Vertical Structures and Physical Properties of the Cold-Season Stratus Clouds Downstream of the Tibetan Plateau: Differences between Daytime and Nighttime

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ABSTRACT

This study compares the daytime–nighttime (DN) differences in the occurrence frequencies and macrophysical, microphysical, and radiative vertical structures of the single-layer stratus clouds downstream of the Tibetan Plateau (TP) during the boreal cold season (November–April) using four CloudSat products. The stratus cloudy profiles are selected and the midtopped stratus profiles are further classified into nimbostratus (NI) and altostratus (AS) according to the cloud-top height and column-integrated optical depth. It is found that the entire stratus and NI profiles tend to occur more frequently in the daytime, while the AS cloud occurs more frequently in the nighttime. Consistent with the DN differences in the occurrence frequencies, the AS tends to be much thicker with larger cloud fraction in the nighttime, while the NI becomes slightly thicker with larger cloud fraction in the daytime. An analysis of the ambient dynamic and thermodynamic fields associated with stratus formation suggests that it is the DN difference in the large-scale low-level lifting that leads to the corresponding differences of the occurrences and macrophysical properties. In contrast, the optical depths of the NI and AS clouds become larger and smaller from daytime to nighttime, respectively, which is attributed to the microphysical properties. The occurrence frequencies in small droplet particle sizes increase (NI) and decrease (AS) from daytime to nighttime, leading to the corresponding variations of the cloud radiative property.

1. Introduction


As the only continental stratus region (Klein and Hartmann 1993; Wood and Bretherton 2006), the midlevel clouds (primarily nimbostratus and altostratus) over eastern China (EC) downstream of the Tibetan Plateau (TP), which peak in the cold season (Yu et al. 2001; Li et al. 2004), are important to the local climate because of the intense cloud feedback (Yu et al. 2004). Based on the International Satellite Cloud Climatology Project (ISCCP; Rossow and Schiffer 1991) product and observational data from stations, Yu et al. (2004) demonstrated the formation mechanism of the distinctive midtopped stratus over EC and pointed out its great impact to the local climate. Zhang et al. (2013) further presented a physical image to illustrate how the dynamic and thermodynamic

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ambient environmental conditions influence these stratus clouds. They are generated by the large-scale lifting condition under the stable stratification in the cold season and are also subject to the horizontal circulations at middle and low levels, which contribute to both moisture transport and local stability. However, the ISCCP products can detect neither the detailed vertical structures nor the nighttime cloud types, limiting a further view into some key physical properties of these clouds.

Because of the data limitation, knowledge of the stratiform clouds over EC remains insufficient, especially in the diurnal time scale. Previous studies showed that the clouds over EC present distinctive diurnal variations (Li et al. 2003; Chen et al. 2012) and play important roles in modulating the diurnal phase of precipitation (Li et al. 2008). Nevertheless, the vertical structures and physical properties of the cold-season stratus clouds and related daytime–nighttime (DN) differences are so far not understood. The weak knowledge of the stratus cloud features also leads to a large uncertainty in simulating the East Asian climate (Zhou and Yu 2006). Meanwhile, from phase 3 of the Climate Model Intercomparison Project (CMIP3) to CMIP5, climate models show no evident improvement in the simulated shortwave cloud radiative forcing (SWCF) over EC because of a poor simulation of stratus clouds (Zhang and Li 2013).

As a part of the A-Train constellation, CloudSat (Stephens et al. 2002), carrying the Cloud Profiling Radar (CPR), together with the Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO; Winker et al. 2010), an aerosol lidar, offer an unprecedented opportunity for investigating the three-dimensional distributions of clouds in the globe. Meanwhile, CloudSat overpasses eastern continental China (20°–40°N, 100°–120°E) mostly at 0100–0300 local solar time (LST) (middle of night) and 1300–1500 LST (afternoon), enabling a comparison between daytime and nighttime profiles. Some previous studies have employed the CloudSat data for investigating the cloud vertical structures over China (e.g., Luo et al. 2009, 2011; Yin et al. 2013), but there are few studies available in the literature that report the vertical structures and physical properties for the distinctive cold-season stratiform clouds downstream of the TP, especially on the variability in the diurnal time scale.

In this study, we first select the stratus profiles from all cloudy profiles and then investigate the DN differences in the occurrence frequencies and macrophysical, radiative, and microphysical vertical structures of the distinctive stratus clouds downstream of the TP. It is our hope that the results shown here can be helpful for extending our knowledge on the vertical structures and physical properties of these clouds and providing a reference for improving the simulation of them in the numerical model.

The remainder of this paper is organized as follows: Section 2 introduces the data and methods employed in this study. Section 3 presents the spatial distributions of the occurrence frequencies for different stratus types in the daytime and nighttime and describes the macrophysical properties of the stratus, including the cloud-top height ($Z_{\text{top}}$), cloud-base height ($Z_{\text{base}}$), cloud thickness (ΔZ), and profile-averaged cloud fraction. Section 4 documents the vertical structures of the radiative property and several important microphysical parameters. A summary is given in section 5.

