



CALIPSO/CALIOP Cloud Phase Discrimination Algorithm

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ABSTRACT

The current cloud thermodynamic phase discrimination by Cloud-Aerosol Lidar Pathfinder Satellite Observations (CALIPSO) is based on the depolarization of backscattered light measured by its lidar [Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP)]. It assumes that backscattered light from ice crystals is depolarizing, whereas water clouds, being spherical, result in minimal depolarization. However, because of the relationship between the CALIOP field of view (FOV) and the large distance between the satellite and clouds and because of the frequent presence of oriented ice crystals, there is often a weak correlation between measured depolarization and phase, which thereby creates significant uncertainties in the current CALIOP phase retrieval. For water clouds, the CALIOP-measured depolarization can be large because of multiple scattering, whereas horizontally oriented ice particles depolarize only weakly and behave similarly to water clouds. Because of the nonunique depolarization-cloud phase relationship, more constraints are necessary to uniquely determine cloud phase. Based on theoretical and modeling studies, an improved cloud phase determination algorithm has been developed. Instead of depending primarily on layer-integrated depolarization ratios, this algorithm differentiates cloud phases by using the spatial correlation of layer-integrated attenuated backscatter and layer-integrated particulate depolarization ratio. This approach includes a two-step process: 1) use of a simple two-dimensional threshold method to provide a preliminary identification of ice clouds containing randomly oriented particles, ice clouds with horizontally oriented particles, and possible water clouds and 2) application of a spatial coherence analysis technique to separate water clouds from ice clouds containing horizontally oriented ice particles. Other information, such as temperature, color ratio, and vertical variation of depolarization ratio, is also considered. The algorithm works well for both the 0.3° and 3° offnadir lidar pointing geometry. When the lidar is pointed at 0.3° off nadir, half of the opaque ice clouds and about one-third of all ice clouds have a significant lidar backscatter contribution from specular reflections from horizontally oriented particles. At 3° off nadir, the lidar backscatter signals for roughly 30% of opaque ice clouds and 20% of all observed ice clouds are contaminated by horizontally oriented crystals.

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FIG. 1. The phase function and P_{22}/P_{11} for hexagonal ice crystals. The aspect ratios of ice crystals are taken from Yang et al. (2001), and the size distributions are from Baum et al. (2005).

1. Introduction

In passive remote sensing, cloud thermodynamic phase (water or ice) information typically comes from the spectral absorption difference between visible (VIS; 0.65 μ m) and shortwave infrared (SWIR; 1.5–1.6 and 3–4 μ m) wavelengths. Neither ice clouds nor water clouds absorb much visible light. However, absorption by both ice and water increases at near-infrared wavelengths, and multiple scattering enhances the absorption. At SWIR wavelengths, ice clouds when multiple scattering predominates. Furthermore, the brightness temperatures corresponding to three IR window channels centered at 8.5, 11, and 12 μ m are also often used for discriminating cloud thermodynamic phase (e.g., Baum et al. 2000).

Lidar-based cloud phase discrimination differs significantly from passive remote sensing. On the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) space-based platform, there are three coaligned nadir-viewing instruments, one of which is the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP). At CALIOP wavelengths 532 and 1064 nm, neither ice clouds nor water clouds absorb much light. Therefore, it is insufficient to rely on 532- and 1064-nm backscatter differences to differentiate cloud phase.

Ground-based and aircraft-based lidars can readily determine cloud phase using depolarization ratios (Sassen 1991) while pointing the lidar a few degrees off vertically. At normal incidence, linearly polarized backscattered light (at 180° scattering angle) retains the same plane of polarization as the incident light for spherical particle or particles with large smooth surfaces. The backscattered light becomes depolarized after refraction and internal reflection processes in randomly oriented (RO) ice particles. The depolarization resulting from multiple scattering in water clouds (Young et al. 2000) is relatively small because multiple scattering is proportional to the lidar footprint size, which is small (on the order of meters) for these lidars.

As with ground-based depolarization lidars, CALIOP relies on polarization information to determine cloud phase, based on the assumption that water cloud particles are spheres and ice clouds are composed of nonspherical particles. For space-based lidars such as CALIOP, which has a footprint size of 90 m at the earth's surface, water clouds can exhibit a strong depolarization signal because of the presence of multiple scattering (Hu et al. 2001). A failure to account for the additional depolarization induced by multiple scattering can introduce substantial uncertainties in cloud phase discrimination.

