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HORIZONTAL AND VERTICAL DISTRIBUTIONS OF CLOUD COVER OVER EASTERN CHINA AND THE EAST CHINA SEA

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Abstract: Based on data from satellite and surface observations, the horizontal and vertical distributions of clouds over eastern China and the East China Sea are examined. Three maximum centers of cloud cover are clearly visible in the horizontal distribution of total cloud cover. Two of these maxima occur over land. As the clouds mainly originate from the climbing airflows in the southern and eastern slopes of the Tibetan Plateau, they can be classified as dynamic clouds. The third center of cloud cover is over the sea. As the clouds mainly form from the evaporation of the warm Kuroshio Current, they can be categorized as thermodynamic clouds. Although the movement of the cloud centers reflect the seasonal variation of the Asian summer monsoon, cloud fractions of six cloud types that are distinct from the total cloud cover show individual horizontal patterns and seasonal variations. In their vertical distribution, cloud cover over the land and sea exhibits different patterns in winter but similar patterns in summer. In cold seasons, limited by divergent westerlies in the middle troposphere, mid-level clouds prevail over the leeside of the Tibetan Plateau. At the same time, suppressed by strong downdraft of the western Pacific subtropical high, low clouds dominate over the ocean. In warm seasons both continental and marine clouds can penetrate upward into the upper troposphere because they are subject to similar unstable stratification conditions.

Key words: clouds; distribution; eastern China; East China Sea

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1 INTRODUCTION

East Asia, especially eastern China and the East China Sea (20–35ºN, 102–130ºE), has typical monsoon rainfall (Zheng and Liou[1]; Ding[2]), but related cloud distributions and cloud-forming mechanisms are complex and are not clearly understood (Li et al.[3]). Intrinsically coupled with the atmospheric circulations, clouds are considered as a new criterion of climate model evaluation in East Asia (Zhang et al.[4]). Thus some observational facts, such as the horizontal and vertical distributions of clouds and the influencing factors of cloud occurrence, need to be studied closely to produce a wider understanding of cloud phenomena.

Some facts of clouds over China have been disclosed. Trends of cloud cover and cloud types over China have been documented by Endo and Yasunari[5] and Warren et al.[6], the horizontal distribution of total cloud cover over East Asia (Hahn et al.[7]; Kaiser[8,9]; Li et al.[3]; Wang et al.[10]; Zhang et al.[11]) and the vertical distribution of cloud occurrence frequency using by CloudSat data (Luo et al.[12]; Naud et al.[13]; Li et al.[14]; Wang et al.[15]) have been reported, but their formation mechanisms and the vertical distribution of cloudiness are still not very clear. The spatial pattern of mid-level clouds and their formation also have been documented (Yu et al.[16]; Li and Gu[17]), but those in other layers are rarely studied. The continental clouds have been partly studied over China (Wang et al.[10]; Li et al.[18]), but marine clouds over Chinese seas are rarely given attention to. In addition, the orographic effects of the Tibetan Plateau (TP) on its leeside clouds have been studied (Yu et al.[16]; Li and Gu[17]; Li et al.[18]), but the impacts of other main synoptic systems on clouds in eastern China, such as monsoon and the western Pacific subtropical high (WPSH), have not been studied in depth. Therefore, these issues are examined in this study, which primarily attempts to provide a description of the horizontal and vertical distribution of cloud amounts over the eastern part of China and its surrounding seas, and to determine the factors that influence these cloud distributions.

