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A STUDY OF ANTARCTIC CLOUDS USING CLOUDSAT AND CALIPSO MEASUREMENTS

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1. INTRODUCTION

Clouds in the Antarctic region play a key role in the global energy exchange processes through their influence on the atmospheric and oceanic circulation (Lubin, 1994; Lubin and Harper, 1996). Because of the major roles Antarctic clouds play in the global climate, an accurate representation of the Antarctic clouds is necessary to improve the global climate prediction. Lubin et al. (1998) have shown that significant anomalies are observed in the atmospheric circulations because of changes in the radiative properties of Antarctic clouds. However, the Antarctic region presents a unique challenge in the identification of clouds and retrieval of their microphysical properties because of the harsh climatic conditions, very low surface temperatures and perennial snow/ice cover. Surface-based observations are sparse in the Antarctic region. Low surface temperatures coupled with surface inversions and highly reflective surface hinder satellite-based infrared and visible passive remote sensing measurements, which rely on temperature and reflectivity contrasts between the surface and the clouds for cloud detection. Satellite-based active remote sensing observations from radio detection and ranging (radar) and light detection and ranging (lidar) can overcome the shortcomings of the passive remote sensing observations and provide vertical structure of the clouds.

The formation fly of NASA Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) (Winker et al., 2003) and CloudSat (Stephens et al., 2002) provides unique combined lidar and radar measurements to cloud properties globally. Besides, their large concentration of measurements in the polar region up ±82º latitudes provides an ideal platform to study Antarctic clouds. CALIPSO carries Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP), a dual wavelength lidar with depolarization capabilities, and CloudSat carries a 94-GHz cloud profiling radar (CPR). The combination of these two active measurements with different sensitivities to cloud particle size and concentration provide a unique dataset to study Antarctic clouds. In this analysis, seasonal variation of cloud physical properties, variation of cloud occurrence and their vertical distribution in the Antarctic region is presented based on CALIPSO and CloudSat measurements.

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2. DATA ANALYSIS

CloudSat and CALIPSO measurements taken during the period from June 2006 through May 2008 are used in the analysis. The resolution of CALIPSO level 1B data is altitude dependent (Winker et al., 2007), so we have averaged the data to a uniform vertical resolution of 180 m. Then CALIPSO profiles are collocated to CloudSat footprint (1.4 cross track x 1.8 km along track) and averaged to form a collocated CALIPSO and CloudSat dataset at CloudSat horizontal resolution of 1.1 km.

CloudSat radar bins with cloud mask values ≥ 30 in the CloudSat 2B-GEOPROF product are used to identify cloudy bins from radar measurements. Attenuated lidar scattering ratio (ALSR) measurements from CALIPSO are used to identify clouds from lidar measurements. The ALSR is the ratio of the total attenuated backscattering signal to the molecular-only attenuated backscattering signal, which is calculated with Geostationary Operational Environmental Satellite (GOES-4) temperature and pressure profiles included in the CALIPSO level 1B product. Simple threshold values of ALSR are used to identify tropospheric cloud boundaries for each averaged CALIPSO lidar profile, as described in Wang et al. [2008]. Cloudmask obtained from CALIPSO and CloudSat are then combined to describe the cloud structures.

The combined CALIPSO and CloudSat cloud masks are used to calculate the cloud thickness (D_z), cloud base height above ground (B_z), cloud top height above ground (T_z) and maximum equivalent radar reflectivity factor (Z_{max}). Clouds are classified in to high (Bz > 6 km), middle (Bz > 2 km and Dz < 6 km), low (Bz < 2 km and Dz < 5 km) level clouds and vertically-extended deep cloud systems (Bz < 2 km and Dz > 5 km or Dz > 6 km). Cloud properties are then derived for these four types of clouds.

The cloud occurrence in the region is averaged over 2˚ lat × 5˚ long grids. The cloud occurrence is estimated by calculating the ratio of the number of cloudy profiles to the total number of profiles in each grid. Similarly, the lidar and radar measurements are used to calculate the meridionally averaged vertical distribution of cloud occurrence. The vertical distributions are calculated for 5˚ long × 0.25 km vertical bins.