2. Data and methods

a. Data

Four datasets obtained from the CloudSat/CALIPSO project are used in this study, including the level-2 geometrical profile (2B-GEOPROF), 2B-GEOPROF-lidar, level-2 cloud optical depth product (2B-TAU), and level-2 CloudSat radar-visible optical depth cloud water content (2B-CWC-RVOD). We give a brief introduction to each dataset as follows, and more detailed information about the products can be found online (http://www.cloudsat.cira.colostate.edu/).

The CPR in the GEOPROF product identifies those levels in the vertical column sampled by the CloudSat, which contain significant radar echo from hydrometeors, and produces an estimate of the radar reflectivity factor and cloud mask (Mace 2007). The GEOPROF-lidar product extracts the maximum information from the combined radar and lidar sensors (Mace et al. 2007b). The radar and lidar will provide complimentary information regarding the occurrence of hydrometeor layers in the vertical column. The radar can penetrate optically thick layers that will attenuate the lidar signal and observe layers of cloud-free precipitation that may not be observed by the lidar. The original minimum detectable signal of the CPR is approximately $-30\,\text{dBZ}$. It now approaches $-26\,\text{dBZ}$ because of the change of satellite orbit height but is still detectable at $-30\,\text{dBZ}$ sometimes (Stephens et al. 2008; Marchand et al. 2009), which will prevent detections of the clouds that are optically thin or dominated by small particles. The lidar will sense tenuous hydrometeor layers that are below the detection threshold of the radar, the tops of optically thin ice cloud layers that the radar will not observe. The lidar also has higher vertical and horizontal sampling resolution than the radar has, and it can identify the base/top heights of hydrometeor layers (a maximum of 5) in each vertical CPR profile.
Mace et al. (2007a) reported that there is a surface contamination of the CloudSat data due to a strong surface return below ~1 km. Therefore, several studies (e.g., Kay and Gettelman 2009; Rajeevan et al. 2013) ignored the bins in the profile that are lower than 1 km. We have challenged our results by using this threshold, which makes almost no difference, because our samples are mostly from the midtopped stratus clouds whose $Z_{\text{base}}$ values are mostly higher than 1 km. Meanwhile, although we refer our object in this study as cloud, it should be kept in mind that the CloudSat/CALIPSO does not separate cloud from precipitation (Marchand et al. 2008).

The 2B-TAU product provides the estimates of the layer optical depth ($\tau$) and column-integrated total optical depth used in this study. The radar reflectivity measured by the CPR serves as a quantitative basis to produce cloud optical depth profiles (Polonsky et al. 2008). The 2B-CWC-RVOD product contains retrieved estimates of cloud water content, effective radius, and number concentration for each radar profile measured by the CPR (Wood 2008). Retrievals are performed separately for the liquid and ice phases. The two sets of results are then combined to obtain a composite profile that is consistent with the input measurements. The RVOD product uses a combination of measured radar reflectivity factor (from the 2B-GEOPROF) together with estimates of visible optical depth (from the 2B-TAU) to constrain the cloud retrievals more tightly than in the radar-only (RO) product (2B-CWC-RO), presumably yielding more accurate results.

Because we mainly focus on the liquid stratus in this study, it is necessary to document here the retrieval of liquid cloud microphysical properties from the CloudSat/CALIPSO observations, which might add more confidence to this study. The liquid cloud retrieval algorithm is a latest version of the method described in Austin and Stephens (2001), including a forward model and retrieval formulation, which are used to estimate the parameters of the particle size distribution in each bin containing cloud. The retrieval algorithm follows Rodgers (1976, 1990, 2000) and Marks and Rodgers (1993). Such processes need both radar measurements (2B-GEOPROF) to provide a vertical profile of cloud backscatter and retrieved visible optical depth (2B-TAU) values to provide an estimate of the integrated extinction through the cloud column. Previous study has shown consistent results in representing the climate features from the combined use of 2B-TAU and 2B-CWC-RVOD (e.g., Rajeevan et al. 2013).

