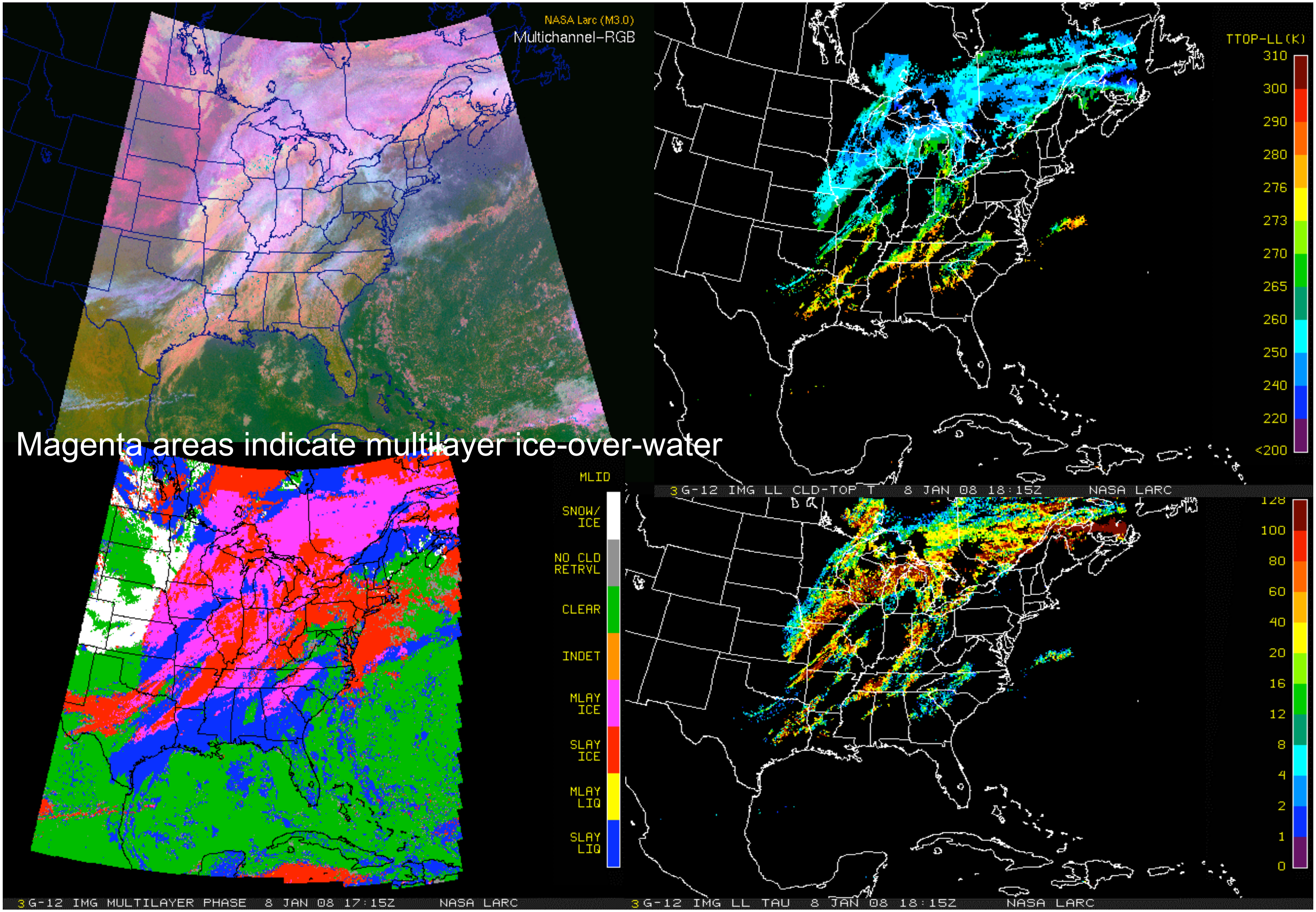
- **Convert $\varepsilon_{11\text{-Upper}}$ to $\tau_{11\text{-Upper}}$**

- **Convert $\tau_{11\text{-Upper}}$ to $\tau_{Visble\text{-}Upper}$**

- **Multi-layer – if $\varepsilon_{11\text{-Upper}} < 0.5$ and $\tau_{VISST} > \tau_{vis\text{-}Upper} + \sigma_{Err}$**