In accounting for multiple scattering in ice clouds, it is convenient to assume that ice crystals have random orientations in radiative transfer and remote sensing studies. However, under conditions of weak updraft velocities, some types of ice cloud particles, such as columns and plates, appear to have preferred horizontal orientations (Platt et al. 1978). Recent measurements suggest that a certain degree of preferential orientation is present in as much as 40%–50% of moderately thick ice clouds (Thomas et al. 1990; Chepfer et al. 1999; Hu 2007; Hu et al. 2007).

CALIOP was pointed near nadir (0.3°) before November 2007, but this was changed subsequently to 3° off nadir. With this geometry, a portion of the backscattered light comes from scattering from nearly horizontally oriented (HO) ice crystals with CALIOP's laser beam normal to the surface of these ice particles. This portion of the backscattered light has the same polarization as



FIG. 2. Frequency of occurrence of clouds as a function of cloud temperature and depolarization ratio. Only those clouds with a layer-integrated backscatter larger than 0.01 sr^{-1} , corresponding to an optical depth greater than about 0.3, are included. The data are from (left) January 2007, when the lidar is pointed 0.3° off nadir, and (right) January 2008, when the lidar is pointed 3° off nadir.

the incident beam; thus, it is depolarized in a way similar to that for the backscatter from spherical particles. The purpose of tilting CALIOP to 3° was to reduce the influence of the high and variable reflectance from horizontally oriented ice particles on the determination of cloud phase and to permit more accurate retrievals of extinction profiles in ice clouds.

The prelaunch CALIPSO cloud phase algorithm, which is used in the release 2 data product, is based primarily on theoretical model simulations of lidar backscatter and polarization (Hu et al. 2001). In the prelaunch CALIPSO phase algorithm, the depolarization threshold values that separate water and ice clouds are a function of layer-integrated attenuated backscatter coefficients. With this approach, we have found that horizontally oriented ice (HOI) cloud particles may be classified as either ice or water clouds. Clouds with very high layerintegrated attenuated backscatter ($>0.2 \text{ sr}^{-1}$) and very low depolarization (<0.1) are identified as ice clouds. For very thin clouds and the lower layers of multilayered clouds (i.e., multiple cloud layers in a vertical column), the depolarization can be noisy. In these cases, cloud temperatures from models are also considered in the cloud phase determination. In the operational algorithm, cloud phase and its likelihood are first estimated based on the depolarization ratio and signal-to-noise ratio (SNR). If the probability is higher than 75%, then a cloud phase is assigned. If the probability is lower than 75%, then the probability of a cloud phase based on temperature is also considered.

Recent algorithm development studies have led to significant advances, with an improved treatment of the multiple-scattering process that includes horizontally oriented ice particles (Hu et al. 2006; Hu 2007; Hu et al. 2007). Although CALIOP information on cloud phase primarily comes from cloud particulate depolarization measurements, other information such as spatial coherence, cloud-top height and temperature, and wavelength dependence of the lidar backscatter provides additional information for lower SNR cases such as optically thin clouds and multilayered cloud occurrences, such as for the case when optically thin cirrus overlies a lower-level water cloud. The satellite lidar measurements provide the needed statistics for the new algorithm.

In this paper, we first briefly reiterate the theoretical basis (Hu 2007) for lidar-based cloud phase discrimination. We then describe the operational procedure and the performance of a new cloud phase algorithm. This new approach will be implemented as part of the operational CALIPSO level 2 algorithms in a future data product release.

2. Depolarization for cloud phase discrimination: Theoretical basis

The linear depolarization ratio δ of lidar backscatter by cloud particles is defined as the ratio of the crosspolarization component β_{\perp} and the copolarization component β_{\parallel} as follows:

$$\delta = \frac{\beta_{\perp}}{\beta_{//}}.$$
(1)

CALIOP's laser beam is linearly depolarized; that is, the Stokes parameters associated with the beam are given by $U_0 = V_0 = 0$ and $I_0 = Q_0$. For single-scattering events, the depolarization ratio can be linked to the scattering phase matrix (Hovenier and van der Mee 1983) via



FIG. 3. Frequency of occurrence of optically thin clouds (with a layer-integrated attenuated backscatter less than 0.01 sr⁻¹) having a low volume depolarization ($\delta < 0.2$). The frequency of occurrence is shown as functions of (top) temperature and layer-integrated volume depolarization ratio and (bottom) temperature and the equivalent layer-integrated particulate depolarization ratio for (left) January 2007 and (right) January 2008.

$$\begin{split} \delta &= \frac{\beta_{\perp}}{\beta_{//}} = \frac{I - Q}{I + Q}, \\ &= \frac{I_0 [P_{11} - P_{21} \cos(2\phi_2)] + Q_0 [P_{12} \cos(2\phi_1) - P_{22} \cos(2\phi_1) \cos(2\phi_1) + P_{33} \sin(2\phi_1) \sin(2\phi_1)]}{I_0 [P_{11} + P_{21} \cos(2\phi_2)] + Q_0 [P_{12} \cos(2\phi_1) + P_{22} \cos(2\phi_1) \cos(2\phi_1) - P_{33} \sin(2\phi_1) \sin(2\phi_1)]}, \end{split}$$
(2)

where P_{ij} are the elements of the scattering phase matrix and ϕ_1 and ϕ_2 are the azimuthal angles of the incident and scattering planes, respectively. For randomly oriented particles, $P_{12} = P_{21}$. For the backscattering direction, $\cos(2\phi_1) = \cos(2\phi_2) = 1$ and $\sin(2\phi_1) = \sin(2\phi_2) = 0$. Thus, the depolarization ratio associated with a singlebackscattering event is given by

$$\delta = \frac{P_{11} - P_{22}}{P_{11} + P_{22}}.$$
(3)

For spherical particles such as liquid water droplets, $P_{11} = P_{22}$. Thus, the depolarization ratio is zero. For ice clouds composed of randomly oriented particles, P_{22} from theoretical calculations is most likely between 0.3



FIG. 4. Frequency of occurrence of clouds as a function of layer-integrated attenuated backscatter and depolarization ratio for (left) January 2007 and (right) January 2008. The lines show the theoretical relation derived from Monte Carlo simulations (blue; Hu 2007; Hu et al. 2006, 2007), the threshold for separating water from ice (red), and the threshold for separating water from HO nonspherical particles (green).

and 0.6 (Hu et al. 2001) and thus the particulate depolarization is between 0.25 and 0.54, depending on particle shape and size. Figure 1 shows the phase function and P_{22}/P_{11} for hexagonal ice columns with various effective sizes. The aspect ratios of ice crystals used in the computation are consistent with those in Yang et al. (2001), and the size distributions are from Baum et al. (2005). We note that the departure of P_{22}/P_{11} from unity may be thought of as a "particle-nonsphericity index" because P_{22}/P_{11} is always unity for spheres.

Particulate depolarization is not directly measured by CALIOP. The instrument measures the volume depolarization ratio, which includes the contribution of both molecular and particulate backscatter. The volume and particulate depolarization ratios are not significantly different from each other for dense and moderately dense clouds.

Figure 2 shows the cloud backscatter volume depolarization as a function of temperature for clouds with layer-integrated backscatter larger than 0.01 sr⁻¹, corresponding to an ice cloud optical depth greater than 0.3. The left panel shows data for January 2007, when the lidar is pointed 0.3° off nadir. The right panel shows data for January 2008, when the lidar is pointed 3° off nadir. Globally, the volume depolarization ratios of ice clouds with cloud-top temperatures colder than -40° C are between 0.25 and 0.45. The depolarization ratio is negatively correlated with cloud-top temperature (the colder the cloud-top temperature, the larger the depolarization ratio). This is consistent with the depolarization statistics of ground measurements and theoretical calculations (Platt et al. 1987, 1998; Sassen and Benson 2001; You et al. 2006).

For cloud-top temperatures between -10° and -40° C, the depolarization ratios are mostly between 0.05 and 0.3. In contrast to the signals from colder clouds, the depolarization ratios increase with cloud-top temperature. At these temperatures, water, ice, and mixed-phase clouds can coexist, making the thermodynamic phases difficult to define based on the cloud temperature and depolarization.

For optically thin clouds with extinction coefficients less than 0.2 km^{-1} , the molecular backscatter accounts for more than 10% of the 532-nm lidar return. Thus, for optically thin clouds, the volume depolarization ratio measured directly by CALIOP can be significantly lower than the corresponding particulate depolarization ratio.

Assuming that the cloud particulate backscatters of 532 and 1064 nm are equivalent and the molecular backscatter is negligible at 532-nm cross-polarization and 1064-nm channels, we can estimate the cloud particulate depolarization as

$$\delta_{p} \approx \frac{\beta_{532,\perp}}{\beta_{1064,//}} \approx \frac{\beta_{532,\perp}}{\beta_{1064} - \beta_{532,\perp}} \approx \frac{1}{\frac{\beta_{1064}}{\beta_{532,\perp}} - 1}.$$
 (4)

The errors in the estimated particulate depolarization ratio can be as high as 0.1. Cloud backscatter measurements at 1064 nm can be 70%–125% of the 532-nm cloud backscatter because of uncertainties in the 1064-nm



FIG. 5. January 2007 statistics: frequency of occurrence of clouds as a function of layer-integrated attenuated backscatter and depolarization ratio for four different cloud-top temperature ranges.

calibration (Reagan et al. 2002) and differences in the extinction-to-backscatter ratios and multiple scattering between the two wavelengths. This leads to the uncertainty in the estimated particulate depolarization ratio, which is taken into account in the cloud phase algorithm.

Figure 3 shows the difference between using Eqs. (3) and (4). The bottom panels of Fig. 3 show that the estimated particulate depolarization ratio using Eq. (4) looks quite reasonable, because the temperature dependence of depolarization ratio mimics the pattern of thicker clouds in Fig. 2. Figure 3 indicates that by combining 1064- and 532-nm cloud measurements, it is possible to estimate the particulate depolarization reasonably well without going into a complicated molecular correction procedure. For clouds with layer-integrated at-

tenuated backscatter less than 0.01 sr^{-1} , the particulate depolarization ratios estimated from Eq. (4) are used in the cloud phase algorithm.

a. Simple depolarization–backscatter $(\delta - \beta)$ thresholds for cloud phase discrimination

For single scattering, water cloud does not depolarize. Depolarization increases at each scattering event before being backscattered into the receiver field of view (FOV). Because of CALIOP's relatively large FOV, multiple scattering can contribute as much 75% of the measured water cloud–integrated backscatter and create significant depolarization.

Simulations of water cloud depolarization using a full-Stokes-vector Monte Carlo multiple-scattering model



FIG. 6. As in Fig. 5, but for January 2008.

(Hu et al. 2001, 2003) indicate that there is a simple relationship between layer-integrated depolarization ratio and multiple scatter of layer-integrated backscatter. This relationship agrees reasonably well with groundbased measurements (Hu et al. 2006) and CALIPSO observations (Hu 2007; Hu et al. 2007):

$$\gamma_{\text{total}}' = \gamma_{\text{single}}' \left(\frac{1+\delta}{1-\delta}\right)^2 = \frac{1}{2S_c} \left(\frac{1+\delta}{1-\delta}\right)^2 \approx 0.0265 \left(\frac{1+\delta}{1-\delta}\right)^2.$$
(5)

This relationship is shown as the curved blue line in Fig. 4. The water cloud observations are clustered close to the theoretical curve in both the left (January 2007; lidar pointing at 0.3° off nadir) and right (January 2008; lidar pointing at 3° off nadir) panels. Ice clouds with randomly

oriented particles are clustered at the top-left region (high depolarization and relatively low layer-integrated backscatter). In both panels of Fig. 4 (bottom-right part), with low depolarization and relatively high backscatter, are clouds with horizontally oriented particles. The ice clouds with horizontally oriented particles, such as plates, scatter light either in the forward or in the specular reflection direction. Very few forward-scattered photons leave the FOV. As a result, for the same amount of backscatter, the effective extinction of clouds composed of horizontally oriented particles is much smaller than that of water clouds. Thus, the integrated backscatter signal from ice clouds with horizontally oriented particles is substantially larger than that from water clouds.

As a first step in the cloud phase discrimination, we use thresholds for separating clouds containing randomly



FIG. 7. Histogram of the correlation between layer-integrated particulate depolarization ratio and attenuated backscatter for (left) HOI cloud particles and (right) warm water clouds.

oriented ice particles, clouds containing water cloud droplets, and clouds with horizontally oriented particles. The red and green lines in Fig. 4 are the thresholds for separating ice from water (red) and water from horizontally oriented particles (green) starting from the top left and progressing to the bottom right. Ice clouds with randomly oriented particles are above the red line. Horizontally oriented particles are below the green line. Those clouds between the red and the green lines are mostly likely water clouds. The thresholds (red and green lines) are based on Monte Carlo simulations of clouds (Hu et al. 2001; Hu 2007).

Figure 5 shows the depolarization ratio layer–integrated backscatter (δ – β) relationship for clouds with different cloud-top temperatures. There are very few cases where the measured δ – β relationship falls into the water cloud region when the cloud-top temperature is lower than –40°C (Fig. 5, top left). The frequency of such cases is even lower in Fig. 6 (January 2008), when the lidar is pointed at 3° off nadir.

Some supercooled water cloud cases can be found in both the top-right (cloud-top temperature between -20° and -40° C) and bottom-left (cloud-top temperature between 0° and -20° C) panels of Figs. 5 and 6.

When CALIOP is pointed at 0.3° (Fig. 5), horizontally oriented particles are found at all cloud-top temperatures, especially at temperatures between 0° and -40° C. The highest frequency of horizontally oriented ice particles occurs between 0° and -20° C, where most ice clouds show the signature of horizontal orientation. This finding is consistent with ground observations (Ryan et al. 1976; Platt 1977; Platt et al. 1998). Horizontally oriented ice particles appear infrequently when cloudtop temperature is warmer than 0°C. If all ice cloud particles are either randomly oriented particles or uniform platelike particles with horizontal orientation, this simple δ - β method should be sufficient for cloud phase discrimination and the spatial coherence technique described by Hu (2007) would be unnecessary. In reality, ice cloud particles with horizontal orientation are mixed with randomly oriented particles creating nondiscrete depolarization dependences. When the threshold technique identifies a layer as ice cloud, it is almost certain that the clouds are composed of ice. For water clouds, the threshold method can incorrectly identify the phase because of the overlapping signatures of water and horizontally oriented ice particles. The spatial coherence method provides a method to differentiate ice clouds with horizontal orientation from water clouds.

b. Spatial coherence correlation of δ - β for identifying horizontally oriented particles

The spatial coherence method (Hu 2007) effectively separates light backscattered from predominantly horizontally oriented particles and the light backscattered from spherical water cloud particles. Although this concept is based on a physical understanding of multiple scattering, it needs to be tested on observations. The technique is based on the fact that water clouds and ice clouds with horizontally oriented particles have drastically different δ - β spatial correlations:

 For water clouds or ice clouds with randomly oriented particles, the cloud footprint with high layer-integrated backscatter should have a higher depolarization ratio. For the adjacent cloud footprint within the same cloud system, the cloud footprint with larger backscatter



FIG. 8. (top) Distinct clusters of water clouds and HO particles found using the depolarization– backscatter correlation for (left) January 2007 and (right) January 2008. These are the "water" clouds indicated by the depolarization–backscatter relation for clouds falling between the green and red lines in Fig. 4. (bottom) As in (top), but for the "ice" clouds determined by the depolarization–backscatter relation, because these are the clouds above the red line of Fig. 4.

values are thicker/denser clouds and have enhanced multiple scattering resulting in an increased measured depolarization.

• Conversely, for ice clouds with horizontally oriented particles, lower depolarization is expected for the adjacent cloud footprints having larger layer-integrated backscatter. This is because the higher layer-integrated backscatter from oriented particles is likely a result of a higher percentage of horizontally oriented particles being present in the cloud layer. Thus, the cloud footprint with higher backscatter has lower depolarization because the specular reflection from horizontally oriented particles does not depolarize the signal.

Thus, we expect a positive correlation between the layer-integrated attenuated backscatter β and the particulate depolarization δ for water clouds and for ice clouds with randomly oriented particles. Conversely, we expect a negative correlation between β and δ when the lidar backscatter signal comes primarily from horizon-tally oriented particles.

This spatial coherence concept can be easily tested with well-known targets such as the highly reflecting horizontally oriented particles, as well as opaque water clouds with cloud-top temperatures greater than 0°C. Figure 7 shows that the correlation coefficients of depolarization and layer-integrated backscatter are greater



FIG. 9. Separation of (top left) HO and (bottom right) RO cloud particles with similar particulate depolarization using the correlation between the layer-integrated particulate depolarization ratio and attenuated backscatter. The lidar off-nadir angle is 0.3°.

than 0.5 for more than 90% of warm water clouds. Similarly, for most ice clouds with obviously horizontally oriented particle backscatter signals, the δ - β correlation coefficients are less than -0.5.

