Seasonal Variations of Antarctic Clouds Observed by CloudSat and CALIPSO Satellites

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Seasonal variations of Antarctic clouds observed by CloudSat and CALIPSO satellites

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[1] The multiyear lidar and radar measurements obtained from the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) and CloudSat between June 2006 and May 2010 were used to investigate the seasonal and interannual variabilities of the vertical and horizontal cloud distributions, cloud top height above ground (H\text{top}), thickness (CTH), effective radius (r\text{e}), and ice water content (IWC) over the southern high latitudes poleward of 60°S. The collocated lidar and radar data were used to derive the cloud mask, which was used to classify the clouds into four classes according to the cloud base height above ground (H\text{base}) and CTH. The Amundsen/Bellingshausen Sea region showed the highest cloud occurrence (>80%) and Antarctic Plateau had lowest cloud occurrence (<30%). The low-level clouds accounted for more than 60% of the total cloudiness, and their occurrence was greater during summer than during winter, but deep and high-level cloud occurrence, CTH, and H\text{top} were greater during winter than during summer. CTH and H\text{top} of deep and high-level clouds were greater over ocean than over land, but both CTH and H\text{top} of low-level clouds were greater over land than over ocean. The mean IWCs for high-level clouds over land and ocean were 0.85 (2.0) and 1.3 (3.1) mg/kg, respectively, and the mean r\text{e} over land and ocean were 18.0 (22.1) and 21.5 (26.4) µm, respectively, for winter (summer). The study provides a high-quality data set of cloud properties over the Antarctic region to improve our understanding and model simulations of Antarctic clouds.


1. Introduction

[2] Clouds play an important role in the radiation and hydrological balance of the Earth-atmosphere system and are the most important regulators of the Earth’s climate [Liou, 1986; Ramanathan et al., 1989; Hatzianastassiou et al., 2001]. The Intergovernmental Panel on Climate Change [2007] lists cloud feedback as one of the main uncertainties in climate sensitivity to the increased CO\text{2} emissions. Because clouds exhibit large spatial, seasonal, and diurnal variability and they are poorly represented in climate models, climate models show large differences in the strength and direction of the cloud feedback [Dufresne and Bony, 2008; Sun et al., 2009; Trenberth and Fasullo, 2010]. Accurate information about the cloud cover, including its vertical distribution, microphysical properties, and phase, is required to better understand the role of clouds in the dynamic climate system [Wang et al., 2005]. The clouds in the polar regions are especially important because of their influence on the radiative balance, which plays a major role in the climate system, both directly at high latitudes and globally through the modulation of local circulation and teleconnections [Lachlan-Cope, 2010]. In addition, clouds provide the precipitation that maintains the ice mass balance of the largest freshwater reservoir in the world [Spinhirne et al., 2005; Arthern et al., 2006].

[3] The Antarctic region is the coldest region in the world. Because it acts as global energy sink, the variations in the local cloud cover and the radiative properties of the Antarctic region can affect the general circulation of the atmosphere. Modeling studies [e.g., Lubin et al., 1998] have shown that significant anomalies can be observed in the atmospheric circulation as a result of changes made to the radiative properties of Antarctic clouds. Atmospheric teleconnections studies [e.g., Mo and White, 1985; Simmonds and Jacka, 1995; Turner, 2004; Fogt and Bromwich, 2006; Pezza et al., 2008] show that the weather and climate in the Antarctic region, the tropics, and the midlatitudes are intricately linked; therefore, the Antarctic clouds are an important part of the global climate dynamics. Although the Antarctic clouds can significantly affect the global climate, they have attracted very little scientific attention, which is primarily due to the lack of an observational database, and they remain a very weak link in our understanding of global climate and change. Hence, an accurate representation of the clouds in the Antarctic region and their radiative properties is necessary to better understand the global climate.

[4] Several studies have used passive satellite remote sensing data to estimate the cloud microphysical properties...
in the Antarctic region. Lubin and Harper [1996] used AVHRR 11 and 12 μm radiance measurements to estimate the emissivity and effective radius of all of the ice clouds over the South Pole. Their analysis showed that the effective particle radii are larger in the summer than in the winter, but their analysis was limited by radiometric uncertainties and the lack of unique solutions to the radiative transfer equation. The cold surface temperatures and regular near-surface temperature inversion present additional challenges for the detection of clouds using infrared (IR) satellite remote sensing over the Antarctic region. Mahesh et al. [2001a, 2001b] used ground-based IR remote sensing to overcome the limitations of the satellite-based passive remote sensing. Their analysis used emissivity measurements at 10 and 11 μm and the cloud base height and atmospheric profiles from the radiosondes and the ozonesondes to estimate the effective particle radii and optical depths of ice clouds. Their analysis also showed that the effective radii over the South Pole are larger in the summer than in the winter.

These analyses provided useful information regarding the clouds in Antarctica, but they are based on short time point measurements, and they lack information regarding the vertical distribution of the clouds.

The shortcomings of passive remote sensing can be overcome by using active remote sensing, which provides the vertical distribution of cloud properties [Sassen and Campbell, 2001; Wang and Sassen, 2002a, 2002b]. Besides, the active remote sensors are not affected by the cold surface temperature, and the high surface albedo only affects the solar background noise [Spinhrne et al., 2005]. Although ground-based active cloud observations provide high temporally and vertically resolved data, the satellite-based active remote sensing of clouds provides the much-needed geographical coverage. Spinhrne et al. [2005] used lidar data from the Geoscience Laser Altimeter System (GLAS) that was collected in October 2003 to analyze the Antarctic clouds. This was the first analysis that was based on space-based lidar measurements, and it showed that there are predominantly two types of clouds over Antarctica: stratus clouds below 3 km and cirrus clouds. A larger data set is required to better understand the clouds in the Antarctic region and to characterize their seasonal dependence. Furthermore, a more complete picture of these clouds can be obtained by combining the lidar and the radar data instead of using the lidar data alone. The lidar signals are often attenuated by optically thick clouds and fail to detect clouds beyond the optically thick layer. However, the radar signals typically have weak attenuation from the clouds. The lidar and radar signals also have different sensitivities to the cloud droplet size and concentration [Wang and Sassen, 2002a]. Therefore, the combined lidar-radar measurements provide a more reliable cloud vertical structure and improved cloud microphysical properties.

