CALIPSO Lidar Measurement of Water Clouds and Its Applications

Y. Hu, D. Winker, J. Hair, M. Vaughan, C. Hostetler, C. Trepte, S. Zeng, X. Lu,
S. Rodier, Z. Liu, A. Omar, D. MacDonell, C. Butler, W. Sun

NASA Langley Research Center

Overview of the talk

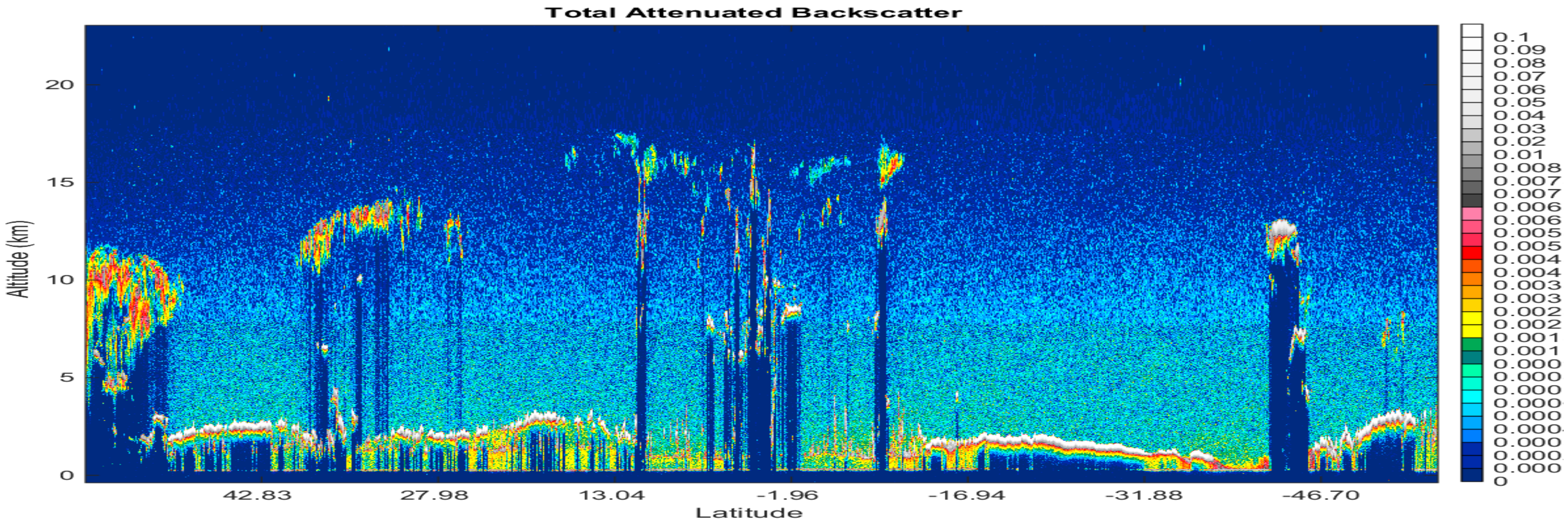
1. **CALIPSO backscattering signal from water clouds: what does it tell us?**

2. **Other applications of CALIPSO measurements of water cloud backscatter**

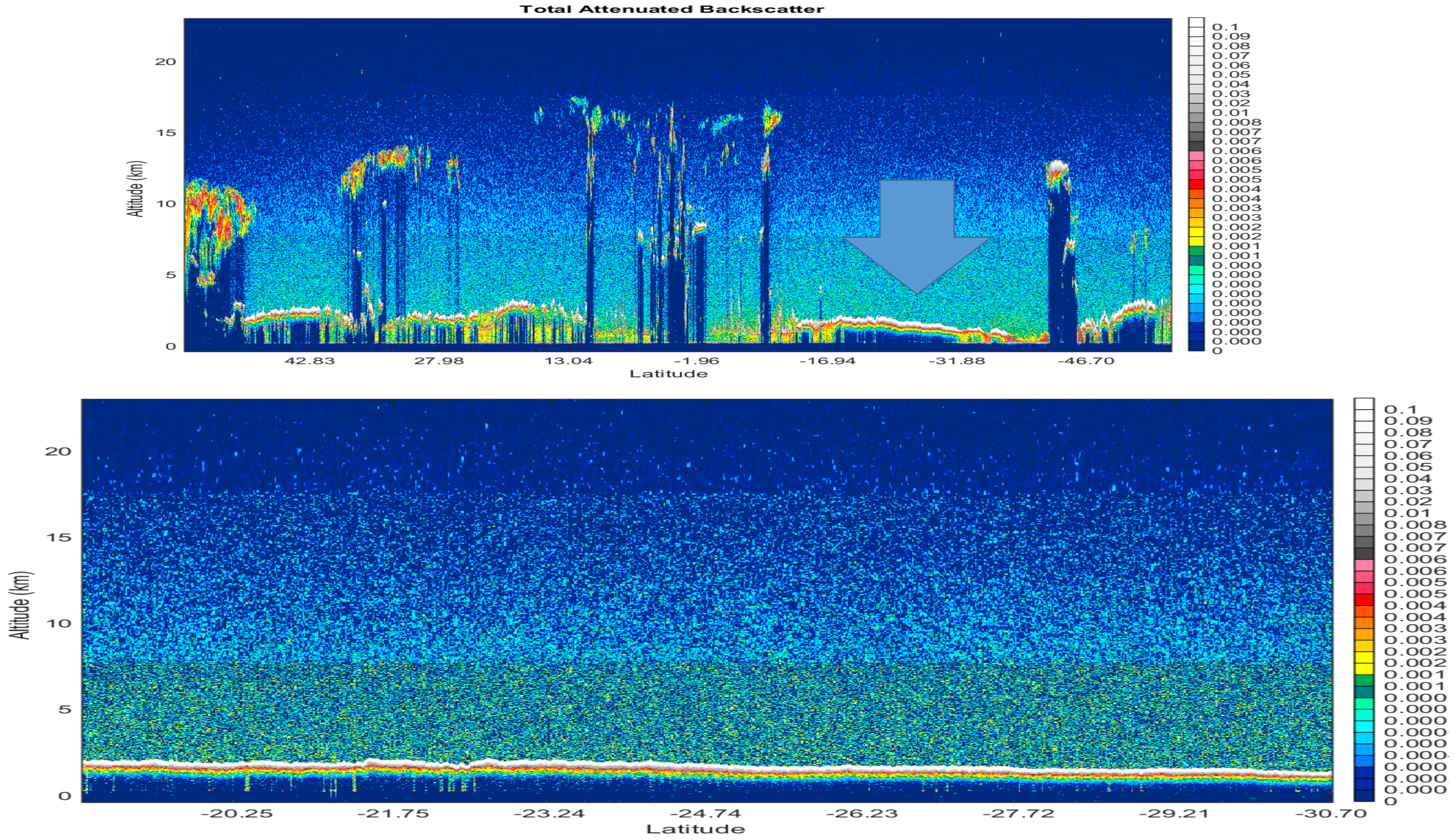
3. **Ongoing studies with HSRL measurements**

CALIPSO 532nm backscattering signal from water clouds: what does it tell us?

- Effective cloud extinction coefficient σ'_e
- Ratio of effective extinction to backscatter efficiency S'_c (also called “effective lidar ratio”, and is a proxy of droplet size)



