HSRL applications, Part 1:
A 2-Year climatology of Arctic clouds for Eureka, Canada prepared from high spectral resolution lidar data

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Millimeter wave radar $\lambda=8.6\text{ mm}$

Arctic HSRL $\lambda=532\text{ nm}$
Radar backscatter cross section  11-Jan-2006
Lidar optical depth cloud base determination

Backscatter cross section $1/(m \, sr)$

Optical depth

Cloud base
Thresholds \( B_a = 10^{-6}, \quad B_r = 10^{-15} \), OD = 0.03
Thresholds \( B_a = 2 \times 10^{-7}, \ B_r = 1 \times 10^{-15} \) OD = 0.03
Steps to HSRL cloud boundary detection

Data quality checks
• Mask data where transmit wavelength is not locked to iodine absorption cell
• Mask data where laser transmitter is not single mode.
• Average data from the raw 7.5 m range resolution to 45 m
• Average data from the raw 2.5 s time resolution to 3 min
• Mask portions of image where molecular signal is lost due to attenuation
• Mask where the photon counting signal-to-noise in backscatter cross section $< 10$
• Mask where the photon counting signal-to-noise in molecular count $< 12$
• If none of the points in a profile meet data quality checks mark profile as bad

Cloud Thresholds
• Find first point in each profile with backscatter cross section larger than $1e-6 \text{ 1/(m sr)}$
Measuring upward from this point determine when the optical depth reaches threshold value. Mark this altitude as the cloud base and mark the profile as cloudy. If the optical depth threshold is not met mark profile as clear.
Cloud cover fraction averaged by month of the year
Best fit with optical depth threshold of 0.3
Collocated AHSRL and MODIS

Modis Cloud Fraction vs. AHSRL Optical Depth
Cloud fraction as function of radar threshold, 2-Aug-05 --> 31-Oct-07

Cloud fraction

Radar threshold (dBz)

Jun Jul Aug Sep Oct Nov
all months
Dec Jan Feb Mar Apr May
Comparison of radar cloud fraction with station record, 1-Sep-2005---1-Nov-2007

\[ \Sigma (\text{Radar cloud fraction - station record})^2 \]

-60 -55 -50 -45 -40 -35 -30 -25 -20 -15

Radar cloud threshold (dBZ)
Snowfall measurements using combined lidar and radar measurements
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Models have great difficulty predicting the lifetime of Arctic clouds.
Lidar-Radar Measurement of Effective Diameter

Radar scattering cross section ~ \( <\text{Mass}^2> \sim \rho <\text{Volume}^2> \sim D^6 \)

Lidar scattering cross section ~ \( <\text{Area}> \sim D^2 \)

\[
D_{\text{eff_prime}} \sim \sqrt{\left( \frac{<\text{Radar scattering cross section}>}{<\text{Lidar scattering cross section}>} \right)}
\]

Notice that this differs for the usual definition:

\[
D_{\text{eff}} = \frac{<\text{Particle volume}>}{<\text{Particle area}>}
\]

Total particle volume = \( D_{\text{eff}} \times \) Total particle area \( \sim D_{\text{eff}} \times \) Lidar scattering cross section
Problem:
Ice crystals are not spherical
Spheroid model to represent measurable properties of a snowflake

Top view

\[ h = a D^\zeta \quad \text{(Auer and Veal)} \]

mass = \( \frac{\pi}{6} D^2 h \)

Side view

projected area = \( \frac{\pi}{4} D^2 \)

Bottom view

We assume a modified Gamma distribution

\[ N(D) \sim D^\alpha \exp(-bD^\gamma) \]

Radar backscatter \sim particle concentration \( <mass^2> \)
Lidar extinction \sim particle concentration \( <\text{projected area}> \)
Fall Velocity \sim F(\text{mass, projected area})
The size distribution and the spheroid model are used to compute the observable quantities:

Integrating over the size distribution $N(D)$ to derive $D'_{\text{eff}}$

$$D'_{\text{eff}} = 4\sqrt{9\frac{\langle V^2 \rangle}{\pi <A>}} = 4\sqrt{\int \frac{a^2 D^4 D^2 \zeta N(D) dD}{D^2 N(D) dD}} = 4\sqrt{\frac{2\lambda^4 \beta_{\text{radar}}}{\pi^3 K^2_{\text{ice}} \beta_s}}$$

Radar reflectivity weighted fall velocity:

$$\langle V_f \rangle = \frac{\int V_f D^4 D^2 \zeta N(D) dD}{\int D^4 D^2 \zeta N(D) dD}$$

Fall velocity is parameterized in terms of $X$, the Best #:

$$V_f = \left( \frac{\eta}{\rho_{\text{air}} D} \right) \{(d_0^2/4)[(1+C_1 X^{1/2})^{1/2} - a_o X^{bo}]$$

$$X = \frac{(2 \text{ mass } \rho_{\text{air}} g D^2)}{\text{(area } \eta^2)}$$
Using the gamma size distribution model, the Best # based fall velocity model, and spheroid representation of particles we can generate the following plot.
Doppler velocity vs. $D_{\text{eff}, \prime}$ below melting layer

Zeta--water, $dt = 600$ s, $z = 200$ m, $\alpha = 1, \gamma = 1$, 19-jun-06 12:30---> 15:00

Radar weighted fall velocity (m/s)

$D_{\text{eff}, \prime}$ (microns)
Doppler velocity vs. $D_{\text{eff}}'$ in snow layer

Zeta-ice, $dt=600$ s, $z=500$ m, $\alpha=1$, $\gamma=1$, 19-jun-06 12:30 --> 15:00
The fall velocity spectrum may be broadened by turbulence within the radar averaging volume—here we show spectra for very slowly falling particles broadened by turbulence.

When the low velocity edge is assumed to be generated by particles with negligible fall velocity, the particles appear to be falling much faster in a rising air mass.
Error due to the absence of small particles detected by radar

Small particles may not be present or their returns may be below the noise floor of the radar. Larger, faster falling particles may be detected generating spectra displayed from zero without any vertical motion of the air.

When the low velocity edge of the spectra is assumed to be generated by particles with negligible fall velocity, the particles appear to fall too slowly in a downward moving air mass.
Doppler Velocity  27-Nov-07

Particle fall velocity

zeta,  h=d^z

Number density

Ice water content

Precipitation rate
Doppler Velocity  27-Nov-07

Particle fall velocity

zeta,  h=d^z

Fall velocity vs d_{eff}', 1-hr median high pass

Number density

Precipitation rate
Average particle velocity, $z = 1.6 \rightarrow 2$ km

Average air velocity, $z = 1.6 \rightarrow 2$ km
Thresholds \( B_{a} = 1 \times 10^{-6}, \quad B_{r} = 1 \times 10^{-15}, \quad OD = 0.03 \)
Thresholds \( B_a=10^{-6}, \quad B_r=10^{-15}, \quad OD=0.2 \)
Looking for more information and better algorithms
Clouds defined by lidar threshold of $1 \times 10^{-6}$ and radar threshold of $6 \times 10^{-12}$ $1/(m \text{ sr})$