The formation fly of CALIPSO [Winker et al., 2003, 2007, 2009, 2010] and CloudSat [Stephens et al., 2002] satellites that carry a depolarization-capable dual wavelength lidar Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) and a 94 GHz Cloud Profiling Radar (CPR), respectively. The measurements from CALIPSO and CloudSat provide unique, combined lidar and radar measurements to study the global cloud properties. Although lidar and radar measurements have limited spatial coverage compared to satellite passive measurements, CloudSat and CALIPSO have good coverage in the polar region (up to the ±82° latitude), and hence provide an ideal platform to study the Antarctic clouds. In this study, we used multiyear collocated CloudSat and CALIPSO measurements, which spanned from June 2006 through May 2010, to analyze the seasonal and interannual variabilities in the vertical and horizontal cloud distribution and the cloud thickness. The effective radius and ice water content of the high-level ice clouds were compared in the summer and winter seasons. We have also used the CloudSat equivalent radar reflectivity factor ($Z_e$) to estimate the near-surface precipitation frequencies and rates in the Antarctic region.

Section 2 presents a brief outline of weather and climate in the southern high latitudes. Section 3 provides the details regarding the data that were used and the methodology that was applied. Section 4 discusses the results, and section 5 describes the conclusions that were drawn from the study.

2. Weather and Climate in Antarctica

The weather and climate in Antarctica and the Southern Ocean is highly influenced by the topographic features of Antarctica [Walsh et al., 2000] and the sea ice extent of the seas that surround the continental landmass. Figure 1 shows the topography of Antarctica and the surrounding seas. The interior portion contains the elevated plateau that slopes toward the coast. A perennial anticyclone resides in the elevated plateau in east Antarctica, and it is surrounded by a circumpolar trough of low pressure (Figure 2). The majority of the landmass is covered by snow and ice throughout the year. The boundary layer is stratified with a persistent strong low-level inversion, especially in the continental region [Phillpot and Zillman, 1970] and the ice shelves [Andreas et al., 2000]. The presence of the sustained strong low-level inversion and the sloping terrain aids in the formation of a strong downslope flow, which is called the katabatic winds [Parish, 1992; Parish and Bromwich, 1998]. The katabatic surge to the coastal region is compensated by a weak poleward circulation aloft and subsidence over the plateau, which creates a thermally direct circulation [Parish and Bromwich, 1998].

The circumpolar trough is an active region of synoptic and mesoscale disturbance. High baroclinic instability is provided by the sea ice transition zone, and it provides a condition that is suitable for cyclogenesis in the circumpolar trough [Schlosser et al., 2011]. The circumpolar trough is also the region where the migrating midlatitude cyclonic disturbances dissipate. All of these factors contribute to the high density of cyclonic disturbances in and around the Southern Ocean and the seas surrounding Antarctica. The cyclonic activity is more frequent in the winter than in the summer [Simmonds et al., 2003], when there is a stronger temperature gradient between the poles and the midlatitudes. However, the cyclonic activity can be observed throughout the year.

Mesoscale cyclones are prominent features in the Antarctic coastal area. These mesoscale vortices are more commonly found over open water [Carrasco and Bromwich, 1994; Irving et al., 2010; Bromwich et al., 2011; Uotila et al., 2011]; however, they have been observed in the ice shelves over the coastal regions, in the northern margin of
the sea ice zone and over open water [Carrasco et al., 2003]. One of the major mechanisms contributing the formation of these cyclones includes the low-level baroclinic instability that is caused by the confluence of cold continental air with warmer maritime air; this confluence is derived either from the surge of cold katabatic flow toward the coast [Parish, 1992] or the warm maritime air advected toward the continental air blowing from the Antarctic plateau. The complex terrain, especially in the coastal areas of the Weddell Sea and the Ross Sea (RS), also support the formation of mesocyclones [Heinemann and Klein, 2003]. In the absence of strong upper level forcing these mesoscale cyclones are primarily low-level features, but in the presence of strong synoptic forcing they can develop into deep cyclones.

3. Data Analysis and Methodology

[10] The CloudSat 2B-GEOPROF product (available at http://www.cloudsat.cira.colostate.edu/dataICDlist.php?go=list&path=2B-GEOPROF) was used to identify cloudy bins (cloud mask values ≥30) from radar measurements. The CALIPSO level 1 data products were collocated and averaged to match the horizontal resolution (~1.1 km) of CloudSat and a uniform 180 m vertical resolution. The attenuated lidar scattering ratio (ALSR), which is the ratio of the total backscattering to the molecular backscattering, was used to identify clouds from the CALIPSO measurements. The simple threshold values of ALSR were used to identify the cloud boundaries as described by Wang et al. [2008]. The cloud masks that were obtained from CALIPSO and CloudSat were combined to describe the cloud structures as illustrated in Figure 3. Figures 3a and 3b show $10 \log_{10} \beta'_{532}$, where $\beta'_{532}$ is the total attenuated backscattering coefficient of the 532 nm CALIPSO channel, and $Z_e$ from the CloudSat radar, respectively. Figure 3c shows the clouds detected by CALIPSO, CloudSat, or both, and it clearly shows that the combination of the lidar and radar measurements provides a more complete picture of the vertical cloud distributions. Figure 3d shows the volume depolarization ratio of the cloud particles.

[11] The combined CALIPSO and CloudSat cloud masks were used to calculate the cloud thickness (CTH), cloud base height above ground ($H_{base}$), cloud top height above ground
(H_{top}) and mean maximum equivalent radar reflectivity factor (Z_{max}) for each cloud layer. The clouds were classified into high- (H_{base} ≥ 6 km), middle- (6 > H_{base} ≥ 2 km) and low- (H_{base} < 2 km and CTH < 6 km) level clouds and vertically extended deep cloud systems (CTH ≥ 6 km and H_{base} < 2 km). The cloud properties were then derived for these four categories. Figure 3e shows a sample of the cloud classification based on the above criteria.

The cloud occurrences in the region were calculated as the ratio of the number of cloudy profiles to the total number of profiles in the 2° latitude × 5° longitude grids. Similarly, the meridionally averaged vertical distribution of cloud occurrence was calculated for the 5° longitude × 0.25 km vertical bins.