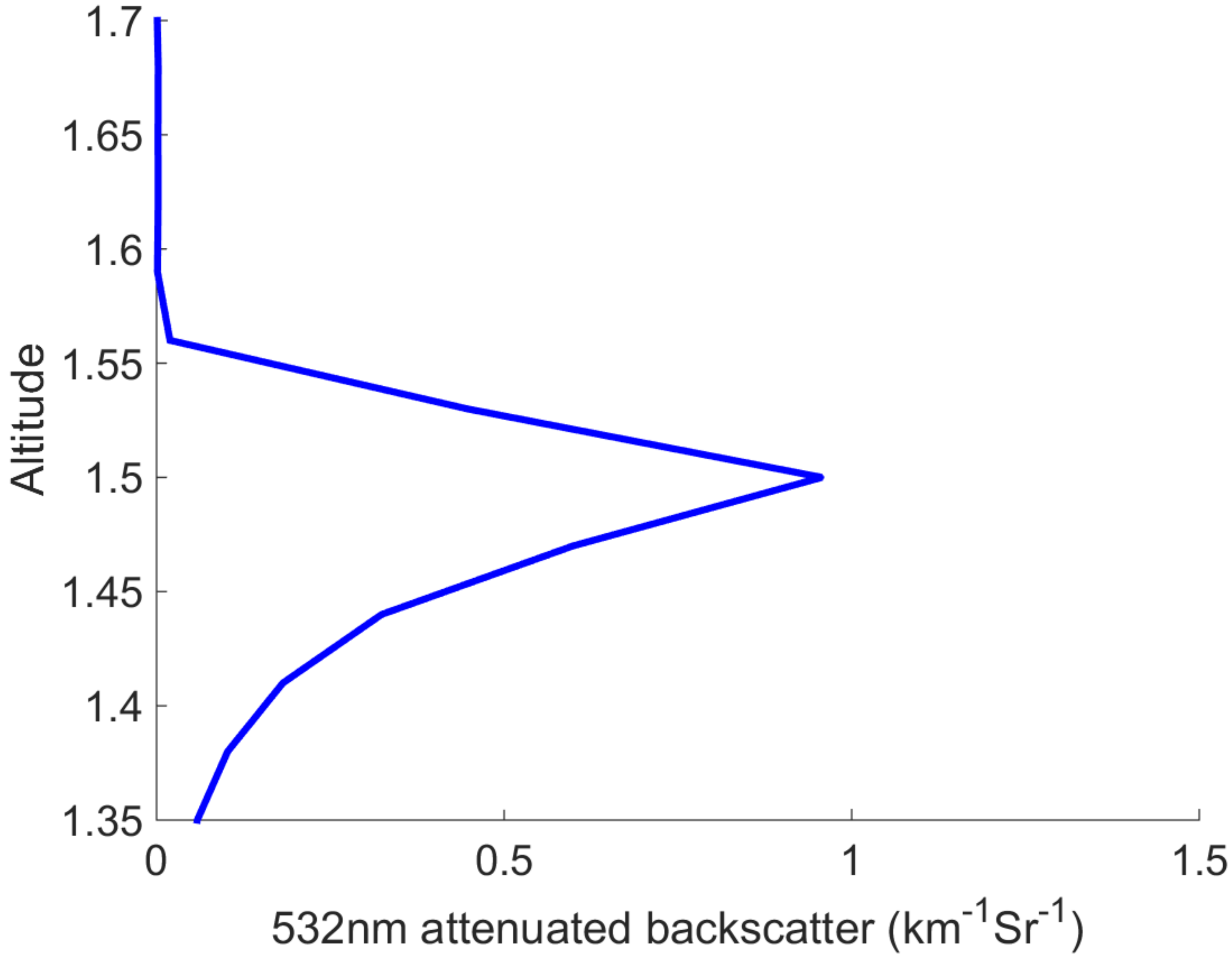
Total Attenuated Backscatter
Altitude (km)
Latitude
0
5
10
15
20
42.83
27.98
13.04
-1.96
-16.94
-31.88
-46.70
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.008
0.007
0.007
0.006
0.006
0.005
0.005
0.004
0.004
0.003
0.003
0.002
0.002
0.001
0.001
0


Total Attenuated Backscatter
Altitude (km)
Latitude
42.83
27.98
13.04
-1.96
-16.94
-31.88
-46.70
-20.25
-21.75
-23.24
-24.74
-26.23
-27.72
-29.21
-30.70

Estimating water cloud effective extinction coefficient (σ'_e) from CALIPSO lidar measurement

For a typical cloud lidar backscatter profile, backscatter attenuates exponential with range below the cloud top

$$\beta(r) = \sigma_b e^{-2\sigma'_e r} = \frac{\sigma'_e}{S'_c} e^{-2\sigma'_e r}$$



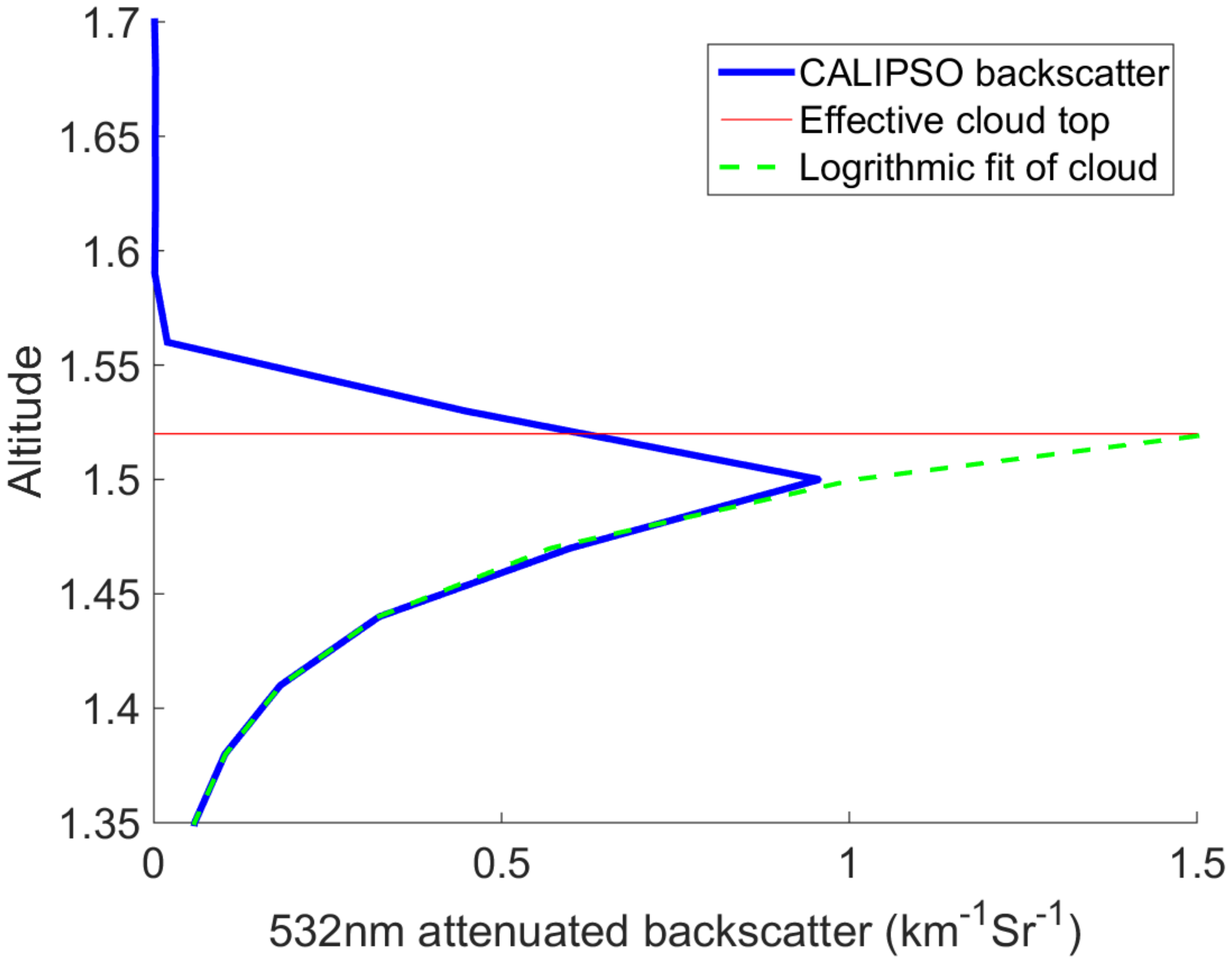
Estimating water cloud effective extinction coefficient (σ'_e) from CALIPSO lidar measurement

For a typical cloud lidar backscatter profile, backscatter attenuates exponential with range below the cloud top

$$\beta(r) = \sigma_b e^{-2\sigma_e' r} = \frac{\sigma'_e}{S'_c} e^{-2\sigma_e' r}$$

