Microphysical Properties of Single and Mixed-Phase Arctic Clouds Derived From Ground-Based AERI Observations

Dave Turner

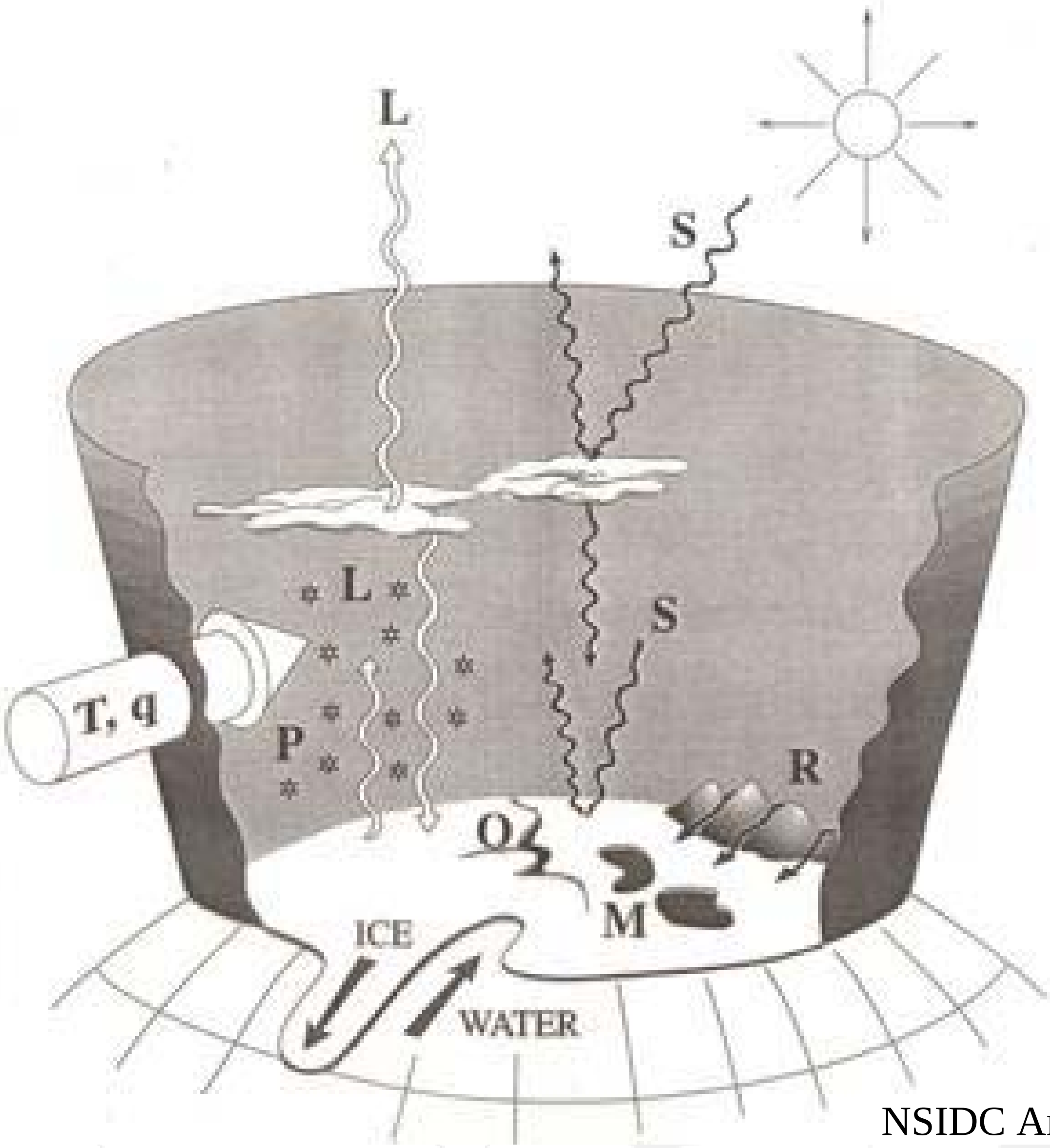
University of Wisconsin-Madison

Pacific Northwest National Laboratory

8 May 2003

Sounding from High Spectral Resolution Infrared Observations Workshop
Madison, Wisconsin

The Arctic Energy Budget



S = Shortwave radiation
L = Longwave radiation
T = Temperature (heat) advection
q = Moisture advection
P = Precipitation
O = Ocean heat (sensible and latent, from leads, etc)
M = Melt (snow and ice)
R = Runoff (freshwater)
Ice = Net ice production and export
Water = Influx of relatively warm water into Arctic Ocean

To first order, the outgoing longwave cooling balances the advection of heat into the Arctic (over an annual cycle).

Figure by N. Untersteiner
NSIDC Arctic Climatology and Meteorology Primer

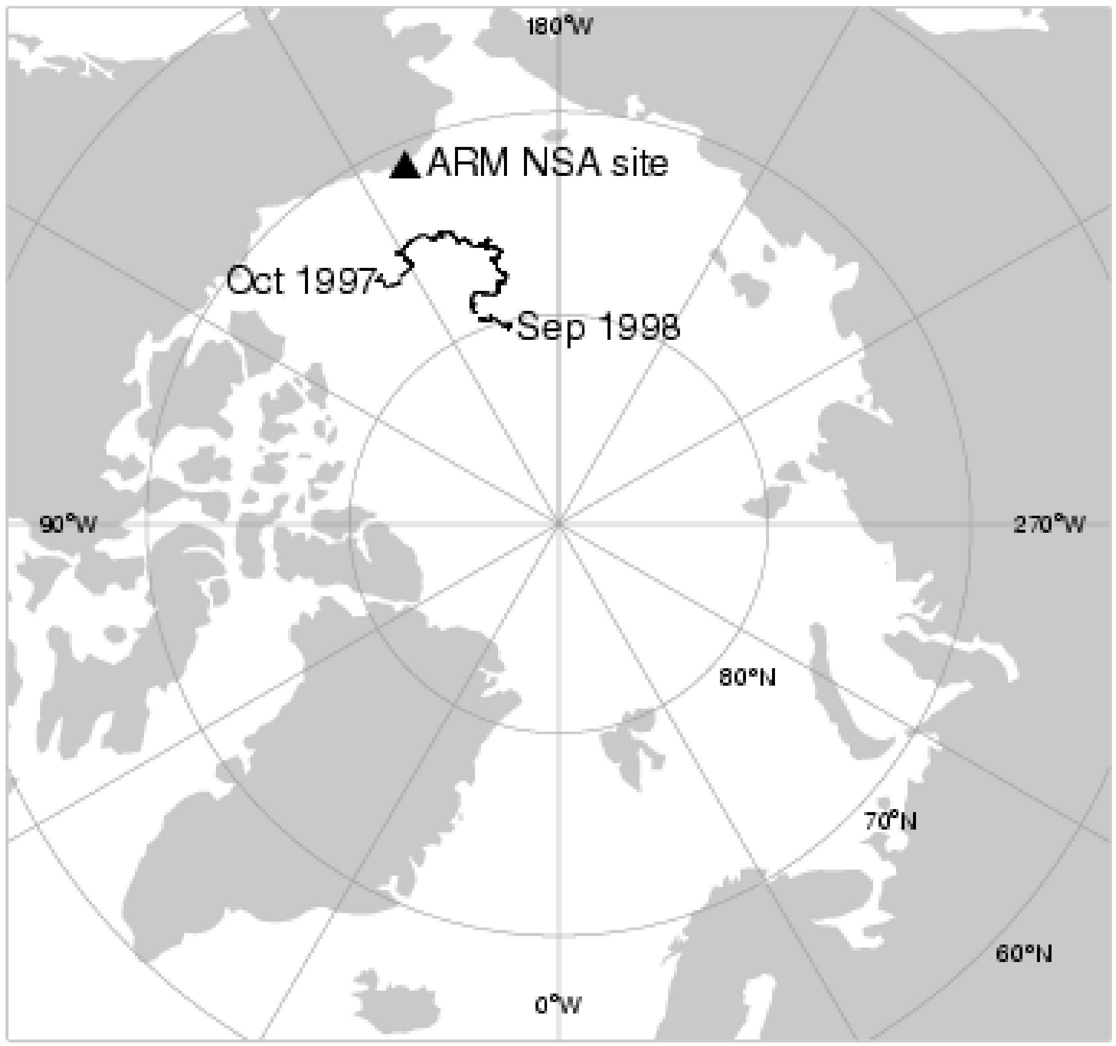
Statement of the Problem

- The magnitudes of the cloud-radiation feedbacks in simulations of the Arctic climate are very uncertain. Long-term (i.e., multi-season) observations are critical to reducing these uncertainties.
- There are relatively few direct observations of cloud structure in the Arctic

  For example, there are **NO** in-situ winter observations of Arctic cloud microphysics

- The remote sensing data collected at the ARM NSA site and at SHEBA are important data sets that can help fill this void
- However, the ARM North Slope of Alaska (NSA) site has no active, polarization sensitive instrument (lidar or radar)!

SHEBA's path and the ARM NSA site



Objectives

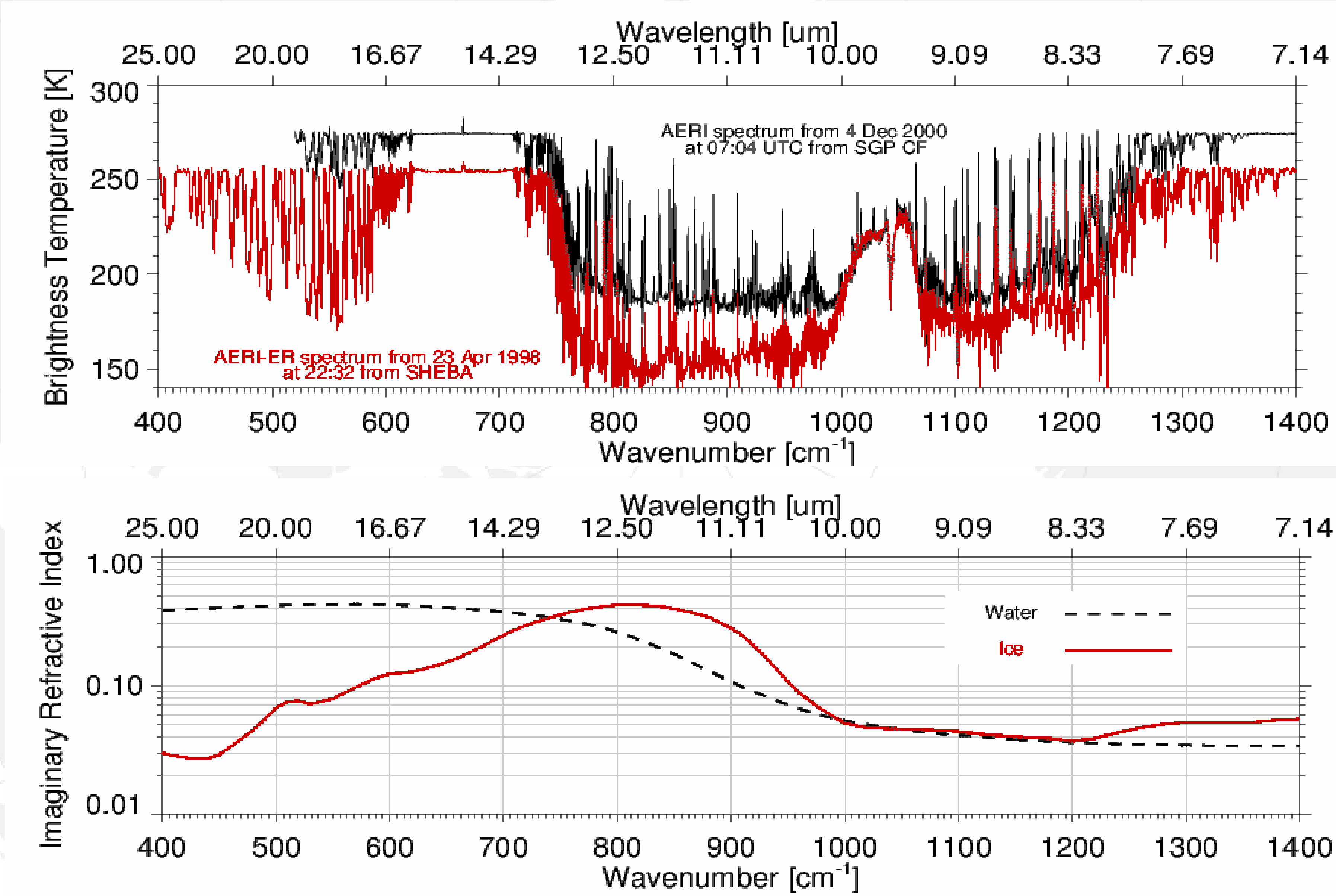
- Determine if cloud phase can be unambiguously determined from high-spectral resolution ground-based radiance measurements (i.e., from AERI obs)
- Develop retrieval algorithms that utilize these observations to retrieve microphysical cloud properties such as cloud phase, total water content, ice fraction, and effective particle size.
- Compile monthly and seasonal statistics on cloud properties derived from these observations in the SHEBA and ARM NSA sites to evaluate current cloud-radiation feedback mechanisms and suggest possible improvements to them

Atmospheric Emitted Radiance Interferometer (AERI-ER)