The bulk microphysical properties of clouds are qualitatively analyzed based on the attenuated backscattering coefficients at 532 nm and 1064 nm, depolarization ratios at 532 nm and equivalent radar reflectivity factor. Color ratios (CR) are calculated as ratios of attenuated backscattering coefficients at 1064 nm to 532 nm CALIOP channels. The depolarization ratios for clouds (δ) are estimated by correcting for molecular scattering, which can be significant at low ALSR (R) values. δ is estimated with the following equation:

$$\delta = \frac{(R\delta' - \delta_m)}{(R + \delta_m - \delta' - 1)} \tag{1}$$

where, δ' and δ_m are volume depolarization ratios and depolarization ratio due to molecular signal respectively. In the present analysis δ_m is taken as 0.0035.

3. RESULTS AND DISCUSSION

3.1 Distribution of Cloud Occurrence

The spatial distribution of clouds in the Antarctic region is influenced by the topography of the region. The eastern part contains bulk of the continent while the western part contains small portion of the continent (Fig. 1).

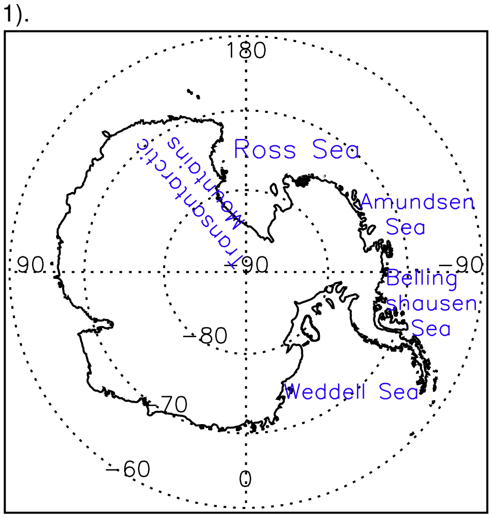

Figure 1: Map of Antarctica and adjoining seas

Mesocyclones are prominent features in the coastal Antarctica that results due to the complex coastal terrain (Heinemann and Klein, 2003). Strong Katabatic winds (Parish, 1992) transport cold air onto the shore causing low-level baroclinicity. These conditions help in the formation of mesocyclones (Bromwich, 1991; Heinemann and Klein, 2003), and in the presence of synoptic scale forcings, they can develop into deep cyclones (Simmonds et al., 2003). The western coastal region presents suitable condition for the formation of these mesocyclones, so this region experiences more cloudiness than the eastern part. Figure 2 shows mean seasonal maps of cloud occurrence for the Antarctic region (poleward of 60 deg S) for June – August (winter), September – November (spring), December – February (summer), and March – May (fall) of 2006 – 2007 and 2007 – 2008.

Figure 2 shows that the eastern part of Antarctica has lower cloud occurrence (mean annual cloud occurrence of 61 %) than the western counterpart, which has a mean annual cloud occurrence of 77 %. The coastal region between 60 ºS and 70 ºS show the highest cloud occurrence. The western coastal region, Amundsen Sea and Bellingshausen Sea, shows the highest mean annual cloud occurrence of 83 %. The eastern continental Antarctica and east of Transantarctic Mountains have the lowest cloud occurrence. Cloud occurrence also shows profound seasonal variability. In winter, both the Ross Sea and the Weddell Sea regions show cloud occurrence of 50 – 60 %, with highest occurrence observed off the western coast of Marie Byrd Land. However, in summer, both the Ross Sea and Weddell Sea regions show cloud occurrence of 80 – 90 %, and the high cloud occurrence region covers the whole of western coastal region. The region of highest cloud occurrence falls in the region that have the highest occurrence of cyclones (Simmonds and Keay, 2000) and the region that have high occurrence of mesoscale cyclones, which are sub-synoptic scale cyclonic vortices frequently observed in coastal Antarctic region, (Carrasco et al., 2003).