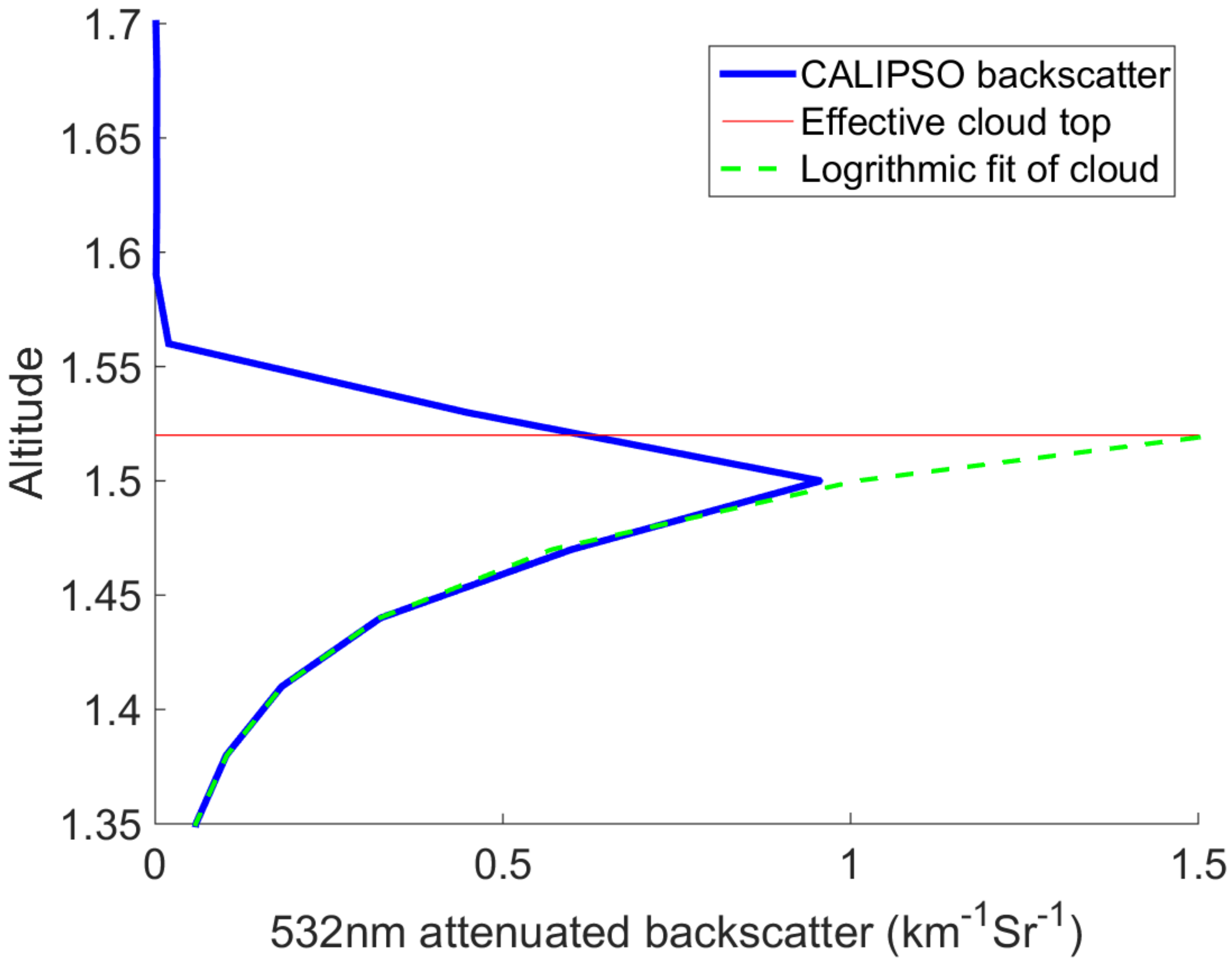
$$\approx 1.5\, e^{-21.3r}$$

σ'_e = slope of the logarithmic attenuation / 2 (green dash line) = 10.65 (km^{-1})



Estimating water cloud effective lidar ratio (S'_c) from CALIPSO 532nm backscatter profile

$$\int \beta(r)\,dr = \int \frac{\sigma'_e}{S'_c} e^{-2\sigma'_e r}\,dr = \frac{1}{2S'_c}$$



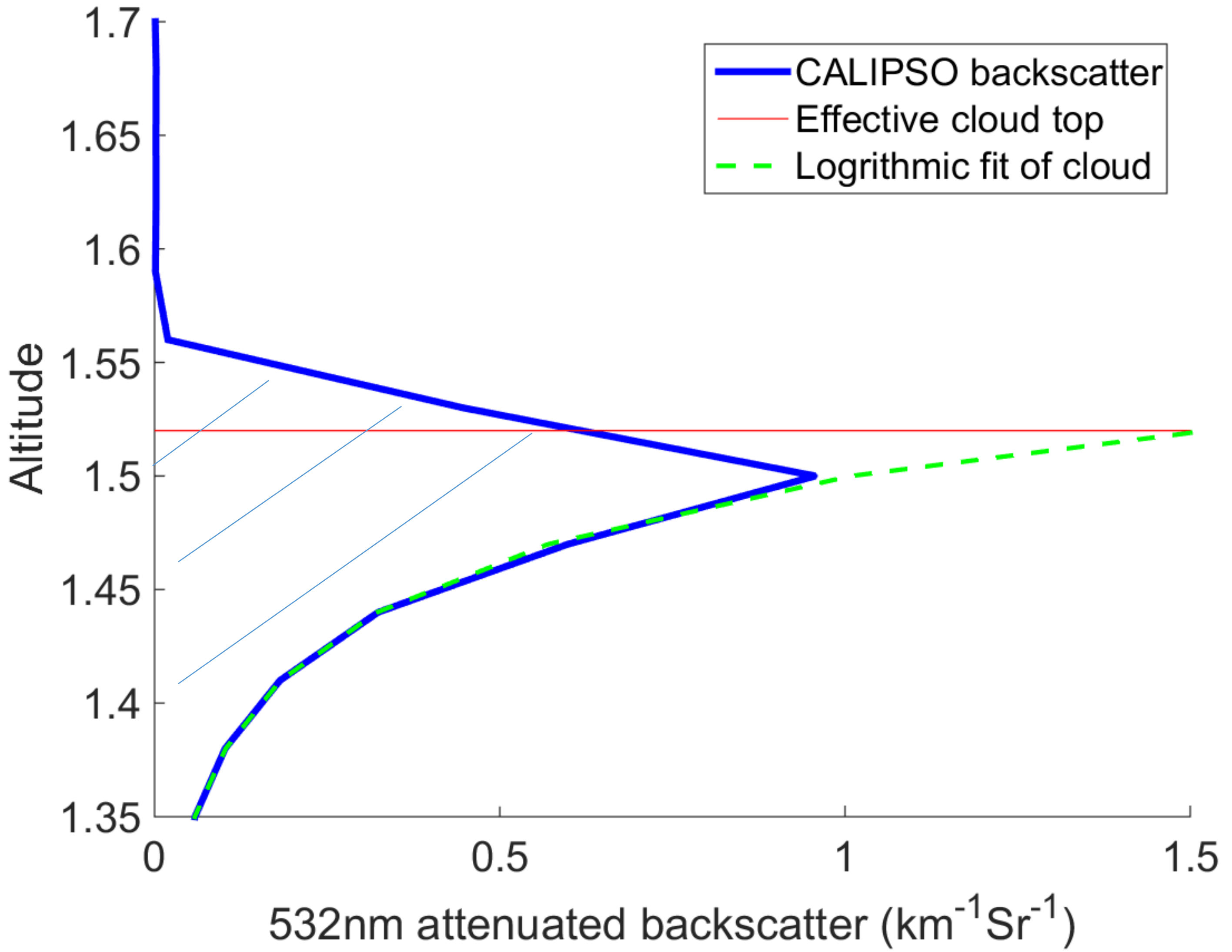
Estimating water cloud effective lidar ratio (S'_c) from CALIPSO 532nm backscatter profile

1. **Deriving S'c from layer integrated attenuated backscatter (Shaded area)**

$$a = \int \beta(r)\, dr = \int \frac{\sigma'_e}{S'_c} e^{-2\sigma'_e r}\, dr$$

$$= \frac{1}{2S'_c}$$

S'_c = 1 / (2 a) =7.1



Estimating water cloud effective lidar ratio (S'_c) from CALIPSO 532nm backscatter profile

1. **Deriving S'c from layer integrated attenuated backscatter (Shaded area)**

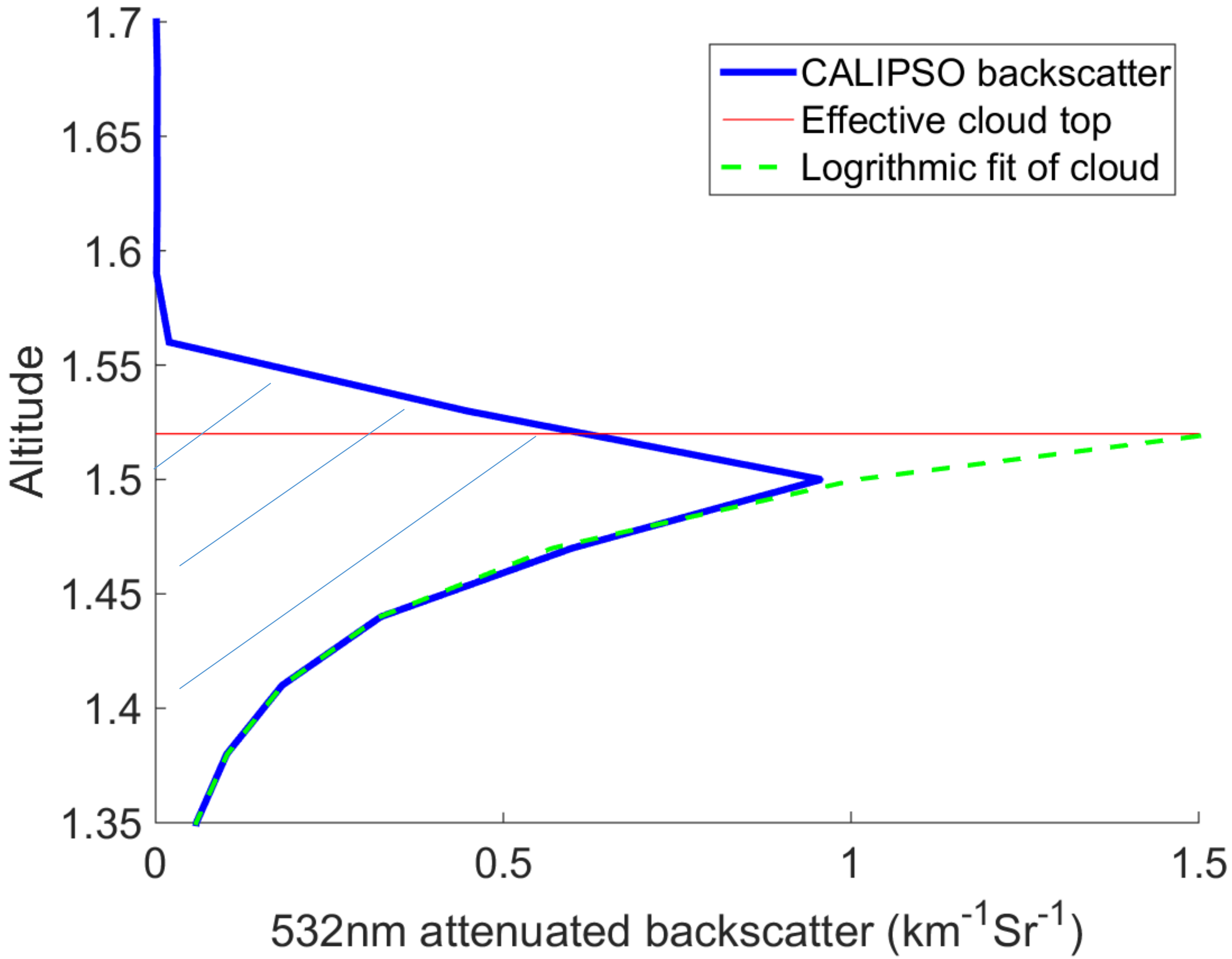
$$a = \int \beta(r)\,dr = \int \frac{\sigma'_e}{S'_c} e^{-2\sigma'_e r}\,dr = \frac{1}{2S'_c}$$

