Ground-based Retrieval of Seasonal Cloud and Precipitation Properties in the Arctic

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1 Introduction

Clouds and precipitation play an important role in the energy and moisture budget of the Arctic region (Curry et al. 1996). While their properties are difficult to determine from space because the underlying snow/ice surface has little visible, thermal or microwave contrast with clouds, ground-based retrievals can be obtained from the Department of Energy (DOE) Atmospheric Remote Sensing Measurement (ARM) program North Slope of Alaska (NSA) site near Barrow, Alaska. Here, a new set of retrieval techniques suited to NSA are described, from which seasonal variability of low-level Arctic clouds and precipitation are obtained.

2 Retrieval Algorithm

2.1 Precipitation retrieval

ARM Doppler radar velocity and reflectivity are used to obtain precipitation properties. Precipitation is assumed to be present when laser determined cloud base \( H_{\text{base}} \) is higher than radar determined cloud base \( H_{\text{radar}} \) by 45 m, where 45 m is half of the radar range gate. Precipitation phase is assumed to be ice when temperature at precipitation level \( T_p \) is below 273.15 K, and water when \( T_p \) is above 273.15 K.

The precipitation particle terminal velocity \( V_T \) is related to its particle spherical radius \( r_{\text{sphere}} \) (Gelbard et al. 1980; Heymsfield 1972) through

\[
V_T = \begin{cases} 
K_1 r_{\text{sphere}}^2 / f, & r_{\text{sphere}} < 40 \mu m \\
K_2 r_{\text{sphere}} / f, & 40 \mu m < r_{\text{sphere}} < 0.6 \text{ mm} 
\end{cases}
\]

where \( f \) is a shape factor, \( K_1 = 1.19 \times 10^6 \text{ cm}^{-1}\text{s}^{-1} \) and \( K_2 = 8 \times 10^3 \text{ s}^{-1} \) are empirical parameters, and \( r_{\text{sphere}} \) is the radius of a spherical droplet with a mass equivalent to the precipitation particle. It is assumed that \( f = 1 \) for liquid droplet and \( f = 4 \) for column ice particles (Heymsfield 1972; Ohtake et al. 1982).

Here, we assume that the mean terminal velocity \( \bar{V}_T \) and log-normal mode radius \( r_n \) of precipitation are equivalent to \( V_T \) and \( r_{\text{sphere}} \), respectively. Frisch et al. (2002) argued that averaged over several minutes, the measurements of radar Doppler velocity of precipitation \( \langle V_D \rangle \) approach the mean precipitation particle velocity \( \bar{V}_T \). Assuming further that \( \bar{V}_T \) and \( V_T \) are similar because the Arctic is generally stable with low updraft speeds relative to \( V_T \), the precipitation mode radius \( r_n \) can be obtained from \( \langle V_D \rangle \) according to

\[
r_n = \begin{cases} 
\langle V_D \rangle / K_1^{1/2} & r < 40 \mu m \\
\langle V_D \rangle / K_2 & 40 \mu m < r < 0.6 \text{ mm} 
\end{cases}
\]

Assuming a log-normal size distribution for precipitation (Frisch et al. 1995),

\[
\begin{align*}
r_{\text{eP}} &= r_n \exp(2.5 \ln^2 \sigma_g) \\
N_P &= Z / (2^6 r_{n}^6 \exp(18 \ln^2 \sigma_g)) \\
P_P &= \frac{4}{3} \pi \rho_i V_T r_{\text{eP}}^3 N_P / \rho_w
\end{align*}
\]

where \( Z \) is the radar reflectivity, \( r_{\text{eP}} \) and \( N_P \) are the effective radius and number concentration of the precipitation, \( P_P \) is the precipitation rate, \( \rho_i \) and \( \rho_w \) are the bulk density of ice and water, respectively, and \( \sigma_g \) is the assumed standard deviation of a log-normal size distribution.

2.2 Cloud retrieval

To obtain the cloud properties of single-layer stratus in the Arctic, we have modified an ice cloud retrieval

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algorithm developed by Mahesh et al. (2001) for application to the Antarctic. The retrieval method requires ARM NSA-AAO ground-based remote sensing measurements, and Global Ozone Monitoring (GOME) stratospheric ozone profile measurements from the European Remote Sensing (ERS-2) satellite.

As illustrated in Fig. 1, the retrieval method consists of six parts: 1) subtraction of precipitation effects on surface downwelling infrared radiation, 2) determination of cloud phase, 3) selection of emissivity (ε) microwindows at which ε varies monotonically with cloud effective radius (r_e) and geometric optical depth (τ_g), 4) calculation of a look-up table for emissivity (ε) and transmittance (τ_c) as a function of r_e and τ_g, 5) calculation of ε and τ_c based on measurements, and 6) retrieval of r_e and τ_g through a minimization process based on an intercomparison between calculated ε, τ_c and those from the look-up table.