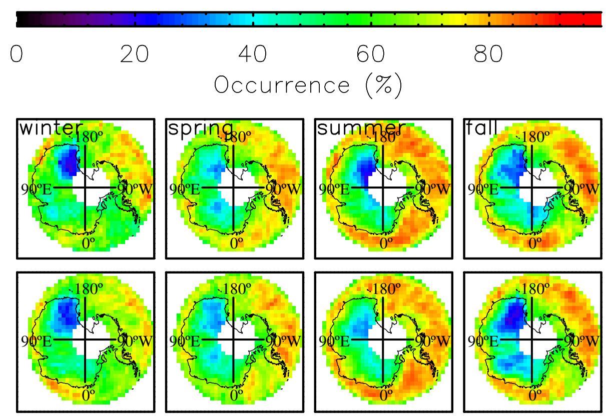

Figure 2: Seasonal cloud occurrence map for 2006-2007 (upper row) and 2007-2008 (lower row).

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Figure 3 shows high-level cloud occurrence maps. These high-level clouds are more frequent on either side of the Antarctic Peninsula. High inter-annual and inter-seasonal variability is observed in their occurrence. Fall and spring seasons show the lowest and highest occurrence of these high-level clouds.

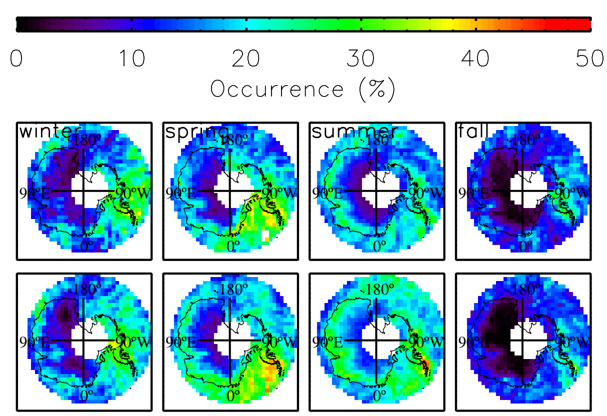

Figure 3: Same as for Fig. 2, but for high-level clouds

3.2 Vertical Distribution of Cloud Occurrence

Low-level stratus clouds are the major clouds in the regions in all the seasons. Besides, deep tropospheric cloud systems extending beyond 7 km in depth are observed throughout the year in coastal Antarctica. Figure 4 shows meridionally averaged vertical distribution of cloud occurrence for the region. The figure shows the prevalence of high occurrence of clouds at low levels. The highest occurrence is observed at 1 km above the surface around 100 ˚S (region between Bellingshausen Sea and Amundsen Sea). Most of these clouds occurring at low levels constitute stratus clouds. Inter-seasonal variability in cloud occurrence is also evident from the graph of vertical distribution of cloud occurrence in Fig. 4. High occurrence extends to above 8 km above ground in all the seasons except during summer. High occurrences extending up to high elevations indicate the presence of deep vertically extended clouds. Higher occurrence of these deep clouds is observed more during winter than in summer. However, summer season shows larger occurrence of low-level clouds. Besides the inter-seasonal variability in cloud occurrences, a marked inter-annual variability is also observed from Fig. 4.

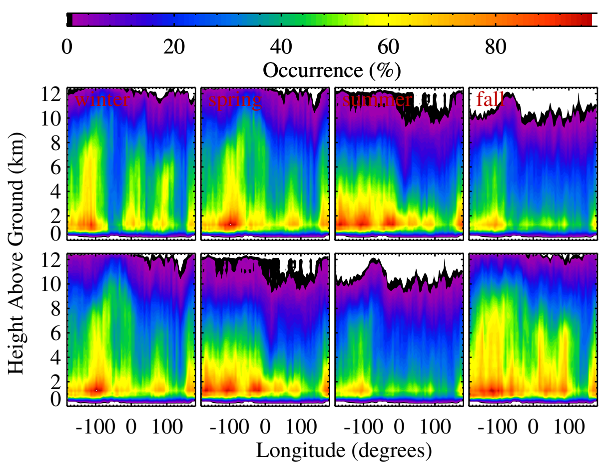

Figure 4: Meridionally averaged vertical distribution of cloud occurrence for June 2006 – May 2007 (upper row) and June 2007 – May 2008 (lower row).

