Macrophysical properties of specific cloud types from radiosonde and surface active remote sensing measurements over the ARM Southern Great Plains site

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ABSTRACT

Accurate observation of clouds is challenging because of the high variability and complexity of cloud types and occurrences. By using the long-term cloud data collected during the ARM program at the Southern Great Plains central facility during 2001–2010, the consistencies and differences in the macrophysical properties of clouds between radiosonde and ground-based active remote sensing are quantitatively evaluated according to six cloud types: low; mid-low (ML); high-mid-low; mid; high-mid (HM); and high. A similar variability trend is exhibited by the radiosonde and surface observations for the cloud fractions of the six cloud types. However, the magnitudes of the differences between the two methods are different among the six cloud types, with the largest difference seen in the high clouds. The distribution of the cloud-base height of the ML, mid, and HM clouds agrees in both methods, whereas large differences are seen in the cloud-top height for the ML and high clouds. The cloud thickness variations generally agree between the two datasets for the six cloud types.

1. Introduction

Clouds play a crucial role in the earth–atmosphere system owing to their effect on the energy budget and hydrological cycle (Webster 1994). Good understanding of the macrophysical properties of the cloud fraction, cloud boundaries, and cloud thickness (CT) is required to improve our understanding of cloud radiative effects (Webb, Bony, and Morcette 2006). The various cloud types, which can be classified according to cloud height and CT, are strongly related to the dynamics and thermodynamics of the atmosphere and have different radiative forcings (Stephens 2005). Unfortunately, accurate observation and modeling of cloud profiles remains a challenging task owing to the high diversity and complexity of cloud variations, both spatially and temporally.

Space-borne passive and active instruments can collect cloud data on the global scale along a satellite track (Weisz et al. 2007; Marchand et al. 2008). Additionally, ground-based instruments collect temporal and long-term cloud data at regional scales. For example, as part of the ARM program of the U.S. Department of Energy, surface remote sensing instruments have been deployed for over two decades at the Southern Great Plains (SGP) central facility near Lamont, Oklahoma, which is characterized by a wide variability of cloud types. By combining the data collected by ground-based radar, ceilometers, and lidar, vertical cloud profiles have been generated over this site (Clothiaux et al. 2000; Kollias, Tselioudis, and Albrecht 2007) and used in numerous studies (Xi et al. 2010; Qian et al. 2012; Yoo et al. 2013). In addition to ground-based measurements, radiosonde launches have also been conducted for many years at the SGP site.

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atmospheric temperature and humidity profiles provided by the radiosonde sensors can be used to determine cloud boundaries (Chernykh and Eskridge 1996; Wang et al. 1999; Chernykh, Alduchov, and Eskridge 2000; Wang, Rossow, and Zhang 2000; Naud, Muller, and Clothiaux 2003; Minnis et al. 2005). The method of Wang and Rossow (1995), denoted as WR95, made use of radiosonde-based relative humidity profiles to determine the locations of the cloud layer. Developing a modified version of WR95, Zhang et al. (2010), hereafter ZH10, used the 2008 radiosonde data from an ARM mobile facility in China to analyze the cloud distribution over a site in southeastern China. Zhang et al. (2013) performed a preliminary validation of the ZH10 method by using radiosonde data from different climate regimes, and reported good results.

Presently, an increasing number of instruments are providing long-term cloud data. A challenging task associated with this is to evaluate the various datasets in order to derive reliable cloud data for validating climate models. The long-term co-existence of radiosonde and surface active remote sensing measurements over the SGP site can be used to evaluate their consistencies and differences in terms of macrophysical properties as a function of various cloud types, which is the primary objective of this study. To achieve this, the cloud fraction, cloud locations (cloud-base height (CBH) and cloud-top height (CTH)) and CT from the radiosonde and remote sensing measurements are compared and evaluated according to different cloud types in this study.

2. Methods and data

2.1. Radiosonde-based cloud detection

At the SGP site, the radiosondes are generally launched four times each day at 0530, 1130, 1730, and 2330 local standard time (LST). By using the method described in Zhang et al. (2013), radiosonde data with a vertical resolution of ~10 m were used to derive the cloud layers during 2001–2010. We only give a brief description of the method because it is already described in detail in Zhang et al. (2013). The algorithm that we used is based on the WR95 method, which we significantly modified. The algorithm uses height-resolving relative humidity thresholds to determine the cloud layers after transforming the relative humidity with respect to ice for layers with temperatures below 0 °C.