$S'_c = 1 / (2\ a) = 7.1$

2. Deriving S'c from the green dash line

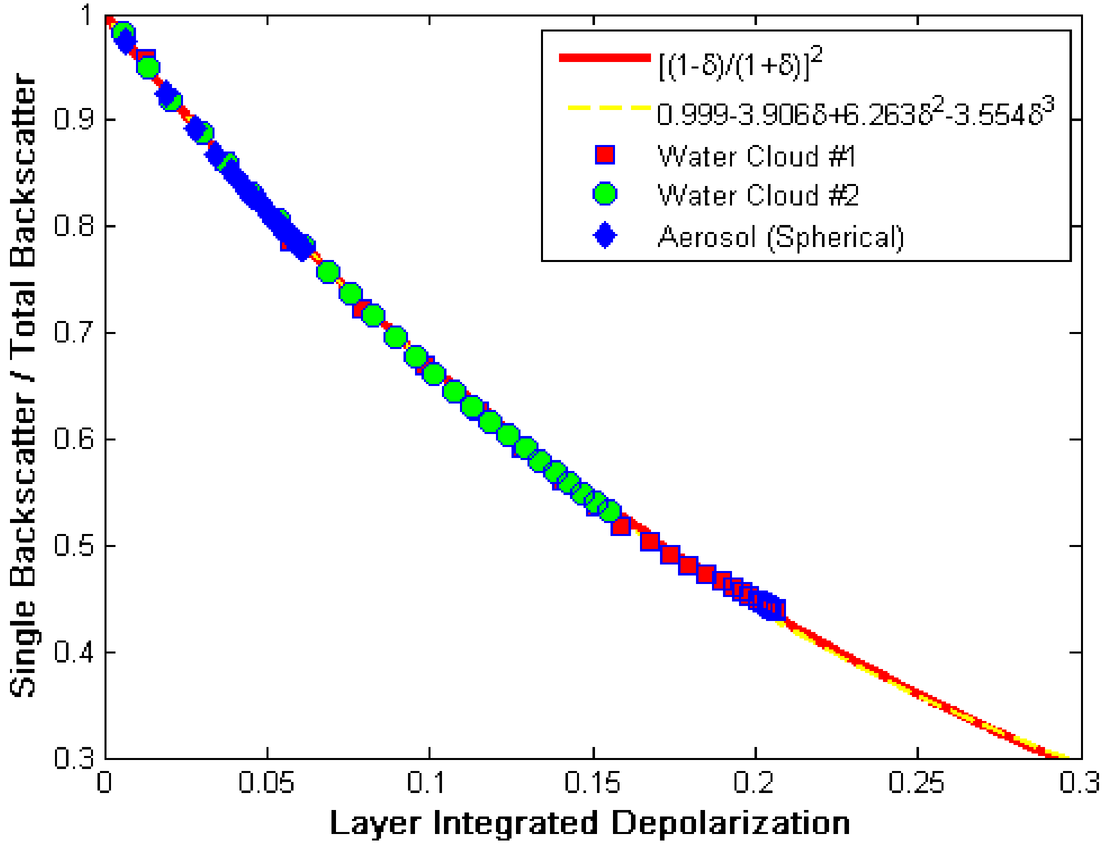
$$\frac{\sigma'_e}{S'_c} e^{-2\sigma'_e r} = 1.5\ e^{-21.3r}$$

$S'_c = \sigma'_e / 1.5 = 10.65/1.5 = 7.1$



Backscattering depolarization measurements (δ) of water clouds: The property that links effective σ'_e and S'_c to true extinction coefficient σ_e and Lidar Ratio S_c

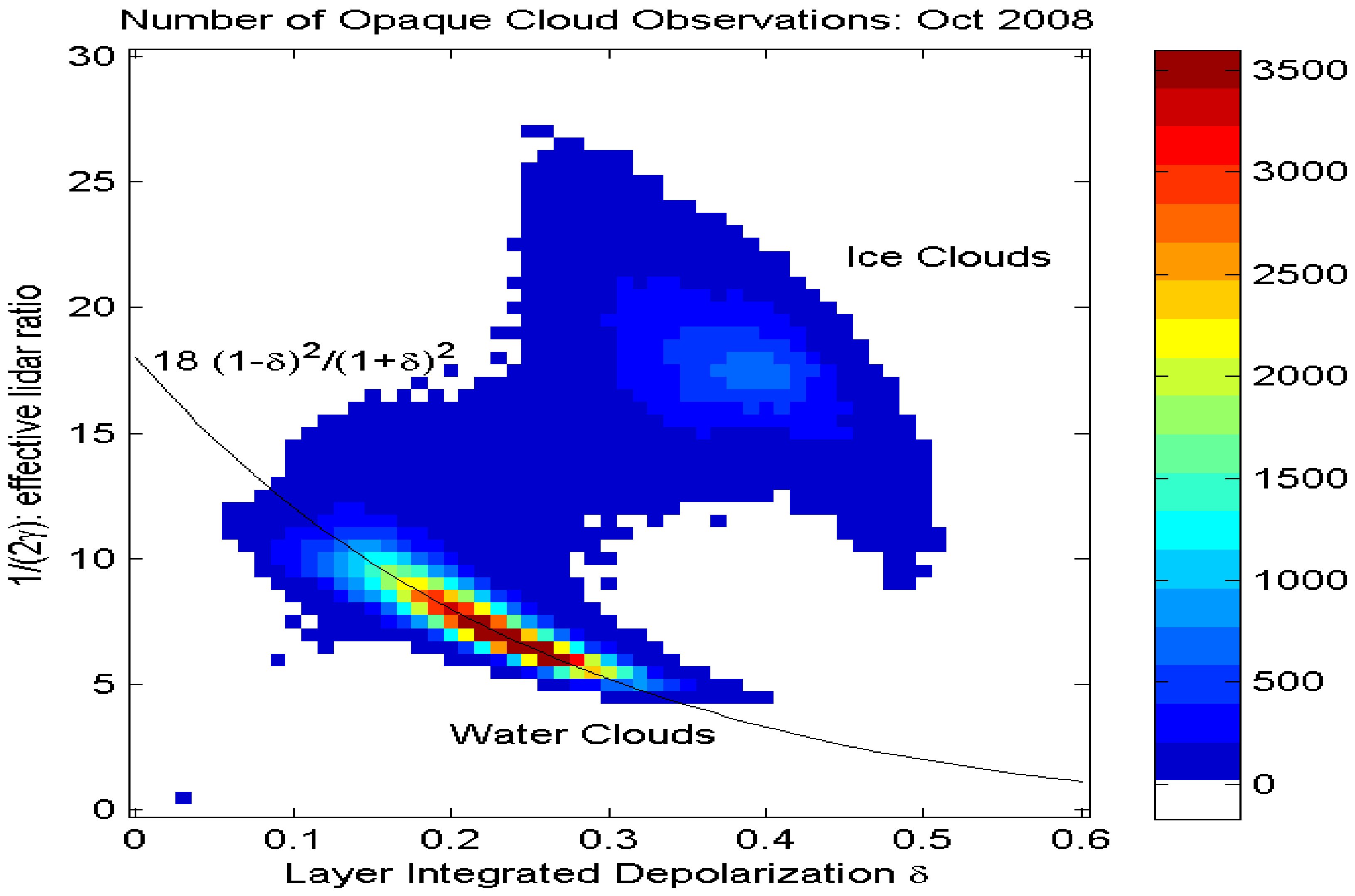
$$\frac{\sigma_e'}{\sigma_e} = \frac{S_c'}{S_c} = \eta = \left(\frac{1-\delta}{1+\delta}\right)^2$$