In this study, we use the following variables from the above four datasets: (i) the common temporal and spatial information, including profile time, coordinated universal time (UTC) and international atomic time (TAI) start time, longitude, latitude, and altitude; (ii) the CPR cloud mask and radar reflectivity from 2B-GEOPROF; (iii) the cloud fraction, number of cloud layers, $Z_{\text{top}}$, and $Z_{\text{base}}$ from 2B-GEOPROF-lidar; (iv) total and layer optical depth from 2B-TAU; and (v) the RVOD liquid water content (LWC), liquid effective radius ($r_e$), and liquid number concentration ($N_d$) from 2B-CWC-RVOD. The Interim European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-Interim; Dee et al. 2011) is also used to represent the dynamic and thermodynamic meteorological states of the atmosphere.

b. Methods

1) STRATUS CLASSIFICATION

Each data file from the CloudSat contains a complete granule (an orbit of data) beginning at the first profile. We select the common granules in all four datasets. Only the profiles that fall into the eastern continental China area ($20^\circ$–$40^\circ$N, $100^\circ$–$120^\circ$E) during the boreal cold season (November–April from 2006 to 2011) are considered, yielding a total of 2,351,686 profiles (clear and cloudy) in this temporal and spatial range. In this paper, the eastern continental China area ($20^\circ$–$40^\circ$N, $100^\circ$–$120^\circ$E) is only used to show the map of occurrence frequency (in Fig. 2) and the variation of ambient fields (in Figs. 5 and 6). Other plots focus on the region downstream of the TP (box in Fig. 2: $27^\circ$–$32^\circ$N, $103^\circ$–$118^\circ$E).

Since the 2B-GEOPROF-lidar provides the $Z_{\text{top}}$ for single-layer and multilayer clouds, we only focus on the single-layer clouds in this study, which account for ~60% of the total cloudy profiles, and the percentage is higher for stratus clouds. One single-layer cloudy profile is further counted as a stratus profile depending on the $Z_{\text{top}}$ and column-integrated total optical depth according to the following criteria:

All stratus profile (AL): $Z_{\text{top}} \leq 7$ km, $3.6 \leq \tau$

Midtopped optically thick nimbostratus (NI): $3 \leq Z_{\text{top}} \leq 7$ km, $23 < \tau$

Midtopped optically intermediate altostratus (AS): $3 \leq Z_{\text{top}} \leq 7$ km, $3.6 \leq \tau \leq 23$
That is, as long as a profile conforms to one of the criteria above, all bins on this profile belong to a particular stratus type. This definition of stratus clouds here mimics the ISCCP cloud classification in Rossow et al. (1996), except that we use altitudes of 3 km to separate low-topped and midtopped clouds and 7 km to separate midtopped and high-topped clouds. The 2B-GEOPROF-lidar product also provides flags to identify whether the cloud top and base are detected by (i) only radar, (ii) only lidar, (iii) both lidar and radar, or (iv) neither of them. In this study, the cloud top and base are counted as long as either the radar or lidar finds it.

2) DETERMINATION OF STRATUS DEVELOPMENT PERIOD

Because we are interested in the daytime and nighttime environmental conditions associated with the formation of stratus, it is important to extract those days that witness heavy stratus occurrences. We take nimbostratus (NI) cloud as an example. Figure 1 shows all days that the NI profiles occur downstream of the TP (27°–32°N, 103°–118°E) during the cold season, for daytime (277 days; Fig. 1a) and nighttime (292 days; Fig. 1b). The solid line in each panel shows the occurrence frequencies represented by the ratio between the number of the NI profiles in any particular day and the total number of NI profiles. The dashed line shows the occurrence frequencies that are sorted from small to large. To achieve significant synoptic ambient fields associated with the NI development, we only select those days whose occurrence frequencies are higher than that of the 90th and 95th percentiles at the dashed line. For the daytime NI case, there are 28 (90th) and 15 days (95th); for the nighttime NI case, there are 31 (90th) and 15 days (95th). We then select the time slices from the daily ERA-Interim fields according to these days and construct the composite mean fields during these days, for daytime [0600 UTC or 1400 Beijing standard time (BST)] and nighttime (1800 UTC or 0200 BST).

3) CALCULATION OF CLOUD FRACTION

The cloud fraction in each profile is determined by a combination of the CPR cloud mask and radar reflectivity from the GEOPROF and the cloud fraction from the GEOPROF-lidar. The cloud fraction in each vertical bin is set to 100% for a cloud mask $Z < 30$ dBZ; otherwise, it equals the cloud fraction from the GEOPROF-lidar. This approach is similar with that used in Luo et al. (2009), which determines the cloud fraction as long as one of the radar and lidar detects the cloud. Meanwhile, since the cloud occurrence frequencies will be given in Fig. 2, the mean cloud fraction presented in this paper is a cloudy profile-averaged one: namely, an “amount when present.” A time-averaged cloud fraction during a period is the product of the cloud occurrence frequency and cloud amount when present. This approach is also used to represent the vertical structures of mean layer optical depth, liquid water content, number concentration, and effective radius.
4) REMOVING THE LONG TAIL

The samples from the cloud liquid water content and layer optical depth profiles exhibit a long tail distribution. The occurrence frequency in the tail part is very small but with a large value (e.g., liquid water content higher than 2000 mg m\(^{-2}\)). To alleviate this problem and achieve more solid result, we only select...
samples whose values are lower than the 99th percentile for each type of stratus. Tests suggest our results are not sensitive to this operation.