3.3 Seasonal Variation of Cloud Properties

Clouds in the Antarctic show a distinct seasonal dependence in their physical and optical characteristics. Figure 5 shows time series of D_z, Z_{max}, T_z and cloud occurrence (%) for high, middle, low level clouds and deep clouds. The figure shows a distinct seasonal cycle of all these cloud properties. Low and mid level clouds consist of mostly of physically thin clouds ranging from

0.5 to 1.0 km in thickness. The mean thicknesses for low and mid level clouds for summer are 0.77±0.0.08 and 0.81±0.05 km and the mean thickness for winter are 0.88±0.09 and 0.89±0.08 km respectively. High-level clouds range in thickness from 0.8 to 2.2 km. The thickness is maximum during late winter/early spring and minimum during summer. The mean thickness for summer and winter for high-level clouds are 1.03±0.17 and 1.90±0.35 respectively. A similar trend is observed in the thickness of deep clouds. The mean thickness in summer and winter for deep clouds are is 6.39±0.21 and 6.96±0.31 km respectively.

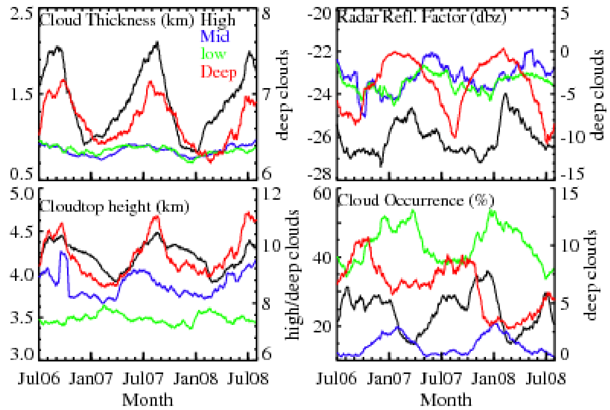

Figure 5: Daily averaged cloud properties for high, mid, low level and deep clouds

The Z_{max} shows opposite trends for low/mid level clouds and high/deep clouds. The reflectivity factors attain maximum values in summer and minimum values in winter for the high clouds and deep clouds. The variation is large in the case of deep clouds, which show a fluctuation of more than 10 DBZ between summer and winter. In summer the mean maximum values reach 0 DBZ, while the corresponding values in winter are -10 DBZ. Low and mid level clouds show a minimum in summer and maximum in winter.

Cloud top heights show a seasonal trend similar to that of the cloud thickness. The mean cloud top heights for low and mid level clouds are 3.5 and 3.9 km respectively. A seasonal trend is more evident for the high-level clouds and the deep clouds. The mean cloud top height for high level clouds range from 8.5 km in summer to 10 km in winter/spring. The cloud top height fluctuation between the two seasons for deep clouds is even more significant, with values ranging from about 8 km in summer to 11 km in winter.

Low clouds form the major cloud types in the Antarctic region. These low-level clouds have a mean annual occurrence of 44 %, with 49.8±5.78 and 37.6±5.31 % for summer and winter respectively. High-level clouds are also ubiquitous in the region and have an annual occurrence of around 25 %. High-level cloud occurrence is highest in spring (25 – 30 %) and lowest in fall (15 – 20 %). Mid-level clouds contribute 10 – 20 % with their maxima during summer and minima during winter. Deep cloud occurrence shows interannual variations, but seasonal dependence of their occurrence frequency is evident from the figure. Their maximum is during winter/spring and minimum is during summer.

Figure 6 shows 2-Dimensional plots of 10 log $_{10}$ (total attenuated backscatter) versus equivalent radar reflectivity factor for high, mid, low level clouds and deep clouds. The figure shows similar attenuated backscatter and larger radar reflectivity factor for high clouds. Large radar reflectivity factor indicates a presence of larger particles during summer than in winter. The results are consistent with those of Mahesh et al (2001), who used ground-based infrared measurements over the South Pole and Lubin and Harper (1996), who used advanced very high resolution radiometer (AVHRR) data and showed that particle sizes are larger in summer than in winter. The Z_{max} shown in fig 5 also indicates presence of larger particles in summer than in winter. Frequency distribution of equivalent radar reflectivity factors (Ze, shown in Fig. 7) also shows that Ze values are larger in summer than in winter. Student's t-test was applied to test whether the means of Ze for summer and winter are statistically significant. The results show that statistically significant differences exist in the Ze values at 0.01 level between summer and winter.