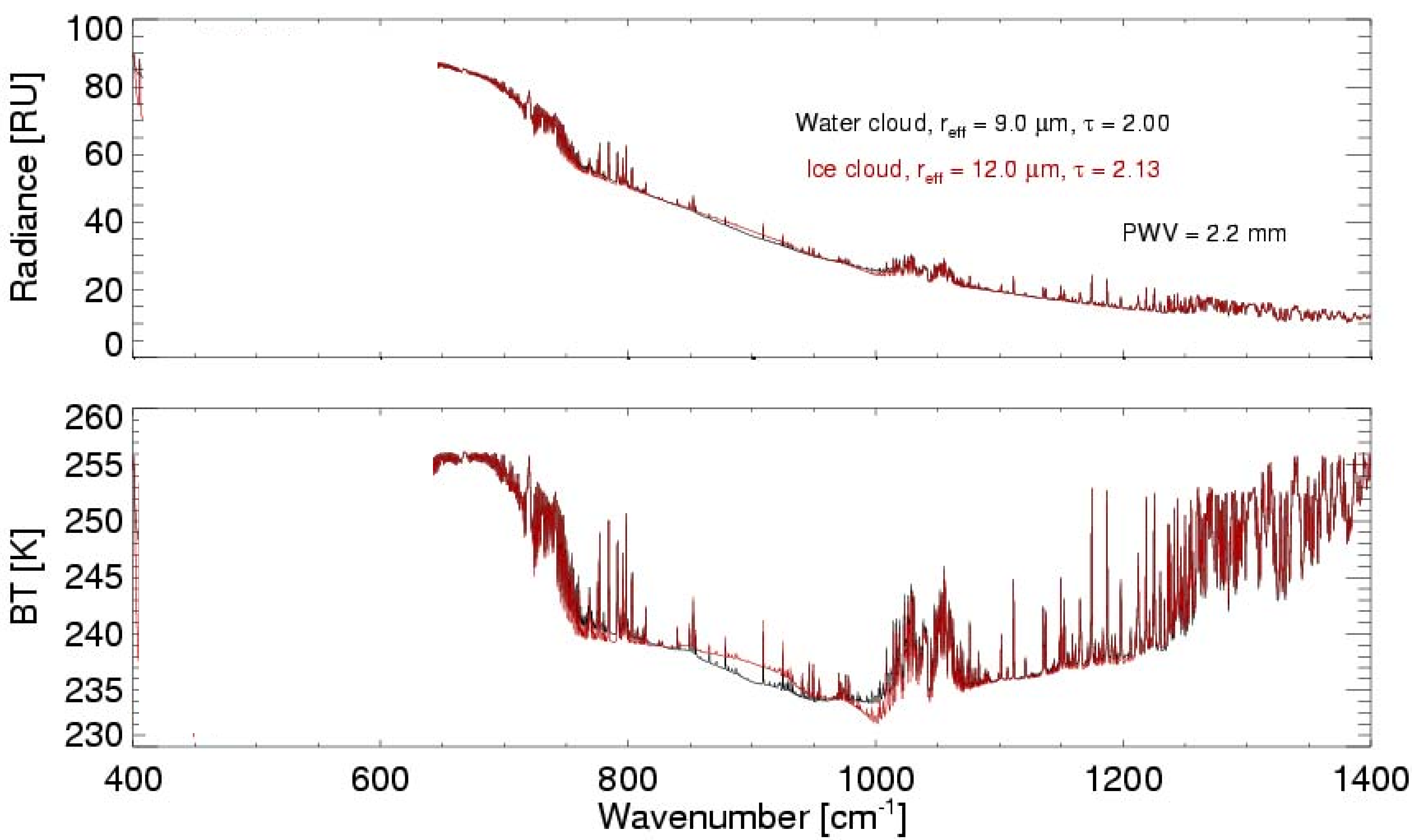
- Designed and manufactured by SSEC/UW-Madison
- Measures downwelling radiance from 3.3 - 25 μm with ~1 wavenumber resolution

Absolute calibration accuracy of better than 1% of the ambient radiance

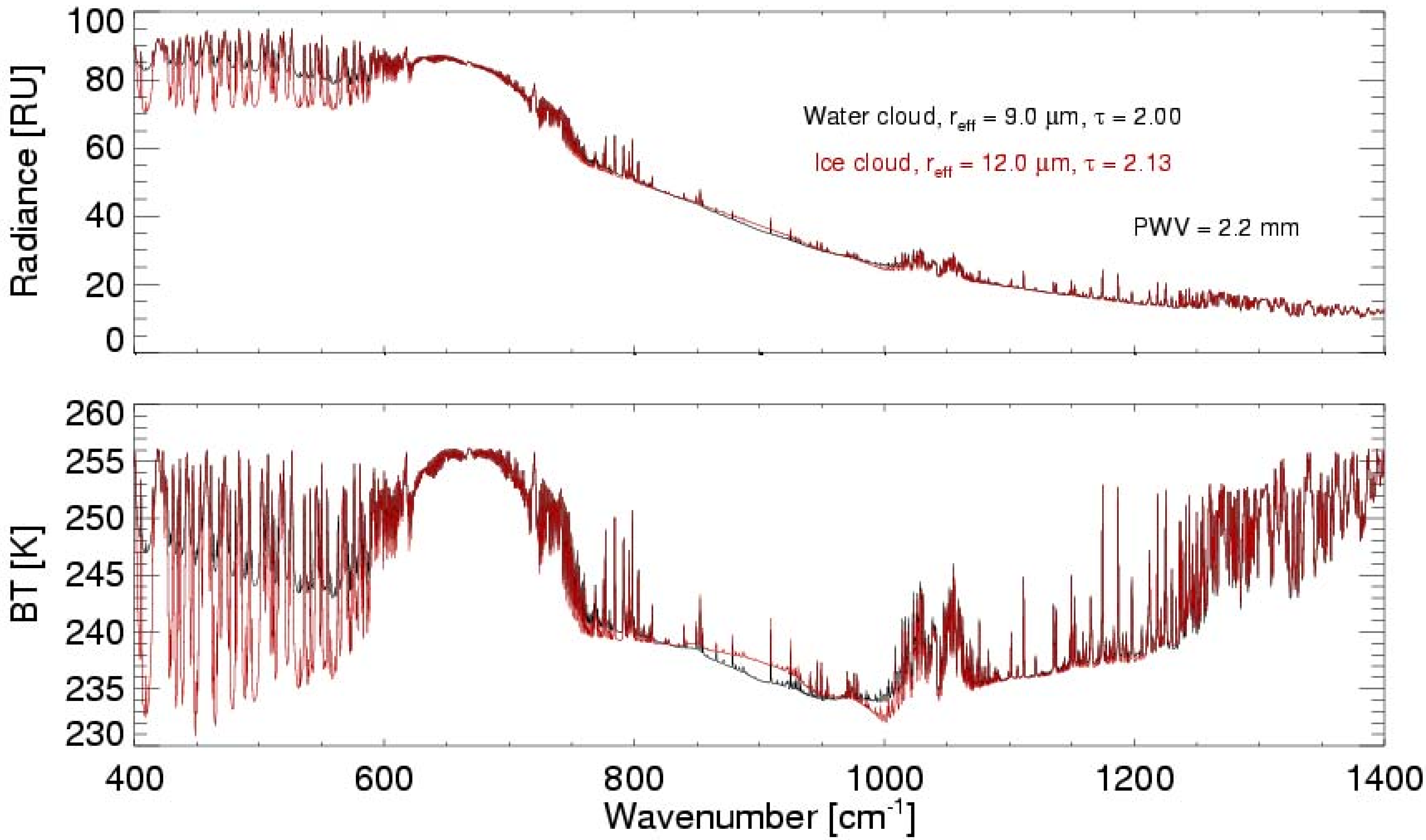
Phase Determination in the Infrared



Importance of 16-25 μm data



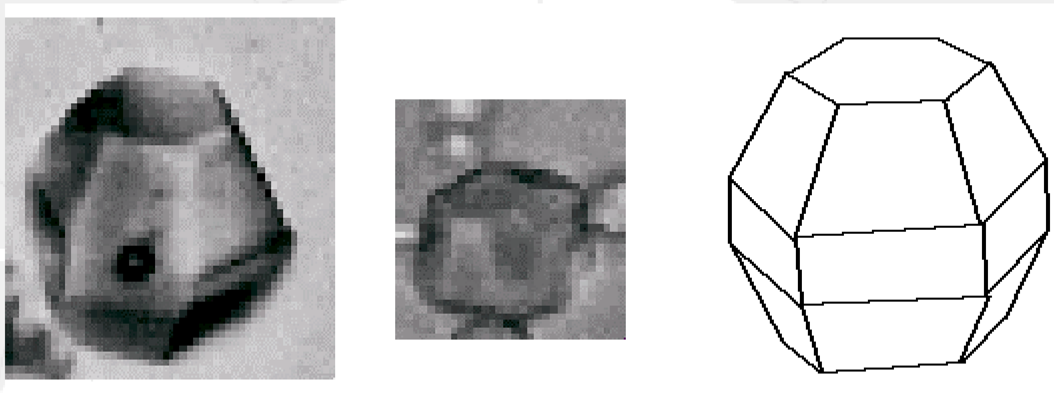
Importance of 16-25 μm data



Forward Model

- Gaseous optical depths computed with Line-by-line radiative transfer model (LBLRTM)
  - Uses latest spectroscopic line database (HITRAN 2000)
  - Uses latest water vapor continuum model (CKD 2.4)
- Discrete Ordinates Radiative Transfer (DISORT) used for the cloudy sky radiative transfer
  - Single scattering properties for water droplets computed from Mie code (MIEV0 from Warren Wiscombe)
  - Ice crystals treated as hexagonal columns, droxtals, and/or spheres. Single scattering properties of non-spherical crystals computed by FDTD and IGOM methods by Ping Yang
  - Single scattering properties for mixed-phase clouds computed by linearly combining in optical depth the single scattering properties of liquid and ice clouds (Sun and Shine 1995)

Droxtals



- First imaged by T. Ohtake in an ice fog (JAS 1972)
- Droxtals are being used to model the crystals at the top of cold cirrus layers where the particles are small and semi-spherical (Yang, Baum, others…)
- CPI images of ice crystals in Arctic cirrus and mixed-phase clouds show large numbers of small "spheroids" (Lawson et al. 2001)

Single Scattering Properties for Mixed-Phase Clouds

Optical depth $\tau_m = \tau_i + \tau_w$

Single scatter albedo $\omega_{0,m} = \left(\tau_i \omega_{0,i} + \tau_w \omega_{0,w}\right) / \tau_m$

Asymmetry parameter $g_m = \left(\tau_i \omega_{0,i} g_i + \tau_w \omega_{0,w} g_w\right) / \left(\tau_m \omega_{0,m}\right)$

Scattering phase function $p_m = \left(\tau_i \omega_{0,i} p_i + \tau_w \omega_{0,w} p_w\right) / \left(\tau_m \omega_{0,m}\right)$

Following Sun and Shine 1995

Computing Cloud Emissivity

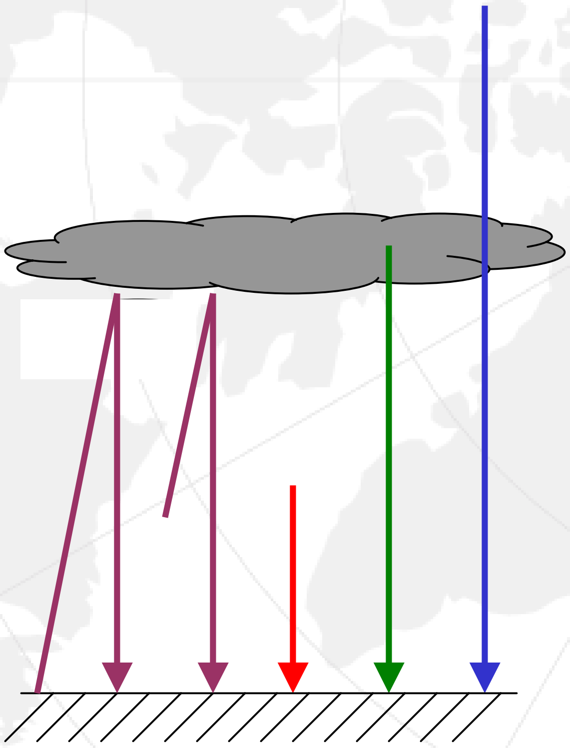
Assuming that the cloud is infinitesimally thin

$$R^{\downarrow} = \int_{p_s}^{p_c} B(T(p)) \frac{d\Im}{d \ln p} d \ln p \; +$$

$$\Im_{p_c}^{p_s} \varepsilon_c B(T_c) \; +$$

$$(1 - \varepsilon_c - r_c) \int_{p_c}^{0} B(T(p)) \frac{d\Im}{d \ln p} d \ln p \; +$$

$$r_c \Im_{p_c}^{p_s} \left[B(T_s) \varepsilon_s \Im_{p_s}^{p_c} + \int_{p_c}^{p_s} B(T(p)) \frac{d\Im}{d \ln p} d \ln p \right]$$



With simplifying assumptions

$$\varepsilon_c = \frac{R^{\downarrow} - R_{clr}^{\downarrow} - r_c \left(\Im_{p_s}^{p_c} \right)^2 B(T_s) \varepsilon_s}{\Im_{p_c}^{p_s} B(T_c)}$$

Mechanics of the Physical Retrieval

(Optimal Estimation following Rodgers 2000)

$$\mathbf{X_{n+1}} = \mathbf{X_a} + \left\{\mathbf{S_a^{-1}} + \mathbf{K}^T\mathbf{S_m^{-1}}\mathbf{K}\right\}^{-1} *$$

$$\left\{\mathbf{K}^T\mathbf{S_m^{-1}}\left(\mathbf{Y}_{obs} - F\left(\mathbf{X_n}\right) + \mathbf{K}\left(\mathbf{X_n} - \mathbf{X_a}\right)\right)\right\}$$