The most frequent misidentification made by the simple δ - β threshold method is for the specific case where a cloud is classified as water phase by the simple δ - β threshold method when it may actually be an ice cloud containing at least some horizontally oriented particles. This is the drawback of selecting fixed thresholds and applying them to all the data. The thresholds for water clouds are set relatively loosely so that no water clouds will be misidentified as ice because of SNR issues or calibration errors. However, by applying the spatial

coherence technique, some mitigation is expected for this misclassification between water clouds and ice clouds composed of horizontally oriented ice particles.

The top panels of Fig. 8 show that the "water" clouds identified by the simple δ - β threshold method are clustered into two groups, clearly separated by the δ - β correlation. The water clouds are the ones with positive correlation coefficients and the ice clouds with the horizontally oriented ice particles are the ones with negative correlation coefficients. This clear separation between water clouds and horizontally oriented ice clouds is obvious for both January 2007 (Fig. 8, top left), when the lidar is pointed at 0.3°, and January 2008 (Fig. 8, top right), when the lidar is pointed at 3° off-nadir. When the lidar is



FIG. 10. As in Fig. 9, but for a subset of ice clouds with cloud-top temperatures colder than -40° C.

pointed at 3° off nadir, almost all the clouds colder than -40° C are correctly classified as ice clouds (Fig. 8, top right). When the δ - β threshold mistakenly classifies some clouds colder than -40° C as "water" clouds (Fig. 8, top left; lidar pointing 0.3° off nadir), the spatial coherence technique clearly identifies those clouds colder than -40° C as horizontally oriented ice particles. This is because the δ - β correlation for those clouds is close to -1.

The spatial coherence method also finds the signature of specular reflection from some of the clouds identified as "randomly oriented ice" clouds by the simple δ - β threshold standard (Fig. 8, bottom). A four-dimensional (4D) histogram provides a way to effectively visualize the effectiveness of the spatial coherence technique. The first two spatial coordinates are the layer-integrated attenuated backscatter at 532 nm and the 532-nm partic-

ulate depolarization ratio. The third coordinate is the spatial cross correlation of the first two.

Figure 9 (January 2007; all clouds) and Fig. 10 (January 2007; clouds colder than -40° C) are substrates of the 4D histogram of cloud backscatter properties, each with a different δ - β correlation. The color represents the number of occurrences for the month. Both figures suggest that the clouds are clustered clearly in the 3D space. The clouds are either water clouds (Fig. 9, bottom right) or randomly oriented ice clouds (Fig. 10, bottom right) because the δ - β correlations are greater than 0.8, or they are horizontally oriented particles because the δ - β cross correlations are less than -0.8 (top-left panels of Figs. 9, 10). The frequency of occurrence for clouds belonging to the δ - β cross-correlation categories having low positive or negative δ - β cross-correlation values



FIG. 11. (left) HOI particles and (right) warm water clouds have very different values of color ratio and depolarization rms/mean. The lidar off-nadir angle is 0.3°.

(between -0.4 and 0.4; top-right and bottom-left panels of Figs. 9, 10) is relatively small.

For the few cases of clouds with low positive or low negative δ - β cross-correlation values, cloud phase discrimination can be improved by other information, such as the ratio of 1064- and 532-nm layer-integrated attenuated backscatter, known as the color ratio, or by the standard deviation of the vertical depolarization profile. For example, clouds containing horizontally oriented particles have lower values of color ratio and smaller standard deviations of the depolarization ratio (Fig. 11, left) than water clouds (Fig. 11, right).

The techniques suggested in this section are designed to optimize the performance of the cloud phase discrimination of the uppermost cloud layer, which has less uncertainty in layer-integrated attenuated backscatter. For cloud layers residing underneath another layer of cloud or aerosol, the layer-integrated backscatter may be less reliable (Young and Vaughan 2009), and a deterministic approach may not necessarily always provide the best solution for these cloud layers. In these situations, cloud temperature, volume depolarization ratio, and the standard deviation are the more reliable indicators and should be weighted more in the algorithm.

3. Algorithm description and performance

The algorithm implementation process is quite straightforward. All input parameters of the cloud phase algorithm are standard parameters in the level II single-shot 1- and 5-km lidar products. The procedure is as follows:

1) Estimate the particulate depolarization ratio of the cloud layer.