3. Occurrence frequencies and macrophysical properties

Figure 2 shows the spatial distributions of observational times and occurrence frequencies for three types of single-layer stratus profiles during the total time (left), daytime (center), and nighttime (right) over EC. The samples are binned to each 2° × 2° bin on the map. The observational numbers (the number of observed profiles) in each bin are generally close with each other (Figs. 2a–c).

The occurrence frequency in each bin is the ratio between the occurrence numbers of stratus profiles and the observational times (number of total profiles) during each time. The geographical patterns of the occurrence frequencies from different stratus profiles resemble the time-averaged cloud amount from the ISCCP product (not shown). For the entire stratus profiles in the total time (Fig. 2d), they occupy a large area over the eastern continent (primarily to the south of 35°N). The all stratus (AL) profiles occur more frequently in the daytime (Fig. 2e) than in the nighttime (Fig. 2f), with a maxima center over the Sichuan basin (27°–32°N, 103°–108°E).

The NI profiles occur (Fig. 2g) most frequently downstream of the TP (the box region), especially over the Sichuan basin. The occurrence frequencies tend to decrease from daytime (Fig. 2h) to nighttime (Fig. 2i), especially in the box region, which is consistent with the AL profiles. The altostratus (AS) profiles are more uniformly distributed than the NI profiles (Fig. 2), and they tend to occur slightly more frequently in the nighttime (Figs. 2k,l), especially over the southeastern part of the continent. The occurrence frequencies of the AS profiles are generally smaller than those of the NI profiles. The largest occurrence frequencies of the AS profiles are lower than 0.1, which is much smaller than that of the NI profiles. The following study will concentrate on those profiles in the box region, which is the major occurrence area of two types of midtropospheric stratus clouds.

Figure 3 shows the daytime (solid) and nighttime (dashed) probability distribution functions (PDFs) of the $Z_{\text{top}}$, $Z_{\text{base}}$, and $\Delta Z$ values for each type of stratus. The mean value for each PDF is summarized in Table 1. For the AL profiles, the $Z_{\text{top}}$ values (Fig. 3a) between 2 and 6 km account for a dominant portion. From daytime to nighttime, the $Z_{\text{top}}$ values become more concentrated on the large values (above 4 km) and less on the small values, resulting in an increase in the mean $Z_{\text{top}}$ value by ~0.6 km. The $Z_{\text{base}}$ values (Fig. 3b) are mainly located between 1 and 3 km, exhibiting a normal distribution. The DN differences in the PDF of $Z_{\text{base}}$ values are much smaller than that of the $Z_{\text{top}}$ ones. Hence, the DN differences of the $\Delta Z$ values (Fig. 3c) are dominated by the $Z_{\text{top}}$. The nighttime $\Delta Z$ values have larger frequencies in the regime higher than 1 km, leading to an increase of the mean value during the nighttime by ~0.5 km.

From daytime to nighttime, the $Z_{\text{top}}$ values of the NI profiles (Fig. 3d) occur more frequently between ~4.5 and ~5.5 km and less frequently in other ranges. Compared with the daytime $Z_{\text{base}}$, the nighttime $Z_{\text{base}}$ values have larger frequencies above ~1.6 km and smaller frequencies below this altitude. The nighttime $\Delta Z$ values have larger frequencies between ~1 and ~3.5 km and smaller frequencies in other ranges. Both the mean $Z_{\text{top}}$ and $Z_{\text{base}}$ values increase in the nighttime, similar with those of the AL profiles. However, the mean $\Delta Z$ value decreases by ~0.1 km from daytime to nighttime. Generally, the DN differences in the $Z_{\text{top}}$, $Z_{\text{base}}$, and $\Delta Z$ values from the NI profiles are relatively small.

In contrast with the NI profiles, there are larger DN differences in the $Z_{\text{top}}$, $Z_{\text{base}}$, and $\Delta Z$ values of the AS profiles. The nighttime frequencies of the $Z_{\text{top}}$ values exhibit a uniform distribution with a value around 6%. Above ~2 km, the frequencies of the nighttime $Z_{\text{top}}$ values are smaller than those of the daytime ones. Hence, the mean $Z_{\text{top}}$ ($Z_{\text{base}}$) value significantly increases (decreases) from daytime to nighttime, resulting in a large increase of $\Delta Z$ by ~0.9 km. Because the low-level stratuscumulus (SC) and stratus (ST) are geometrically thin and occur less frequently in this region (not shown), it can be inferred that the AS dominates the DN difference of the $\Delta Z$ of the entire stratus profiles.