The bulk cloud microphysical properties of the high-level clouds were analyzed on the basis of the calculated values of the depolarization ratios from the CALIPSO lidar 532 nm channel and the attenuated backscattering coefficients at the 532 nm and 1064 nm channels. The contribution of molecular scattering at the 532 nm channel can be significant, especially for thin cirrus clouds that have low ALSR values; therefore, equation (2) of Adhikari et al. [2010], given as

\[ \delta' = \frac{(R\delta - \delta_m)}{(R + \delta_m - \delta - 1)}, \]

where, \( \delta' \), \( \delta_m \), \( \delta \) and \( R \) are the depolarization ratio of the cloud particles, depolarization ratio due to molecular signal, uncorrected volume depolarization ratio and the ALSR, respectively, was applied to derive the volume depolarization ratio of the cloud particles.

The seasonal dependency of the high-level ice cloud properties, such as ice water content (IWC) and effective radius (re), was assessed with the CloudSat 2C-ICE product [Deng et al., 2010]. The 2C-ICE was designed as a CloudSat operational standard data product that combines CloudSat radar and CALIPSO lidar to retrieve both thick and thin ice cloud re, IWC and extinction. The algorithm identifies the
lidar-only, the lidar-radar overlap and the radar-only regions within a cloud layer. In the lidar-only region, where $Z_e$ is below minimum detectable signal, the $Z_e$ profile is parameterized using the statistics obtained from the Atmospheric Radiation Measurement (ARM) millimeter cloud radar (MMCR), and in the radar-only region, the extinction and attenuated backscattering profiles were estimated using the $Z_e$ profiles. Therefore, the algorithm performs retrievals for a wide range of ice clouds, ranging from tenuous upper tropospheric cirrus clouds to geometrically and optically thick ice clouds. The validation of the algorithm done by using the Tropical Composition, Cloud and Climate Coupling Experiment (TC4 [Toon et al., 2010]) and the Small Particles in Cirrus (SPARTICUS [Mace et al., 2009]) in situ measurements showed that the 2C-ICE products provide reliable ice cloud properties.

4. Results and Discussion

4.1. Cloud Occurrence

[15] Figure 4 shows the seasonal mean maps for the cloud occurrence for June–August (winter), September–November (spring), December–February (summer) and March–May (fall), and the data were averaged over for a 4 year period from June 2006 through May 2010. Figure 4 shows that there is a marked contrast in the cloud distribution between the Antarctic continent and the surrounding Southern Ocean. The subsidence region of the Antarctic plateau is characterized by little cloud occurrence whereas the circumpolar trough is characterized by little cloud occurrence whereas the circumpolar trough is characterized by persistent cloud coverage.

[16] Figure 4a shows that the highest total cloud occurrence of 80–90% is observed near the 60–65°S latitudes in the Amundsen/Bellinghausen Sea (ABS) sector of West Antarctica in all four seasons, and the lowest occurrence of 20–30% is observed in the eastern portion of the Transantarctic Mountains around 150°E. There were distinct interseasonal variations; a greater cloud occurrence within the circumpolar trough in the summer and fall seasons than in the winter and spring seasons. During the summer and fall, the entire circumpolar trough experienced persistent cloudiness, and the cloud occurrence was greater than 80%. However, during the winter, when the northern extent of the sea ice extends up to 60°S [Simmonds et al., 2005], the persistent high cloud occurrence was confined to the

Figure 4. The 4 year average (from June 2006 through May 2010) seasonal cloud occurrence maps for (a) all clouds types, (b) deep clouds, (c) high-level clouds, (d) midlevel clouds, and (e) low-level clouds for austral winter, spring, summer, and fall seasons.
location north of the 65°S latitude; one exception was the ABS sector, which displayed protruding tongues of high cloud occurrence, which extended from 60 to 65°S southward over the sea ice and West Antarctica. These high cloud occurrence streaks can be attributed to the advection of the moist maritime air that is caused by the cyclonic circulations over the RS and Amundsen Sea regions [Nicolas and Bromwich, 2011]; these cyclones bring moist maritime air to the eastern side of the cyclonic circulation and dry continental air to the western side. The largest contrast between the cloud occurrences in the summer and winter seasons was observed over the Ross Ice Shelf (RIS) and sea ice region in the surrounding RS, the Filchner-Ronne ice shelf (FRIS) and the Weddell Sea. These regions have a cloud occurrence of ~60% during the winter but ~90% during the summer. During the winter and spring, very low surface temperatures in and around the RIS, FRIS and the surrounding sea ice covered region result in a very low moisture content that inhibits cloud formation [Carrasco et al., 2003]. However, during the summer, these cyclonic dry features are less abundant. Although the sea ice extent in the spring season is similar to that in the winter, the advection of marine air over the sea ice causes a higher cloud occurrence during the spring than during the winter, especially over Weddell Sea. During the spring, the cyclonic circulation over the Bellingshausen Sea causes the intrusion of warmer maritime air over Weddell Sea.

[17] The Antarctic coastal region (60–70°S latitude belt) is one of the most active regions of synoptic-scale cyclonic storms. The region, especially the RS and the northern part of the Antarctic Peninsula, are two of the most active regions of cyclogenesis in the Southern Hemisphere [Simmonds and Keay, 2000; Fyfe, 2003]. In addition, the migrating mid-latitude cyclones also dissipate in the Antarctic coastal region around the ABS. These cyclones are responsible for the latitudinal transport of heat and moisture from the low and middle latitudes toward the poles [Hoskins and Hodges, 2005]. The synoptic-scale cyclonic disturbances are associated with deep and high-level clouds and precipitation. Hence, the occurrence of deep clouds closely follows the distribution pattern of these synoptic disturbances. The largest occurrence of deep clouds was observed within the circumpolar trough in the 60–70°S latitude belt (see Figure 4b). The highest occurrence frequency of deep clouds was 15–20% and was observed around the ABS and RS regions in West Antarctica and to the south of Australia (120–150°E longitudes). There was also a marked seasonal variation in the distribution and occurrence of deep clouds between the winter and summer months. During the winter and spring seasons, the occurrence of deep clouds was greater than 15% for the ABS, the eastern RS and the coastal region of East Antarctica. The highest occurrence of 20% was observed off the coast of Marie Byrd Land in the Amundsen Sea. However, during the summer and fall, the largest occurrence of the deep clouds was ~15%, and was localized to some regions within the circumpolar trough. Most of the region that extends from the RS to the Antarctic Peninsula showed deep cloud occurrence frequency of 10–15%. The larger occurrence frequency of deep clouds in the winter can be attributed to the greater occurrence of synoptic-scale cyclones in the winter than in the summer.