X is the state variable vector; i.e., $\mathbf{X} = [\tau, f_i, r_{eff,w}, r_{eff,i}]^T$

Y is the measurement vector; i.e, the cloud emissivity spectrum

$\mathbf{S_m}$ is the covariance matrix of the observations

K is the Jacobian of the forward model *F*, i.e., $K_{ij} = \frac{\partial F_i}{\partial x_j}$

$\mathbf{X_a}$ is the *a priori*, with its covariance matrix $\mathbf{S_a}$

n is the iteration number

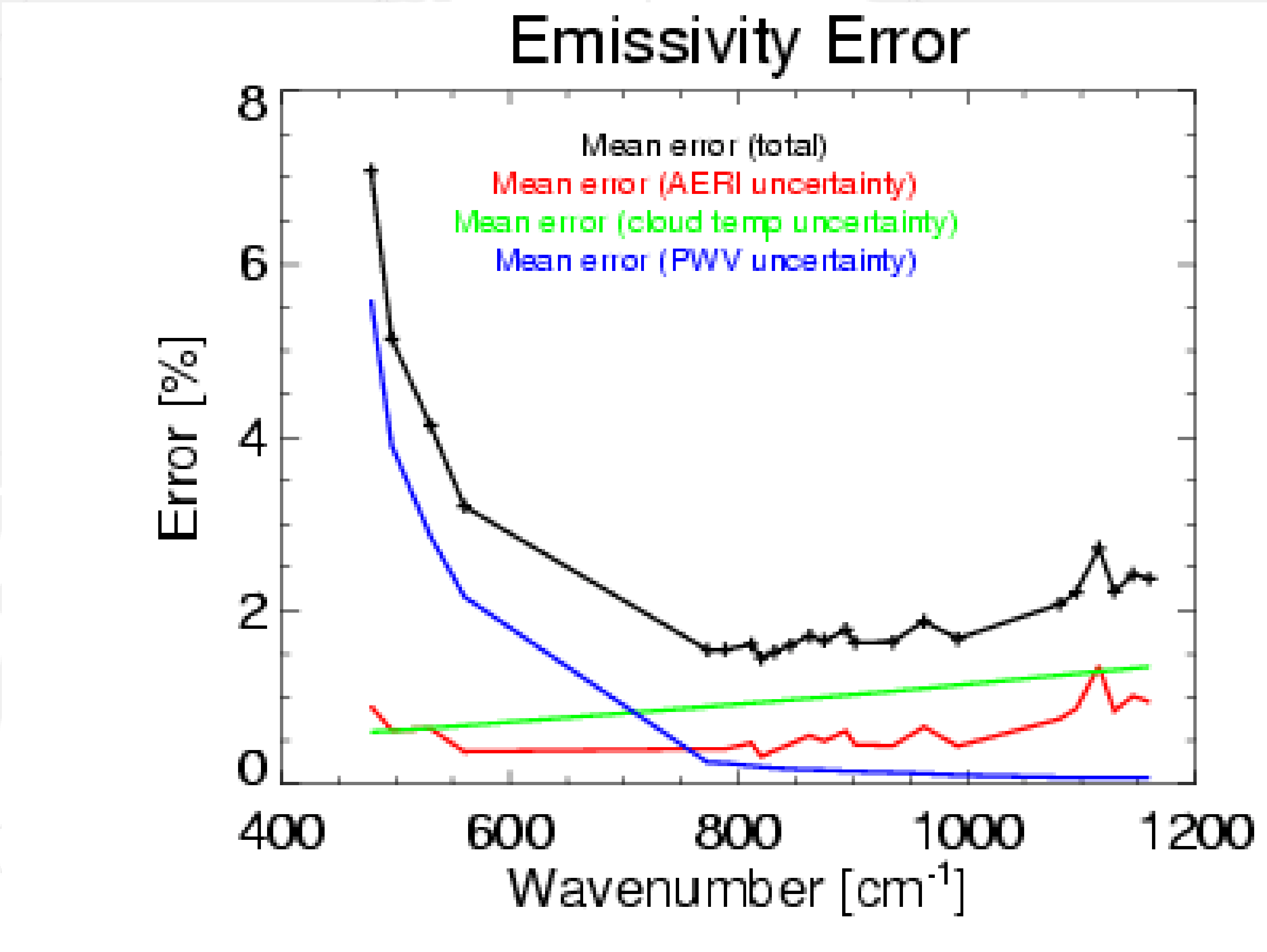
Note that the 1-σ errors of the retrieved quantities are given by $\varepsilon_\mathbf{X}$

$$\boldsymbol{\varepsilon}_x^T\boldsymbol{\varepsilon}_x = \left\{\mathbf{S_a^{-1}} + \mathbf{K}^T\mathbf{S}_m^{-1}\mathbf{K}\right\}^{-1}$$

Calculating the Observation Covariance Matrix S_m

- Observed variable is cloud emissivity
- Sources of uncertainty:
  - Clear sky radiance (primarily driven by PWV)
  - Cloud temperature
  - Instrument noise
  - Sky variance during sky dwell
- Instrument noise is only source that is assumed to be uncorrelated across the spectrum
- Difficult to determine the off-diagonal elements of the covariance matrix associated with the variance of the sky conditions during sky dwell, thus this isn't incorporated into $\mathbf{S_m}$ yet (captured as a flag)

Typical Errors in Cloud Emissivity

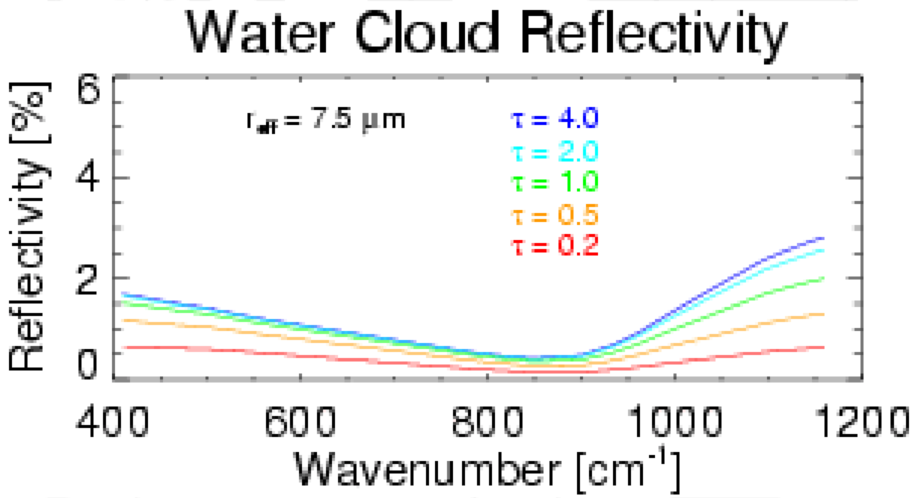


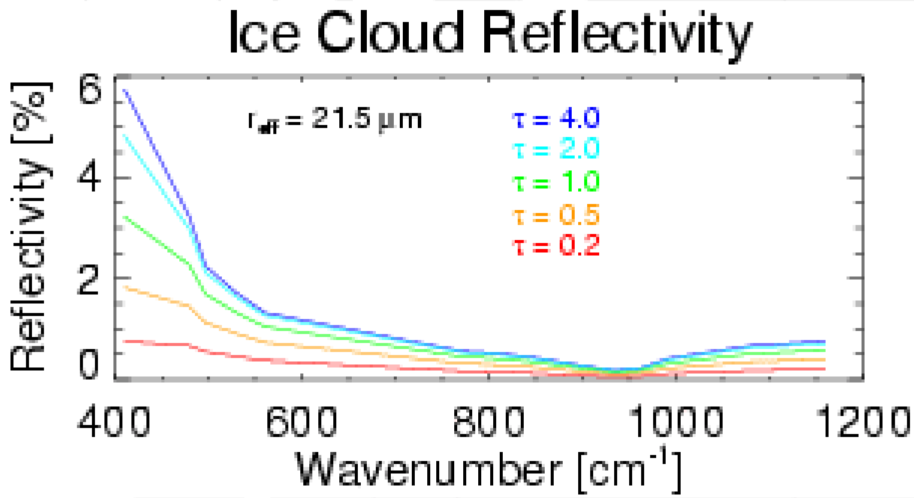
For a cloud with an IR optical depth of 1

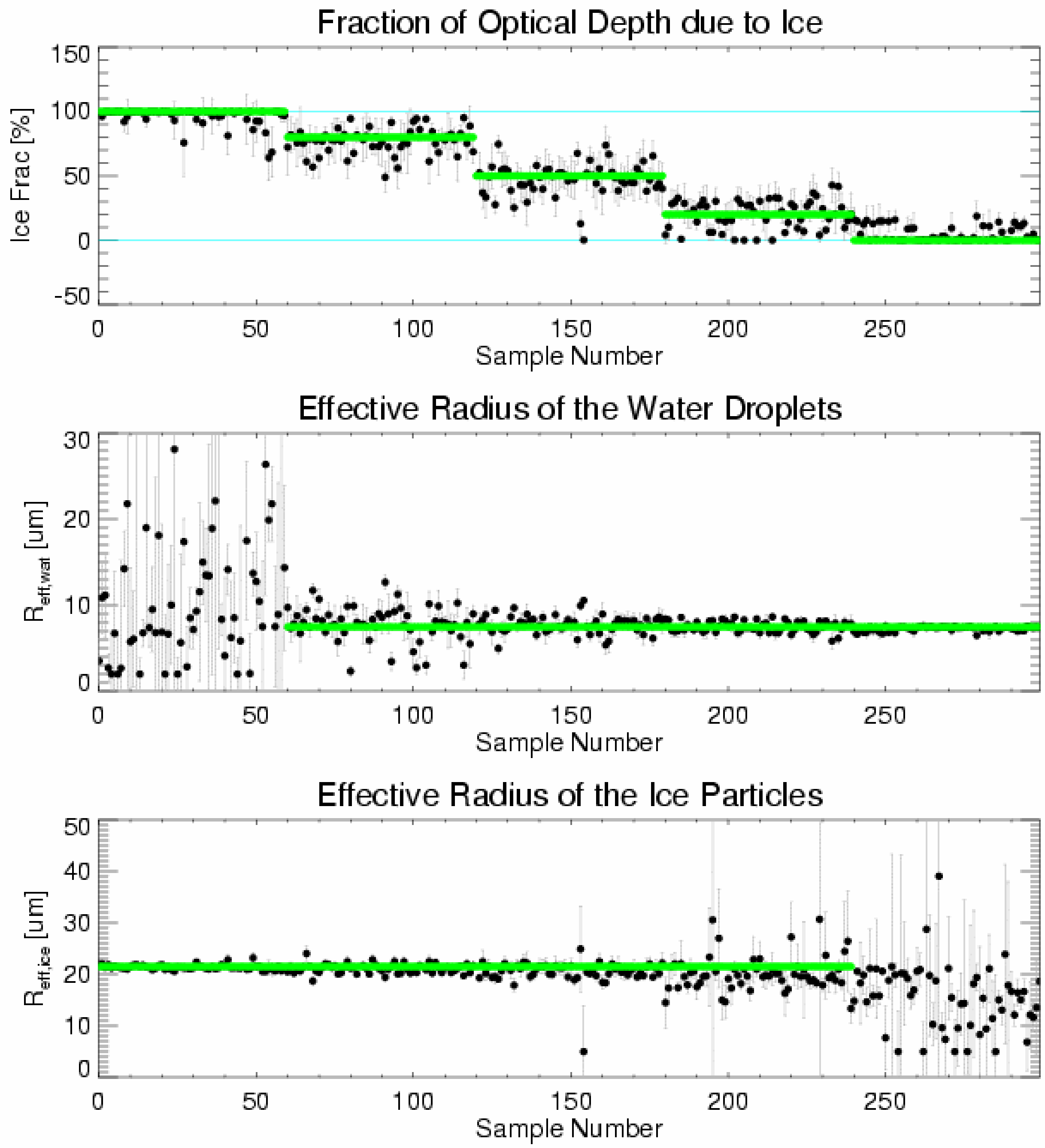
Computing Cloud Reflectivity

- Use cloud properties from current iteration
- Use forward model to compute downwelling radiance for two different surface temperatures

$$r_c = \frac{R_1^{\downarrow} - R_2^{\downarrow}}{\left(\Im_{p_c}^{p_s}\right)^2 \left(B(T_{s,1})\varepsilon_{s,1} - B(T_{s,2})\varepsilon_{s,2}\right)}$$