The vertical structures of the profile-averaged cloud fraction amounts for the AL, NI, and AS profiles are shown in Fig. 4. The layer-averaged cloud fraction value from 0 to 10 km is also shown in parentheses for each profile. Consistent with the mean $\Delta Z$, the cloud fraction values of the AL (Fig. 4a) increase from daytime to nighttime, which is largely attributed to the corresponding increase from the AS (Fig. 4c), while the DN differences of the NI (Fig. 4b) are relatively small. The two gray lines indicate the cold-season mean altitudes at 600 and 850 hPa from ERA-Interim. It can be found that the largest cloud fraction amounts of all profiles are concentrated within these two lines. As revealed in earlier studies (Yu et al. 2004; Li and Gu 2006; Zhang et al. 2013), the divergence difference between middle and low levels causes a large-scale moisture lifting, leading to the accumulated cloud fraction values between these two levels.
Combined with the analysis of occurrence frequencies, it can be concluded that the occurrence frequencies, mean $\Delta Z$ value, and cloud fraction values of the NI profiles tend to be slightly larger during the daytime, which is opposite to the images shown by the AS profiles. To understand the different diurnal differences of these two stratus types, we further examine the dynamic and thermodynamic ambient environmental conditions associated with the stratus formations. As suggested in Zhang et al. (2013), the stability (potential temperature difference between 500 and 850 hPa) and vertical velocity at 700 hPa ($\omega_{700}$) are two primary influencing factors that govern the formation of stratus downstream of the TP. Therefore, it is worthwhile investigating the DN differences of these two fields during the development of the NI and AS clouds.

Using the method illustrated in section 2b(2), we calculate the daytime and nighttime composite means of the stability and $\omega_{700}$ for the NI and AS profiles. Figures 5a,b show the DN stability difference (daytime

![Figure](image_url)
minus nighttime) for the NI and AS by using the 90th percentile. It is found that, for both the NI and AS, there is a consistent increase of stability downstream of the TP, in phase with the cold-season mean DN stability difference (Fig. 5c). The 95th percentile (Figs. 5d,e) results show similar images with the 90th percentile results. The results from Fig. 5 suggest the DN difference in the thermodynamic field is not a primary reason for the DN differences of these two stratus types.

Figures 6a,b show the nighttime composite means of $\omega$700 for the NI and AS by using the 90th percentile. There are common rising motions downstream of the TP, indicating the dominant large-scale lifting environmental conditions when the NI and AS occur. However, the DN differences exhibit opposite results. In the daytime, the NI result (Fig. 6c) suggests a strengthening of the large-scale lifting downstream of the TP, while the AS result (Fig. 6d) shows a weakening of the rising motion. Figures 6e–h

|       | Daytime $Z_{\text{top}}$ | Nighttime $Z_{\text{top}}$ | Daytime $Z_{\text{base}}$ | Nighttime $Z_{\text{base}}$ | Daytime $\Delta Z$ | Nighttime $\Delta Z$
<table>
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<tbody>
<tr>
<td>AL</td>
<td>3.804</td>
<td>4.391</td>
<td>1.860</td>
<td>1.921</td>
<td>1.945</td>
<td>2.470</td>
</tr>
<tr>
<td>NI</td>
<td>4.441</td>
<td>4.506</td>
<td>1.788</td>
<td>2.002</td>
<td>2.653</td>
<td>2.503</td>
</tr>
<tr>
<td>AS</td>
<td>4.447</td>
<td>4.934</td>
<td>2.385</td>
<td>1.977</td>
<td>2.062</td>
<td>2.957</td>
</tr>
</tbody>
</table>
Fig. 5. Daytime minus nighttime difference of the stability (K) for the (a) NI and (b) AS using the 90th percentile and (c) the cold-season mean DN difference of stability. (d),(e) As in (a),(b), but using the 95th percentile; see the text for details. The solid lines are for positive values, dashed lines are for negative values, and thick solid lines are for the zero contour. Note the different contour level of (c) from other four panels.
FIG. 6. Nighttime composite mean (see text for details) of \( v_{700} \) (hPa day\(^{-1}\)) for the (a) NI and (b) AS occurrences and the daytime minus nighttime difference of the \( v_{700} \) for the (c) NI and (d) AS using the 90th percentile. (e)–(h) As in (a)–(d), but using the 95th percentile. The solid lines indicate positive values, dashed lines indicate negative values, and thick solid lines indicate the zero contours.
further present the results from the 95th percentile, which exhibit more significant DN variations in the $\omega700$ field. Therefore, it is the DN difference in the dynamical condition that causes the different variations in the occurrences, $\Delta Z$, and cloud fraction of the NI and AS from daytime to nighttime. This indicates that the dynamical condition is more important in determining the formation of stratus clouds, which is consistent with findings in Zhang et al. (2013).