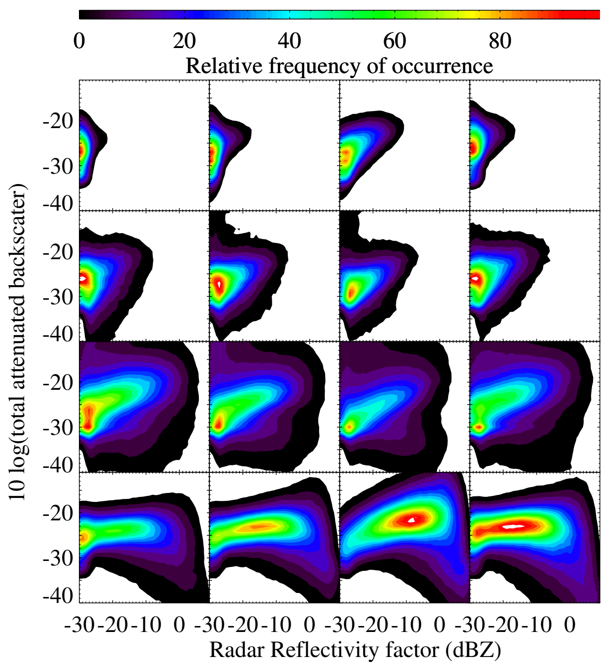

Figure 6: 2-dimensional plots of 10 $\log_{10}$ (total attenuated backscatter, km^{-1}, Sr^{-1}) and equivalent radar reflectivity factor (dBZ) for high-level clouds (top row), mid-level clouds (second row from top), low-level clouds (third row from top) and deep clouds (bottom row). The columns 1 – 4 represent winter, spring, summer and fall seasons respectively.

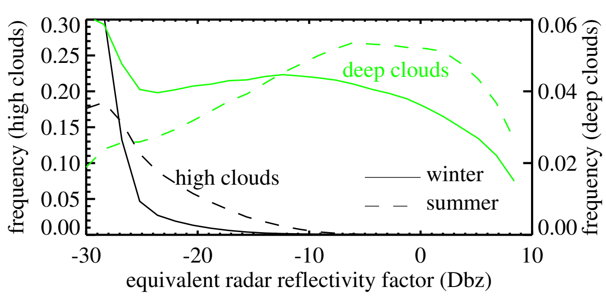

Figure 7: Probability density function of equivalent radar reflectivity factors for high clouds (black lines) and deep clouds (green lines) for summer (dashes) and winter (solid).

4. CONCLUSION

The study of Antarctic clouds based on CALIPSO and CloudSat data from June 2006 through May 2008 show distinct seasonal variabilities in their physical and optical properties. The western part of Antarctica contains active regions of mesocyclogenesis and extra-tropical cyclone occurrence. It results in larger cloud occurrence in the western part (77 %) in comparison to the eastern part (61 %). The Bellingshausen Sea and Amundsen Sea regions experience the most frequent occurrence of clouds, while the eastern slope of Transantarctic Mountains show the least cloud occurrence.

Low-level stratus clouds are the major cloud types in the Antarctic region, and have a mean annual occurrence of 44 % in the region. Vertically extended deep clouds are most common in the western coastal Antarctica, the regions characterized by frequent cyclogenesis and cyclone occurrence. Cloud occurrences show a high inter-seasonal variability with greater occurrence during summer than in winter. Low and mid-level clouds show higher occurrence in summer, 49.8 and 18.4 % respectively, than in winter, 37.6 and 12.0 % respectively. High and deep clouds are more frequent in winter than in summer and deep clouds have larger vertical extent in winter than in summer.

All the four cloud types have larger thickness in winter than in summer. A similar trend is observed in the cloud top heights, with larger cloud top heights observed for all the four cloud types in winter than in summer. The distribution of mean maximum equivalent radar reflectivity factors show opposite trends for low/mid level clouds and high/deep clouds. The Z_{max} values for high/deep clouds are larger in summer than in winter and for low/mid level clouds are larger in winter than in summer. Higher radar reflectivity factors are observed in high-level clouds during summer than during winter, which suggests that particles in high-level clouds are large in summer than in winter.

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