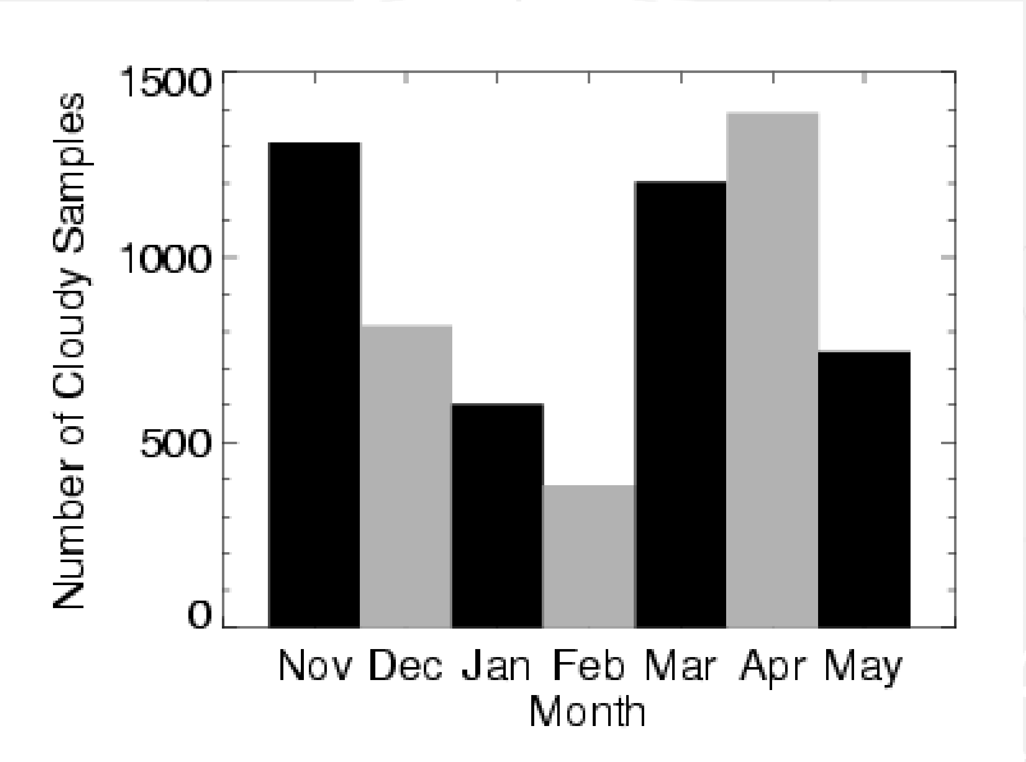




Example Simulation Results

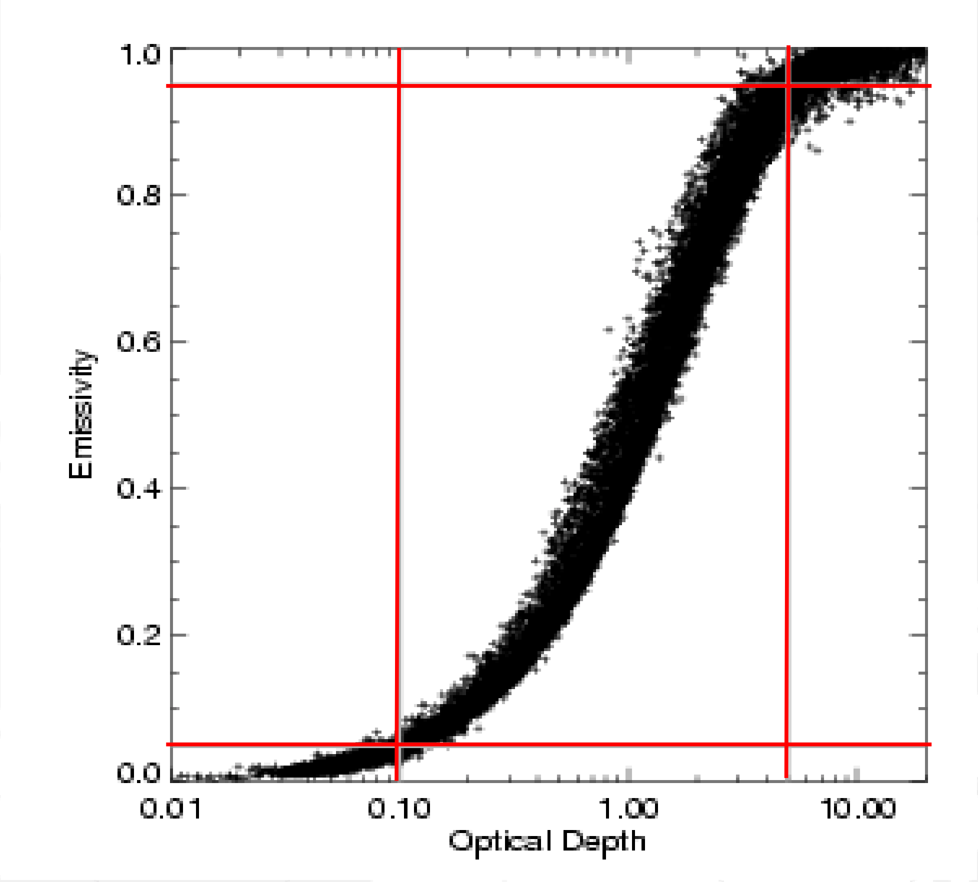
- Five different cases, 60 samples per case
- $\tau = 1.0$
- $r_{e,w} = 7.5\ \mu m$
- $r_{e,i} = 21.5\ \mu m$
- Ice fraction ranges from all ice to all water
- Green lines are truth

Number of Retrievals During SHEBA



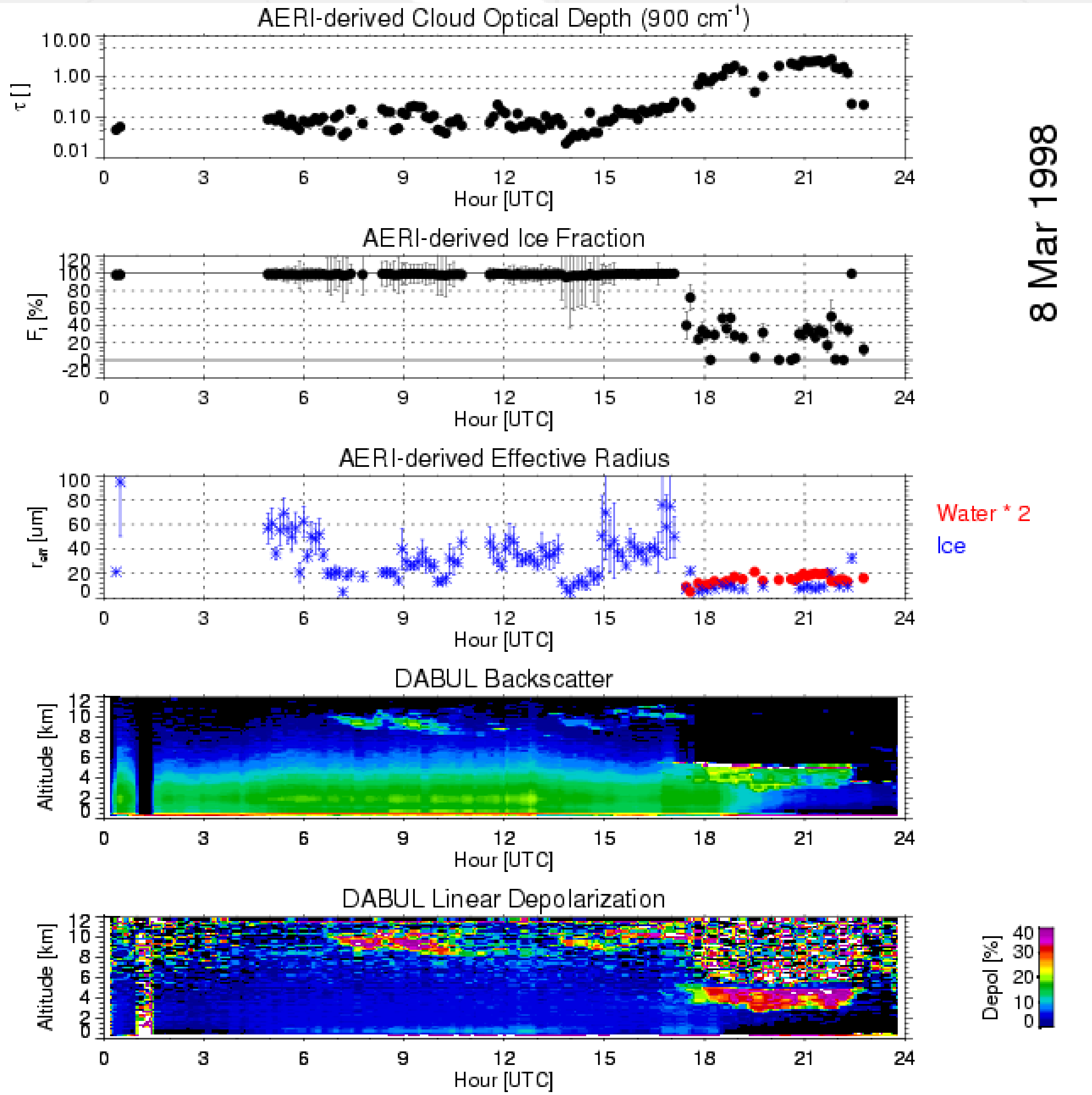
- Decline in samples in Dec and Jan due to increased occurrence of clear skies
- Reduction in Feb due to laser failure in the DABUL
- Reduction in May due to clouds becoming too thick optically for the AERI...

Optical Depth to Cloud Emissivity

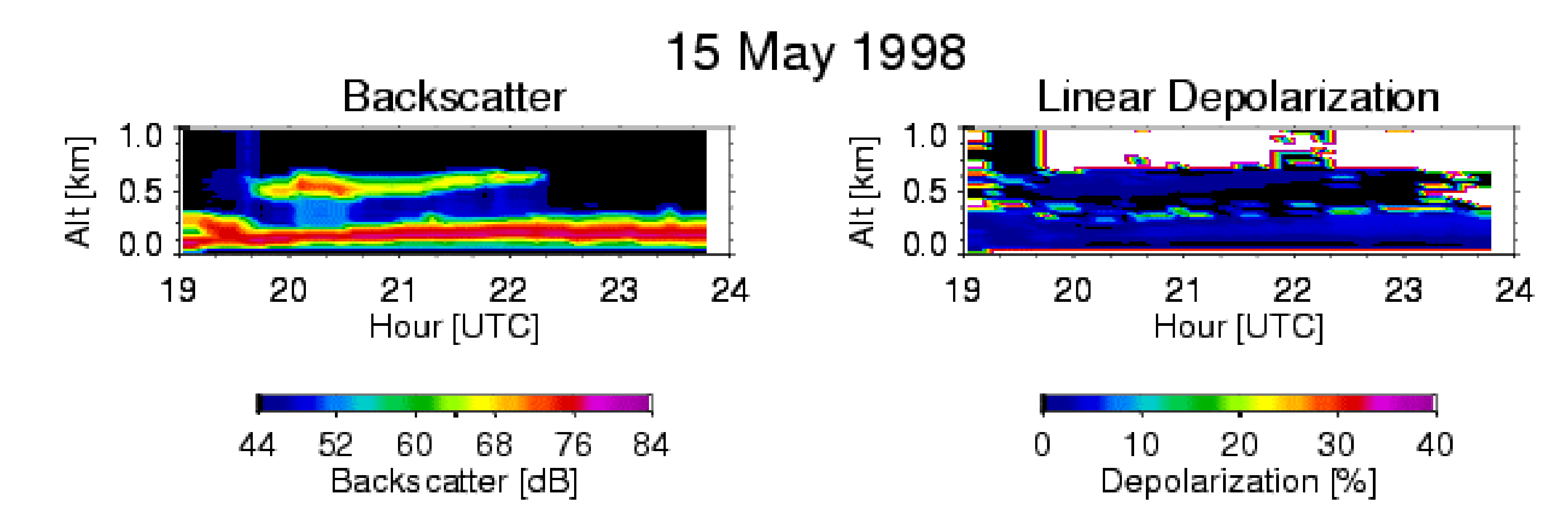


- Data from SHEBA analysis: Nov 1997 - May 1998
- Spread in ε is primarily due to changes in phase
- Little sensitivity to f_i, $r_{e,w}$ and $r_{e,i}$ for $\varepsilon > 0.95$ or $\varepsilon < 0.05$