[18] Similar to the deep clouds, high-level clouds are also associated with large-scale synoptic features and are closely associated with the distribution of deep clouds (see Figure 4c). However, cirrus clouds persist longer than deep clouds, and they drift with the upper level wind, which results in both the greater overall occurrence frequency and the greater frequency in the downwind region of the deep clouds. Because there were strong westerly winds in the upper troposphere of the circumpolar trough, the highest occurrences of high-level clouds were observed to the east of the deep clouds. The largest occurrence frequencies of high-level clouds were found around the Antarctic Peninsula, which lies downwind of the ABS. Similar to the deep clouds, there was a greater occurrence of high-level clouds during the winter and spring seasons than the summer and fall seasons. During the spring season, an occurrence frequency of 40% was observed on the eastern side of the Antarctic Peninsula on the Weddell Sea. The lowest occurrence frequency for high-level clouds was observed during the fall season. The low occurrence during the fall can be partly attributed to the less intense cyclonic storms during the fall season, when the deep clouds have the smallest vertical extent and lower cloud tops.

[19] The occurrence of midlevel clouds (see Figure 4d) in most parts of the Antarctic region ranged from 20 to 30%; the lowest occurrence of 10–20% was observed in continental Antarctica, and the highest occurrence of 30–40% was observed around the seas in West Antarctica. The continental part of West Antarctica, including Marie Byrd Land and the Antarctic Peninsula, had an occurrence frequency in the range of 30–35%. During the winter season, the east Antarctic plateau also had a high occurrence of midlevel clouds.

[20] In terms of the frequency of occurrence, the low-level clouds constituted the major cloud type in Antarctica (see Figure 4e). These clouds were more frequent around the circumpolar trough, and similar to the high-level and deep clouds, they were least frequent in the continental part of Antarctica. However, unlike the high-level and deep clouds, the low-level clouds were more frequent during the summer than the winter. Because low-level clouds were the most dominant clouds, the spatial and temporal patterns of total cloud occurrence were dominated by the distribution of the low-level clouds. Therefore, although the deep and high-level clouds were more frequent during winter months, the total cloud cover was larger in the summer because of the significantly higher occurrence of low-level clouds in the summer than in winter. During the summer, the whole region outside of continental Antarctica had a low-level cloud occurrence above 60%, and in the 65–70°S belt of West Antarctica and the Weddell Sea, the occurrence was greater than 80%. During the winter, sea ice covers most of the region to the south of 65°S, which inhibits transfer of heat, moisture and momentum [Godfred-Spenning and Simmonds, 1996]. The differences in the extent of sea ice around the Antarctic seas may be a factor that affects the low-level cloudiness differences between the summer and the winter seasons.

[21] Changes in the cloud cover in Antarctica can impact the climate system through changes in the surface heat budget. Antarctica has a net positive cloud radiative forcing on the surface, which depends largely on the amount of
cloud cover [Pavolonis and Key, 2003]; therefore, the variabilities in the cloud cover affect the surface radiation budget. Studies conducted over the Arctic [e.g., Zhang et al., 1996] indicate that the persistent cloud cover can cause the onset of arctic snowmelt to occur one month earlier than under clear sky conditions. Although to our knowledge, there are no studies concerning the feedback between the extent of sea ice and the cloud cover over Antarctica, the surface warming that is associated with clouds can affect the sea ice cover in the region.

In the 4 years of data that were analyzed in this study, signals of interannual variabilities were found in the occurrence of all four cloud classes. Figure 5 shows the normalized standard deviation of the mean cloud occurrence frequency (the ratio of the standard deviation to the mean). The interannual variability within the continental region was large in all of the seasons; the variability ranged from 25% to 35% with maximum of ~50% in the eastern side of the Transantarctic Mountains. The variability was the lowest (5–10%) in the 60–65°S region, which had the largest cloud occurrence frequency.

The highest normalized standard deviation was observed for the deep clouds (Figure 5b) and the high-level clouds (Figure 5c). Because the deep and high-level clouds are associated with synoptic-scale cyclonic disturbances, the interannual variability in the cyclone movement and distribution can affect the deep and high-level clouds. During the winter season, Weddell Sea experienced the highest variability in the deep clouds. The high variability in the Weddell Sea was due to the anomalously low occurrence of deep clouds during winter of 2006. The mean sea level pressure (MSLP) analysis that was performed using the NCEP-2 reanalysis data (not shown in Figure 5) showed a high positive MSLP anomaly >5 hPa that was centered over the northern tip of the Antarctic Peninsula and extended to the Weddell Sea. The high positive MSLP anomaly suggests a lower number of cyclonic disturbances and smaller occurrence of deep clouds in the region. In addition, the Southern Oscillation Index (SOI), which is an important mode of interannual variability in the Southern Hemisphere [Pezza et al., 2007; Yuan and Li, 2008], also suggested the presence of anomalous cyclone behavior during the 2006 winter. Kwok and Comiso [2002] suggested that the SOI correlates well with the MSLP anomalies in the Pacific sector of the Southern Ocean. The negative SOIs are associated with the positive MSLP anomalies and the ridging on the western portion of the Antarctic Peninsula [Turner, 2004]. The reduced number of cyclonic activities during

Figure 5. Same as Figure 4 but for normalized standard deviation of the mean occurrence.
the winter of 2006, which displayed a large negative SOI of −10.1 (Troup SOI values taken from Australian Bureau of Meteorology Web site http://www.bom.gov.au/climate/current/soihtm1.shtml), may be responsible for the negative anomalies in the cloud occurrence around the Weddell Sea region.

[24] As shown in Figure 4, the low-level stratus clouds were the major component of the clouds in the coastal regions in all of the seasons. However, the high-level cirrus clouds and the deep tropospheric cloud systems that extended beyond 7 km vertically were observed throughout the year in Antarctica. Figures 6a and 6b show the meridionally averaged vertical distributions of cloud occurrence for the 4 year period from June 2006 through May 2010 for continental Antarctica and Southern Ocean/seas that lie to the south of 60°S, respectively. Figures 6a and 6b show the presence of a high occurrence of clouds at low elevations at all of the longitudes. However, there were distinct differences between clouds over land and ocean. Over the land, one of the major features of vertical cloud distribution was the abrupt discontinuity in the cloud occurrence at 60°W, the eastern edge of the Antarctic Peninsula that separates the ABS in the west from the Weddell Sea, with higher cloud occurrence to the west and lower cloud occurrence to the east. The western continental region adjacent to the ABS recorded cloud occurrence of up to 50% at low levels

Figure 6. Meridionally averaged vertical distribution of cloud occurrence for winter, spring, summer and fall for the 4 year period for (a) continental Antarctica and (b) southern seas/oceans. The meridional average for southern seas/oceans is taken for the region poleward of 60°S.
(1–2 km) with cloud occurrence of 30% extending up to 8 km above the surface. On the other hand, the continental region in the east (east of the Prime Meridian) that includes the Antarctic Plateau experienced cloud occurrence of 25–30% at low levels (1–3 km) and less than 10% above 5 km. The major reason for this hemispherical difference is the position of the Antarctic continent; most of continental Antarctica (including the dry Antarctic plateau) lies in the eastern part whereas the western part contains a small fraction of the continental Antarctica. High elevation of the Antarctic plateau, along with low water vapor amount resulting from perennial snow covered surface can result in smaller cloud occurrence on the eastern continental region compared to the western continental region that lie adjacent to southern seas.

The clouds over sea showed greater cloud occurrences and greater vertical extent than the clouds over land. The highest cloud occurrences (80%) were observed around 1 km and cloud occurrence >30% was observed at altitudes up to 10 km. The ABS region in the west, southern Atlantic near the Prime Meridian, and the southern Indian Ocean around 100°E showed consistently large cloud occurrence throughout the year. A notable region of low cloud occurrence at all the elevations is around 45°W, which includes the Weddell Sea and the FRIS.

Along with the land-sea differences in cloud occurrences, there were seasonal and interannual variations in both clouds over land and over ocean. Over land, cloud occurrences >25% was observed up to heights of 8 km west ward of the Antarctic Peninsula in all the seasons except during the summer. Similarly, for clouds over ocean, winter and spring seasons had cloud occurrences >25% extending over 11 km, whereas during the summer and fall seasons, the clouds rarely extended up to 10 km above the surface. One of the noticeable differences between the winter seasons among the 4 years was the significantly lower cloud occurrence around 45°W, which includes the Weddell Sea, during 2006.

Figure 7 shows the time series of daily averaged CTH and \( H_{\text{top}} \) for three regions of the southern high latitudes, (1) west seas (latitudes between 60°S and 75°S and longitudes between 70°W and 180°W, hereafter referred to as WS) that include RS and ABS, (2) Antarctic Plateau (latitudes between 73°S and 82°S and longitudes between

\[ \text{Cloudtop Height (km)} \]

\[ \text{Cloud Thickness (km)} \]

**Figure 7.** Time series of daily averaged cloud thickness (CTH) and cloud top height (\( H_{\text{top}} \)) for high-level clouds, midlevel clouds, low-level clouds, and deep clouds for west seas (WS), Antarctic Peninsula (AP) and the coastal Antarctic region (CR), averaged over the 4 year period. The vertical bars represent the standard deviations of the daily mean values.
Table 1. Mean Cloud Top Height (Htop) for High-Level, Midlevel, Low-Level and Deep Clouds for Clouds Over West Seas (WS), Antarctic Plateau (AP) and the Coastal Region (CR)\(^a\)

<table>
<thead>
<tr>
<th>Cloud Class</th>
<th>WS</th>
<th>AP</th>
<th>CR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Winter</td>
<td>Summer</td>
<td>Winter</td>
</tr>
<tr>
<td>High-level</td>
<td>9.9 (0.60)</td>
<td>9.4 (0.41)</td>
<td>9.6 (0.56)</td>
</tr>
<tr>
<td>Mid-level</td>
<td>6.4 (0.43)</td>
<td>5.7 (0.31)</td>
<td>6.3 (0.43)</td>
</tr>
<tr>
<td>Low-level</td>
<td>2.5 (0.20)</td>
<td>2.4 (0.18)</td>
<td>2.8 (0.23)</td>
</tr>
<tr>
<td>Deep</td>
<td>8.6 (0.56)</td>
<td>8.3 (0.30)</td>
<td>8.5 (0.64)</td>
</tr>
</tbody>
</table>

\(^a\)Parameters are defined in the text, based on the cloud statistics for July 2006 through June 2010. The standard deviation of the mean is given in parentheses.

10\(^\circ\)W and 160\(^\circ\)E, hereafter referred to as AP), and (3) coastal regions of Antarctica (latitudes northward of 80\(^\circ\)S on western Antarctica and northward of 73\(^\circ\)S on eastern Antarctica, hereafter referred to as CR). These three regions were selected because they represent highly contrasting environments for cloud formation in the southern high latitudes. The time series is averaged over the 4 year study period and the vertical bars represent the standard deviations of the daily mean values. To preserve the clarity of Figure 7, the standard deviations are only shown for the first day of each month. The mean and the standard deviations of the 4 year data of Htop and CTH for high-level, midlevel, low-level, and deep clouds are shown in Tables 1 and 2, respectively. Both Figure 7 and Table 1 show that clouds extended up to higher elevations during winter than during summer and the mean cloud top heights over the WS were greater than over the AP. The highest (lowest) Htop of 10.21 (8.82) km were observed over the WS during November (March) and the mean Htop for high-level clouds over the WS, AP and CR were 9.9 (9.4), 9.6 (8.7) and 9.8 (9.0) km for winter (summer), respectively. A similar trend of higher Htop during winter than during summer was observed for midlevel and deep clouds. Because the cloud top heights for the upper tropospheric high-level clouds and deep clouds depend on the height of the tropopause, the seasonal cycle of the Htop closely follows the seasonal cycle of the tropopause heights. The Antarctic tropopause height exhibits a cycle of oscillation that is not observed in any other part of the world, because it is at a higher elevation in the winter than in the summer [Zängl and Hoinka, 2001]. Therefore, the clouds can be expected at higher elevations in the winter than in the summer. However, low-level clouds showed Htop maxima during spring and fall seasons and minima during winter and summer. Besides, the cloud top heights over the AP were greater and exhibited larger amplitude in the seasonal cycle than those over the WS. The interannual variabilities of Htop for clouds were less than 10% for both winter and summer seasons over all the three regions, and the interannual variabilities for CTH were in the range 10–20% for high-level, midlevel, and low-level clouds and less than 10% for the deep clouds. Statistical analysis showed that there were no systematic differences in CTH among WS, AP and CR for high-level, midlevel, and deep clouds and in Htop for midlevel and deep clouds. High- and low-level Htop and low-level CTH showed systematic differences among the three locations. Student’s t test applied to test the whether the mean of the summer and winter Htop and CTH and the mean of the Htop and CTH at WS, AP, and CR were statistically different at 0.01 significance level. The test results showed that the summer and winter Htop means were statistically different for all the cloud classes except for the low-level clouds. However, for the low-level clouds both Htop and CTH means among WS, AP and CR were statistically different.

Table 2. Same as Table 1 but for Mean Cloud Thickness (CTH)

<table>
<thead>
<tr>
<th>Cloud Class</th>
<th>WS</th>
<th>AP</th>
<th>CR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Winter</td>
<td>Summer</td>
<td>Winter</td>
</tr>
<tr>
<td>High-level</td>
<td>1.8 (0.35)</td>
<td>1.0 (0.18)</td>
<td>1.7 (0.38)</td>
</tr>
<tr>
<td>Mid-level</td>
<td>2.4 (0.41)</td>
<td>1.8 (0.28)</td>
<td>2.3 (0.31)</td>
</tr>
<tr>
<td>Low-level</td>
<td>1.1 (0.21)</td>
<td>1.0 (0.20)</td>
<td>1.4 (0.24)</td>
</tr>
<tr>
<td>Deep</td>
<td>7.0 (0.53)</td>
<td>6.8 (0.27)</td>
<td>7.0 (0.61)</td>
</tr>
</tbody>
</table>
observed in August/September and January/February, respectively, for all of the clouds except the low-level clouds, which had the highest and the lowest CTH in November and February, respectively. Because deep clouds have their origin in the deep cyclonic storms, they are closely related to the horizontal and vertical extent of the cyclonic disturbances. In the Antarctic region, the synoptic-scale cyclonic disturbances have a deeper vertical extent in the winter season than in the summer season [Simmonds et al., 2003]; therefore, the deep clouds have a greater vertical extent in the winter than in the summer. High-level cirrus clouds are also directly associated with large-scale synoptic features and form along the leading edge of frontal or low-pressure weather disturbances [Liou, 1986]. The thicker anvil cirrus clouds can be expected to be more frequent during the winter, when the frequency of deep clouds is higher. The CTHs for the high-level and deep clouds showed an interannual variability of 19% (14%) and 7% (7%) in the winter (summer), respectively. Similarly, the interannual variability of the CTHs in the midlevel and low-level clouds were 12% (19%) and 15% (17%) in the winter (summer), respectively.

[29] Multilayer clouds commonly occur in all of the seasons in the Antarctic region. Among all of the profiles that detected clouds, 32% showed more than one cloud layer. Figure 8 shows a bar graph of the frequency distributions of the $H_{\text{top}}$, $H_{\text{base}}$ and CTH based on the statistics that were obtained over WS, AP and CR for all of the cloud layers during June 2006 through May 2010. The $H_{\text{base}}$ showed two distinct maxima. The first maximum was present in the range of 1 to 2 km above the ground, and the second maximum was present in the 4–5 km range for clouds at WS and CR and at a lower level (3–4 km) for clouds at AP. Stratus clouds comprised a large portion of the clouds with a base of 1–2 km. The frequency of occurrence decreased sharply from 5 km to 13 km. Similar to $H_{\text{base}}$, the cloud top heights showed two maxima for clouds at AP and CR. Over AP cloud top maxima were observed at 2–3 km and 4–5 km range, whereas over CR the cloud top maxima were observed at 1–2 km and 5–7 km ranges. The higher altitude of the $H_{\text{top}}$ local maxima at AP is related to the larger thickness of low-level clouds over the continental region than over the Ocean. The frequency of cloud top heights at WS exhibited a gradual decrease with height with local maxima at 1–2, 5–6 and 8–9 km ranges. However, unlike the $H_{\text{base}}$, a sharp decrease in the $H_{\text{top}}$ was not identified in all the three regions. CTH had a distinct maximum at 0.5–1.0 km, which constituted more than 25% of the total observed clouds at all the three regions. Altogether, geometrically thin clouds that were less than 1 km thick constituted ~60% of all of the clouds at WS and more than 45% at AP and CR. The lower fraction of clouds with thickness less than 1 km at AP and CR can be attributed to larger CTH of low-level clouds in these regions compared to those at WS. The low-level and summertime midlevel and high-level clouds constituted most of the geometrically thin clouds with CTH less than 2 km. The geometrically thin low-level and midlevel clouds that were near the Antarctic coastal region were often mixed phase clouds that contained an ice layer below the supercooled water dominated mixed phase layer. Zhang et al. [2010] identified the Antarctic coast and the Seas around Antarctica as one of the regions that had the highest occurrence of liquid-layer topped stratiform clouds. The wintertime midlevel and high-level clouds contributed to the clouds with a thickness that ranged from 1 to 2 km. The clouds that were thicker than 5 km comprised approximately 10% of the total clouds, and the clouds above 7 km deep comprised 1–2%. These deep clouds were observed mostly outside of the continental region that is around the Antarctic coast and the southern seas.

4.2. Microphysical Properties of High-Level Clouds

[30] The depolarization ratio provides information about the particle shape, orientation and internal structure [Takano and Liou, 1995]. Spherical particles do not cause depolarization at a scattering angle of 180° whereas irregularly shaped ice crystals cause depolarization. Ice crystals have a polycrystalline structure at temperatures colder than ~20°C, they are highly irregular in shape with little symmetric structure and the crystal habits are strongly dependent on temperature [Hobbs and Scott, 1965; Bailey and Hallett, 2004, 2009]. However, ice crystals align themselves so
that the largest dimension is orthogonal to the gravitation force [Sassen and Benson, 2001]; therefore, for plate-like crystals, the depolarization ratio may be small for the nadir/zenith viewing lidar, e.g., the nadir viewing CALIOP. As a result, the effect of the lidar pointing angle on the depolarization ratio can depend on the ice crystal habit and thus, temperature. Sassen and Benson [2001] analyzed the measurements of the cirrus cloud depolarization ratio and found that a significant change in the depolarization ratio between the nadir and off-nadir measurements can be observed at temperatures warmer than $-45^\circ$C. Table 3 shows the mean depolarization ratios and their standard deviations in $5^\circ$C temperature intervals for the Antarctic high-level clouds. The CALIPSO lidar beam was nominally pointed in a near-nadir direction ($0.3^\circ$) before 28 November 2007, but it was changed to $3^\circ$ off-nadir after that date. The measurements obtained in the winters of 2006 and 2007 represent the measurements made in the near-nadir direction, and the measurements for the winters of 2008 and 2009 represent those made at off-nadir angles. Our results showed that Antarctic high-level clouds that are mostly colder than $-40^\circ$C did not show significant differences in the depolarization ratio values between the near-nadir and off-nadir measurements. There was no statistically significant difference between the depolarization ratios in the near-nadir and off-nadir directions.