  Single-layer – otherwise

Multi-layered Cloud Detection, 13.3/10.8 µm, 1815 UTC, 8 Jan 2008



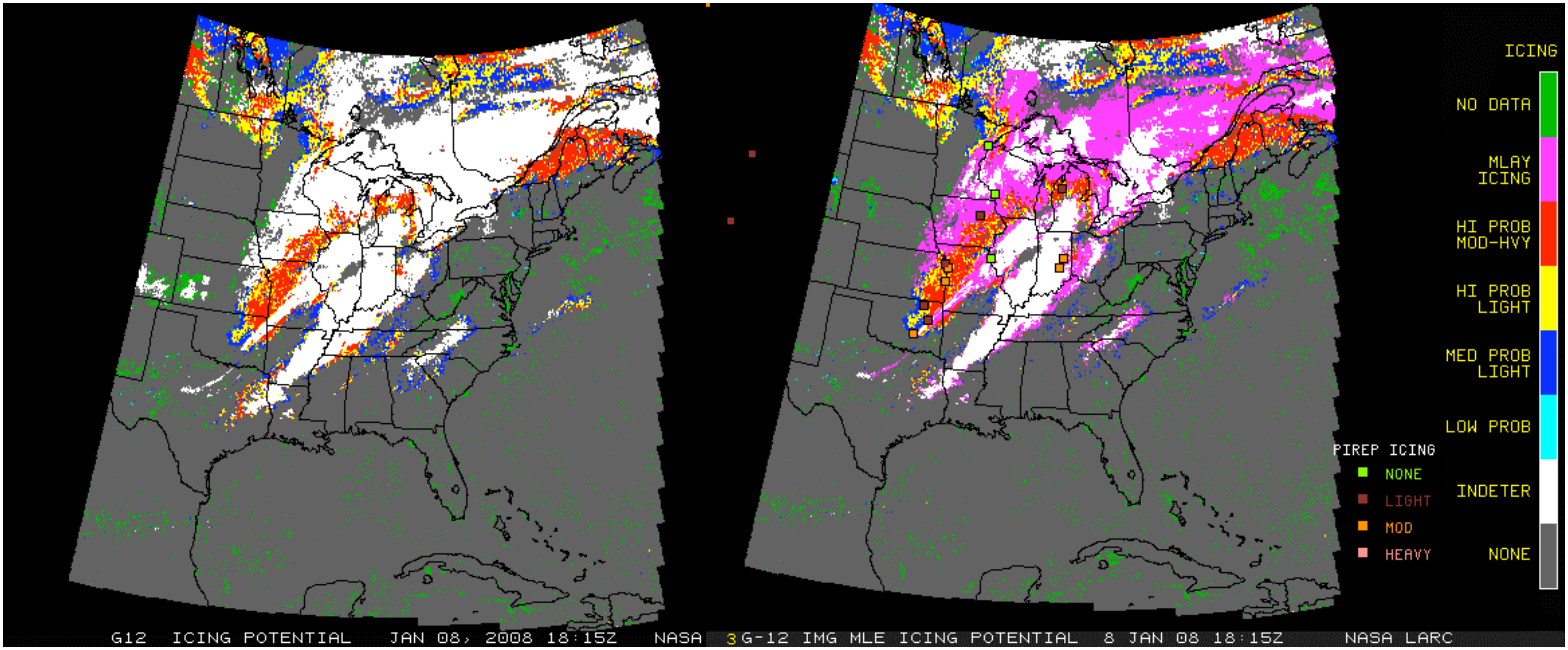
Magenta areas indicate multilayer ice-over-water