Example of a mixed-phase retrieval

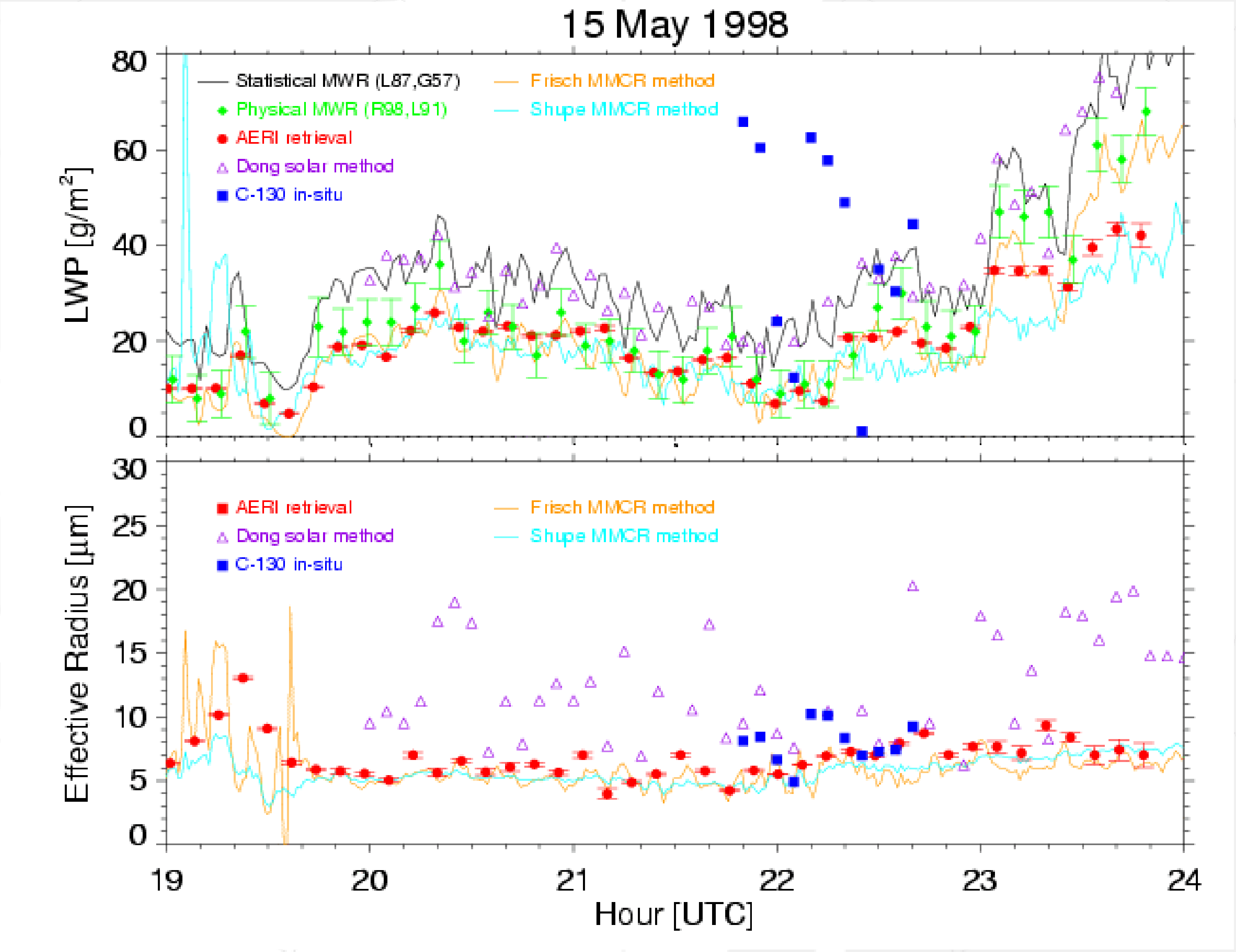


DABUL Data

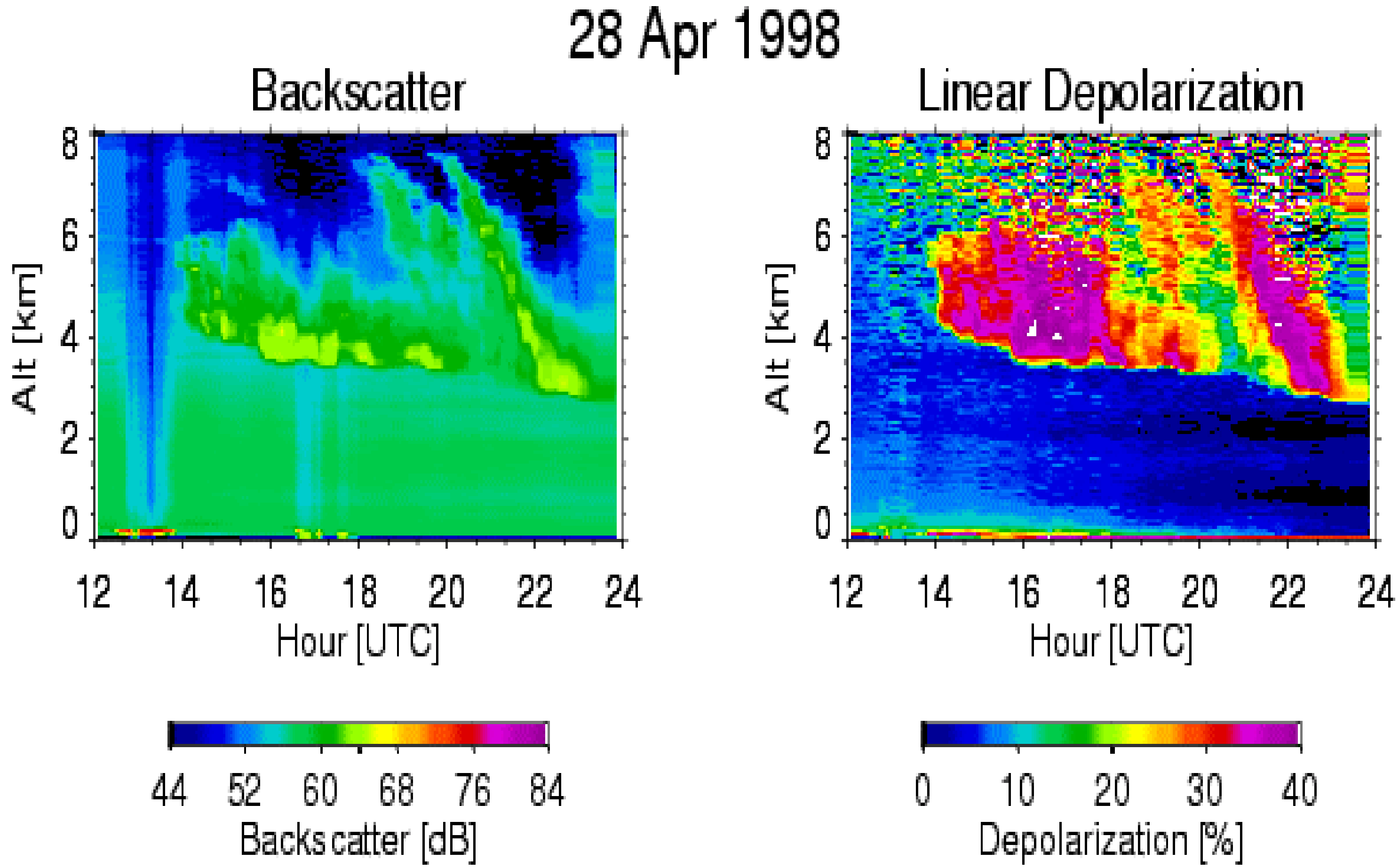

15 May 1998
Backscatter
Alt [km]
1.0
0.5
0.0
19
20
21
22
23
24
Hour [UTC]
44
52
60
68
76
84
Backscatter [dB]
Linear Depolarization
Alt [km]
1.0
0.5
0.0
19
20
21
22
23
24
Hour [UTC]
0
10
20
30
40
Depolarization [%]

Liquid Water Example

Retrieved LWP and $r_{e,w}$



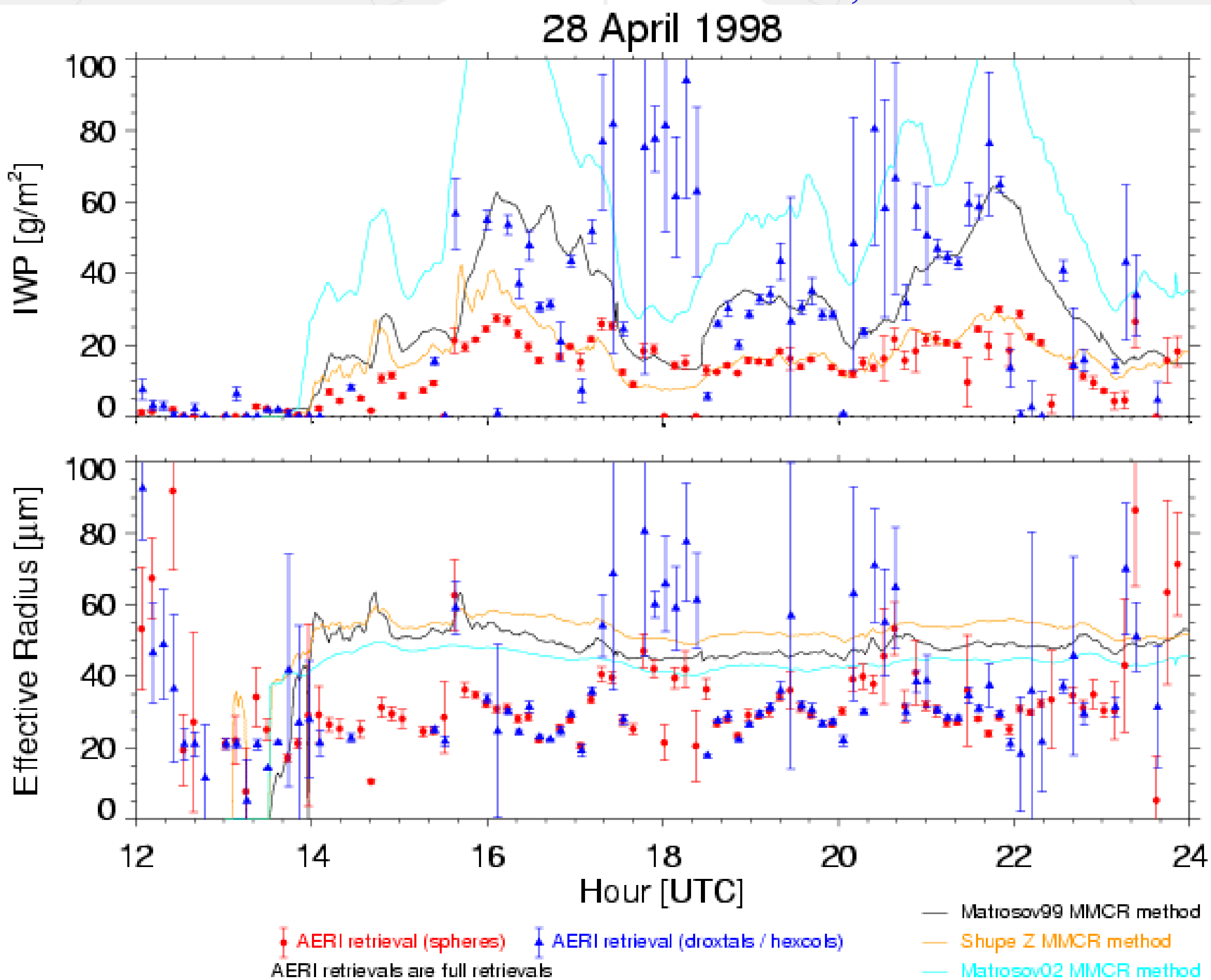
DABUL Data



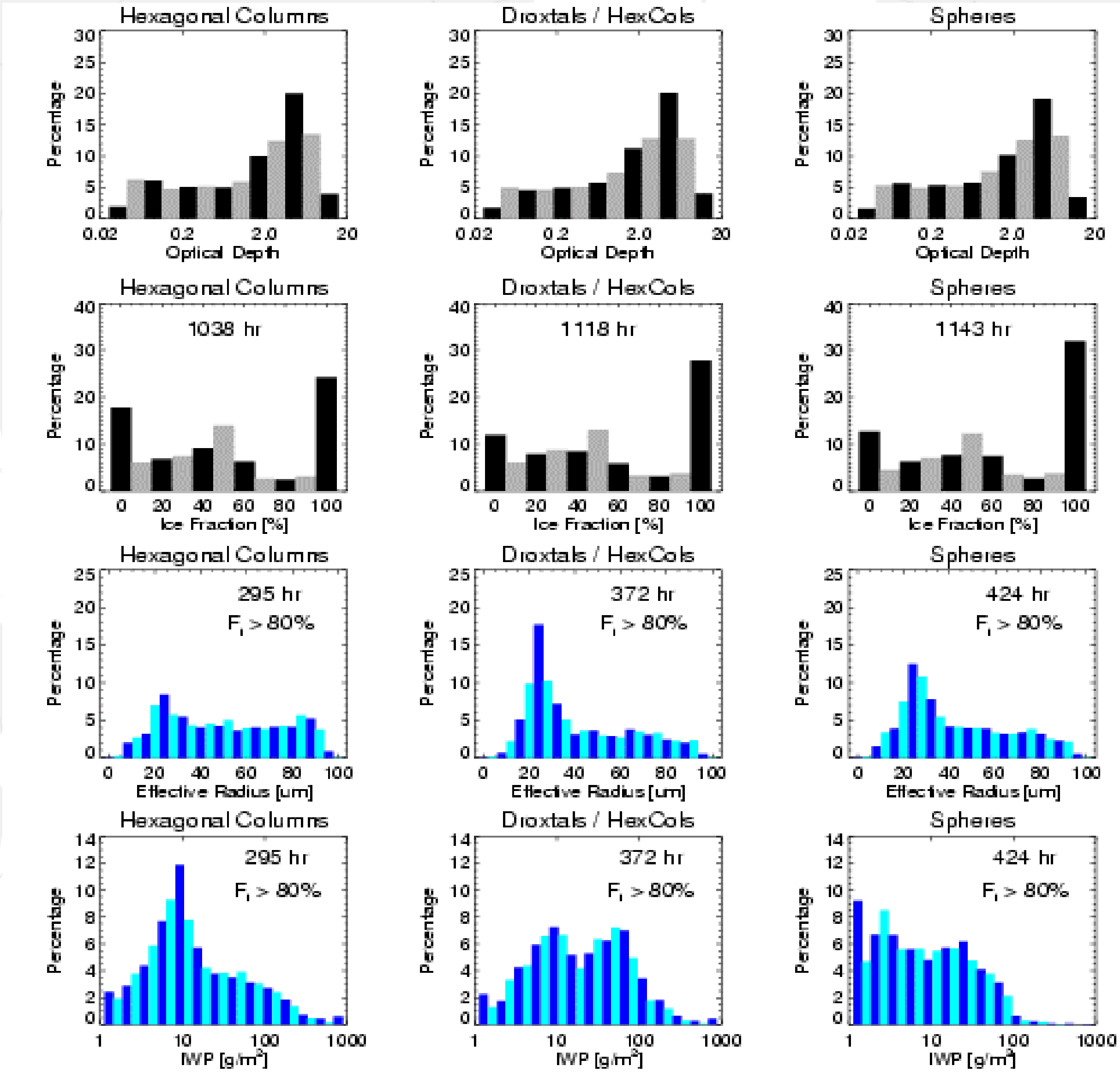
28 Apr 1998
Backscatter
Linear Depolarization
Alt [km]
0
2
4
6
8
12
14
16
18
20
22
24
Hour [UTC]
44
52
60
68
76
84
Backscatter [dB]
0
10
20
30
40
Depolarization [%]

Ice Cloud Example

Retrieved IWP and $r_{e,i}$



Impact of Choice of Habit on retrievals



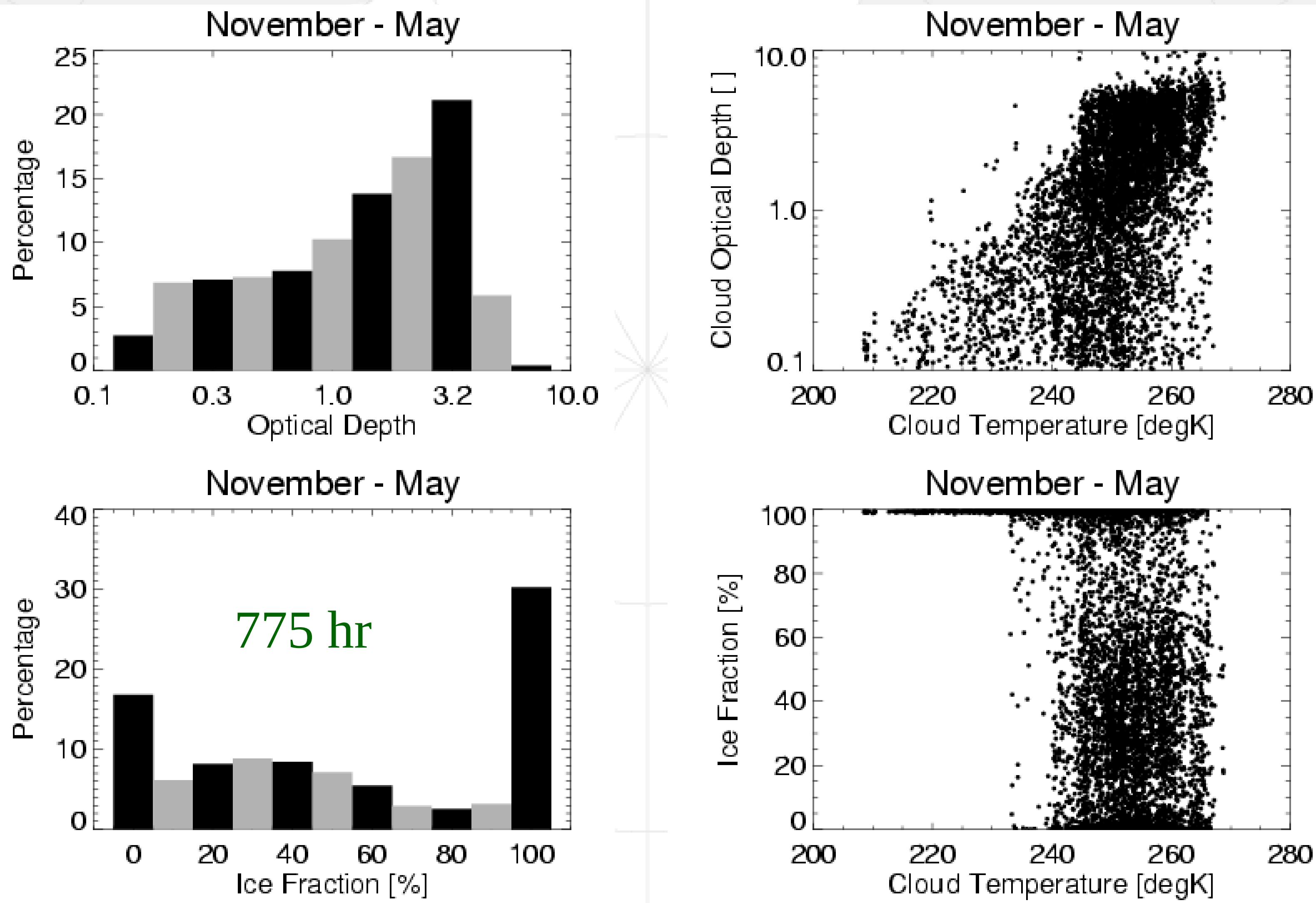
Optical Depth

Ice Fraction

Ice particle size

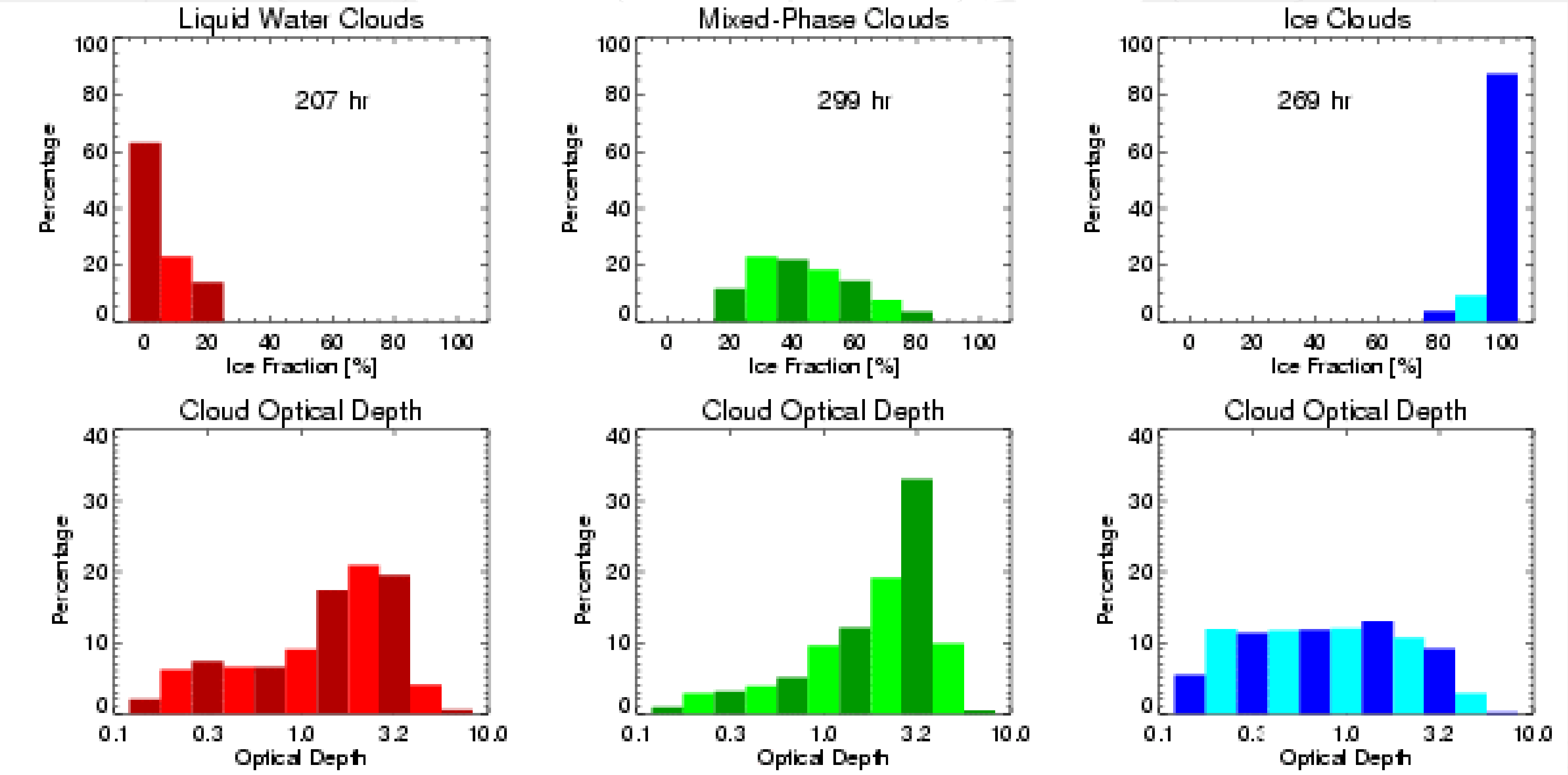
IWP

τ and f_i distributions for Nov 97 - May 98



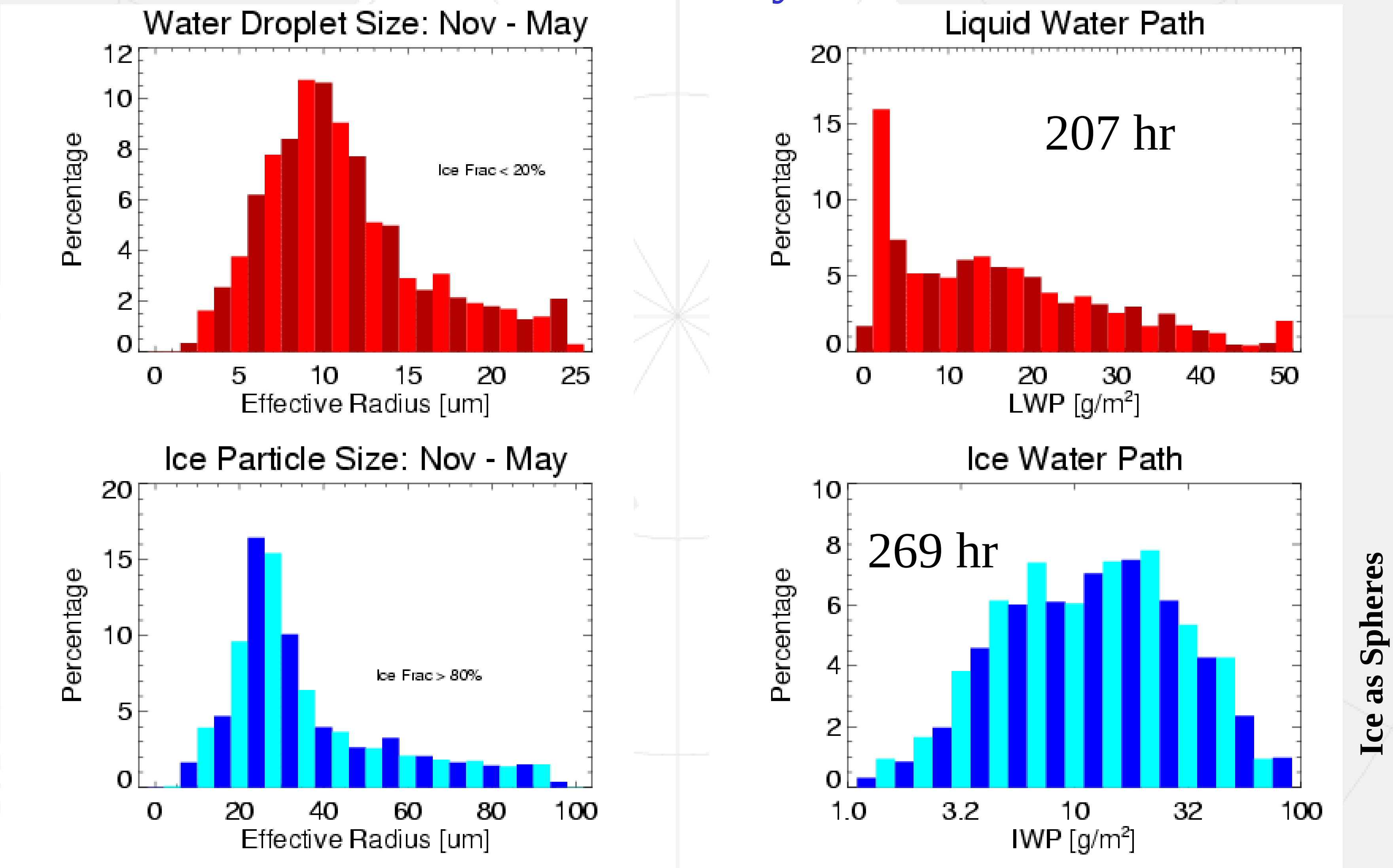
Single-Phase vs. Mixed-Phase Clouds

Distribution of Optical Depths



Particle Size and Water Path Distributions for Single-Phase Clouds