2.2. Ground-based cloud detection

A 35-GHz Millimeter Microwave Cloud Radar (MMCR) and Micropulse Lidar (MPL), as well as laser ceilometers, were deployed at the SGP site during the period of our study (Moran et al. 1998). By combining the data from these three types of remote sensing sensors, ground-based Active Remote Sensing of Cloud (ARSCL) data were generated by the ARM project (Clothiaux et al. 2000, 2001; Kollias et al. 2009). The ARSCL cloud data have a temporal resolution of 10 s and vertical resolution of 45 m. A maximum of 10 cloud layers can be obtained from each ARSCL vertical profile. A combination of the variables produced by ARSCL was used to derive the combined MMCR + MPL cloud mask for each (10 s, 45 m) sample in this study, as follows. First, only ARSCL samples with both MMCR detections and MPL columns that were not entirely marked as beam-blocked or attenuated were selected and utilized. Second, cloudy scenes were determined if MMCR or MPL detected clouds. Finally, the best estimate of the cloud-base field, which used a mixture of ceilometer and MPL information, was deployed to filter hydrometeors below the cloud base. The cloud fraction and locations of specific cloud types were obtained on the basis of the MMCR + MPL cloud mask collected during the radiosonde launch period in this study.

2.3. Cloud classification algorithm

To allow for comparisons with the ISCCP (Rossow and Schiffer 1999), Kennedy, Dong, and Xi (2014) used a cloud classification system that takes advantage of the actively sensed cloud tops and bases at the SGP site while using a pressure coordinate system. We used the same cloud classification algorithm as Kennedy, Dong, and Xi (2014). The height–pressure conversion was achieved by using the atmospheric height and pressure vertical profiles in the radiosonde data. It should also be noted that with information from passive remote sensing platforms it is possible to further constrain the clouds over the SGP site to match the ISCCP categories, as was the case in Wang and Sassen (2001). However, considering that the primary objective of this study is to evaluate the consistencies and differences between radiosonde and ground-based active remote sensing data, this was not adopted here. As stated in Kennedy, Dong, and Xi (2014), the cloud classification system used here should be viewed as a good compromise between simplistic height-based classifications (e.g. Kennedy et al. 2010) and more comprehensive classification systems (e.g. Wang and Sassen 2001). As shown in Figure 1(a) (adopted from Kennedy, Dong, and Xi 2014), the six cloud types over the SGP are low, mid-low (ML), high-mid-low (HML), mid, high-mid (HM), and high. The cloud types are named according to their extension in the troposphere, e.g. HML refers to the thick clouds that are present at pressures higher than 680 hPa (low troposphere), extend through the middle troposphere, and top at pressures lower than 440 hPa (high troposphere).
among the six cloud types. Overall, the radiosonde- and ARSCL-based cloud fractions are quite close for the ML, HML, and HM clouds, with a bias of less than 3%. Compared to the ARSCL data, more cloud layers are detected by the radiosonde in the remaining three cloud types. The biases are 6% for both the low and mid clouds. The maximum bias is 13% for the high clouds.

The ground-based observations provide cloud information over the observational site, but the radiosonde measurements generate cloud information along a slanted pathway. The mismatch in the objects detected by the two instruments will have a certain impact on the agreement of the cloud fractions from the two cloud retrievals. It is difficult or maybe impossible to resolve the spatial discrepancies because of the different observational characteristics of the two datasets, i.e. fixed ground-based instruments and drifting radiosondes. However, due to the cloud horizontal motion caused by the wind field, the ground-based data collected during a period of time could to some extent represent the cloud distributions over the areas surrounding the SGP site.

Moist layers at low altitudes may be associated with fog, drizzle, or rain. Given the difficulty in discriminating these hydrometeors in sounding data, the radiosonde-based cloud retrieval method may misclassify some near-surface clear moist layers as clouds. Further improvements are required to determine more accurate low clouds from radiosonde, such as discriminating the hydrometeors at low altitudes by combining with other surface observational data. When no lower-level clouds (low, ML, and mid clouds) are present, the occurrence frequencies with high clouds detected are very close between the radiosonde (22%) and ARSCL (20%) approaches. However, when one or more of the lower-level cloud types (low, ML, and mid clouds) is/are present, the occurrence frequencies with high clouds detected are 10% larger for the radiosonde (19%) relative to the ARSCL (9%) results. Therefore, aside from the spatial discrepancy of the two datasets mentioned above, the attenuation effect of the lower-level clouds on the radar–lidar signals may also lead to a detection deficiency in terms of high clouds in the ARSCL data (Protat et al. 2014). The occurrence frequencies of overlap between low and HM clouds are 4% for the radiosonde and 2% for the ARSCL data, respectively.