Multi-layered Low Cloud Retrieval, ML VISST

1815 UTC 8 Jan 2008

Icing Potential, Single Layer

Icing Potential w/multilayer



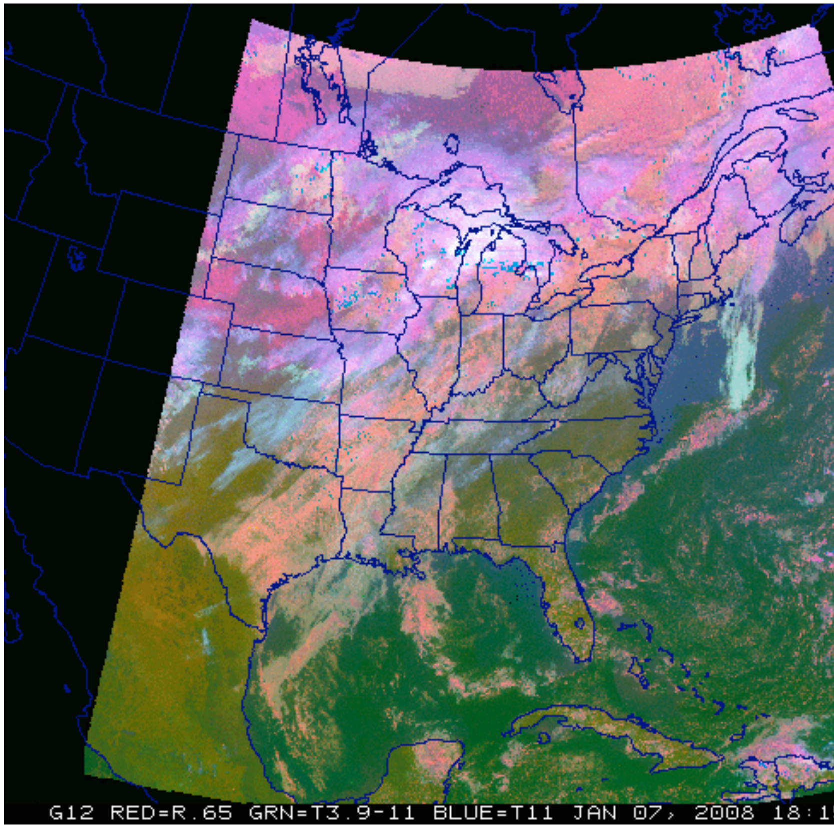
Large increase in number of med-hi probability of icing