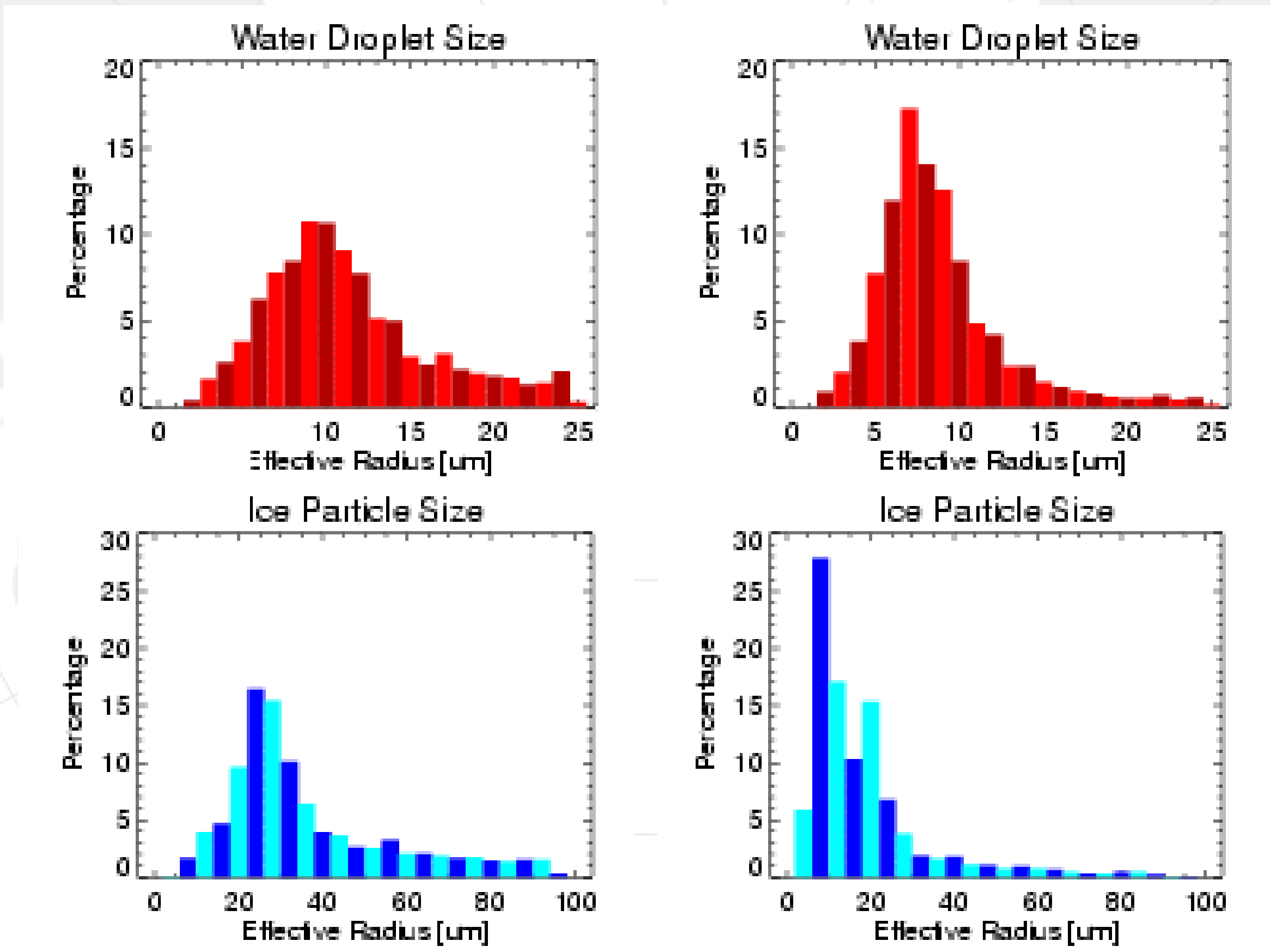
Nov 97 - May 98



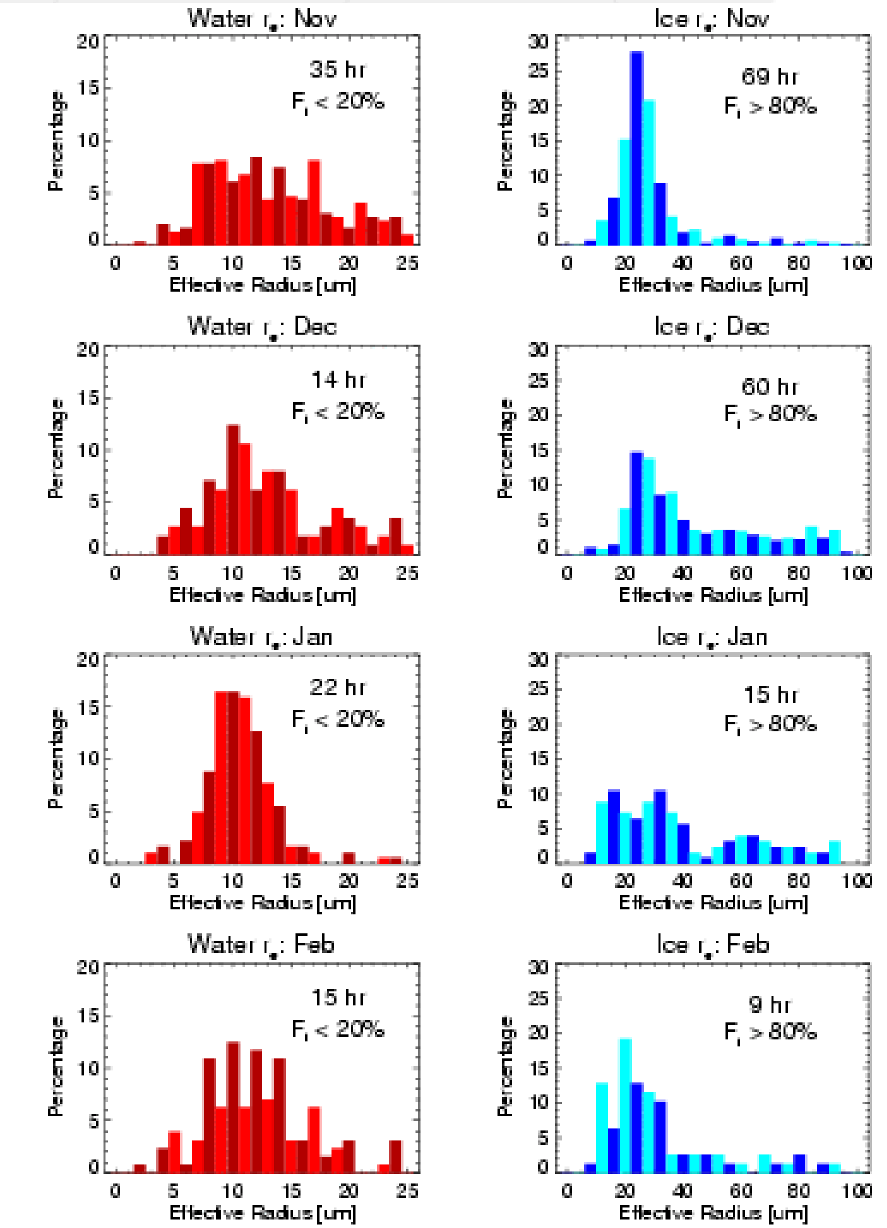
Single-Phase vs. Mixed-Phase Clouds

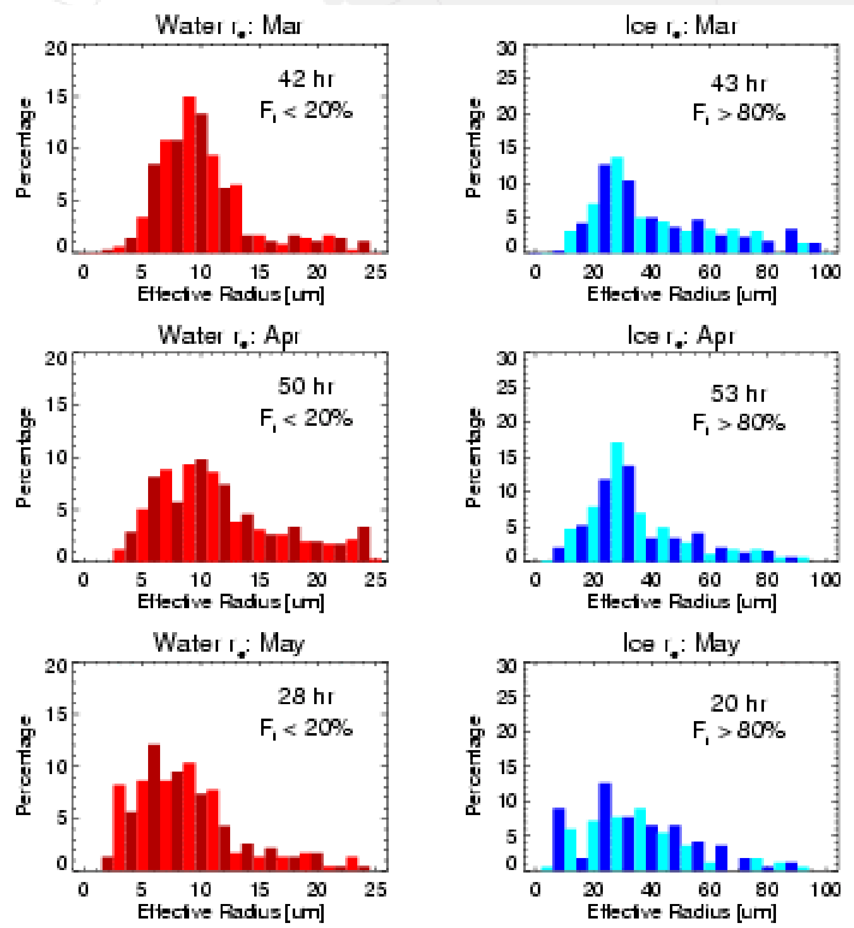
Particle Size Distributions

Single-phase Clouds *Mixed-phase Clouds*

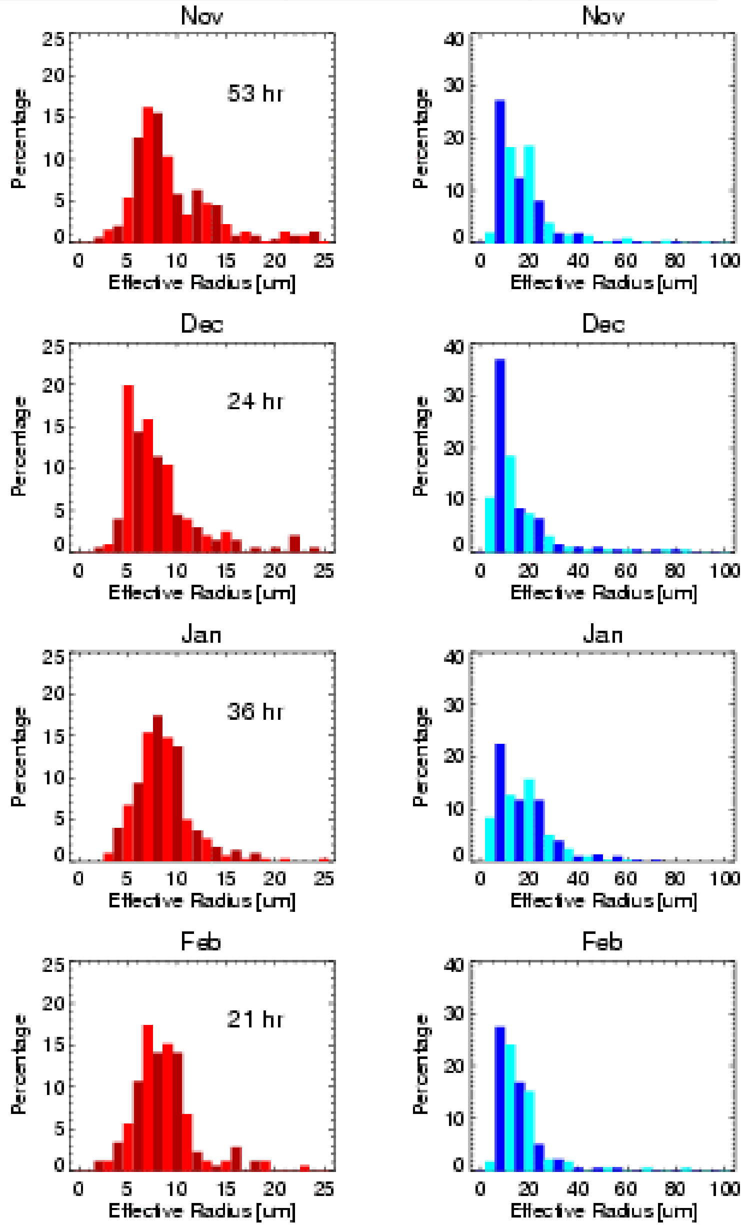


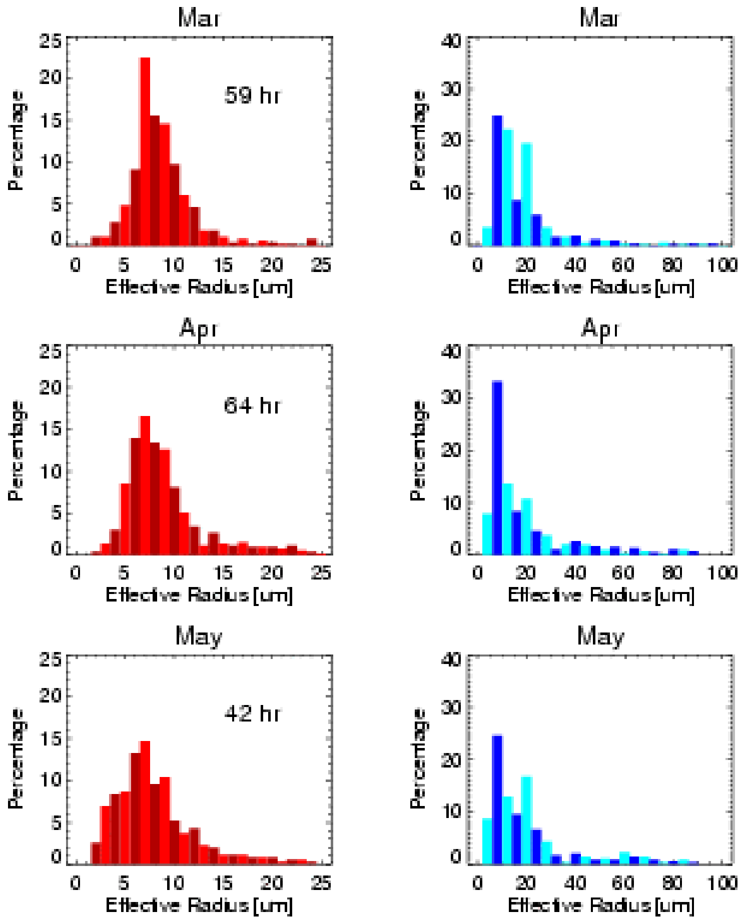
Cloud Particle Size for Single-Phase Clouds per Month