This retrieval algorithm is similar to Mahesh et al. (2001) with the exception that it includes the subtraction of precipitation radiance, that cloud phase is determined based on the cloud emissivity between 800 and 900 nm (Turner et al. 2003) and the cloud brightness at 8.4 μm and 10.7 μm (King et al. 2004), and that cloud base is determined using laser instead of the CO2 slicing method.

Cloud water path (WP) and particle number concentration (N) can be computed from

\[ WP = 2p r_e τ_g / 3 \]  
\[ N = 3 WP \exp(3.0 σ^2)/(4π r_e^3 ΔH) \]

where ρ is bulk density, σ is the standard deviation for cloud particle size distribution, and ΔH (H_top − H_base) is the cloud depth.

We should note that this retrieval method is applicable only to single-layer graybody clouds. Fig. 2 shows the values of monthly fraction of clouds which are single-layer, and the fraction of single-layer clouds which are graybodies. In each month, over 60% of clouds are single-layer, and over 65% single-layer clouds are graybodies. Even 90% of single-layer clouds are graybodies in winter. However, the fraction of clouds which are graybodies ranges from 40% in summer to 60% in winter. Thus, the cloud properties retrieved with our method are just for part, not all of the Arctic clouds, and the retrieved cloud liquid water path will be low biased.

3 Results

Fig. 3a shows retrieved ice crystal precipitation (ICP) properties between 2000 and 2003. ICP effective radius (r_eICP) and number concentration (N_ICP) median values are 0.052 l⁻¹ and 226 μm, respectively, with a standard deviation of 64.6 l⁻¹ and 130 μm, respectively. For comparison, Ohtake et al. (1982) observed Arctic column ice crystals with size range of 30-300 μm on the c-axis and 15-25 μm on the a-axis at low temperatures. Girard and Blanchet (2001) described Arctic diamond dust with particle number concentrations less than 4 cm⁻³.

Fig. 3b, c and d show monthly distributions of precipitation effective radius (r_eP), number concentration (N_P) and precipitation rate (P_P) between 2000 and 2003. Precipitation effective radius r_eP increases during spring and decreases during fall, and precipitation number concentration N_P is nearly uniform in spring and decreases in fall, indicating reduced precipitation in winter. r_eP is a minimum
retrievals are limited to gray-body clouds with LWP generally less than 150 \( \mu m \) during winter and spring. Garrett and Zhao (2006) have shown these changes can be attributed to Arctic haze events from mid-latitude pollution sources, which are common during winter and spring.

(30–50 \( \mu m \)) and \( N_P \) is a maximum (1–10 \( cm^{-3} \)) in summer, which may be caused by precipitation liquid phase and sufficient water sources from ocean. The monthly mean precipitation rate increases in spring and reaches a maximum (3.57 mm/day) in July, and it decreases in fall and reaches a minimum (0.01 mm/day) in February. The annual mean values for \( r_{eP} \), \( N_P \), and \( P_P \) are about 107 \( \mu m \), 393 \( l^{-1} \) and 0.88 mm/day, respectively.

Estimates of cloud phase indicate that most low-level thin clouds are liquid clouds in all seasons, but especially so in summer. Ice and mixed-phase clouds form mainly in winter, when their incidence is about 40% and 4%, respectively (Fig. 4a). Fig. 4b, c and d show the properties of liquid clouds. Liquid cloud particle effective radius \( r_e \) ranges from 2 to 25 \( \mu m \), and cloud number concentration \( N \) ranges from 3 \( cm^{-3} \) to 300 \( cm^{-3} \). The annual mean values of retrieved \( r_e \) and \( N \) are 10.1 \( \mu m \) and 112 \( cm^{-3} \), respectively. Clouds are thinnest in winter, although retrievals are limited to gray-body clouds with LWP generally less than 150 g m\(^{-2}\). Cloud number concentration \( N \) decreases about 80 \( cm^{-3} \) and effective radius \( r_e \) increases about 4 \( \mu m \) between winter and summer. Garrett and Zhao (2006) have shown these changes can be attributed to Arctic haze events from mid-latitude pollution sources, which are common during winter and spring.

Figure 3: The properties of retrieved precipitation. (a) the range of retrieved ice crystal precipitation effective radius (\( r_{eICP} \)) and number concentration (\( N_{ICP} \)) values. (b, c and d) the monthly distributions for median values of precipitation effective radius (\( r_{eP} \)), number concentration (\( N_P \)) and precipitation rate (\( P_P \)).

Figure 4: (a) monthly distribution of water (blue), ice (green) and mixed-phase (brown) clouds between 2000 and 2003. (b, c and d) monthly mean cloud properties (\( r_e \), \( N \) and \( LWP \)).

4 Bibliography


Mahesh, A., V. P. Walden, and S. G. Warren, 2001:
