A Climatological View of Horizontal Ice Plates in Clouds: Findings From Nadir and Off-Nadir CALIPSO Observations

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Abstract We study horizontal ice plates in clouds using satellite lidar measurements of the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO). This study investigates global microphysical and geographical properties of horizontal ice plates to obtain insights into ice-plate climatology based on lidar’s long-term measurements during 2006–2014. We then summarize the effects of the lidar’s viewing angle change from 0.3° to 3.0° in 2007 on satellite particle phase/shape classifications. Using a classification algorithm developed in the previous studies, we show that the ice plate detection decreases by 81.7% due to the tilting. With an updated version of this algorithm, 30.8% of these are recovered, although 50.8% remain undetected. Nevertheless, this study also shows that geographical characteristics of ice plates are still preserved during the off-nadir period (within the remaining 50%), suggesting the undiscovered climatological information on ice plates in the post-2007 observations. According to our analysis, the tilting mainly affects horizontal ice plate detection, while the impacts on water and randomly oriented ice detections are limited. The temperature of the ice plates ranges from −25.5°C and −7.5°C, with a mode temperature of −13.5°C, although the ice plates also occur ubiquitously across mid- to high-latitudes between −20°C and −40°C, which is much colder than what found in previous nadir studies. This study offers a detailed discussion on the fundamental characteristics of horizontal ice plates that will provide robust information for the algorithm preparation for future satellite lidar observations such as the Earth, Clouds, Aerosol and Radiation Explorer (EarthCARE).

1. Introduction

The thermodynamic phases of liquid, ice, and mixed-phase have distinct impacts on cloud radiative effects (Matus & L’Ecuyer, 2017; Morrison et al., 2012; Shupe & Intrieri, 2004; Sun & Shine, 1994; Van Tricht et al., 2016) and on cloud feedback (Tan & Storelvmo, 2019; Tan et al., 2016, 2019; Tsushima et al., 2006). Cloud radiative properties are determined by the particle size distribution and concentration, and in the case of ice clouds, further by the habit and orientation (Ishimoto et al., 2012). Ice particles exist in various orientations in three dimensions, depending again on size and habit as well as on the turbulence of the ambient air. Of the various types, plate crystals tend to preserve their horizontal state in the atmosphere, giving them dynamically and optically unique characteristics compared to other, randomly orienting habits (Cho et al., 1981; Hashino et al., 2014; Keat & Westbrook, 2017; Sassen, 1980; Westbrook et al., 2010). This preferential orientation is attributed to a balance between gravitational fall and updraft velocity, which orthogonalizes the largest plane normal to the axis of gravity to maximize its air resistance, consequently affecting the sedimentation speed and cloud lifetime. This aerodynamic behavior gives rise to specular reflections that impact cloud radiative effects, as suggested by radiative transfer models (Takano & Liou, 1989) and ground-based lidar observations (Stillwell et al., 2019). Recent studies suggest that ice plates are often correlated in precipitating clouds and that their ice nucleation processes are related to precipitation formation (Ross et al., 2017; Kikuchi & Suzuki, 2019).

More technically, knowledge of ice habits is necessary for estimating microphysical properties of clouds in remote sensing algorithms, where ice habits are occasionally assumed to simply be spheres, or more intrinsically, non-spherical habits or a mixture of different habits (e.g., Austin et al., 2009; Delanoë & Hogan, 2010; Deng et al., 2010; Donovan & van Lammeren, 2001; Okamoto et al., 2010; Platnick et al., 2017; Protat...
et al., 2007; Sato & Okamoto, 2011; Yang et al., 2018). Analyses such as those done by Benedetti et al. (2003) and Letu et al. (2016) have shown that habit assumption in ice particle models induces sensitive impacts on the microphysics retrievals, which require accurate estimation given that clouds remain the largest source of uncertainty in radiative forcing estimations.

The global measurement of ice plates essentially started with the Polarization and Directionality of the Earth’s Reflectance (POLDER-1) in 1996 (Bréon & Dubrulle, 2004; Chepfer et al., 1999; Noel & Chepfer, 2004). POLDER has enabled horizontal distribution measurements during its eight months of observations. Following passive multidirectional and polarized measurements by POLDER-2 and the Multi-angle Imaging SpectroRadiometer (MISR), vertical measurements were made by the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) onboard the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) satellite (Winker et al., 2007, 2010). CALIOP is a Mie-scattering lidar that emits 0.532 and 1.064 µm laser beams toward the ground and, with a polarization measurement capability of 0.532 µm, it measures vertical profiles of particle shapes within clouds. Since 2006, over a decade of observations have been accumulated and widely used in cloud climatology studies (e.g., Alfaro-Contreras et al., 2016; Chepfer et al., 2013; Papagiannopoulos et al., 2016).

In lidar observations, the polarization state of laser light is fundamentally influenced by particles that change the polarization plane during internal skew scattering that is off-normal to the particle surface. As such, non-spherical ice crystals generally return depolarized light with respect to the incident. However, ice plates that often oriented horizontally (with slight fluctuations) induce unpolarized backscatter (i.e., zero depolarization) for a lidar pointing vertically from the ground or a satellite. Accordingly, this effect is strongly reduced when the pointing angle is moved away from the norm. Considering this characteristic, a few studies (e.g., Noel & Sassen, 2005) used depolarization measurements to investigate the tumbling angle of ice plates (or more specifically, the transient orientation of plates centering at the normal). Spherical water droplets also cause strong backscatter and preserve the polarization state under single-scattering regimes, as seen in ground-based observations. However, in satellite measurements, such droplets exert large, depolarized backscatter due to multiple scattering within their large footprints. These depolarization and backscatter characteristics have been compiled for discrimination algorithms of cloud particle shapes from CALIOP observations, some with the companion Cloud Profiling Radar (CPR) onboard CloudSat. Here, horizontally oriented ice plates are classified by their low depolarization, while large depolarizations are inferred as being either due to randomly oriented ice crystals or liquid water particles, depending essentially on the degree of backscatter (Cesana & Chepfer, 2013; Hu et al., 2009), attenuation (Hirakata et al., 2014; Kikuchi et al., 2017; Yoshida et al., 2010), or both (Ceccaldi et al., 2013).

From the start of its operation in June 2006, CALIOP was pointing 0.3° off the nadir until November 2007, when the viewing angle was increased to 3.0° to avoid specular backscatter from horizontally oriented ice plates (Winker et al., 2009). Although unexpectedly, this unique set of observation data has leveraged global studies on horizontal ice plates. To the authors’ knowledge, Sassen and Zhu (2009) were the first to analyze the magnitude of the depolarization ratio $\delta$ (the degree of depolarization in the backscatter signal; see Section 2 for the definition) using the one-year data set of nadir and off-nadir measurements, followed by Sassen et al. (2012) who deduced the presence of oriented ice plates attributed to increasing $\delta$ in more detail. In the meantime, Noel and Chepfer (2010) used 18 months of measurement data to analyze $\delta$ and the backscatter coefficient, $\beta$, integrated over the cloud layer. Zhou et al. (2012) and Zhou et al. (2013) also analyzed the layer-integrated $\delta$ and $\beta$ to understand the effect of quasi-horizontally oriented plates on the $\delta$–$\beta$ plane using one-year of the nadir and off-nadir datasets.

Motivated by observations of these distinct ice plates, this study incorporates the CALIOP nadir and off-nadir measurements in the nadir and off-nadir periods for the following two objectives. First, we aim to quantify the geographical and microphysical characteristics of the ice plates on a global scale to investigate the climatological behavior of those ice plates. The second objective is to summarize the robust information on the effect of the lidar viewing angle on the satellite cloud phase/shape classification algorithm. For the first objective, the data set with the two tilting angles is studied to understand the ubiquitous distribution and variability of horizontal ice plates over the globe. For the second objective, we intend to clarify the effect of lidar tilt on the classification algorithm and evaluate its influence quantitatively. A detailed summary is
expected to provide insights for preparing the upcoming coming satellite mission Earth Clouds, Aerosol, and Radiation Explorer (EarthCARE), which will carry a 3.0° off-nadir pointing lidar (Illingworth et al., 2015).

2. Data Set and Evaluation Parameters

2.1. CALIOP Observation Data Set

In this study, the microphysical characteristics of horizontally oriented ice plates were investigated using CALIOP observation data from the JAXA A-Train Product Monitor (http://www.eorc.jaxa.jp/EARTH-CARE/research_product/ecare_monitor_e.html), which provides a suite of A-Train satellite constellation measurements by CALIPSO/CALIOP, CloudSat/CPR and the Aqua/Moderate Resolution Imaging Spectroradiometer (MODIS). These products have a uniform resolution of 240 m vertical and 1.1 km horizontal per CloudSat profile, according to the collocation method described in Hagihara et al. (2010). In the current study, we used: (1) CALIOP 532 nm total and cross-pol attenuated backscattering coefficients, originally provided by the CALIPSO L1b Lidar product; (2) atmospheric temperature profiles from the European Center for Medium Range Weather Forecast (ECMWF), originally provided by the CloudSat ECMWF-AUX product; and (3) the CALIOP classification of cloud particle phase and shapes (hereafter referred to as “cloud particle type”; see Section 2.3 for classification algorithm details). We analyzed the observation data set from 2006 to 2014 (the entire period of the product available at the time of writing), where June 2006–November 2007 corresponds to the nadir measurements (accounting for 170 million profiles and 4,800 orbits), while January 2008–December 2014 corresponds to the off-nadir measurements (accounting for over 750 million profiles and 25,000 orbits). This long-term data set was used to explore the existence of ice plates oriented horizontally over the globe and provide a more comprehensive climatological perspective than previous studies.

2.2. Evaluation Parameters

In evaluating cloud phase and shape properties, we employed the following three parameters: the attenuated backscattering coefficient (\( \beta \)), depolarization ratio (\( \delta \)), and lidar attenuation (\( \chi \)). These parameters induce distinctive responses to the CALIOP tilt for different cloud particle types. Together with the \( \beta \) and \( \delta \) which are commonly used in CALIOP phase/shape studies (Cesana & Chepfer, 2013; Hu et al., 2007; Noel & Chepfer, 2010; Zhou et al., 2012, 2013), we also explored analyzing \( \chi \), introduced by Yoshida et al. (2010), as a third parameter to gather independent cloud phase information.

The first parameter, \( \beta \), is essentially the ratio of the lidar signal received from a cloud (and aerosols) with respect to the emitted signal, given by the lidar equation that includes atmospheric attenuation and lidar system specifications. The second parameter, \( \delta \), is defined as follows:

\[
\delta = \frac{\beta_{\text{perp}}}{\beta_{\text{parallel}}} \times 100 \%.
\]

where \( \beta_{\text{perp}} \) and \( \beta_{\text{parallel}} \) are the perpendicular and parallel components of the total attenuated backscattering coefficient at 532 nm, \( \beta_{\text{total}} \). In other words, \( \beta_{\text{total}} = \beta_{\text{perp}} + \beta_{\text{parallel}} \). The last parameter, \( \chi \), is defined as:

\[
\chi = \log_{10} \left( \frac{\beta_{\text{total}}(i)}{\beta_{\text{total}}(i + 1)} \right).
\]

where \( \beta_{\text{total}}(i) \) and \( \beta_{\text{total}}(i + 1) \) are \( \beta_{\text{total}} \) at the \( i \)th and \( (i + 1) \)th layers, respectively. Here, the ratio of the vertically adjacent \( i \)th and \( (i + 1) \)th layers gives a measure of the lidar attenuation induced in the \( i \)th cloud layer. If the microphysical properties of the two adjacent layers are homogenous within the 240 m vertical pixel, \( \chi \) is regarded as a measure of the extinction of the \( i \)th cloud layer (Yoshida et al., 2010).
2.3. YOKI Algorithm

In this study, we used cloud particle phase/shape classification data, estimated from the algorithm originally developed by Yoshida et al. (2010) and later improved by Hirakata et al. (2014), hereafter referred to as the “YOKI algorithm”. Before applying the YOKI algorithm, all the CALIPSO bins are collocated to CloudSat bins in 240 m vertical × 1.1 km horizontal samplings. Then the algorithm is applied to each 240 m × 1.1 km bin detected as “cloud” by a cloud mask scheme (Hagihara et al., 2010). The YOKI algorithm calculates the two lidar parameters δ and χ, and classifies a type from the δ-χ diagram (which will be shown in Figure 5), followed by a “spatial consistency test” which amends outliers found in a 3 × 5 pixel box and determines the final cloud particle type (one of Warm Water, Supercooled Water, 3D-ice, 2D-plate, Mixture of 3D-ice and 2D-plate, Unknown1, and Unknown2). Among the cloud particle types, we mainly discuss the following types that accounted for 95.6% of the total (estimated from one year in 2007): 2D-plate, 3D-ice and Water (sum of “Warm Water” and “Supercooled Water” types). Note that 2D-plate refers to quasi-horizontally oriented ice plates, while 3D-ice refers to randomly oriented ice crystals including columns, plates, bullets, droxtals, aggregates and randomly oriented plates (Iwasaki & Okamoto, 2001; Okamoto et al., 2019; Sato & Okamoto, 2006). The validations/comparisons of the YOKI algorithm against independent observations are highlighted as follows. Cesana et al. (2016) compared the YOKI retrievals (noted as “KU Product” therein) against airborne field campaigns. The YOKI cloud phase detections showed good agreements with the in situ measurements for homogeneous ice clouds at mid-latitudes (100%, 94.6%, and 100% in three individual cases), while the agreement varied for more complex mixed-phase clouds in the Arctic (79.8% and 37.5% in two individual cases). In global analyses, Yoshida et al. (2010) found that the correlation coefficients between the YOKI and MODIS monthly mean retrievals were 0.91 for water and 0.76 for ice. Hirakata et al. (2014) compared the zonal mean YOKI cloud-top coverage against MODIS coverage and the correlation coefficients were 0.88 for water and 0.82 for ice.

Exploiting CALIOP’s capability to resolve the internal structure of clouds, the YOKI algorithm estimates vertically resolved profiles of particle types (within cloud layers), which are expected to be suitable for the present study in identifying horizontal plate layers that often lie underneath a bulk of randomly oriented crystals (Noel et al., 2004).

3. Results

3.1. Case Study

With the three lidar parameters defined above, we first investigated one case in the southern Indian Ocean to understand the fundamental characteristics of particle phase and shape, and how they are observed in natural clouds. Figure 1 shows a CALIOP measurement taken on January 4, 2007 when the lidar was pointing at the nadir. The three lidar parameters β, δ, and χ are shown with the cloud particle classified by the YOKI algorithm. In each figure, the ECMWF ambient temperature is overlaid as gray contour lines. As mentioned, the classification algorithm uses a combination of δ (Figure 1b) and χ (Figure 1c) to classify the particle type (Figure 1d) but does not use β (Figure 1a).

According to β in Figure 1a, the scene consisted of a number of multi-layered clouds, involving a deep convective structure toward the north (at latitudes over −50.0°) and a combination of convective and stratiform systems toward the south (between −56.0° and −50.0°) with underlying stratocumulus cloud layers, many of which were coaligned along the −10°C and 0°C isothermal lines. One notable feature was recognized in the strong backscatter (over 10−4 m/sr) of clouds located between −52.0° and −50.0° (Figure 1a), where the depolarization ratio was considerably lower than its surroundings (Figure 1b), indicating the presence of horizontal ice plates. Because of its near-zero depolarization, “2D-plate” was assigned to this region (Figure 1d). The strong χ syntheses demonstrated the characteristic of horizontal ice plates that cause specular reflections. These plate crystals were found to form in ice clouds of relatively warm temperatures, between 0°C and −20°C, as often found in previous laboratory and ground-based studies (e.g., Libbrecht, 2005; van Diedenhoven et al., 2018; Westbrook et al., 2010).

At higher altitudes (lower temperatures), randomly oriented ice clouds were recognized (and characterized as “3D-ice” in Figure 1d), where the observed β was much lower and δ much higher than that of the 2D-plate region. Interestingly, the 2D-plate and 3D-ice share a similar characteristic of low lidar attenuation...
$(-0.5 < \chi < 0.5)$ in Figure 1c, as opposed to the strong attenuation ($\chi > 1$) found in the thin water layers along the $-10^\circ$ and $0^\circ$C contour lines. Liquid droplets in these clouds showed strong backscatter and large depolarization (Figures 1a and 1b), which is expected in satellite lidar measurements. Note that, in Figure 1c, the strong negative attenuation (i.e., shown in blue and the signal increase from layer $i$ to $i+1$) was
recognized just above the strong attenuation layer \( i + 1 \) (shown in red) classified as Water. This artificial layer with low \( \chi \) (in blue) was associated with the calculation of Equation 2, where \( \chi \) at the corresponding clear-sky pixel was derived by dividing its weak backscatter over the strong backscatter of the water cloud underneath. In contrast, these features were not found near ice clouds in Figure 1c since they gave a more gradual \( \beta \) increase. While this artificial layer was discarded during the cloud-masking before the particle type classification, the “double-band” \( \chi \) structure is found to be another independent signature of the observed liquid clouds, distinguishing them from ice clouds.

3.2. Global Statistics of Nadir and Off-Nadir Measurements

3.2.1. Mean Backscatter, Depolarization, and Attenuation

The case study in the previous section illustrated the backscatter, depolarization, and attenuation characteristics of cloud particles from CALIOP’s snapshot observation. Next, we extend the investigation to a multiyear analysis, comparing the nadir and off-nadir measurements to address zonal characteristics of the three lidar parameters.

Figure 2 shows the latitude–temperature distribution of the mean \( \beta, \delta, \) and \( \chi \) for clouds detected by CALIOP during the nadir (top row) and off-nadir periods (bottom row). The latitudes and temperatures were sampled every 2° and 1°C, respectively. Previous studies by Sassen and Zhu (2009) and Sassen et al. (2012) also examined the effect of lidar tilt on cloud depolarization of ice clouds with cloud top temperatures colder than \(-40°C\). This study extends the analysis on backscatter and attenuation, as well as to all ice and water clouds, considering that the tilting would affect the planar crystals most abundant in ice clouds warmer than \(-20°C\). To link the lidar parameters to particle types, the discussion below also refers to Figure S1-a2–S1-a4 (in the Supporting Information), which show the latitude–temperature distributions of the particle type frequencies during the nadir observations (similar to that shown in Yoshida et al. (2010) and Hirakata et al. (2014) during different nadir periods). The other figures in Figure S1 will be discussed in Section 3.4.

Overall, the distribution of the lidar parameters showed strong temperature and latitude dependences globally. A notable feature in Figure 2 is the low \( \delta \) layer at temperatures around \(-15°C\), which is considered to be due to signals from horizontal plate crystals (Figure S1-a2). This low \( \delta \) layer was pronounced particularly during the nadir measurement (Figure 2-a2), where the corresponding \( \beta \) was found to be exceptionally high (>0.06/m/sr; Figure 2-a1). At warmer temperatures (above \(-10°C\)), similar strong backscatter was observed but this time induced from water droplets (Figure S1-a4) rather than the specular reflection from ice plates, also confirmed by the distinctively large \( \chi \) (>0.7; Figure 2-a3) due to strong attenuation of optically thick water clouds dominantly distributed in latitudes over ±30°. Below \(-30°C\), where 3D-ice dominates
(Figure S2-a3), $\chi$ was found to give similar attenuation as seen in the 2D-plate temperature range, sharing a similar attenuation characteristic as the ice phase (Figure 2-a3). The differences among the ice habits were clearly seen in $\beta$ and $\delta$, where 2D-plate gave much higher $\beta$ and lower $\delta$ than 3D-ice.

After the lidar tilting, a significant increase in $\delta$ was found around $-15^\circ$C (Figure 2-b2), where the corresponding $\beta$ decreased (Figure 2-b1). Theoretical explanation to this $\delta$ increase are described as follows. The $\delta$ in Equation 1 can be described separately for the contributions of 2D-plate and 3D-ice components:

$$\delta = \frac{\beta_{2D,\perp} + \beta_{3D,\perp}}{\beta_{2D,\parallel} + \beta_{3D,\parallel}} \times 100\%,$$

where $\beta_{2D,\perp}$ and $\beta_{3D,\perp}$ are 2D-ice and 3D-ice components of $\beta_{\parallel}$, respectively, and $\beta_{2D,\parallel}$ and $\beta_{3D,\parallel}$ are 2D-ice and 3D-ice components of $\beta_{\perp}$, respectively. Assuming that 3D-ice particles orient randomly ideally in three dimensions, $\beta_{2D,\parallel}$ and $\beta_{3D,\parallel}$ are not affected by the tilting. $\beta_{2D,\perp}$ would also not change significantly due to the tilting, according to a theoretical crystal model simulation by Okamoto et al. (2019). As such, the significant increase in $\delta$ after the tilting in Figure 2-b2 was attributed to the significant decrease in $\beta_{2D,\parallel}$, as consistently indicated in Figure 2-b1. From Figure 2, the major change from the nadir to off-nadir was found in this temperature range, suggesting that the tilting affected the detection of horizontal ice plates more than other particle types. Closer investigation of the latitude-temperature domain where 2D-plates were abundant ($-14.0^\circ$C $\leq T \leq -12.5^\circ$C [hereafter referred to as the "2D-plate temperature range"] and $-30.0^\circ$C $\leq$ Lat $\leq 30.0^\circ$C) show that the mean $\beta$ decreased significantly, by 42.9% (from $7.0 \times 10^{-3}$ to $4.0 \times 10^{-3}$/m/sr) after the tilting, while $\delta$ almost doubled (from 11.97 to 20.44) and $\chi$ increased slightly by 12.1% (from 0.29 to 0.33) in the same temperature–latitude region.

### 3.2.2. Covariabilities of Backscatter, Depolarization, and Attenuation

The analysis described in the last section outlined the general properties of $\beta$, $\delta$, and $\chi$ in global clouds and how they differ among particle shapes. In this section, we examine the covariability of the three parameters, beginning with the depolarization–attenuation relation (Figure 3) then examining the backscatter–depolarization relation (Figure 4). Figure 3 shows the joint probability density function (PDF) for $\delta$ and $\chi$ during the nadir (Figure 3, top row) and off-nadir (Figure 3, middle row) periods, and their differences (Figure 3, bottom row). This depolarization–attenuation analysis was introduced by Yoshida et al. (2010), who used the $\delta$–$\chi$ diagram to build the particle classification scheme (cf. the classification thresholds of the YOKI algorithm overlaid in Figure 3-a2). Here we extended the $\delta$–$\chi$ analysis from one month (October 2006) to nine years, populating seasonal and interannual variabilities of clouds and the changes induced by the tilting. Given the strong dependence of cloud particle shape on temperature, the analysis was divided into water-dominated ($0^\circ$C $\leq T < 0^\circ$C), mixed-phase ($-20^\circ$C $\leq T < 0^\circ$C), and ice-dominated ($T < -20^\circ$C) ranges. The plots were constructed with intervals of 0.05 and 1% for $\chi$ and $\delta$, respectively. The definition of the PDF is explained in the supporting information (Text S1).

In the mixed-phase temperature range during the nadir measurement (Figure 3-a2), the diagram showed two features, one with a triangular shape (centered at $\chi = 0$ in the range $-0.7 < \chi < 0.7$ and $0\% < \delta < 10\%$) and the other with a “tail” feature that stretches toward higher $\delta$ and $\chi$. The latter is consistent with the distribution above the melting temperature (Figure 3-a1), indicating supercooled liquid clouds and, accordingly, is classified as Water in the algorithm. The triangular feature was attributed to horizontally oriented ice plates, where the majority were clustered below 5% depolarization and classified as 2D-plate. The 3D-ice is assigned to higher depolarization, as seen in the ice-dominated temperature range (Figure 3-a3), where $\chi$ was generally concentrated between $-0.5$ and 0.5 (i.e., much lower than water), explained by the optically thinner nature of ice clouds and multiple scattering not being as prevalent as in water clouds.

During the off-nadir period, the frequencies of the triangular feature were significantly lower (Figure 3-b2). According to Figure 3-c2, a portion of them was redistributed to larger $\delta$ with low $\chi$, stretching into the 3D-ice region. An increase of water clouds (larger $\delta$ and $\chi$) was also recognized in Figure 3-c2, although this was believed to be due to a relative increase of water detection resulting from the decrease in ice plate detection, as explained in Section 3.4. In fact, this relative increase of water contributed to the slight increase in the mean $\chi$ seen in the previous section (i.e., 12.1%). Figure 3-c3 shows the $\delta$ for ice crystals shifted upward...
increasing $\delta$ for 30%–60% while decreasing $\delta$ below 30%), without changing the magnitude of the attenuation: the mean $\delta$ increased by 3.5% from 31.2 $\pm$ 15.2% to 34.7 $\pm$ 14.0%. To investigate this shift in more detail, we derived the $\delta$–$\chi$ diagrams at every 10°C in Figure S2 (in the Supporting Information). Figures S2b–S2e show a clear transition of the distributions from “2D-plate-dominant” to “3D-ice-dominant” frequencies. Furthermore, Figures S2d–S2e indicate that the frequency change seen after the tilt in $T < -20^\circ$C in Figure 3c actually occurred at warmer temperatures of $-40^\circ$C $\leq T < -20^\circ$C (rather than at the colder temperatures below $-40^\circ$C), suggesting the existence of horizontally oriented ice plates at a much lower temperature range ($-40^\circ$C $\leq T < -20^\circ$C) than what was previously found using the CALIOP nadir measurements. Lastly, Figure 3-c1 shows that water clouds were not significantly affected by the tilting.

Following the first cloud phase/shape detection algorithm by Hu et al. (2009), it has been common in CALIOP phase analysis to study the backscatter–depolarization relation in interpreting the cloud phase (Cesana & Chepfer, 2013; Noel & Chepfer, 2010; Ross et al., 2017; Zhou et al., 2012, 2013). A few studies compared the $\beta$–$\delta$ based classification (CALIPSO L2 VFM) and $\delta$–$\chi$ based classification (YOKI algorithm), and investigated their differences in case-studies and statistical global analysis (Cesana et al., 2016; Hirakata

Figure 3. Joint PDF diagram of the depolarization ratio ($\delta$) and lidar attenuation ($\chi$) for clouds observed at (1) 0°C $\leq T$, (2) $-20^\circ$C $\leq T < 0^\circ$C, and (3) $T < -20^\circ$C, during (a) the nadir measurements, (b) the off-nadir measurements, and (c) their differences. In Figure 3-a2, the thresholds of the particle type classification in the YOKI algorithm are overlaid as white lines.
Here, we derived the $\beta$–$\delta$ diagram in Figure 4 to confirm the consistency between the past studies and the findings from the $\delta$–$\chi$ diagram above. The definition of the PDFs is described in Text S1 (in the Supporting Information). Note that $\beta$ and $\delta$ are layer-integrated in some studies, while in others (including this study) they are vertically resolved; hence the units of the axes are not always the same, although we believe the general tendency of the backscatter–depolarization relation can still be discussed. During the nadir measurements, water clouds showed a linear $\delta$ and $\beta$ increase (Figure 4-a1) from multiple scattering effects where $\beta$ increases as clouds become optically thicker (Hu et al., 2007; Sato et al., 2019). A similar feature was recognized in the mixed-phase temperature (Figure 4-a2), indicating the presence of supercooled water clouds, identical to the tail found in Figure 3-a2. A triangular cluster of ice plates was recognized near the origin of the diagram (Figure 4-a2), the majority of which increased $\delta$ after the change in lidar angle (Figures 4-b2 and 4-c2), as expected from the previous studies and Figure 3. In contrast, water clouds above the melting temperature did not change significantly (Figure 4-c1), and ice crystals

Figure 4. Joint PDF diagram of backscattering coefficient ($\beta$) and depolarization ratio ($\delta$) for clouds observed at (1) $0^\circ$C $\leq$ T, (2) $-20^\circ$C $\leq$ T $<$ $0^\circ$C, and (3) $T$ $<$ $-20^\circ$C, during (a) the nadir measurements, (b) the off-nadir measurements, and (c) their differences.
at low temperature shifted positively without much change in $\beta$ (Figure 3-c3), showing general agreement with those found in Figure 3-c1 and Figure 3-c3, respectively.

The findings in this section are summarized in Table 1, highlighting the relative characteristics of the three lidar parameters and the changes due to the lidar tilting. The table presents the backscatter/attenuation/depolarization characteristics of particles types, all of which have unique combinations of lidar parameters. These unique characteristics are incorporated in satellite algorithms, typically using a combination of $\delta$–$\chi$ or $\delta$–$\beta$. In the next section, we describe how the change in tilting affects the $\delta$–$\chi$ based estimations of the particle types.

### 3.3. Effects of Lidar Tilting on Satellite Estimation

#### 3.3.1. Algorithm Configuration

Given its significant influence on ice plate detection, we evaluated the effect of tilting on the satellite algorithm developed for cloud type classification. We focused particularly on demonstrating whether and by how much horizontal ice plates are captured when the depolarization assumption in the algorithm was altered. The YOKI algorithm was selected in this analysis since it suits the digesting of vertically resolved $\delta$ and $\beta$, given that ice plates are dependent on the vertical extent of altitude/temperature. Figure 5-a1 shows the PDF for cloud occurrence during the nadir measurements, with the classification thresholds of the YOKI algorithm overlaid. Figure 5-a2 is similar to Figure 5-a1 but for the off-nadir measurements (with the thresholds of the updated algorithm overlaid; as explained later). Both diagrams populated the observed clouds for all temperature ranges (i.e., the sums of the three temperature ranges shown in Figure 3). A deeper analysis of the mixed-phase temperature range ($-20^\circ C \leq T < 0^\circ C$) is shown in Figure 5-b1 and 5-b2. The presented PDFs are the same as those in Figure 3-a2 and 3-b2. Note that Figure 5-a1 is identical to the figures shown in Yoshida et al. (2010) and Hirakata et al. (2014) but extending the observation period from one month to nine years.

We recall that the triangular population of 2D-plates seen before the tilting (Figure 5-b1) increased their depolarization after the tilting (Figure 5-b2). In Figure 5-b2, we also recognized that the lower limit of the 3D-ice $\delta$ standard deviation increased after tilting (Figure 3-c3). As such, we introduced an updated algorithm for the off-nadir measurements, as shown by the overlaid thresholds in Figure 5-a2 and 5-b2. In the updated algorithm, the $\delta$ threshold of 2D-plate detection was relaxed from 3% to 10% (which had been categorized as a “Mixture of 2D-plate and 3D-ice”), given that $\delta$ of both 2D-plates and 3D-ice shifted positively. For simplicity and based on the discussion in previous sections (summarized in Table 1), the thresholds for 3D ice, Water, and Unknown were not changed. For reference, a sensitivity test of the YOKI algorithm overlaid. Figure 3-a2. In Figure 5-a1 the PDF for cloud occurrence during the nadir measurements, with the classification thresholds of the YOKI algorithm overlaid. Figure 5-a2 is similar to Figure 5-a1 but for the off-nadir measurements (with the thresholds of the updated algorithm overlaid; as explained later). Both diagrams populated the observed clouds for all temperature ranges (i.e., the sums of the three temperature ranges shown in Figure 3). A deeper analysis of the mixed-phase temperature range ($-20^\circ C \leq T < 0^\circ C$) is shown in Figure 5-b1 and 5-b2. The presented PDFs are the same as those in Figure 3-a2 and 3-b2. Note that Figure 5-a1 is identical to the figures shown in Yoshida et al. (2010) and Hirakata et al. (2014) but extending the observation period from one month to nine years.

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phase cloud temperature range in both the nadir and off-nadir periods. The detailed methodology and numbers of the accuracy estimation per particle type are described in Text S3 and Table S1 in the Supplemental Information.

3.3.2. Algorithm Experiment

Next, we applied the YOKI and updated YOKI algorithms to the CALIOP profiles. Figure 6 presents the change in 2D-plate detection during the nadir and off-nadir periods using the YOKI algorithm, and during the off-nadir period using the updated algorithm. Since the algorithms do not use temperature data, the fact that 2D-plates were observed most frequently between −25°C and −5°C in all cases confirms the climatological characteristic of ice plate formation depending strongly on temperature. During the nadir period, the mode temperature (i.e., the temperature that appears most frequently) was −13.5°C, and 75% of the occurrence frequency fell between −25.5°C and −7.5°C. After the lidar tilt, the frequency dropped significantly (Figure 6b) which was in part recovered by the updated algorithm (Figure 6c). In summary, the frequency dropped by 6.43% (from 7.87% to 1.44%, corresponding to 81.7% of the frequency decrease) for off-nadir data when using the YOKI algorithm. Applying the updated algorithm, the frequency recovered by 2.43% (from 1.44% to 3.87%, corresponding to 30.8% recovery), while the rest of 4.0% (from 7.87% to 3.87%, corresponding to a 50.8% decrease) remained undetected.
3.4. Diagnostic Method to Distinguish Between Natural Variability and Tilting Effects

Having confirmed horizontal ice plate detection reduction after lidar tilting, the next question to ask is: Where have the missing plates gone? Here, we hypothesize that a portion of them was redistributed to other types of particles, while the rest remained undetected as a feature. To test this hypothesis quantitatively, we initially compared the differences in occurrence frequencies of cloud particle types before and after the tilting, as shown in Figure S1 (in the Supporting Information). In the figure, the 2D-plate frequency decreased at around −13°C after the tilting (Figure S1-c2), although a substantial increase was not seen in either 3D-ice (Figure S1-c3) or Water (Figure S1-c4) at the corresponding temperature, while a slight increase in 3D-ice was recognized. This suggested that the majority of ice plates was no longer detected but a slight portion of them was redistributed to 3D-ice.

Although Figure S1 roughly suggests that a small portion of 2D-plate was redistributed to 3D-ice, this simple frequency difference includes effects from both the tilting and the natural variability of the occurrence. As such, we further explored a simple diagnostic method to distinguish the effect of tilting from the natural variability. To this end, we started by formulating the occurrence frequency difference as follows:

$$
\Delta \text{freq} = \Delta \text{freq}_{\text{natural}} + \Delta \text{freq}_{\text{tilt}},
$$

where $$\Delta \text{freq}$$ is the occurrence frequency difference between 2007 and 2008 (i.e., adjacent years before/after the tilting) for a given latitude, temperature, and cloud type (i.e., either Total Cloud, 2D-plate, 3D-ice, or Water). More specifically, this $$\Delta \text{freq}$$ is derived for each latitude–temperature pixel in each of Figures S1-c2–S1-c4. $$\Delta \text{freq}_{\text{natural}}$$ and $$\Delta \text{freq}_{\text{tilt}}$$ are the differences in occurrence frequency due to the lidar tilt and natural variability, respectively. Under the assumption that the natural variability follows a Gaussian distribution and that it does not exceed two standard deviations of the frequency over a sufficient period (corresponding to the 95% confidence level of the Gaussian distribution), $$\Delta \text{freq}_{\text{natural}}$$ can be described as:

$$
|\Delta \text{freq}_{\text{natural}}| \leq 2\sigma,
$$

where $$\sigma$$ is the standard deviation at the corresponding latitude, temperature, and type (see the definition of $$\sigma$$ in Text S1 in the Supporting Information). Taking advantage of CALIOP’s long-term observations, the standard deviation was calculated from 2008 to 2014. Substituting Equation 5 into Equation 4 gives

$$
\Delta \text{freq} = \begin{cases} 
\Delta \text{freq}_{\text{natural}}, & |\Delta \text{freq}_{\text{natural}}| \leq 2\sigma \\
\Delta \text{freq}_{\text{natural}} + \Delta \text{freq}_{\text{tilt}}, & |\Delta \text{freq}_{\text{natural}}| > 2\sigma 
\end{cases} 
$$

In other words, if the occurrence frequency difference between 2007 and 2008 ($$\Delta \text{freq}$$) was within the $$2\sigma$$ variance for 2008–2014, the difference was considered to be within the natural variability. Otherwise, the difference was split into the two effects, where the natural variability term was defined as being twice the standard deviation (i.e., $$\Delta \text{freq}_{\text{natural}} = 2\sigma$$) and the tilting term was defined as the frequency that exceeded the natural variability range during the 2008–2014 period (i.e., $$\Delta \text{freq}_{\text{tilt}} = \Delta \text{freq} - \Delta \text{freq}_{\text{natural}} = \Delta \text{freq} - 2\sigma$$).
Having formulated the effects of tilting and natural variability, Figure 7 illustrates the terms $\Delta \text{freq}_{\text{tilt}}$ and $\Delta \text{freq}_{\text{natural}}$ in Equation 6. According to the figures in the bottom row, the interannual variabilities of 2D-plates and Water (Figures 7-b1 and 7-b3) are found to be exceptionally lower than that of 3D-ice (Figure 7-b2), suggesting that the formation of horizontal ice plates and water droplets is relatively stable regardless of geographical location. A comparison of the 2D-plate frequency differences (Figures 7-a1 and 7-b1) confirms that the decrease due to lidar tilting was much larger than its natural variability. A small portion of this decrease was reclassified to the same ice category of 3D-ice (Figure 7-a2) but not to Water (Figure 7-a3). Within the 2D-plate temperature range, the frequency decrease of 2D-plate was 1.9% and the frequency increase for 3D-ice was 0.2%, suggesting that a small portion of 10.5% of the missing 2D-plates was categorized as 3D-ice. In contrast, the difference in the frequencies of Water occurrence was within the magnitude of the interannual variability (Figure 7-b3), indicating that the effect of tilting on liquid water detection was negligible (Figure 7-a3). Surprisingly, slight decreases in 3D-ice and 2D-plate attributed to the lidar tilting were found between $-40°C$ and $-20°C$ (Figures 7-a1 and 7-a2). This suggests the presence of ice plates within clouds in the range $-40°C \leq T < -20°C$, at lower temperatures than those found in the previous CALIOP nadir studies, distributed ubiquitously in mid-to high-latitudes. Indeed, there is still a possibility that the 3D-ice decrease was due to the remaining 5% probability of the natural variability, given that the natural variability of 3D-ice in the temperature region $-40°C \leq T < -20°C$ was reasonably large (Figure 7-b2). Nevertheless, the fact that the decrease in 2D-plate (Figure 7-a1) did not overlap with the temperature range of the 2D-plate natural variability ($-20°C \leq T < -10°C$) still implies the presence of 2D-plate in the temperature range $-40°C \leq T < -20°C$.

It is also worth noting the significant negative impact of 3D-ice frequency after the tilt in the tropical tropopause layer (TTL). In this cold temperature range, a positive shift of depolarization was also found (Figure S2i), similar to those recognized in the range $-40°C \leq T < -20°C$. This may suggest that the frequency decrease is related to subvisible cirrus clouds (SVCs) that may contain plate crystals, given that SVCs frequently form in the TTL (Martins et al., 2011; Reverdy et al., 2012), although further investigation would be needed in future for their clarification.

In summary, the present analysis showed that the global mean $\Delta \text{freq}_{\text{tilt}}$ and $\Delta \text{freq}_{\text{natural}}$ of 2D-plate were $-0.2642$ and $-0.0269$, respectively, indicating that the differences due to the tilting effect were one order of magnitude higher than that due to the natural variability. In contrast, the global mean $\Delta \text{freq}_{\text{tilt}}$ and $\Delta \text{freq}_{\text{natural}}$ for 3D-ice were $-0.0169$ and $-0.1519$, respectively, and those for Water were $-0.0018$ and $-0.0273$, showing that the tilting effect was much lower than the natural variabilities for 3D-ice and Water (see Table S2 for
the summary of $\Delta \text{freq}_{\text{ini}}, \Delta \text{freq}_{\text{natural}}$ and $\Delta \text{freq}$). More broadly, the diagnostic method proposed here incorporates CALIOP’s long-term observations and demonstrates an approach to determining the location and particle types affected by the change of the lidar’s viewing angle that gives a considerably larger variance than those in nature that CALIOP observed (experienced) before the change of the viewing angle.

3.5. Climatological Characteristics of Horizontal Ice Plates

3.5.1. Geographical Distribution

Having an algorithm applicable to the off-nadir periods, we investigated the climatological characteristics of horizontal ice plates. Figure 8 shows the global maps of 2D-plate. The latitude and longitude were sampled every 2°. The figure illustrates 2D-plate cloud covers during the nadir and off-nadir periods, taking into account 2D-plate at cloud tops, as well as those embedded within the clouds.

During the nadir measurement, the global ubiquitous distribution of 2D-plate is clearly shown in Figure 8b. In particular, 2D-plate was recognized in tropical clouds in the Intertropical Convergence Zone (ITCZ), over storm track regions at mid-lattitudes, and in the Southern Ocean where low-level shallow convective clouds are abundant. 2D-plate was most prevalent in latitudes above 55°N and was more evident in Asia and Europe than in Greenland and Canada. The 2D-plate occurrence frequencies during the off-nadir measurements are shown using the YOKI algorithm (Figure 8a) and the updated YOKI algorithm (Figure 8-c1). As expected, the 2D-plate frequency by the original YOKI algorithm significantly decreased after the tilting, except at higher latitudes. The decrease in the 2D-plate detection suggested that, theoretically, the majority of horizontal ice plates were stable in the atmosphere, except those at higher latitudes with much larger tumbling angles, which were captured even after the lidar tilting. When applying the updated YOKI algorithm, the 2D-plate frequency increased (Figure 8-c1), though not as much as in the nadir measurement. According to the results in Section 3.3.2, the global mean 2D-plate frequency before the tilt was 2.03 times larger ($= 7.87\% / 3.87\%$) than that after the tilt (using the updated YOKI algorithm). From this result, we derived the simple figure in Figure 8-c2, increasing the occurrence frequency of the updated YOKI off-nadir
Surprisingly, this geographical distribution of 2D-plate during the off-nadir measurements was generally similar to the distribution observed during the nadir measurement (Figure 8b). Indeed, some regions were not consistent (e.g., the underestimation at high latitudes in the Northern Hemisphere and the overestimation in the southern Indian Ocean), attributed to the inclusion of the original “Mixture of 3D-ice and 2D-plate” types into the “2D-plate” category in the updated algorithm. Nevertheless, the result in Figure 8 underscores that the off-nadir CALIOP observation (with over 10 years of observation) still possesses climatological information on the ice plate geographical distribution to a certain extent.

3.5.2. Temperature Characteristics

Given their strong temperature dependence, we studied the temperature characteristics of the cloud particle types (Figure 9). For each particle type, Figure 9a shows the temperature dependence of the occurrence frequency while Figure 9b shows the temperature dependence of the occurrence ratio, where the frequencies for the three particle types add up to 1.0 in each temperature bin, illustrating the dominant particle type at the temperature. The definitions of the occurrence frequency and ratios are described in Text S1 (in the Supporting Information). Figure 9a illustrates that the dominant temperature dependence characteristics of 2D-plate for $-20^\circ C < T < 5^\circ C$ (seen in the previous sections) did not change significantly after the tilt. We also recognize in the figure a slight frequency decrease for $-30^\circ C < T < -20^\circ C$ and an increase for $-5^\circ C < T$, which may be related to the habit orientation preference in these temperature ranges (i.e., a more stable orientation for colder temperatures $-30^\circ C < T < -20^\circ C$), although further investigation is required to confirm this. Figure 9b shows the decrease in the occurrence ratio for 2D-plate after the tilt and the con-

![Figure 9](image_url)
sequent relative increases in those for Water and 3D-ice. Figure 9b also show the general characteristics of supercooled water existence at temperatures as low as −35°C. The Water ratio gradually increases toward 1.0 as the temperature increases, while 3D-ice is widely found at temperatures of −80°C < T < −10°C. Further, Figure 9a highlights that the occurrence frequency for Water and 3D-ice did not change significantly even after the tilt, indicating that Water and 3D-ice were generally not impacted by the tilting.

4. Discussion

This study illustrated that undetected ice plates due to lidar tilting were partly recovered by changing the algorithm's δ threshold (Figure 6) and partly redistributed to the 3D-ice category (Figure 7). Yet, the majority was still missing, leading us to reiterate the original question–where have the missing ice plates gone? Theoretically, when a nadir-pointing lidar observes a plate crystal oriented horizontally, the lidar backscatter is dominated by reflection from the front/back surfaces of the ice plate, while the specular reflection weakens when the lidar points away from the surface norm (Platt, 1978). As such, for nadir-pointing lidar, even a small portion of horizontal plates in clouds can induce specular reflection strong enough to be detected as a cloud, though these become undetected (as a cloud feature) once the lidar is tilted, giving significant decrease in 2D-plate frequency. The difference in the 2D-plate detection frequencies can be considered as the probability of the tumbling angle distribution of ice plates (i.e., the 2D-plate frequency at 3.0° represents the probability of the tumbling angle distribution at 3.0°, which is smaller than the probability at 0.3°). This study revealed that even with the 50% frequency decrease, the geographical characteristics of 2D-plate are still preserved during the off-nadir to an extent, suggesting undiscovered climatological information on plate crystal in the post-2007 measurements.