Hu 2007 GRL; Hu et al., 2007 Optics Express

The δ – η relation for water clouds: theory (line) vs CALIPSO data (color)

$$\eta = \left(\frac{1-\delta}{1+\delta}\right)^2$$



Backscattering depolarization measurements (δ) of water clouds: linking effective σ'_e and S'_c to true extinction coefficient σ_e and Lidar Ratio S_c

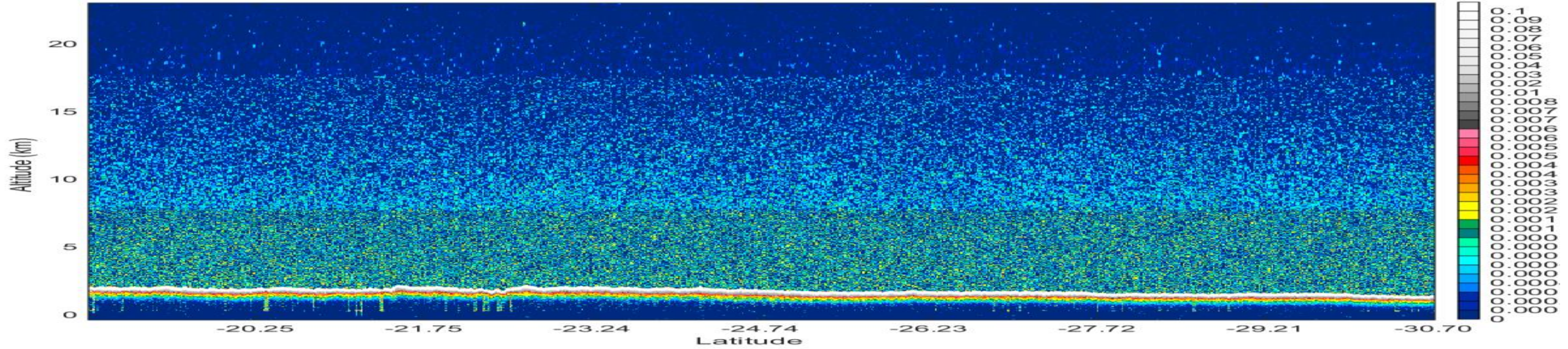
$$\frac{\sigma'_e}{\sigma_e} = \frac{S'_c}{S_c} = \eta = \left(\frac{1-\delta}{1+\delta}\right)^2$$

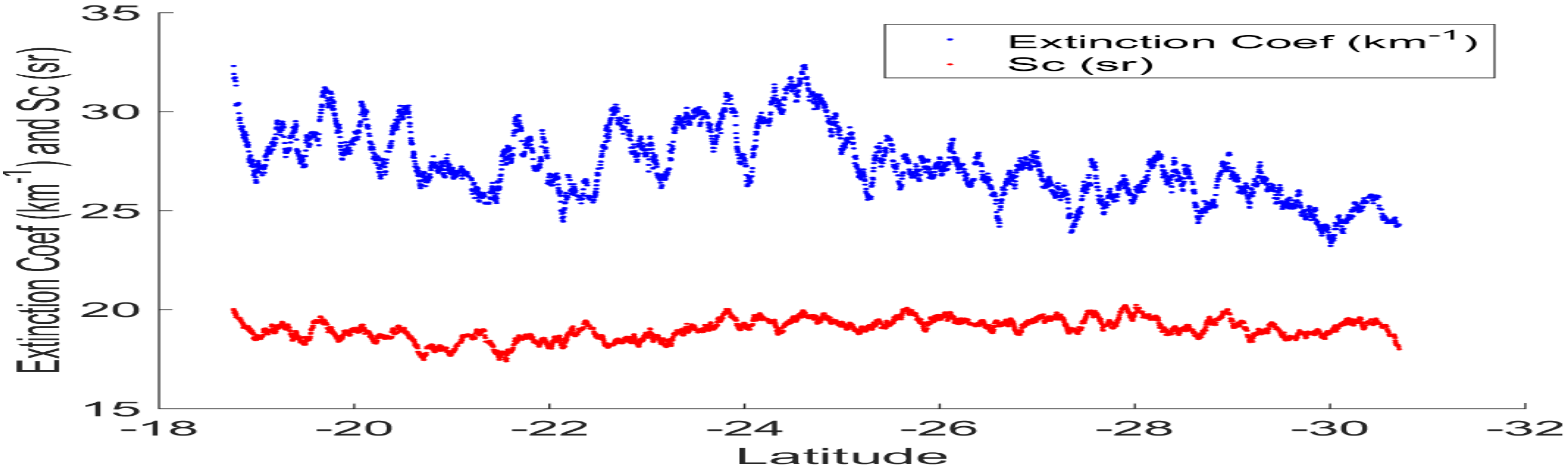
For the cloud profile we just looked at, $\delta = 0.245$

Thus $\sigma'_e / \sigma_e = 0.37$;

$\sigma_e = \sigma'_e / 0.37 = 28.78$ (km^{-1})

$S_c = S'_c / 0.37 = 19.2$ (Sr)


Altitude (km)
Latitude
-20.25
-21.75
-23.24
-24.74
-26.23
-27.72
-29.21
-30.70


Extinction Coef (km-1) and Sc (sr)
Extinction Coef (km-1)
Sc (sr)
Latitude

Retrieving effective cloud droplet size R_e using its relation with water cloud depolarization ratio δ and extinction coefficient σ_e

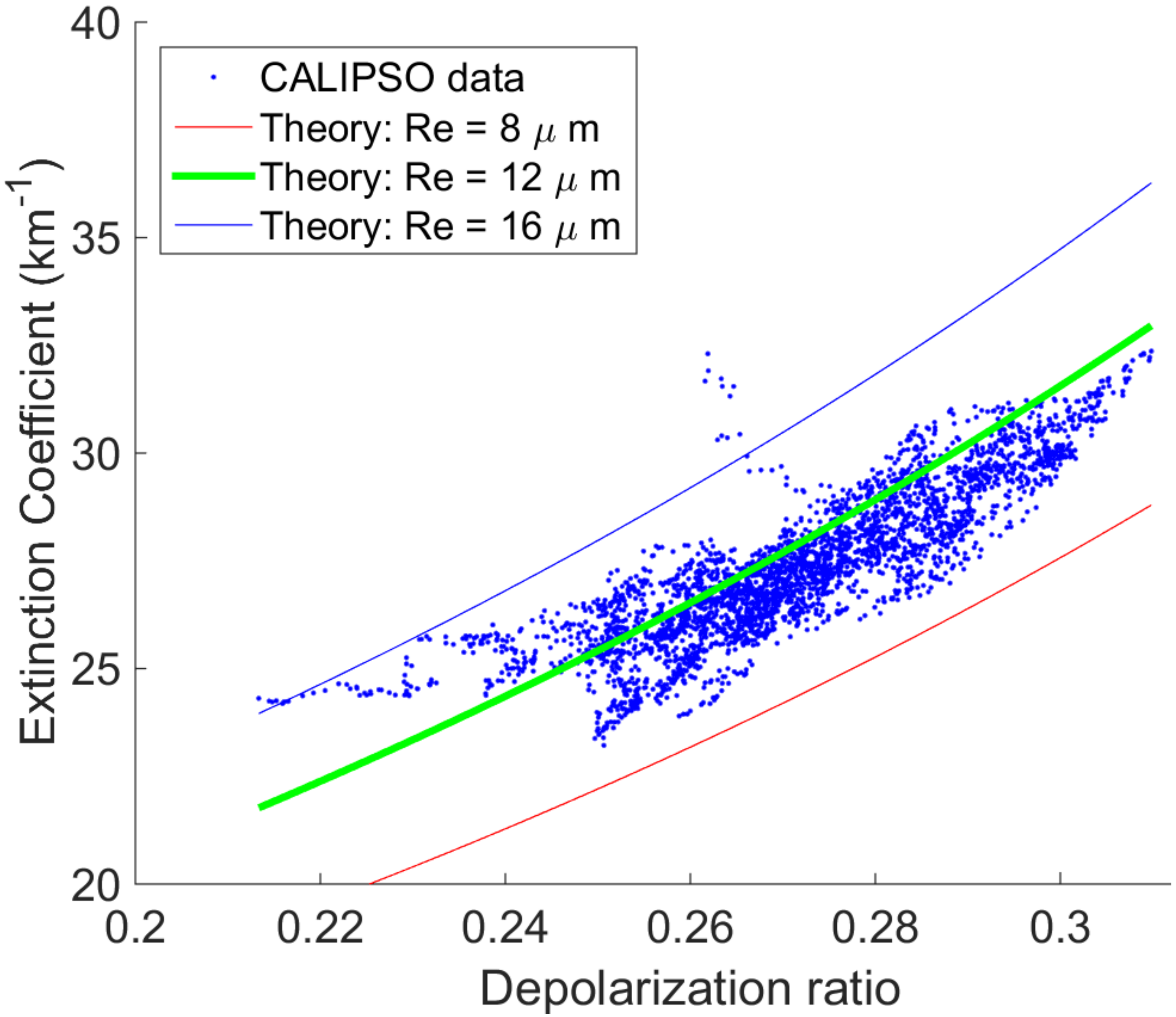
From Monte Carlo lidar radiative transfer modeling with CALIPSO viewing geometry,

