Satellite Remote Sensing of Liquid Water in Cold Clouds for CAM Validation

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Figure 3. PDF of ice mass fraction as a function of temperature for the ICE case (black filled contours). Model output is from 1000–100hPa and 90°S–90°N. In situ observations from Field et al. [2005] shown for ice (diamond) and liquid (asterisk) dominated conditions. Contours are logarithmic, 3 per decade (1,2,5).
Figure 14. Comparison of fraction of ice, mixed- and liquid-clouds from the present and previous studies. Note that the left-hand and right-hand y-axes are in opposing senses. Lines labelled 1 and 2 should be referred to the left-hand axis and all other curves to the right-hand axis.
1. Use the $12/11 \mu m$ absorption optical depth ratio, $\beta$, to estimate the % LW.

2. $\beta$ is quasi-constant for all-ice clouds but increases with a growing presence of a liquid phase.

3. The mean LW fraction can be estimated from the mean departure of $\beta$ from its ice threshold value.
Maximum Estimate of $\beta_{\text{eff}}$ vs. Cloud Temperature
From Giraud et al., 1997 J. Applied Meteorology

$\beta_{\text{eff}} \approx 1.12$
0.63 0.86 11.02 um Color composite  1900 UTC 05 Aug 07
Cirrus-only over-ocean pixels
TC4 5 August 2007
$\varepsilon_{11 \mu m} < 0.7$
$T < -20^\circ C$
TC4 22 July 2007

$\varepsilon_{1\mu m} < 0.7$

$T < -20^\circ C$

$\beta_{\text{eff}}$

Mid-cloud temperature (°K)
Procedure:

1. Use tropical anvil PSD scheme for ice portion & a representative mean diameter & dispersion param. for liquid portion of PSD.

2. Increase LW in droplet PSD until observed and predicted $\beta_{\text{eff}}$ match.
   - Account for changes in $n_r/ n_i$

Evaluate Uncertainties:

1. Mean droplet size
2. Mean ice particle size
3. m-D power laws for ice
4. Dispersion param. for ice PSD
% LW is sensitive to mean droplet size, but range of $\beta$ restricts the possibilities.
Dispersion of $\beta$ at warmer temperatures appears similar to frequency distribution of cloud ice fraction from Korolev et al. (2003, QJRMS).

Frequency vs. ice fraction of cloud for different temperature intervals; From Korolev et al. 2003, QJRMS.
Figure 3. PDF of ice mass fraction as a function of temperature for the ICE case (black filled contours). Model output is from 1000–100hPa and 90°S–90°N. In situ observations from Field et al. [2005] shown for ice (diamond) and liquid (asterisk) dominated conditions. Contours are logarithmic, 3 per decade (1,2,5).
Mean droplet diameter = 10 μm
5 August Case Study Results

TC4 5 August 2007
$e_{11\mu m} < 0.7$
$T < -20^\circ C$

Mean droplet diameter = 10 $\mu m$
Sensitivity of $D_e$ to % Liquid Water

TC4 5 August 2007
$\varepsilon_{1\mu m} < 0.7$
$T < -20^\circ C$

Mean Values
Standard Deviations

$D_e$ ($\mu m$)

Mid-cloud temperature ($^\circ C$)

6% LW
14% LW
85% LW
Summary

1. The 12/11 μm absorption optical depth ratio ($\beta$) exhibits quasi-constant behavior for ice clouds but is sensitive to the presence of a liquid phase, making it a possible metric for estimating the liquid water fraction for LW < 50%.

2. The increase in $\beta$ can be interpreted using a microphysics/optical property algorithm that attributes liquid water to the small mode of a bimodal PSD.

3. The retrieval of %LW is sensitive to the mean droplet diameter, but the dispersion of $\beta$ might help define this value.

4. Retrieval algorithm was tested on 2 case studies filtered to select single-layer cirrus clouds. For -35 °C < T < 20 °C, LW levels up to 14% were detected which greatly affect the overall $D_e$ and optical properties.

5. Variability of LW fraction appears consistent with aircraft measurements and CAM4 predictions.
Effective diameter ($D_{\text{eff}}$) in microns

Temperature in C

TC4 field project

- $b[0] = 157.8297129888$
- $b[1] = 1.5804748997$
- $r^2 = 0.7118906543$
TC4 field project

Ice Water Content (IWC) in mg/m³

Effective diameter ($D_{\text{eff}}$) in microns

IWC-aged v $D_{\text{eff1}}$
IWC-anvil v $D_{\text{eff2}}$
IWC-insitu v $D_{\text{eff3}}$

Plot 1 Regr

$b[0] = 56.6512804656$
$b[1] = 19.8669796787$
$r^2 = 0.4836738339$
TC4 field project

Temperature in C

Fall velocity (cm/s)

T-aged v Fall velocity ($V_t$)
T-anvil v Fall Velocity ($V_t$)
T-insitu v Fall Velocity ($V_t$)

Plot 1 Regr

\[ b[0] = 100.269279103 \]
\[ b[1] = 1.0453354674 \]
\[ r^2 = 0.490196375 \]
TC4 field project

Ice water content (g/cm³)

Fall velocity (cm/s)

- IWC-aged v $V_f$
- IWC-anvil v $V_f$
- IWC-insitu v $V_f$

Plot 1 Regr

$b[0] = 179.1744629541$

$b[1] = 16.9103765546$

$r^2 = 0.5515896312$
TC4 22 July 2007
TC4 5 Aug. 2007
TWP-ICE 2 Feb. 2006

$-73 < T < -35^\circ C$

$\beta_{\text{eff}}$

Emissivity at 11 $\mu$m
Calculation of $\varepsilon_{\text{eff}}$ in Retrieval Algorithm

- Based on Parol et al. (1991, JAM) -

Since some scattering may occur, $\varepsilon$ retrieved in this way is an effective emissivity, $\varepsilon_{\text{eff}}$, which implicitly includes the effects of scattering through its dependence on asymmetry parameter $g$:

$$
\varepsilon_{\text{eff}}(12 \, \mu\text{m}) = 1 - \left[ 1 - \varepsilon_{\text{eff}}(11 \, \mu\text{m}) \right]^{\beta_{\text{eff}}}
$$

$$
\beta_{\text{eff}} = \frac{Q_{\text{abs,eff}}(12 \, \mu\text{m})}{Q_{\text{abs,eff}}(11 \, \mu\text{m})}
$$

$$
Q_{\text{abs,eff}} = \frac{Q_{\text{abs}} (1 - \omega_0 g)}{(1 - \omega_0)}
$$

When $g \rightarrow 1$, all scattering is completely forward scattering and radiation is not redistributed.
Wavelength dependence of tunneling

\[ Q_{\text{abs}} = 1 - \exp\left(-4\pi n_i d_e / \lambda\right) \]

Refractive Index & \(Q_{\text{abs,ADT}}\)

- \(n_r\) increasing
- 25 \(\mu m\)
- 10 \(\mu m\)
- Ice
- Water

Wavelength (\(\mu m\))