Figure 9a shows the two-dimensional plots of the depolarization ratio to assess its temperature-latitude dependence for the four seasons from June 2006 through May 2010, and Figure 9b shows the normalized frequency distributions of the depolarization ratios. Although the dependence of the depolarization ratio on the temperature is apparent, Figure 9 also shows that the depolarization ratio varies greatly for any given temperature range at different latitudes. The temperature alone does not explain the ice crystal habits that were observed in the high-level Antarctic clouds. In addition to temperature, ice supersaturation, vertical motion, and changes in the growth rates in clouds can substantially affect the ice crystal growth [Bailey and Hallett, 2009], which can account for the interseasonal differences in the depolarization ratios at similar temperatures. However, the temperature dependence of the ice crystal shapes was evident from the enhancement in the depolarization ratios in the temperature ranges from $-45^\circ$C to $-50^\circ$C and $-60^\circ$C to $-70^\circ$C, especially during spring and summer.

For solid spherical particles within the Rayleigh scattering regime, $Z_e$ is proportional to the sixth power of the particle diameter. As a result, $Z_e$ is a stronger function of particle size than the number concentration. Therefore, the $Z_{max}$ value within a profile provides information about the particle size in the cloud layer. Figure 10 shows time series

<table>
<thead>
<tr>
<th>Temperature Range ($^\circ$C)</th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
</tr>
</thead>
<tbody>
<tr>
<td>$-35$ to $-40$</td>
<td>0.223 (0.135)</td>
<td>0.248 (0.170)</td>
<td>0.252 (0.164)</td>
<td>0.246 (0.161)</td>
</tr>
<tr>
<td>$-40$ to $-45$</td>
<td>0.252 (0.141)</td>
<td>0.311 (0.182)</td>
<td>0.312 (0.179)</td>
<td>0.313 (0.180)</td>
</tr>
<tr>
<td>$-45$ to $-50$</td>
<td>0.266 (0.139)</td>
<td>0.307 (0.172)</td>
<td>0.306 (0.171)</td>
<td>0.293 (0.161)</td>
</tr>
<tr>
<td>$-50$ to $-55$</td>
<td>0.268 (0.133)</td>
<td>0.287 (0.154)</td>
<td>0.288 (0.153)</td>
<td>0.269 (0.135)</td>
</tr>
<tr>
<td>$-55$ to $-60$</td>
<td>0.285 (0.140)</td>
<td>0.304 (0.154)</td>
<td>0.302 (0.156)</td>
<td>0.282 (0.139)</td>
</tr>
<tr>
<td>$-60$ to $-65$</td>
<td>0.318 (0.154)</td>
<td>0.335 (0.164)</td>
<td>0.328 (0.163)</td>
<td>0.304 (0.151)</td>
</tr>
<tr>
<td>$-65$ to $-70$</td>
<td>0.316 (0.168)</td>
<td>0.348 (0.167)</td>
<td>0.353 (0.163)</td>
<td>0.317 (0.145)</td>
</tr>
<tr>
<td>$-70$ to $-75$</td>
<td>0.333 (0.162)</td>
<td>0.342 (0.163)</td>
<td>0.373 (0.163)</td>
<td>0.322 (0.149)</td>
</tr>
<tr>
<td>$-75$ to $-80$</td>
<td>0.324 (0.164)</td>
<td>0.337 (0.164)</td>
<td>0.377 (0.165)</td>
<td>0.320 (0.152)</td>
</tr>
<tr>
<td>$-80$ to $-85$</td>
<td>0.336 (0.158)</td>
<td>0.326 (0.161)</td>
<td>0.356 (0.169)</td>
<td>0.308 (0.151)</td>
</tr>
<tr>
<td>$&lt; -85$</td>
<td>0.348 (0.151)</td>
<td>0.337 (0.155)</td>
<td>0.362 (0.165)</td>
<td>0.313 (0.141)</td>
</tr>
</tbody>
</table>

*During the winters of 2006 and 2007, the CALIPSO lidar beam was pointed at the near-nadir angle of 0.3°, and during the winter of 2008 and 2009, the lidar beam was pointed at the off-nadir angle of 3.0°. The values in parentheses are the standard deviations from the mean values.
of daily averaged $Z_{\text{max}}$ at WS, AP and CR. The time series is averaged over the 4 year study period and the vertical bars represent the standard deviation of the daily mean values. The time series show seasonal dependencies of the $Z_{\text{max}}$ values, especially in the case of clouds at AP and CR. High-level clouds showed $Z_{\text{max}}$ largest during the spring/summer and smallest during fall/winter seasons. Although $Z_{\text{max}}$ values at all the three regions showed similar seasonal trend for high-level clouds, $Z_{\text{max}}$ values were the largest at WS and the smallest at AP. Low-level clouds at AP and CR showed two maxima during November and March; however, $Z_{\text{max}}$ for low-level clouds at WS did not exhibit significant seasonal trends. In the case of deep clouds, $Z_{\text{max}}$ was the largest from January through mid-March but, similar to low-level clouds $Z_{\text{max}}$ for deep clouds at WS, did not exhibit significant seasonal trends. The 4 year mean $Z_{\text{max}}$ for deep clouds at WS, AP and CR were $-2.6 (-0.3)$, $-7.5 (-0.9)$ and $-6.7 (-0.8)$ dBZ for winter (summer), respectively. The presence of a larger $Z_{\text{max}}$ during the summer than the winter indicates the presence of larger particles during the summer than during the winter.

Figure 10. Time series of mean maximum equivalent radar reflectivity factor ($Z_{\text{max}}$) for high-level, midlevel, low-level, and deep clouds for WS, AP, and CR regions averaged over the 4 year period. The vertical bars represent the standard deviations of the daily mean.