$$\eta = (\frac{1-\delta}{1+\delta})^2 = f(\sigma_e, R_e)$$

Thus Re can be derived from depolarization ratio and extinction coefficient ,

$$R_e = f(\eta, \sigma_e)$$

Hu et al. 2007 ACP



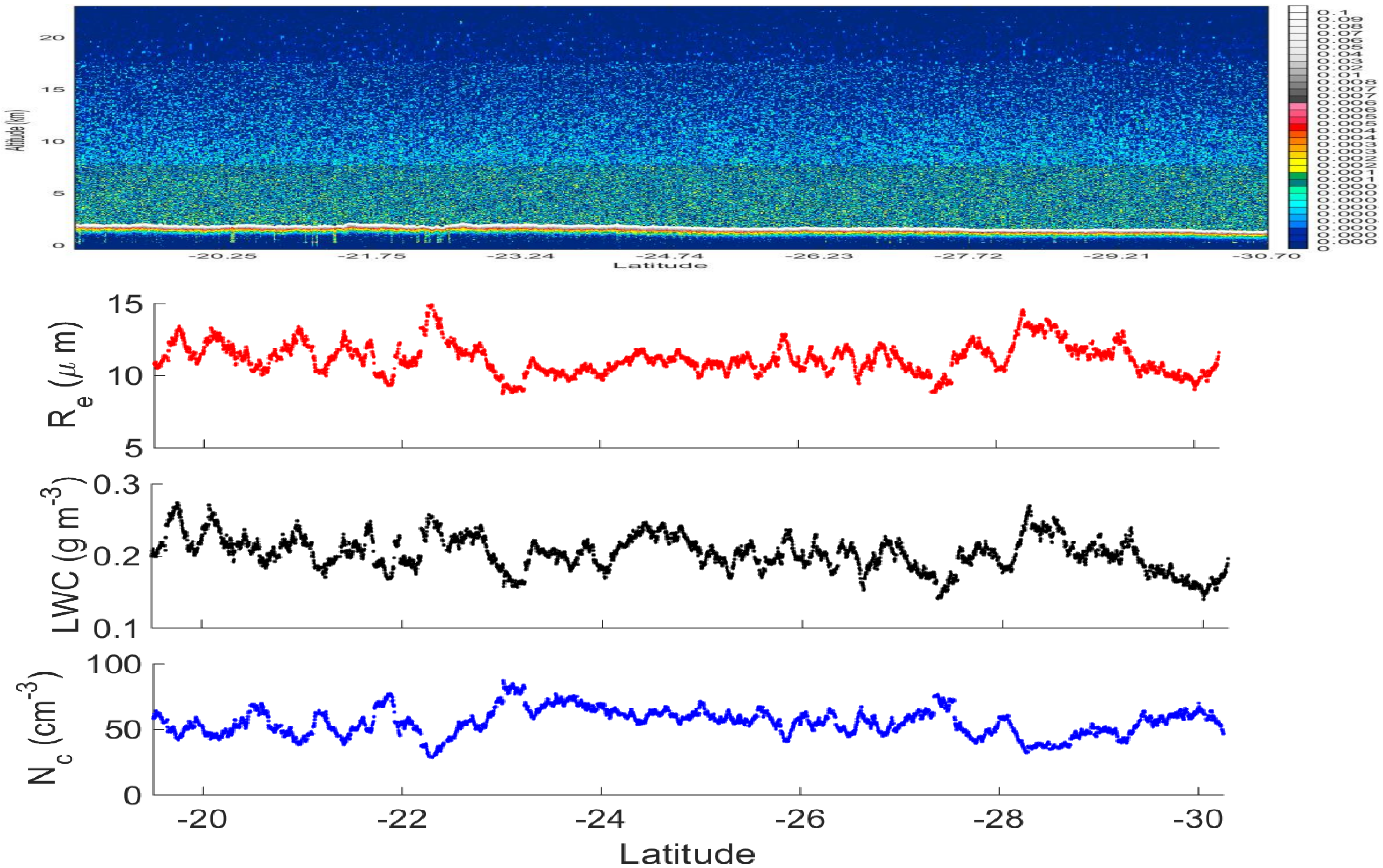
Derive cloud top liquid water content (LWC) and number concentration (N) from depolarization ratio δ and extinction coefficient σ_e

$$LWC \approx \frac{2}{3}\sigma_e R_e$$

$$N = \frac{\sigma_e}{2\pi R_e^2 (1-\nu_r)(1-2\nu_r)}$$

ν_r: variance of size distribution (here we assume it is 0.13)

Hu et al. 2007 ACP



Altitude (km)
Latitude
-20.25
-21.75
-23.24
-24.74
-26.23
-27.72
-29.21
-30.70
R_e (μ m)
LWC (g m^{-3})
N_c (cm^{-3})
-20
-22
-24
-26
-28
-30
Latitude

CALIPSO observations of the Arctic water clouds: reduction of (1) supercooled liquid water cloud fraction; and (2) depolarization ratio (a proxy of water cloud extinction coefficient and droplet number concentration)

Applications of water cloud lidar signal: deriving optical depth of aerosols above water clouds

γ_0': Layer integrated lidar backscatter for a cloud layer with no aerosols above

γ': Layer integrated lidar backscatter for a cloud layer with aerosols above

δ: Layer integrated lidar backscatter depolarization ratio for a cloud layer

Aerosol optical depth above clouds:

$$\tau = -\frac{1}{2}\ln\left(\left[\frac{\gamma'}{\gamma_0'}\right]\left[\left(\frac{1-\delta}{1+\delta}\right)^2\left(\frac{1+\delta_0}{1-\delta_0}\right)^2\right]\right).$$

Hu et al. 2007 Geop. Remote Sens. Lett.

Cloud layer integrated backscatter **without** aerosols above cloud

$$\gamma_0{}' = \int_{top}^{base} \beta'(r)dr = \frac{1 - e^{-2\eta_0\tau}}{2\eta_0 S_c} \approx \frac{1}{2\eta_0 S_c}$$

Sc: lidar ratio of water clouds (~19)

η_0: multiple scattering factor

$$\eta_0 = (\frac{1 - \delta_0}{1 + \delta_0})^2$$

Cloud layer integrated backscatter **without** aerosols above cloud

$$\gamma_0{}' = \frac{1}{2\eta_0 S_c}$$

$$= \frac{1}{2S_c}(\frac{1+\delta_0}{1-\delta_0})^2 \approx 0.0266\left(\frac{1+\delta_0}{1-\delta_0}\right)^2$$

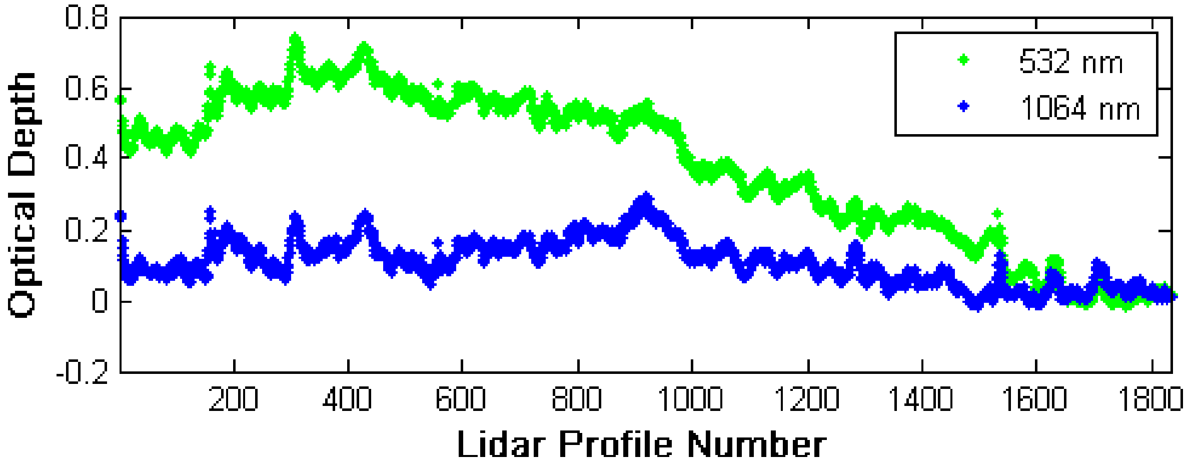
Cloud layer integrated backscatter **with** aerosols above opaque water cloud