4. Radiative and microphysical properties

The most important radiative effect of the stratus cloud is the ability to weaken the incoming solar shortwave flux, usually measured by the SWCF, depending on the cloud albedo, which is further related to the single-scattering albedo, asymmetry parameter, solar zenith angle, and optical depth of cloud itself (Meador and Weaver 1980; Wood 2012). The differences of the profile-averaged layer optical depth between the daytime and nighttime are compared in Fig. 7; the layer-averaged value is also shown. It can be found that the mean layer optical depth of the AL profiles increases from daytime to nighttime (Fig. 7a). The largest layer $\tau$ value is about 3.5 in the daytime, while it can reach above 5.5 in the nighttime. Further analysis of the results from the NI (Fig. 7b) and AS (Fig. 7c) profiles suggest that the increase of the optical depth from the AL is mainly attributed to the corresponding increase of optical depth of the NI, whose largest nighttime layer

![Fig. 7. Daytime (solid) vs nighttime (dashed) profile-averaged layer optical depth for the (a) AL, (b) NI, and (c) AS. The percentage in parentheses presents the 0–10-km-averaged value.](image-url)
The optical depth is related with several important microphysical parameters, including the number concentration, water content, and particle radius. Because the stratus clouds over EC are dominated by large content of liquid droplets, emphasis is laid upon the liquid cloud content, effective radius, and number concentration. Generally, for stratiform water clouds, smaller particles, together with larger number concentration and water content values, tend to increase the optical depth (Twomey 1976; Slingo 1989; Wood 2006), although such empirical relationship may vary for pristine and polluted clouds (Peng et al. 2002).

Figures 8a–c show the profile-averaged LWC values from the AL, NI, and AS profiles and also present the layer-averaged LWC in parentheses. For the AL (Fig. 8a), the optical depth nearly doubles the daytime one. Nevertheless, the AS shows an opposite variation: that is, the optical depth tends to slightly decrease from daytime to nighttime.
the LWC values above 2 km slightly increase in the nighttime. In contrast, the LWC values of the NI are higher in the daytime than those in the nighttime (Fig. 8b). The daytime-to-nighttime increase of the LWC values of the AL is largely due to the corresponding increase of the LWC of the AS (Fig. 8c), whose largest nighttime content almost doubles the daytime one. An examination of the number concentration (Figs. 8d–i) and effective radius (Figs. 8g–i) indicates a similar DN difference for these three types of stratus profiles. Given that the layer optical depth of the NI (AS) enhances (reduces) from the daytime to nighttime and there is a decrease (increase) in the mean liquid effective radius, it is supposed that the DN variations of the liquid effective radius dominate the DN difference of the layer optical depth for both the NI and AS profiles.

To verify this assumption, we investigate the occurrence frequencies of the particle sizes revealed from the radar reflectivity. The contoured frequency by altitude diagram (CFAD; Yuter and Houze 1995), a kind of two-dimensional joint histogram, is a useful technique for illustrating the occurrence frequencies of the radar reflectivity at different altitudes. The normalized occurrence frequency in the CFAD is the ratio between the number in each altitude–reflectivity (km and dBZ, respectively) bin and the total number in the altitude–reflectivity phase space. Meanwhile, only the vertical bins with a CPR cloud mask higher than 30 are included to construct the CFAD; that is, only the cloudy portion is calculated.

Figure 9 shows the total time (Fig. 9a), daytime (Fig. 9b), and nighttime (Fig. 9c) CFADs for each stratus profile. For the total time AL, the distribution pattern is similar with the winter result in Luo et al. (2009), in which they constructed a similar CFAD (their Fig. 6d) by using samples from all cloudy profiles, suggesting the dominance of stratus in the cold season. The occurrence frequency higher than 0.01 covers a wide reflectivity range from about −28 to −8 dBZ, suggesting the radii of stratus particles span a large range from small to large. The results from the daytime and nighttime AL profiles are overall similar, but the nighttime profiles have relatively larger occurrence frequencies between −8 and −18 dBZ at ~3 km.

The CFADs of the NI profiles are shown in Figs. 9d–f. It can be found that the total time NI dominates the CFAD pattern of the AL, suggesting the NI largely determines the vertical extent and particle size distribution of stratus clouds in the cold season. The largest reflectivity occurs at ~3 km, similar with the cloud fraction profile (Fig. 4b). The CFADs of the NI exhibit evident DN difference. The occurrence frequencies in the reflectivity between −28 and −8 dBZ from 2 to 4 km significantly increase from daytime (Fig. 9e) to nighttime (Fig. 9f), suggesting the nighttime NI particles tend to be more concentrated in small sizes.

The bottom panels in Fig. 9 show the results for the AS cloud. Different from the NI profiles, the total time AS profiles (Fig. 9g) have larger occurrence frequencies in the reflectivity range between −10 and 10 dBZ than those in the small range. By further comparing the daytime (Fig. 9h) and nighttime (Fig. 9i) CFADs, it is found that the nighttime distribution pattern dominates the total time result. In the daytime, the result for the AS is similar with that for the NI: that is, the occurrence frequencies distribute more uniformly between −28 and −8 dBZ with maxima from −28 to −18 dBZ. However, in the nighttime, the occurrence frequencies are larger between −10 and 10 dBZ, suggesting the nighttime AS particles are more concentrated in big sizes.