Interestingly, the decrease in 2D-plane detection suggests that horizontal ice plates maintain their orientation and exist in an exceptionally stable condition in the atmosphere. Previous studies estimated the tumbling angle of ice plates to be around 1° (Bréon & Dubrulle, 2004), < 3° by POLDER (Noel & Chepfer, 2004), and ~ 1°–2° from a ground-based scanning lidar (Noel & Sassen, 2005). The present study reinforces these studies with global, vertical cloud-resolving measurements. If ice plates had large tumbling angles and followed a Gaussian distribution, CALIOP would have captured ice plates even 3° from the nadir. This indicates that the majority of ice plates fluctuate very little and are stable over the globe (except for some ice plates in the polar regions; c.f. Section 3.5.1).

Another finding of this work is the presence of ice plates in clouds at temperatures between −40°C and −20°C, which was revealed by the comparison of the nadir and off-nadir measurements (Figures 7a1–7a2, 7d–7e). The presence of plate crystals at low temperatures (to a lesser extent than in warm clouds) has been reported by ground-based observations (Westbrook et al., 2010). This study underscores the previous findings from the global perspective, highlighting that the ice plates are present across the mid- and high-latitudes.

Lastly, a limitation of this work is that the nadir-pointing lidar detects horizontal plate crystals preferentially even if an equal number of randomly oriented ice crystals are present within the cloud. In contrast, the off-nadir measurement has a similar sensitivity to detecting ice plates with other ice habits (i.e., ice plate detection would be less apparent). Using these characteristics, Noel and Chepfer (2010) derived a formula to estimate the fraction of plates in clouds using the nadir and off-nadir measurements, while Okamoto et al. (2010) derived the plate fraction from nadir measurement in the ice microphysical retrieval algorithm, and such studies would be another area to explore in the future study. We believe that, ideally, multangle viewing measurements (with the nadir and multiple off-nadir measurements) from space in future would provide a better understanding of ice habit properties and their climatological characteristics.

5. Summary

In this study, we used the long-term observations of the CALIOP lidar onboard the CALIPSO satellite from 2006 to 2014 to investigate the climatological characteristics of horizontal ice plates in clouds, and reviewed how the change in CALIOP viewing angle affected the detection of the horizontal ice plates. We focused primarily on investigating the backscatter, depolarization, and attenuation characteristics to interpret the li-
dar optical measurements in a microphysical context. We then summarised the effects of the lidar tilting on the satellite particle type algorithm with quantitative evaluations using a cloud particle type classification, namely the “YOKI algorithm” by Yoshida et al. (2010) and Hirakata et al. (2014). Having the long-term observation data set, we further demonstrated a diagnostic method to distinguish the effect of the lidar tilting from that due to natural variability. The main findings of the present study are summarized below:

1. Horizontal ice plates induce strong specular reflection for nadir-pointing lidar signals, maintaining a low depolarization with moderate lidar attenuation. While this low depolarization was expected, this study demonstrates for the first time the latitude–temperature distribution of the backscattering coefficient, depolarization, and lidar attenuation characteristics for all clouds (ice and water) detected by the lidar, together with their sensitivities to the lidar tilting (Figure 2).

2. The majority of horizontal plates (>75%) exist between −25.5°C and −7.5°C, with a mode temperature of −13.5°C (expected results). This study also underscores the presence of ice plates in colder clouds (between −40°C and −20°C) across mid-to high-latitudes where randomly oriented crystals predominate (Figures 7a1–7a2, Figures S2d–S2e). This unexpected result – based on previous CALIOP studies – is found by comparing nadir and off-nadir measurements, confirming the findings of ground-based studies from a global perspective.

3. The natural variability of the 2D-plate occurrence frequency inferred from CALIOP is exceptionally small, implying the constant formation of ice plates, while that of randomly oriented crystals is much higher (Figure 7b1–7b2). The small variability of ice plates is not limited to a specific region but is a common characteristic in different geographical regions. In addition, the absence of specular reflection after the tilt suggests that ice plates preserve their horizontal orientation without much tumbling in nature, except for a fraction at higher latitudes (Figure 6, Figure 8).

4. Using the original YOKI algorithm, horizontal ice plates decrease by 81.7% after lidar tilting. With our updated algorithm, the occurrence frequency recovers by 30.8% although the residual 50.8% remain undetected. A small portion of the residual is reclassified to the 3D-ice category, but not to liquid droplets (Water). The majority remains missing due to the absence of specular reflection after the tilting, and these ice clouds are no longer detected. Overall, the tilting mostly affects horizontal ice plates, while the impact on water and randomly oriented ice is limited (Figure 9). Even so, the geographical characteristics of 2D-plate are captured (within the 50% remaining 2D-plate) to a certain extent (Figure 8), suggesting that there is still undiscovered climatological information on plate crystals in the off-nadir measurements (having over 10 years of observation).

This study presents the fundamental principles of satellite remote sensing of ice plates using nadir and off-nadir lidar measurements, and highlights the characteristics of horizontal plates that are microphysically and geographically unique among ice habits. The next satellite-borne lidar observation is planned for the Earth, Clouds, Aerosol and Radiation Explorer (EarthCARE) mission, which carries a High Spectral Resolution Lidar, ATLID, whose viewing angle is 3.0° off-nadir. The summarized findings of this study are expected to offer insights into cloud microphysics and leverage ice habit studies using satellite lidar observations by CALIPSO, EarthCARE, and future missions beyond.

Data Availability Statement

The CloudSat and CALIPSO data were obtained from the CloudSat - CALIPSO Merged Data set provided by JAXA A-Train Product Monitor (http://www.eorc.jaxa.jp/ECARE/research_product/ECARE_monitor_e.html), which were produced using the CloudSat products from the CloudSat Data Processing Center (http://www.cloudsat.cira.colostate.edu) and the CALIPSO products from the NASA Langley Atmospheric Science Data Center (https://asdc.larc.nasa.gov/project/CALIPSO).

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