2 DATA

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The cloud datasets used in this study include satellite data products and surface data products. The satellite dataset was the International Satellite Cloud Climatology Project (ISCCP) D1 (Rossow and Schiffer[19, 20]), which consists of monthly mean total cloud cover and cloud fractions at seven vertical levels (i.e., 0–180 hPa, 180–310 hPa, 310–440 hPa, 440–560 hPa, 560–680 hPa, 680–800 hPa, and 800–1000 hPa) from 1984 to 2007 on a 2.5-degree grid. The surface dataset used for quality control was compiled by the Chinese Meteorological Administration, and consisted of monthly mean total cloud amounts and cloud fractions of nine cloud types defined by WMO for 127 stations in China from 1985 to 2000. However, six typical cloud types (i.e., cumulus, fractonimbus/nimbostratus, stratus/stratus fractus, stratocumulus, altocumulus, and cirrus) are analyzed in our study because other types are relatively infrequent in China. To facilitate our analysis, the original station data were interpolated onto a 0.5-degree grid by averaging the station data with weights proportional to the inverse of the squared distance between the center of the grid box and the stations within a radius of 3°. If the distance was <0.5°, the weight number of the station data was 1. The two datasets agreed well in total cloud cover over eastern China (Li et al.[3]), and errors were much lower when time and space averages were performed (Harrison et al.[21]).

In addition, zonal and meridional wind data extracted from National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR, USA) reanalysis data (Kalnay et al.[22]) during the same period as that of ISCCP D1 were also used to demonstrate atmospheric circulation.

3 HORIZONTAL DISTRIBUTION OF CLOUDS

The annual mean total cloud cover over East Asia from ISCCP data is shown in Figure 1. A pattern showing three centers of maxima is demonstrated clearly, and all centers are located around 28ºN. Over land, two maxima centers occur over Myanmar and Sichuan Basin, respectively, where clouds are formed from the low-level water vapor that climbs up from the steep southern and eastern sides of the Tibetan Plateau (TP), shown as the two thick arrows in Figure 1. These continental clouds formed from the forced uplifted air and hence can be called dynamic clouds. The maximum of the third center is located over the East China Sea (ECS) over the permanently warm Kuroshio Current (KC). The KC is the second strongest current in the world, famous for its strong heat energy (its main body is shown as a black, thick and solid arrow in Figure 1). The maximum difference of the sea surface temperature and the near-surface air temperature over the KC is about 6 *K*, much larger than the difference on the land. The clouds are mainly formed from the evaporation of the warm current, and the maximum cloud area exactly overlaps the main body of KC. Thus the marine clouds can be called thermodynamic clouds.

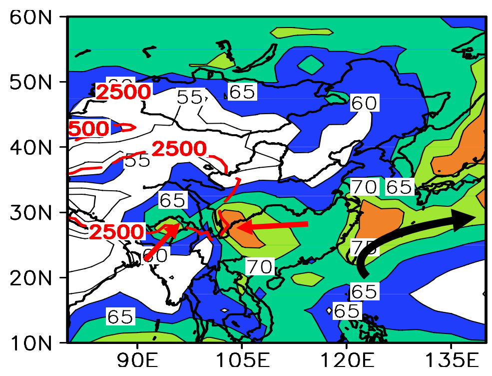
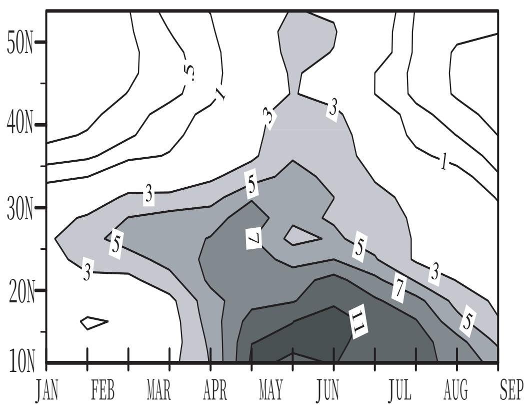


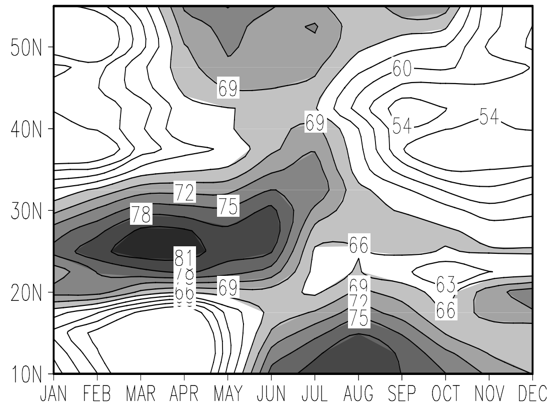
Figure 1. Spatial distribution of annual mean total cloud cover (%) derived from ISCCP data. Red dashed contour line is 2500-m mountain height; the thick red arrows denote surface wind directions, and the solid black arrow denotes main body of the Kuroshio Current.