picks up new matches with PIREPS

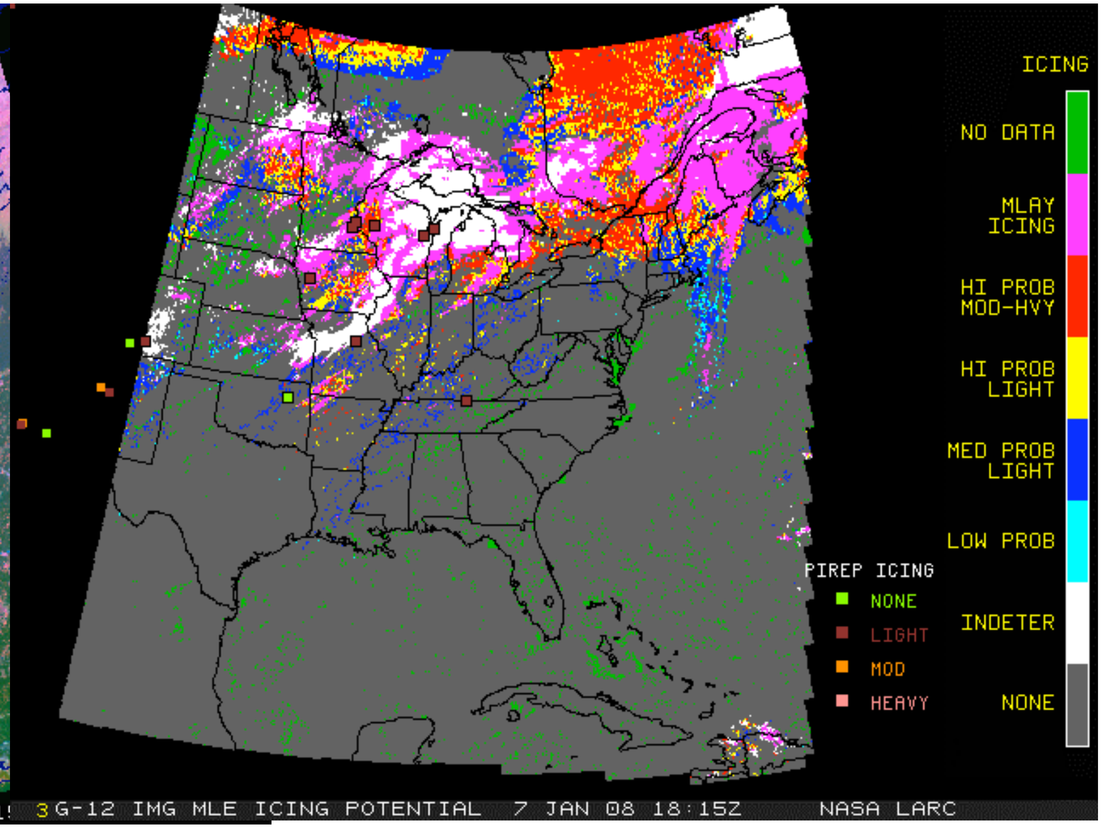
Icing Potential

1815 UTC, 7 Jan 2008

RGB



Standard retrievals + ML results



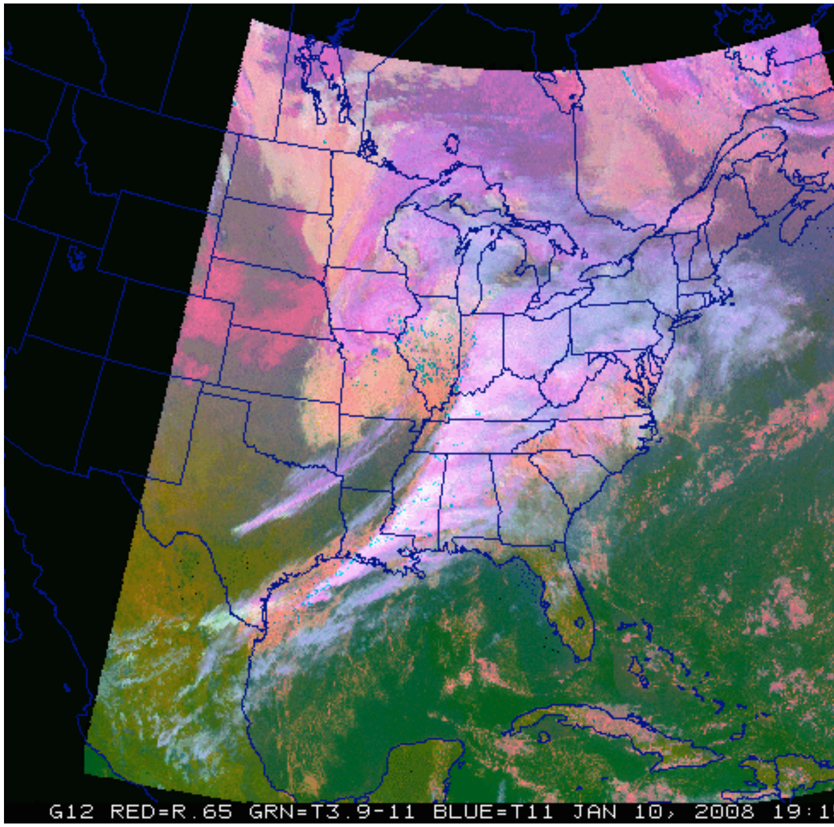
Multilayer retrievals pick up additional areas with icing that were formerly indeterminate