- Provide a first guess of water, ice-random orientation, or ice-horizontal orientation by using the simple δ-β thresholds.
- 3) Remove ice clouds with horizontal orientation from the classes of water clouds and ice clouds with random orientations by using the δ - β spatial correlation information.
- 4) Correct for lower layers of multilayered cloud observations and for water clouds with low δ-β correlations by assessing the probability of them being either water or ice by using the temperature, depolarization ratio, and its standard deviation statistics derived from the top-cloud climatology. To estimate the confidence of the retrieval, a deterministic approach is used for each parameter; these are then multiplied at the end of the retrieval process. If the associated probability is greater than 0.5, then the classification is determined uncertain.
- 5) Identify the cases where water clouds warmer than 0°C are identified as ice, and reassign them as water. For the cases in which clouds colder than -40°C are identified as unknown, reassign the phase as ice. The Goddard Earth Observing System, version 5 (GEOS-5) model temperature profiles provide the temperature at cloud-top altitude.

Figure 12 shows the results of the phase algorithm for two cases: one with the lidar pointing 0.3° off nadir (Figs. 12a–c) and the other with the lidar pointing 3.0° off nadir (Figs. 12d–f). Figures 12a,d show examples of the cloud phase discrimination algorithm output for nighttime orbits. Water clouds are denoted by the orange to red colors. Blue and black colors are ice clouds with randomly oriented particles. The green and light



FIG. 12. Examples of (a),(d) cloud phase output; (b),(e) the corresponding layer-integrated volume depolarization ratio; and (c),(f) 532-nm attenuated backscatter for the cases when the lidar points (a)–(c) 0.3° off nadir and (d)–(f) 3° off nadir. Ice clouds are separated into those composed of RO or HO particles.



FIG. 13. Cloud phase statistics (top layer only) as a function of temperature for ice (red), water (green), and unknown (blue), with results for (right) all clouds and (left) opaque-only clouds from (top) January 2007, when the lidar is pointed 0.3° off nadir, and (bottom) January 2008, when the lidar is pointed 3° off nadir.

blue colors are ice clouds with horizontally oriented particles. Figures 12b,e show the corresponding depolarization ratios, whereas Figs. 12c,f show the log of the attenuated backscatter at 532 nm.

Overall, only a small fraction of the cases are classified as uncertain. These are the clouds with very low signalto-noise ratios and lower layers of multilayer clouds.

Figure 13 shows top cloud layer water/ice frequency of occurrence for January 2007 (Fig. 13, top) and January 2008 (Fig. 13, bottom). The left panels of Fig. 13 are for opaque clouds. The right panels of Fig. 13 are for all first-layer clouds. Although the cloud phase statistics for both months are similar, there is still a noticeable difference in the ice cloud frequency of occurrence between 0° and -40° C. More ice clouds are found in January 2007, when the lidar is pointed at 0.3° . There are two possibilities for the 2007/08 differences: a) the presence of a very thin

layer of horizontally oriented ice particles located above a layer of water clouds. The thin ice cloud layer can be detected in the 0.3° off-nadir month but cannot be detected in 3° off-nadir month. b) The presence of oblate spheroid-shaped water cloud droplets in certain atmospheric conditions may have produced specular reflections at the 0.3° off-nadir angle measurements. The water cloud composed of oblate spheroids could be interpreted as an ice cloud with horizontally oriented particles.

In Fig. 14, the statistics of ice clouds with horizontally oriented particles are provided together with those from water clouds and ice clouds with randomly oriented particles. The top-left panel shows that when the lidar is pointed at 0.3° off nadir, specular reflection is obvious in about 50% of the opaque ice clouds in January 2007 and these clouds are classified as ice clouds with horizontal orientation. In about 30% of the data, lidar backscattering



FIG. 14. Cloud phase statistics (top layer only) as a function of temperature of RO ice (red), HOI (blue), and water (green), with results for (right) all clouds and (left) opaque-only clouds from (top) January 2007, when the lidar is pointed 0.3° off nadir, and (bottom) January 2008, when the lidar is pointed 3° off nadir.

from all ice clouds in January 2007 has a significant contribution from specular reflection; these data are now classified as horizontally orientated particles to reduce potential retrieval bias in the extinction profile. For January 2008 (Fig. 14, bottom), the specular reflection contribution by horizontally oriented crystals decreased significantly because of the larger lidar off-nadir angle. For opaque ice clouds, the likelihood of lidar backscatter measurements with significant contribution from specular reflection is reduced to about 30%, but this number reduces to 20% for all observed ice clouds.