Notably, the cloud-center maxima are not steady, but move along with the monsoon seasonal progression (Figure 2a, cited from Chen et al.[23]) when cloud cover is averaged in the typical monsoon region, 110–125ºE. This progression can be divided into three stages (Figure 2b). The first stage occurs from January to the beginning of May, when clouds are formed frequently, and the maximum center is located near 25ºN. These clouds are related to the strong convergence of westerlies that results from the round airflows from the southern and northern sides of the TP in the lower troposphere during the cold season (Li and Gu[17], see their Figure 2). The maximum value (81%) appears in March, which agrees well with the time of strongest convergence (see Figure 6b). The second stage starts at the beginning of May when the summer monsoon breaks out. The center of maximum cloud cover travels from 23ºN to the north, at the same basic speed as that of the summer monsoon, and arrives at 40ºN in July. Afterwards, the position of greatest cloud cover starts to retreat, and the third stage is formed from July to August. The center of maximum cloud cover returns quickly to 25ºN in one month, a little faster than the average speed of the withdrawing summer monsoon. This migration implies that clouds may be an indicator for summer monsoon movement.

In addition to the impact of the large-scale system such as monsoon circulation, clouds over eastern China exhibit distinct local features. The horizontal distributions of six cloud types defined by the surface observation are illustrated in Figures 3a to 3f. Although inadequate illumination may lead to a 3.3% underestimation of cloud cover at night (Hahn et al.[24]), which is not considered in our study, the figures show cloud-type changes from cumulus (Figure 3a) to altocumulus (Figure 3e) to cirrus (Figure 3f), implying that cloud-bottom height increases from low to middle to high levels with the northward movement. The water vapor in the atmosphere may be related to the geographic location that determines the cloud-bottom height. Further, each cloud type dominates its own realm. Cumulus clouds appear over southwest coastal and mountainous China more frequently (Figure 3a); they are associated with water vapor content and ground properties. Stratus and/or stratus fractus clouds (Figure 3b) occur on the coastal land near the Bohai Sea and the Yellow Sea, and are usually comprised of returning air masses from the seas. Fractonimbus and/or nimbostratus clouds (Figure 3c), which often produce continuous rain, appear along the south of the Yangtze River valley, where cold air from the north often encounters with warm air from the south. Stratocumulus (Figure 3d) is the most frequent cloud type over eastern China both in winter and summer, and has an annual mean pattern similar to that of total cloud amount. In addition, the seasonality of stratocumulus also has some similarity to the seasonal variation of the total cloud amount (figure omitted). Because stratocumulus has mixed characteristics of cumulus and stratus clouds, its high frequency may reflect the complexity of the atmospheric circulation and surface properties over eastern China. Fu et al.[25] also found that, even during summer, >50% of rain is formed from mixing clouds in eastern China. Other than stratocumulus, however, no other cloud types represent similar seasonal variation to the total cloud amount, which suggests that monsoon is an important, but not the unique, factor influencing the clouds. Cloud cover and cloud types are also related to weather systems, surface properties, geographic locations, etc.



(a)



(b)

Figure 2. Seasonal migration zonally averaged between 110ºE and 125ºE of (a) the monsoon rainband (mm day^{-1}) derived from merged analysis of precipitation and (b) total cloud cover (%) derived from the ISCCP data.