Figure 10 further shows the distribution of the liquid effective radius in the altitude–reflectivity regime. Overall, the retrieved $r_e$ value increases monotonically with the reflectivity, and the results from different conditions are generally similar. Between −28 and −8 dBZ, where the occurrence frequencies of the NI (AS) increase (decrease) from daytime to nighttime, the $r_e$ value ranges from ~8 to ~14 μm. Between −10 and 10 dBZ, where the occurrence frequencies of the AS (NI) increase (decrease) from daytime to nighttime, the $r_e$ value ranges from ~14 to ~20 μm. Nevertheless, the LWC value also increases almost monotonically with the reflectivity (not shown). Thus, it is necessary to investigate the competing role played by the liquid water content and effective radius in determining the resultant optical depth.

For this purpose, we construct an LWC–$r_e$ regime (Fig. 11) for measuring their joint occurrence frequencies. In this figure, the vertical bins that have zero values in the profile are ignored. This operation mimics the way that we only count bins with CPR cloud mask higher than 30 in constructing the CFAD. Meanwhile, because there is no cloudy sample whose radius is lower than 5 μm, the $r_e$ regime is set to range from 5 to 35 μm, and that is from 0 to 1000 mg m$^{-3}$ for the LWC.

An overall view on the results for all cases indicates that the largest occurrence frequencies are located in a triangle zone, where the LWC ranges from ~25 to ~400 mg m$^{-3}$ and the $r_e$ value ranges from ~5 to ~15 μm. For the AL, the total time (Fig. 11a), daytime (Fig. 11b) and nighttime (Fig. 11c) results all show maximum occurrence frequencies at around 11 μm ($r_e$) between ~100 and ~250 mg m$^{-3}$ (LWC). For the NI (Figs. 11d–f), the feature in each plot is similar with that in the AL. Meanwhile, it can be found that there is an increase of the occurrence frequencies from
daytime (Fig. 11e) to nighttime (Fig. 11f) in the regime of \( \sim 100 \) to \( \sim 250 \text{ mg m}^{-3} \) at around 11 \( \mu \text{m} \), corresponding to the increase of frequencies in the low reflectivity regime (Figs. 9e,f). For the total time AS (Fig. 11g), the occurrence frequencies in the triangle zone are more uniformly distributed than those of the total time NI. However, there is a decrease of the occurrence frequencies in this zone from daytime (Fig. 11h) to nighttime (Fig. 11i), also corresponding to the decrease of frequencies in the low reflectivity regime (Figs. 9h,i).

Fig. 9. CFADs for the (left) total time, (center) daytime, and (right) nighttime (top) AL, (middle) NI, and (bottom) AS. The height bin (km) ranges from 0 to 10 km with a 0.5-km interval, and the reflectivity bin (dBZ) ranges from -30 to 30 dBZ with a 5-dBZ interval.
The distribution patterns of the liquid number concentration (not shown) in the LWC–$r_e$ regime are found to be overall consistent with each other in the total time, daytime, and nighttime for all three stratus types. The $N_d$ values increase with the decrease of $r_e$ at a constant LWC value, and it increases with the LWC at a constant $r_e$. This retrieved relationship is similar with findings in some previous studies (e.g., Martin et al. 1994; Reid et al. 1999). Hence, we further measure the distribution of the optical depth in the microphysical phase space by only using the LWC–$r_e$ regime.

**Fig. 10.** The (left) total time, (center) daytime, and (right) nighttime distributions of the liquid effective radius ($\mu$m) in the height–reflectivity (km and dBZ, respectively) regime for the (top) AL, (middle) NI, and (bottom) AS clouds.
**Figure 12** shows the layer optical depth binned by the LWC and $r_c$; the results are largely discretized among different conditions. For the total time AL (Fig. 12a), large $\tau$ values occur not only in the high-frequency triangle zone but also in the large LWC ($>700 \text{ mg m}^{-2}$) and $r_c$ ($>25 \mu\text{m}$) regimes. Compared with the daytime AL (Fig. 12b), the nighttime AL result (Fig. 12c) shows a strengthening of the optical depth in the triangle zone and fewer occurrences of particles with large $r_c$ values.

The distribution of the layer optical depth from the total time NI (Fig. 12d) is similar with that from the total time AL profiles but with smaller occurrence frequencies of large particle sizes. From daytime (Fig. 12e) to...
nighttime (Fig. 12f), the $\tau$ value increases in the triangle zone, and there are also larger $\tau$ values strengthening outside this zone. For the total time AS (Fig. 12g), the largest $\tau$ values generally occur at large effective radius regime. From daytime (Fig. 12h) to nighttime (Fig. 12i), there are decreases of the optical depth in both the triangle zone and the regime outside.