During January 2007, the clouds in the subtropical regions are predominantly low-level water clouds (Fig. 15). The uppermost layer clouds at tropics and high latitudes are predominantly ice clouds (Fig. 15, left). Nearly all the clouds over Antarctica, Greenland, and the western Pacific warm pool detected by CALIOP are ice clouds (Fig. 15, right).

Ice clouds with horizontally oriented particles tend to occur over the southern oceans and the middle and high latitudes of the Northern Hemisphere (Fig. 16). Both Figs. 15 and 16 show cloud statistics when the lidar was pointed 0.3° off nadir.

4. Summary and discussion

We present some new thoughts on the inference of cloud thermodynamic phase by using depolarization lidar measurements from the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP), which is one of three sensors on the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite (CALIPSO). Although the current approach is based on



FIG. 15. (left) The fraction of the uppermost layer clouds that are ice clouds, and (right) the fraction of the highest three layers in a column that are ice clouds.

the depolarization measurements of backscattered light, multiple scattering by water clouds can cause difficulties in differentiating water and ice. An additional concern is that horizontally oriented ice particles are nearly nondepolarizing, even with multiple scattering. These are the primary concerns addressed in this article. The new cloud phase algorithm is based on a combination of depolarization–backscatter (δ – β) thresholds and spatial coherence. Both methods are based on theoretical model studies of single-scattering and multiple-scattering properties of polarized light propagation in clouds. The algorithm improves the discrimination between water clouds, ice clouds with horizontally oriented (HO) particles, and ice clouds with randomly oriented (RO) particles.

Based on recent theoretical and modeling studies, this algorithm differentiates cloud phase by looking at the spatial correlation of layer-integrated attenuated backscatter and layer-integrated particulate depolarization ratio. Our approach includes a two-step process: 1) preliminary identification of randomly oriented ice clouds, ice clouds with horizontally oriented particles, and possible water clouds via a simple two-dimensional threshold by using the depolarization and integrated attenuated backscatter method and 2) use of a spatial coherence analysis technique to discriminate water clouds from horizontally oriented ice particles, which tend to have similar depolarization signatures. Other information is also considered, such as temperature, color ratio, and vertical variation of the depolarization ratio.

The algorithm is applied to data collected during two months, January 2007 and January 2008, to demonstrate the performance of the algorithm when the lidar was pointed at 0.3° off nadir (January 2007) and 3.0° off nadir (January 2008). When the lidar is pointed at 0.3° off nadir, 50% of the opaque ice clouds and about 30% of all ice clouds have significant lidar backscatter contributions from specular reflection of horizontally oriented particles. At a 3° off-nadir pointing, our analysis indicates that roughly 30% of opaque ice clouds and 20% of all ice clouds observed are contaminated by horizontally oriented crystals.

Although data from CALIOP provide unambiguous vertical cloud structure and depolarization profiling information, the operational algorithms have not yet fully taken advantage of all the information provided by the lidar measurements. An assessment of the impact of



FIG. 16. (left) The fraction of opaque ice cloud layers classified as having a significant level of HO particles, and (right) the fraction of all ice cloud layers classified as having a significant level of HO particles.

multiple scattering on polarization in a nonuniform cloud structure requires interactive Monte Carlo simulations. Because of the computational expense, this is unlikely to be feasible with the current computational architecture for operational data reduction. The current operational algorithm, which only uses depolarization ratios, can only provide the most likely layer phase information for the whole cloud layer, not the vertical profile.

Although using only lidar for cloud phase discrimination is important, a more productive future direction for cloud phase discrimination may come from combined lidar and multiangle hyperspectral polarization radiometer measurements. This is a topic for future study and is currently underway by the authors. Cloud phase discrimination will also benefit significantly from better cloud microphysics statistics from in situ measurements and theoretical modeling studies of ice cloud singlescattering properties. Offline studies are needed to assess whether random and horizontally oriented crystals are mixed in a single layer or form separate layers. There are still uncertainties in the identification of horizontally oriented particles and in the assessment of its impact on retrieving ice cloud physical properties.

More theoretical and validation studies are needed to prevent false positives of the identification of horizontally oriented particles, especially for thinner ice clouds with lower signal-to-noise ratios. This algorithm only identifies the cloud phase of individual continuous cloud layers using lidar measurements. Furthermore, it would be interesting to examine whether profiling of cloud phase within a cloud layer can be improved with combined collocated Cloudsat observations.

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