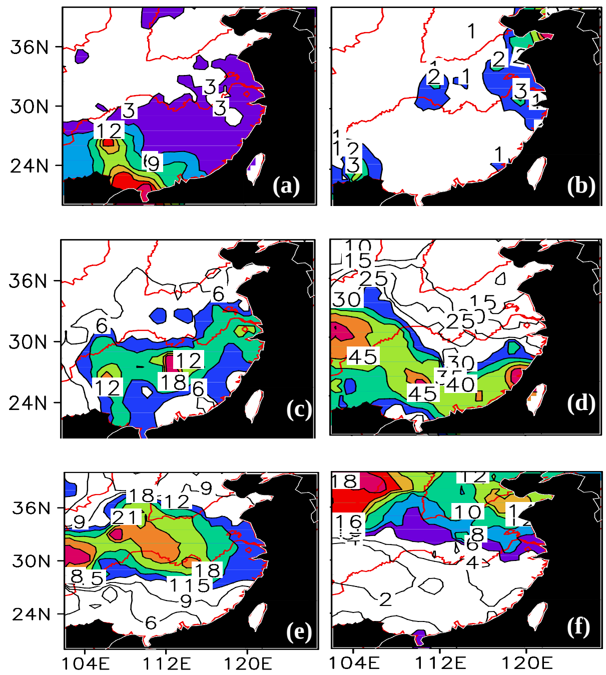


Figure 3. Spatial distributions of annual mean cloud fractions (%) of six cloud types derived from surface observation: (a) umulus, (b) stratus/stratus fractus, (c) fractonimbus / nimbostratus, (d) stratocumulus, (e) altocumulus, and (f) cirrus.

4 VERTICAL DISTRIBUTION OF CLOUDS

The three largest cloud centers are all located near 28ºN (Figure 1). The elevation of terrain along this sample section decreases from the TP at 80–102ºE to the basin and foothill regions at 102–120ºE to the ECS at 120–130ºE. Then during the cold seasons, the corresponding top pressure of maximum cloud cover increases from 310–440 hPa over the TP to 680–440 hPa east of the TP to >800 hPa over the ECS, as analyzed with the ISCCP dataset and shown in Figure 4a. Apparently, the higher elevation influences cloud-top pressure over the TP.

Over eastern China. However, the divergent westerlies in the middle troposphere, caused by the surface-blocking effect of TP (Yu et al.[16]) and the mid-level temperature inversion layer and resulted from temperature advection from TP and the northern China (Li and Gu[17]), set limit to cloud top pressure. Over the ECS, cloud development may be suppressed by the large-scale descending motion of the WPSH, with its western centers at 850 hPa over the south of ECS in February (Figure 4b) where low clouds dominate sea areas. The formation mechanism of these low-level clouds is totally different than that of marine boundary clouds in the eastern Pacific Ocean, where clouds are related to cold sea surface temperatures and strong temperature inversions (Hanson[26]). However, during the summer clouds can develop to higher levels over both land and sea (Figure 5a) because the divergence over the land weakens along with the decrease of westerlies, and because the divergence over the sea also decays along with the departure of the WPSH center. The eastern Chinese continent and surrounding seas are at the edge of the WPSH (Figure 5b) at 500 hPa where the associated frontal system is located and convection occurs frequently and may develop to higher levels, resulting in higher cloud-top heights.

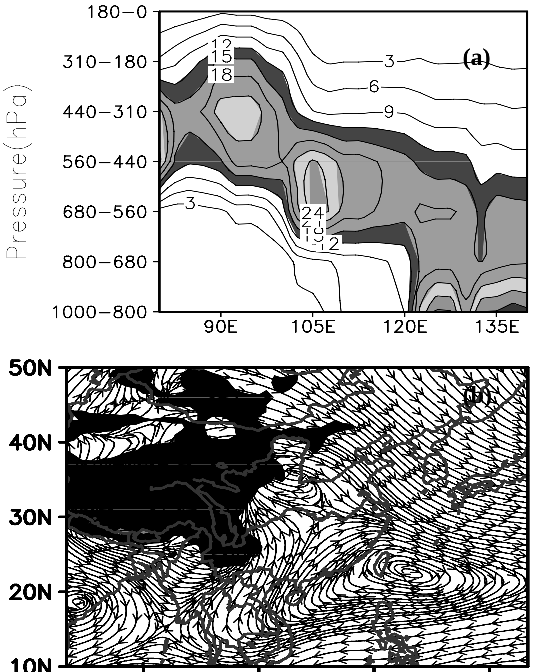


Figure 4. (a) Vertical distributions of cloud cover (%) along 28ºN and (b) streamlines at 850 hPa in February. The shaded area in (b) is the Tibetan Plateau (TP).