… some areas remain undetected

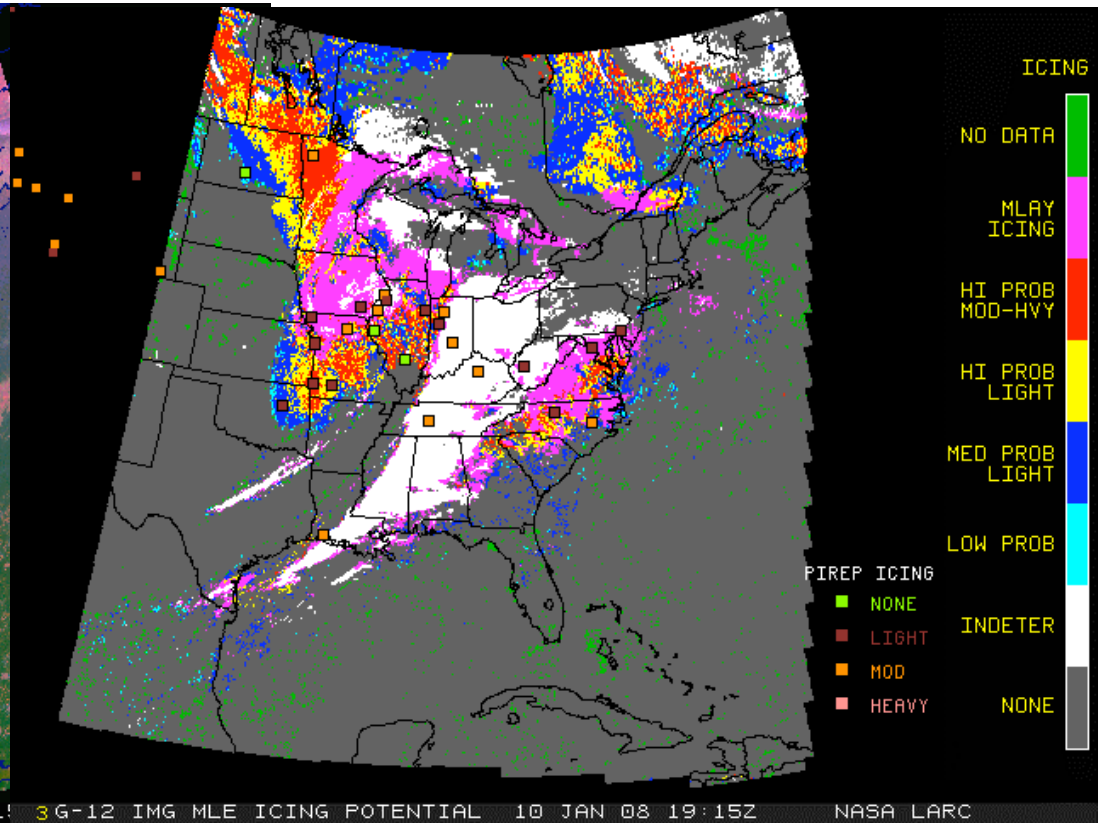
Icing Potential

1915 UTC 10 Jan 2008

RGB



Standard retrievals + ML results



Multilayer retrievals pick up additional areas with icing that were formerly indeterminate

… some areas remain undetected

Summary of PIREPS Comparisons

GOES-12, Jan 1-14, 2008, hourly images from 15-19 UTC

```
  ICING-Non ML                                       ICING-ML enhanced
        PIREP                                              PIREP
---------------------------------          --------------------------------------
S          YES         NO                   S          YES         NO
A   YES   195         32                    A   YES   253         40
T    NO   22          5                    T    NO    24          6
------------------------------              --------------------------------------
pody=yy/(yy+ny)=PODy=89.9%                    PODy = 91.3%
podn=nn/(yn+nn)=PODn=13.5%                    PODn = 13.0%
Ntot=254                                       Ntot=323
Indeterminate GOES icing excluded
```

- Identifies icing ~ 90% of the time
- Multilayer method as accurate as single-layer technique

PIREPS vs GOES icing detection returns: frequency of occurrence

GOES (G) PIREPS (P)

Single-Layer

Icing (G), Icing (P):	50.0%
No Icing (G), No Icing: (P)	1.3%
Indeterminate (G), No Icing (P):	3.9%
Indeterminate (G), Icing (P):	31.0%
No Icing (G), Icing (P):	5.6%
Icing (G), No Icing (P):	8.2%

Multi-layer enhanced

Icing (G), Icing (P):	64.9%
No Icing (G), No Icing: (P)	1.5%
Indeterminate (G), No Icing (P):	1.5%
Indeterminate (G), Icing (P):	15.6%
No Icing (G), Icing (P):	6.2%
Icing (G), No Icing (P):	10.3%

Total number of compared events: 390

- Increases area of knowledge
  - 22% more cloudy area included in base
- Cuts indeterminate area by half

Summary & Future Research

• New method developed to identify thin-ice-over-water cloud pixels and retrieve the properties using 0.65, 3.9, 10.8, & 13.3 µm channels

- applicable to GOES-12+, SEVIRI, MODIS, VIIRS
- potential nocturnal application

• New multilayer method appears to enhance detection of icing conditions

- application to weather and nowcasting problems
- can be used in CIP & other model applications (e.g., RUC)
- accuracy as good as single-layer method

• Future

- tune method for NY-YN cases
- examine nighttime capabilities & limitations
- determine other applications