The larger $r_c$ and IWC values during the summer than during the winter. The strong temperature dependence and a weaker latitudinal dependence for clouds over both ocean and land, with larger $r_c$ at warmer temperatures than at colder temperatures. The strong temperature dependence was the main reason for the large winter and summer differences in $r_c$ frequency distributions in Figure 11c. Besides, land and ocean differences in $r_c$ can also be attributed to the temperature differences, with warmer oceans having larger $r_c$ than the colder land. The mean $r_c$ of high-level clouds over land and ocean were 18.0 (22.1) and 21.5 (26.4) µm for winter (summer), respectively. In the case of IWC, there was a strong dependence on temperature, with greater IWC at warmer temperatures than at colder temperatures. However, there were distinct differences in the IWC during winter and summer even for similar temperatures. The mean IWC of high-level clouds over land and ocean were 0.85 (2.0) and 1.3 (3.1) mg/kg for winter (summer), respectively. The strong dependence of $r_c$ and IWC on temperature was also illustrated by Figure 12, which shows the means of $r_c$ and IWC versus temperature. The $r_c$ and IWC have positive correlation coefficients of 0.98 (0.99) and 0.98 (0.94) with the winter (summer) temperature, respectively. Figure 12a also shows the normalized number of observations versus the temperature at 1 K temperature bins. These results indicate that the seasonal difference in $r_c$ was mostly due to the differences in cloud temperature during the winter and summer. However, factors other than temperatures, including ice supersaturation, vertical motion and changing growth rates, can substantially affect the ice crystal growth [Bailey and Hallett, 2009]. The differences in the slopes of $r_c$ and IWC versus the temperature between the winter and summer can be attributed to these nontemperature effects. The larger $r_c$ and IWC values during the summer than during the winter is also applicable when all of the ice clouds are considered (data not shown in Figure 12), and these results confirmed the findings from previous studies performed over the South Pole [e.g., Lubin and Harper, 1996; Mahesh et al., 2001b].

5. Summary and Conclusion

The Antarctic region is characterized by the presence of a high-pressure subsidence zone in the interior Antarctic Plateau, and it is surrounded by a circumpolar trough of low pressure. The circumpolar trough is a region that has a high occurrence of cyclonic disturbances. However, topographic features greatly influence the distribution of clouds in the region. The eastern part of the region comprises the bulk of the Antarctic continent, whereas the composition of the western part fluctuates between sea ice and the southern seas. The western part of Antarctica contains active regions of mesocyclogenesis and the occurrence of extratropical cyclones. These disturbances result in a larger cloud occurrence in the coastal region of the western part in comparison to the eastern part. The ABS regions experienced the most frequent cloud occurrence (80–90%), while the eastern slope of the Transantarctic Mountains around 150°E experienced the least cloud occurrence (20–30%).

The summer and fall seasons showed a greater cloud occurrence throughout the circumpolar trough region than the winter and spring seasons. During the summer, the entire circumpolar trough region had a cloud occurrence that
was >80%, whereas during the winter, only the latitude belt that stretches from −60 to −65° had a cloud occurrence that was greater than 80%. The RIS, the FRIS and the Weddell Sea regions had a cloud occurrence of 50–70% during the winter. The cold surface temperatures and the presence of sea ice in large portions of the southern seas during the winter greatly influenced the differences in the cloud occurrence between the summer and winter because the combination of the low temperatures and the sea ice resulted in a very low moisture content that inhibited cloud formation. During the winter and spring seasons, the position of low-pressure centers influenced the cloud occurrence by the advection of moist maritime air on the western side and dry continental air on the eastern side of the low. In the winter season, the major low-pressure center was situated over the RS, which resulted in tongues of high cloud occurrence that extended from 60 to 65°S latitude around the ABS. In the spring, the low-pressure centers were more intense, and they extended up to the western part of Antarctic Peninsula, which ushers in moist maritime air to the ABS and the Weddell Sea region.

[36] Although the total cloud cover was larger in the summer and fall than in the winter and spring, high-level clouds and deep clouds were more frequent in the winter and spring because of the greater occurrence of synoptic-scale cyclonic disturbances during the winter and spring seasons. The greater occurrence and intensities of the cyclonic disturbances also caused the clouds to have larger vertical extents during the winter than during the summer. Similarly, the clouds extended to greater heights in the winter, when the tropopause heights are at higher elevations, than in the summer. Low-level clouds were more frequent during the

Figure 11. Dependence of effective radius on latitude and cloud temperatures for high-level clouds over (a) ocean and (b) land. (c) Normalized frequency distribution of effective radius. Dependence of IWC on latitude and cloud temperatures for (d) ocean and (e) land. (f) Normalized frequency distribution of IWC. Winter and summer represent retrievals of effective radius and IWC for June 2007 through August 2007 and December 2007 through February 2008, respectively.
The maxima in the cloud base frequency were in the range 1–2 km and 4–5 km at WS and CR and 1–2 km and 3–4 km at AP. The maxima in cloud top frequency were in the range 2–3 km and 4–6 km. The ice crystal habits were more strongly dependent on temperatures than on latitude, which was shown by the dependence of the depolarization ratio on temperature. However, the depolarization ratio varied a lot at a given temperature range at different latitudes, which suggests that the ice crystal habit also depends on nontemperature factors, e.g., supersaturation and vertical motion. Another reason for the seasonal differences in the depolarization ratio could be due to differences in ice aggregation. Even when the basic shapes at a given temperature are similar, the aggregation of ice crystals can change the depolarization ratio. The temperature dependence was stronger for the \( r_e \) and IWC than for the depolarization ratio. Both \( r_e \) and IWC increased with increasing temperatures and were larger in the summer, when 85% of the high-level clouds had temperatures warmer than \(-55^\circ \text{C}\), than in the winter, when 85% of the high-level clouds had temperatures colder than \(-55^\circ \text{C}\). The mean values of the effective radius for high-level clouds over land and ocean were 18.0 (22.1) and 21.5 (26.4) \( \mu \text{m} \) for winter (summer), respectively.

The CALIPSO and CloudSat measurements have an unprecedented opportunity to allow for the study of the clouds in the Antarctic region. As more data, such as the cloud phase and cloud type, from the combined CloudSat/ CALIPSO measurements becomes available, the seasonal and interannual variabilities in the clouds and their linkages with global circulations can be better characterized.

**References**


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