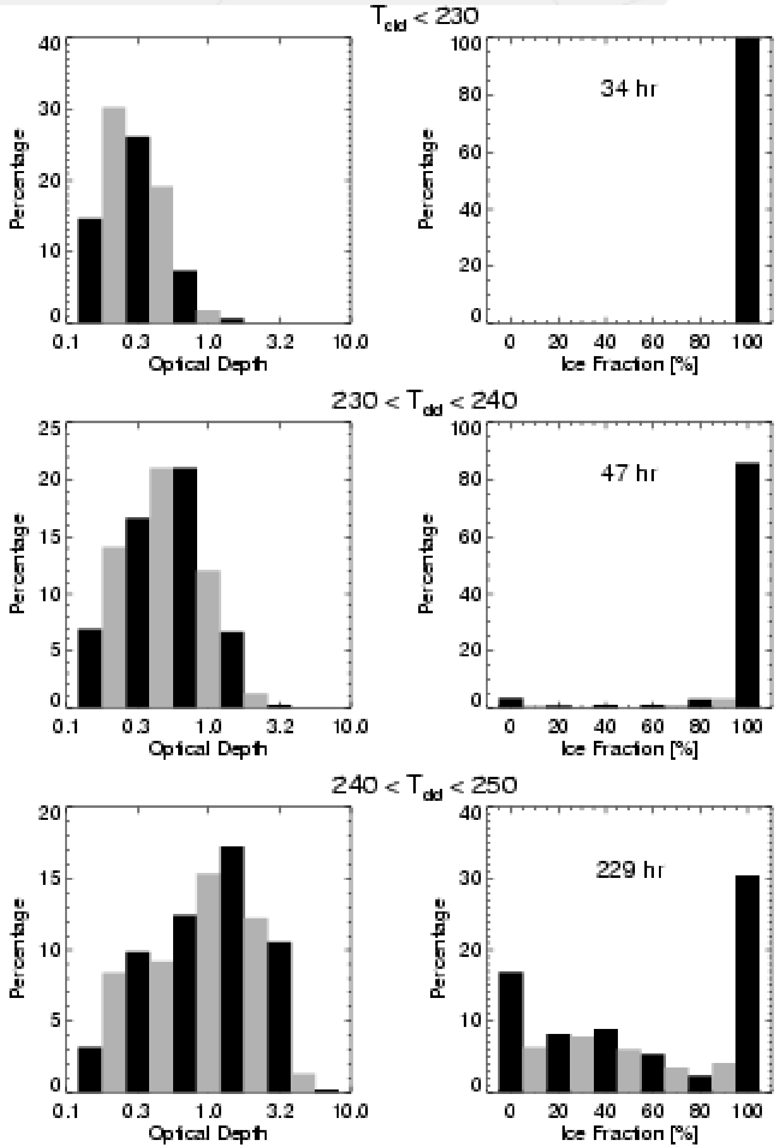


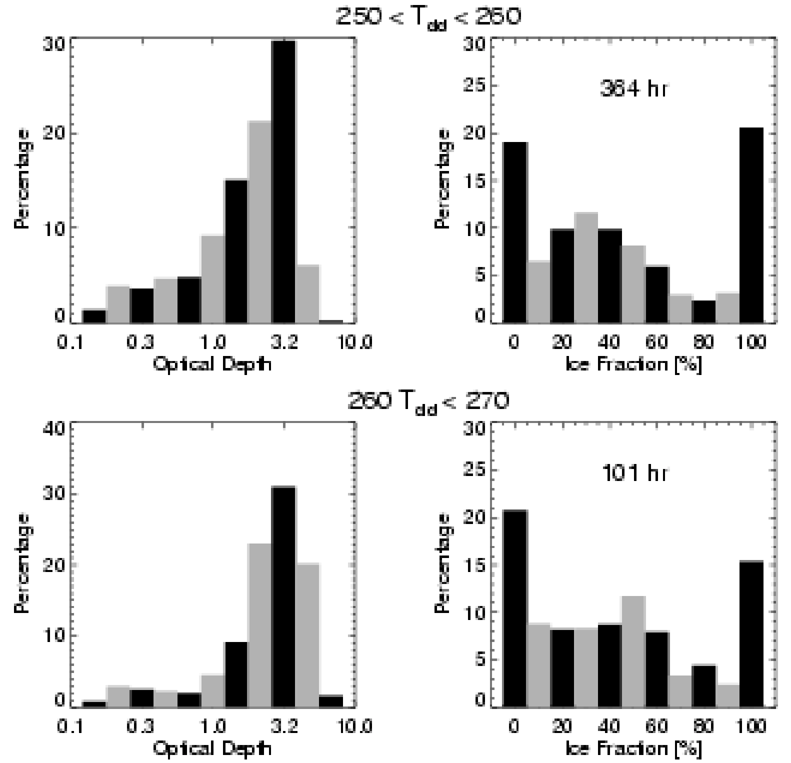
Cloud Particle Size for Mixed-Phase Clouds per Month





Cloud Optical Depth and Ice Fraction by Temperature



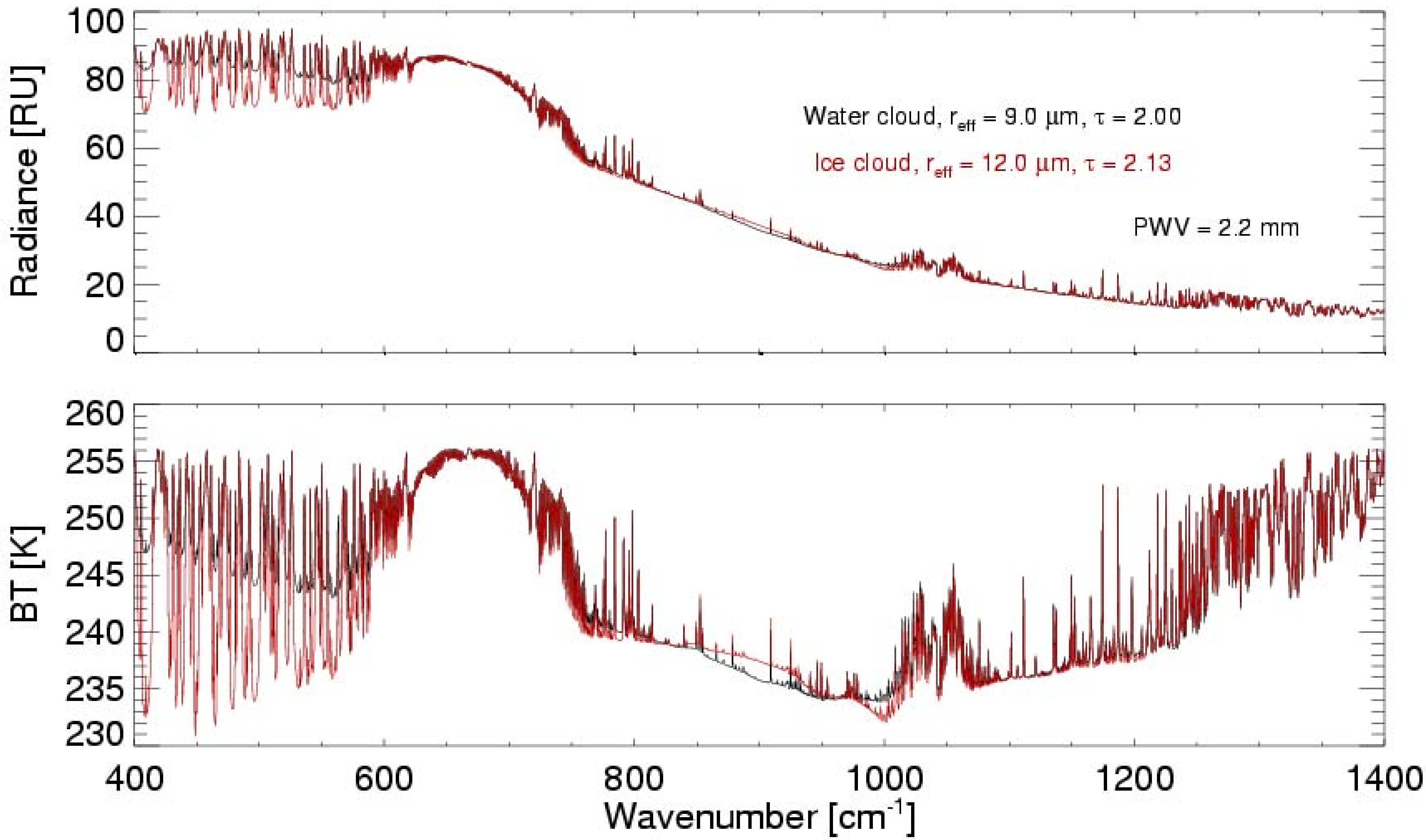


Summary

- Demonstrated that cloud phase can be determined using ground-based infrared radiance data; paper in JAM June 2003
- Developed a physical retrieval to retrieve cloud optical depth, ice fraction, and particle sizes from infrared spectrum
- Simulations were used to characterize the physical retrieval
- Physical retrieval applied to SHEBA data set
- Initial results show:
  - Good agreement in *LWP* and $r_{e,w}$ with physical MWR retrievals and MMCR/MWR retrievals; general agreement in *IWP* compared to MMCR techniques
  - Monthly dependence of $r_{e,w}$ in liquid-only clouds, but not in mixed-phase clouds. The dependence is most likely associated with aerosols
  - Large sensitivity in f_i and *IWP* to crystal habit, little in $r_{e,i}$
  - Possible error in T-dependence of liquid water absorption in the microwave; with more statistics the infrared can reduce this error

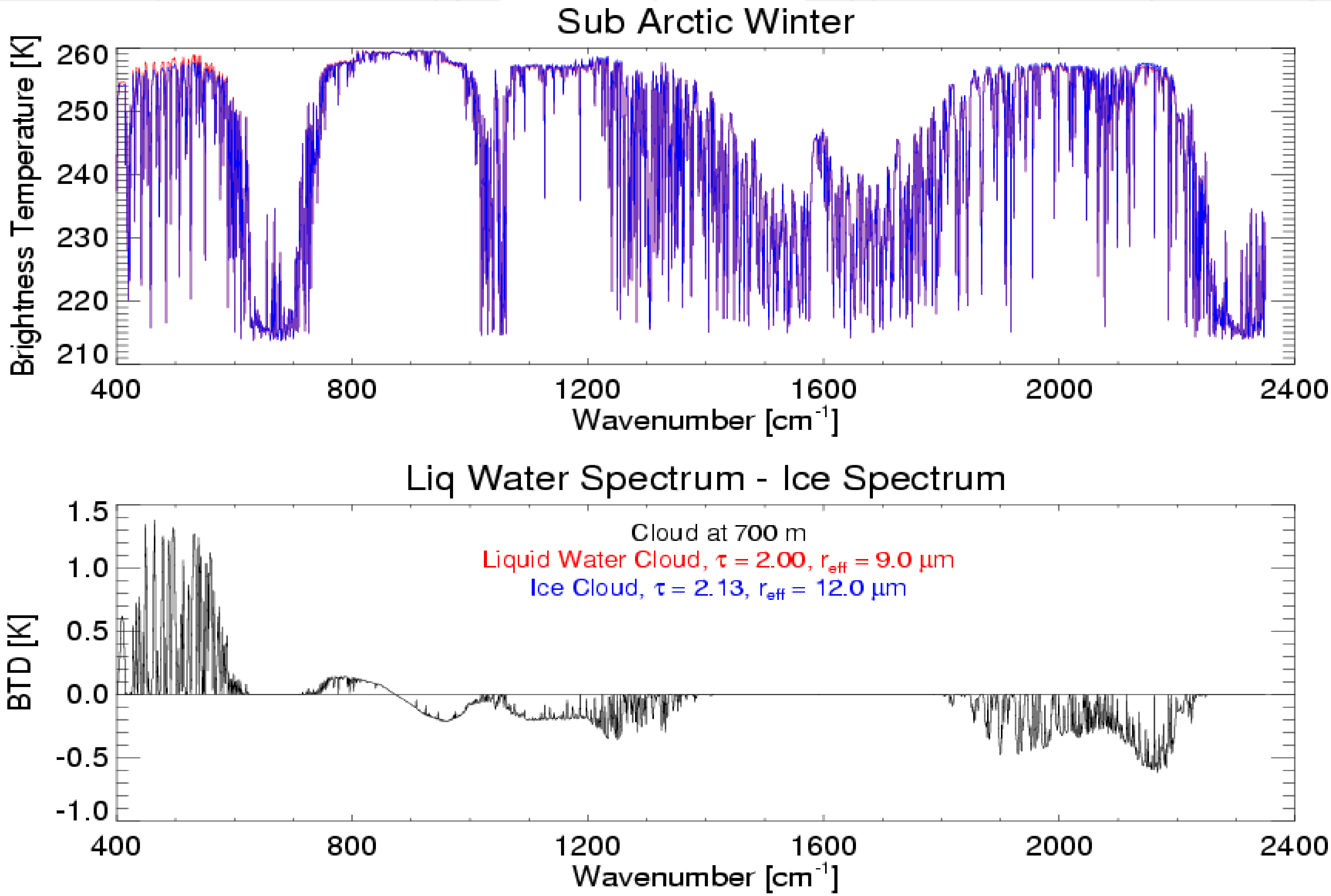
Importance of 16-25 μm data

Downwelling radiation



Importance of 16-25 μm data

Upwelling radiation



A New Day in Arctic Cloud Research!

From NOAA/ETL website