Because large $\tau$ values are not always distributed in the high-frequency regime, it is important to figure out the relative weight between the high- and low-frequency regimes in determining the resultant optical depth. We calculate the sums of $\tau$ values that fall in the high- (LWC: 25–400 mg m$^{-3}$; $r_e$: 5–15 $\mu$m) and low-frequency (outside the high-frequency range) regimes and measure the ratio between these two sums (high/low). As shown in Table 2, for the NI, the numbers are 2.0 (daytime) and 3.9 (nighttime), while they are 1.8 (daytime) and 0.8 (nighttime) for the AS. Another calculation for the liquid number concentration in the same approach suggests the numbers are 2.5 (daytime) and 5.7 (nighttime) for the NI and 2.7 (daytime) and 1.6 (nighttime) for the AS. These results suggest that (i) it is

![Image of distributions](image-url)

**Table 2.** Ratios between the layer optical depth ($\tau$) and liquid number concentration ($N_d$) sums in the high- and low-frequency regimes in Fig. 11.

<table>
<thead>
<tr>
<th></th>
<th>NI daytime</th>
<th>NI nighttime</th>
<th>AS daytime</th>
<th>AS nighttime</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau$</td>
<td>2.0</td>
<td>3.9</td>
<td>1.8</td>
<td>0.8</td>
</tr>
<tr>
<td>$N_d$</td>
<td>2.5</td>
<td>5.7</td>
<td>2.7</td>
<td>1.6</td>
</tr>
</tbody>
</table>
the high-frequency regime largely determining the ultimate mean strength of the optical depth and (ii) for the NI, the high-frequency regime has larger weight in contributing to the optical depth during the nighttime because of the increased concentration of small particles, while for the AS the high-frequency regime is more dominant during the daytime for the same reason. Therefore, the DN difference in the optical depth can be explained for both two types of stratus.

5. Summary and concluding remarks

Through an examination of the occurrences and macrophysical, radiative, and microphysical properties of the midtopped single-layer stratus profiles downstream of the TP during the boreal cold season, this study presents the first attempt to investigate and compare the vertical structures and physical properties of the distinctive stratus clouds between daytime and nighttime. Several important climate features can be concluded.

The spatial distributions of the occurrence frequencies for different stratus types confirm the conclusion from previous studies (e.g., Yu et al. 2001) using the passive remote sensing ISCCP product. The NI cloud is the dominant stratus type in the cold season. The entire stratus and NI profiles occur more frequently in the daytime than in the nighttime, while the AS cloud exhibits an opposite DN difference.

A further analysis of the macrophysical vertical structures of two types of midtopped stratus show that the NI has relatively small DN difference in the mean $\Delta Z$ and profile-averaged cloud fraction (the daytime case slightly larger than the nighttime case), while the mean $\Delta Z$ of the AS increases significantly from 2.062 to 2.957 km accompanied by an evident increase of cloud fraction from daytime to nighttime. An examination of the ambient dynamic and thermodynamic meteorological conditions indicates that it is the DN difference in the $\omega_700$ that leads to the different variations of the NI and AS from daytime to nighttime. The rising motion downstream of the TP becomes stronger in the daytime (nighttime) associated with the frequent occurrences of the NI (AS), while the stability for both stratus occurrences show consistent strengthening during the daytime.

The profile-averaged optical depth values exhibit different DN variations from the $\Delta Z$ and cloud fraction for the NI and AS. From daytime to nighttime, there is an evident increase in the optical depth of the NI, dominating the variation of the AL, while a slight decrease in the optical depth of the AS can be found. The profile-averaged liquid water content, number concentration and effective radius values of the NI (AS) decrease (increase) from daytime to nighttime. An investigation of the normalized CFADs suggests that, during the nighttime, the samples from the NI profiles are more concentrated in the small reflectivity regime, while those from the AS profiles are less concentrated in the same regime: that is, the nighttime NI (AS) profiles have larger (smaller) occurrence frequencies of small particle sizes. A further investigation of the occurrence frequencies of the LWC–-$r_e$ phase space confirms the regime of small particle sizes and low LWC values has dominant occurrences. This high-frequency regime plays a dominant role in determining the ultimate mean $\tau$ value. Because the NI and AS profiles are more concentrated in small particle sizes in the nighttime and daytime, respectively, the DN difference of the small particle concentrations lead to the corresponding DN difference in the resultant optical depth for each stratus type.

This study reveals the different DN changes between the occurrences/macrophysical and radiative/microphysical properties for the midtopped NI and AS, presenting a potentially valuable metric for evaluating the performance in the climate model. The Cloud Feedback Model Intercomparison Project (CFMIP) Observation Simulator Package (COSP; Bodas-Salcedo et al. 2011) will be used in future to expose the model biases in simulating the vertical structures and physical properties of stratiform clouds downstream of the TP.

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