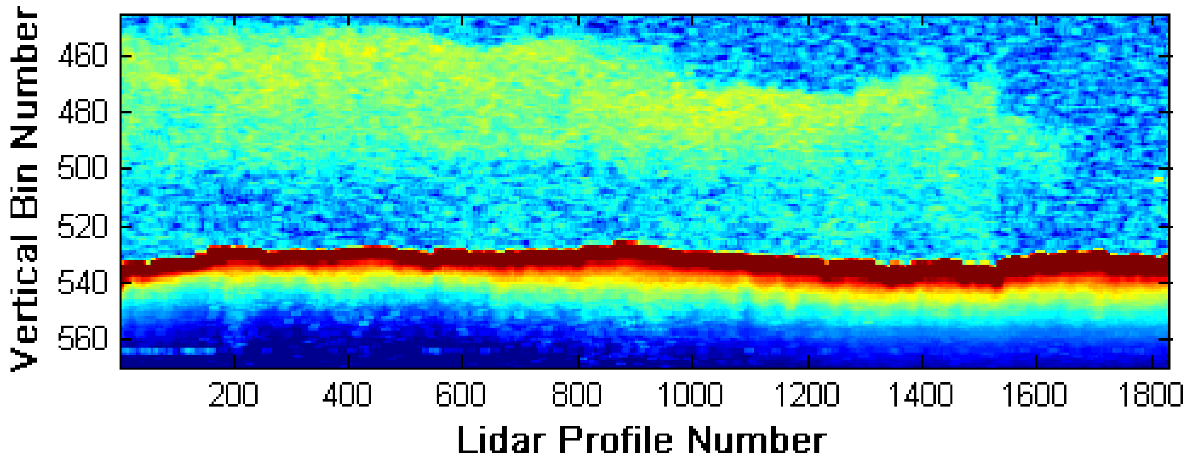
$$\gamma' = \frac{e^{-2\tau}}{2S_c}\left(\frac{1+\delta}{1-\delta}\right)^2 \approx 0.0266\left(\frac{1+\delta}{1-\delta}\right)^2 e^{-2\tau}$$

Aerosol optical depth above clouds:

$$\tau = -\frac{1}{2} ln\left[\frac{\gamma'}{\gamma_0{}'}\left(\frac{1-\delta}{1+\delta}\right)^2\left(\frac{1+\delta_0}{1-\delta_0}\right)^2\right].$$

Using attenuated backscatter of water clouds underneath smoke layer to derive optical depth of smoke above the water clouds (Hu et al., 2007).





Sources of uncertainty in the ACAOD method

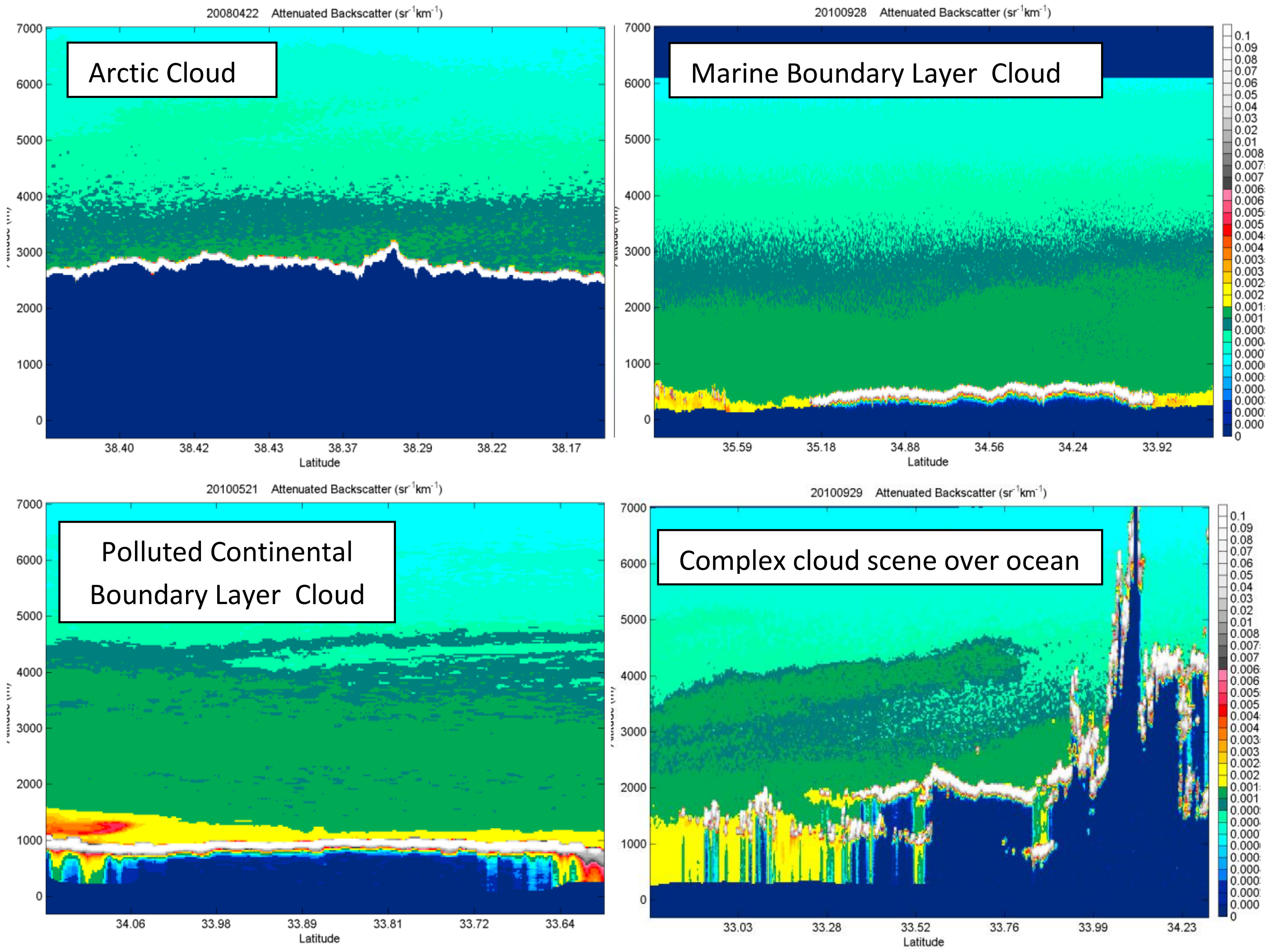
1. Extinction to backscatter ratios of clouds are not always 18 (can change from 17 to 19, and may depend on particle size)