The cloud fractions of the six cloud types are further calculated across the four seasons (spring: March–May; summer: June–August; autumn: September–November; and winter: December–February) and during the four radiosonde launch periods (0530, 1130, 1730, and 2330 LST), as shown in Figure 2. Overall, similar to Figure 1(b), the trends of seasonal cloud fraction variations according to the two cloud products are comparable for the different cloud types (Figure 2(a) and (b)). Smaller frequency values

3. Macrophysical properties of clouds: radiosonde and surface measurements

3.1. Cloud fraction

Ten years (2001–2010) of total cloud fraction and cloud fractions for the six cloud types derived from the radiosonde and ARSCL datasets are shown in Figure 1(b). The total cloud fraction is defined as the number of observational profiles with a cloud layer present anywhere within the whole range of detecting altitudes divided by the total number of observational profiles. For a particular profile, if it is cloudy, it is further classified as one or several definite cloud types among the six according to the locations of the cloud layers. Therefore, a cloudy profile could have more than one coexisting/overlapping cloud type. The difference between the two datasets is 10% for the total cloud fraction. In general, similar variability is seen in both datasets for the six specific cloud types. Most high clouds (radiosonde: 42%; ARSCL: 29%) and least HML clouds (radiosonde: 2%; ARSCL: 2%) are simultaneously detected by the two cloud retrievals. However, the magnitudes of the differences between the two methods are not the same
of low clouds are demonstrated by the two datasets in summer relative to the other three seasons because stratus clouds are less frequent during this season (Dong, Minnis, and Xi 2005). Although the overall cloud fraction patterns derived from the four radiosonde launch periods are similar between the two cloud retrievals, differences exist at a more detailed level (Figure 2(c) and (d)). Compared to ARSCL, larger variations of cloud fraction from the four periods tend to occur in mid, HM, and high clouds in the radiosonde results.

3.2. Cloud location

The cloud locations in terms of CBH and CTH are discussed in this subsection. Figure 3 shows the radiosonde- and ARSCL-retrieved vertical occurrence frequencies of the CBH at 1-km intervals for the six cloud types. For the low and HML clouds, discrepancies exist in the cloud layers with the CBH at 1 km, when the ARSCL data tend to underestimate the low clouds by 16% but overestimate the HML clouds by 7%, relative to the radiosonde data. Overall, the vertical CBH distributions in both methods are consistent in the ML, mid, and HM clouds. Although there is a slight displacement in the vertical profiles of the high clouds, as the ARSCL data place the peak occurrence in the upper troposphere higher than the radiosonde data, the agreement between the two methods for the high clouds is reasonable. The CBH averages derived from the radiosonde and ARSCL data are also shown in Figure 3. Similar mean CBH values, with an absolute difference of less than 0.1 km, are determined by the two methods for the ML, mid, and HM clouds. Relative to the ARSCL data, lower CBHs are seen for the low and high clouds in the radiosonde data, by 0.29 and 0.33 km, respectively; in contrast, higher CBHs of 0.15 km for the HML clouds are recorded by the radiosonde.

Figure 4 shows the vertical CTH structures at 1-km intervals for the six cloud types. The variations of the two datasets are similar at most altitudes for the low, HML, mid, and HM clouds, with differences generally less than 5%. In contrast, large discrepancies in the vertical CTH frequencies between the two methods are seen at a few altitude levels in the other two cloud types. Compared to the ARSCL data, the radiosonde measurements record 11% more CTHs for the ML clouds at 4 km and detect fewer CTHs above 5 km. For the high clouds, the ARSCL data overestimate the CTH by 6% at 11–12 km and underestimate the CTH below 10 km and above 13 km. As shown by the mean CTH values in Figure 4, the average CTHs are nearly the same for the high clouds. Lower CTHs are detected by the radiosonde than the ARSCL retrieval, with a difference of 0.12 km for the low clouds and 0.23 km for the ML clouds. However, the radiosonde-based CTHs are higher than those from the ARSCL data-set in the remaining three cloud types, with a maximum bias of 0.25 km in HML, 0.15 km in mid, and 0.12 km in HM. The thickest layers
of the HML clouds might be responsible for the largest mean bias of the CTHs between the radiosonde and ARSCL datasets, as explained by the following. The capability of the ground-based instruments to detect the CTH deteriorates owing to the attenuation of thick cloud layers on the detecting signals; meanwhile, the accuracy of radiosonde observations may decrease at a certain distance after the balloon travels through these thick cloud layers because of the moisture on the sensors.

### 3.3. Cloud thickness

The frequencies of CT at 1-km intervals for the six cloud types are shown in Figure 5. Overall, the radiosonde data
The results showed that the most high clouds and the least HML clouds are detectable in both the radiosonde and ARSCL data. Similar cloud fractions can be observed by the two methods for ML, HML, and HM clouds, with a bias of less than 3%. The differences in the cloud fractions between the two methods are largest in the high clouds (13%), followed by the low and mid clouds (6%). The detection deficiency of the high clouds in the ground-based cloud data-set might be due in part to the limitations of the ground-based instruments in detecting this type of cloud, because of the attenuation effect of the lower cloud layers on the radar–lidar signals. The vertical distributions of the CBH using the two methods agree better in the ML, mid, HM, and high clouds, as compared to the low and HML clouds. Relatively larger differences are seen in the vertical occurrence frequency of the CTH in the ML and high clouds than the other cloud types. The occurrence frequencies of CT are generally consistent in both methods for the six cloud types.

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