2. The relation between multiple scattering factor and depolarization ratio has never been verified by experiments

Verify the ACAOD method using aircraft based HSRL measurements

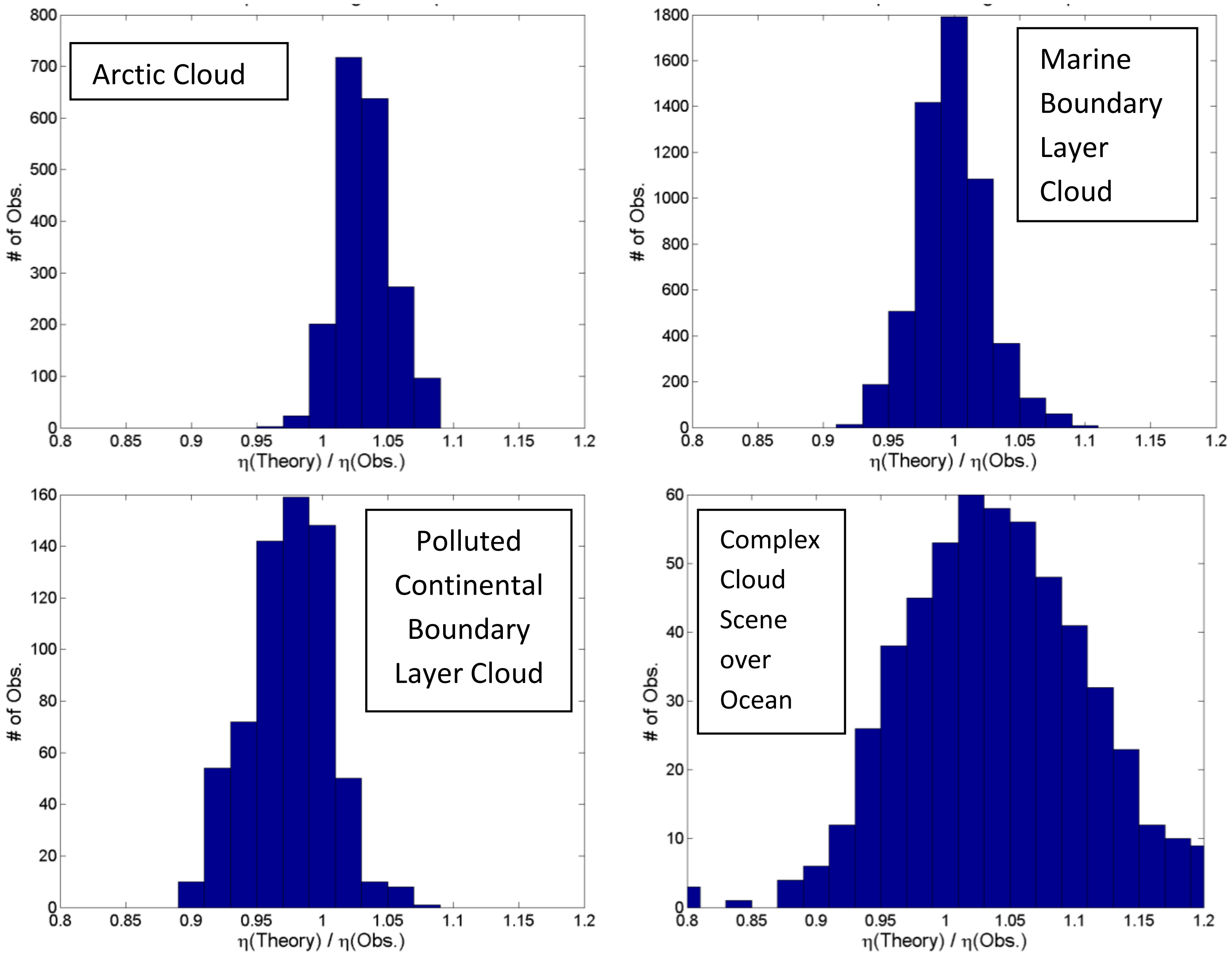
- HSRL measures molecular backscatter profile accurately from the top to the bottom of the aerosol layer
- Aerosol optical depth can be estimated by comparing the difference between the theoretical molecular backscatter without aerosols and the measured molecular backscatter
- HSRL AOD measurements for aerosols above clouds can be compared with the AOD derived from lidar backscatter from the clouds

Examine the δ – η relation using HSRL data

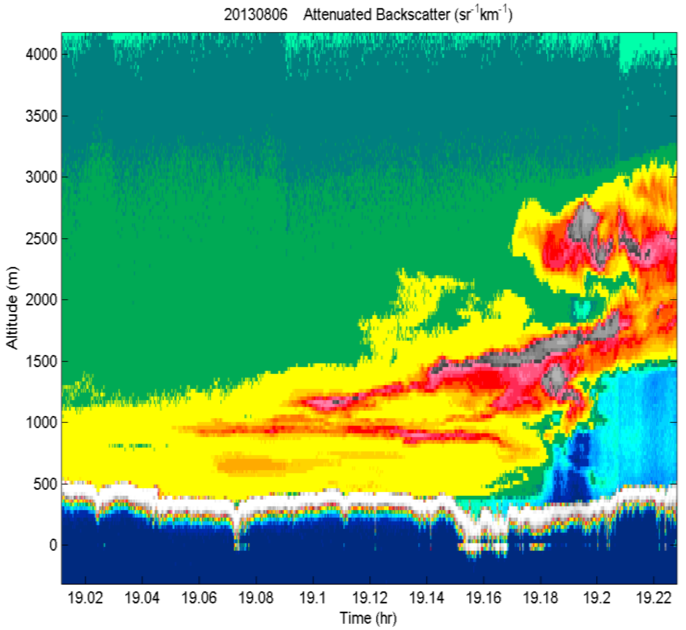


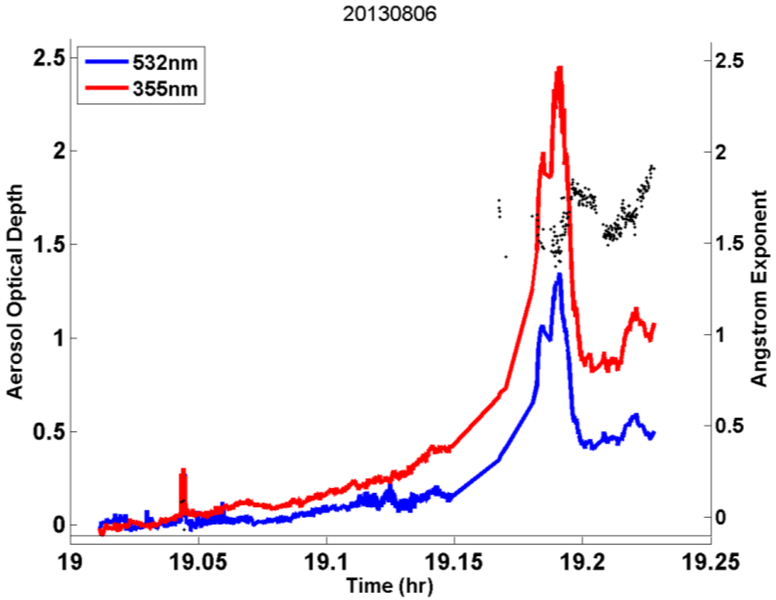
Examine the δ – η relation using HSRL data

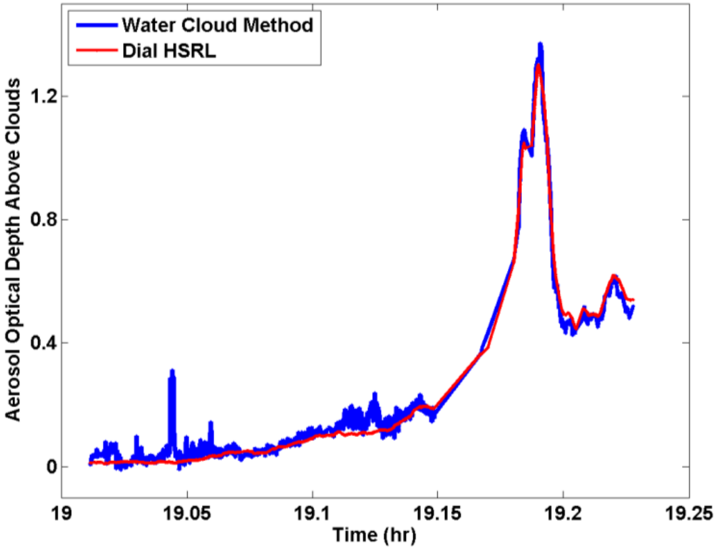
the variance represents the uncertainty of the AOD retrieval method
bias indicate that Sc is slightly different from 18

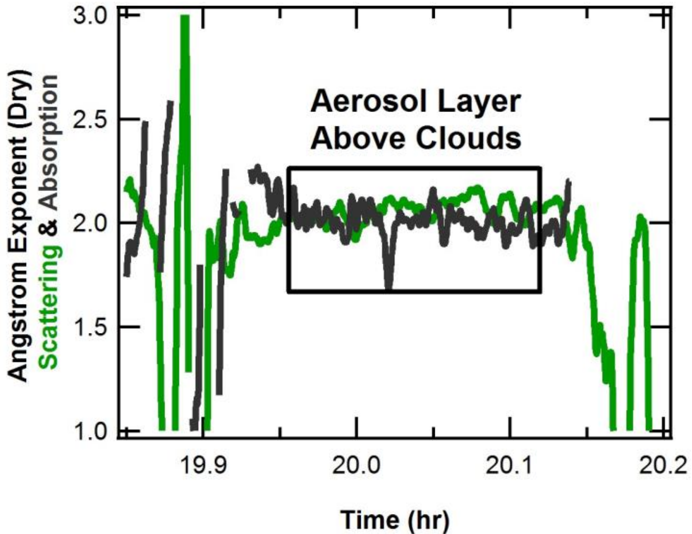


AOD retrievals using water cloud signal vs direct HSRL AOD measurements









Ongoing study: Measurement of Brillouin Scattering for direct liquid water content retrievals

- Brillouin scattering due to molecular density fluctuation of the liquid water droplet is wavelength shifted and thus can be measured using HSRL technique

- Cloud liquid water content increases with the amount of Brillouin scattering signal measured

- The cloud water content and other microphysical properties can be estimated from backscatter together with Brillouin scatter, similar to the measurements of Raman scattering of cloud droplet by GSFC (Whiteman et al)

- Brillouin scattering by water cloud droplets are about an order of magnitude stronger than Raman scattering by liquid water droplet and the Brillouin spectral is very narrow and thus can be measured during daytime

Summary

- CALIPSO provide direct measurements of water cloud microphysical properties such as
  1. extinction coefficient
  2. droplet size
  3. Droplet number concentration

- CALIPSO water cloud measurements can be used for retrieving aerosol optical depth (AOD) of aerosols above water clouds

- Airborne HSRL measurements provide extensive information for CALIPSO water cloud retrievals and AOD retrievals of aerosols above water clouds