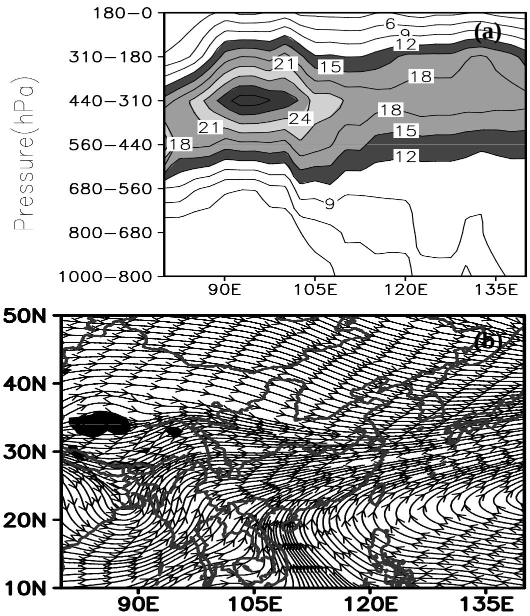


Figure 5. (a) Vertical distributions of cloud cover (%) along 28ºN and (b) streamlines at 500 hPa in June. The shaded area in (b) is the Tibetan Plateau.

Further investigation of the seasonal variation of the vertical cloud distributions shows that the cloud cover matches the divergence very well. Over land, the maximum cloud cover (Figure 6a) occurs at the divergence level (Figure 6b) during both summer and winter. The top height of the maximum cloud cover increases from winter/spring to summer, and decreases from summer/autumn to winter, which agrees well with the changes in the divergence layer throughout the year. From the viewpoint of climatic significance, large-scale cloud cover is considered to be determined by the intensity difference between the divergence in the top troposphere and convergence in the bottom troposphere, or vertical velocity. On the other hand, over the sea, the maximum cloud cover (Figure 7a) also appears in the divergence layer both in summer and winter (Figure 7b), despite a completely different divergence structure compared to that over land. Over the sea, the maximum divergence center during cold seasons occurs near the surface, but its height is similar to that over land during summer, leading to low cloud-top height during cold seasons and high cloud-top heights during warm seasons. Although low-level clouds are considerably underestimated in the ISCCP dataset due to spreads of high-level clouds, especially over Sichuan Basin (where clouds always develop from very low levels to upper levels), the cloud-top pressure is considerably different between land and sea and between summer and winter. The two divergent flows over land and sea also differ. The cloud-top pressure during summer is affected by horizontal wind speed divergence that occurs permanently in the middle troposphere in cold seasons and is only associated with the variation of intensity. The cloud-top pressure during winter is affected by descending flows at lower levels, and the pressure center follows the WPSH from winter to summer, which results in seasonal sensitivity of the cloud-top height.

5 CONCLUSIONS AND DISCUSSIONS

The horizontal and vertical cloud distributions over eastern China are investigated in this study. Our results suggest that the horizontal distribution of the total cloud cover is related to the dynamic effect of the TP, the suppressed effect of the WPSH and the thermodynamic effect of the KC, and that the maximum center of total cloud cover moves along with the summer monsoon, while the presence of various cloud types reflects much more local characteristics. On the other hand, vertical cloud development is limited by the horizontal divergence in the middle troposphere over land (Yu et al.[16]) and by the subsidiary divergence in the lower troposphere over the sea, resulting in continental mid-level clouds and marine low-level clouds during cold seasons. However, due to the similar unstable atmospheric structures, both continental and marine clouds can develop to higher levels during summer than during winter. The vertical velocity may be the most important factor determining the large-scale cloud amount and cloud-top height over eastern China and surrounding seas—a key point to the improvement of cloud simulations in climate models.

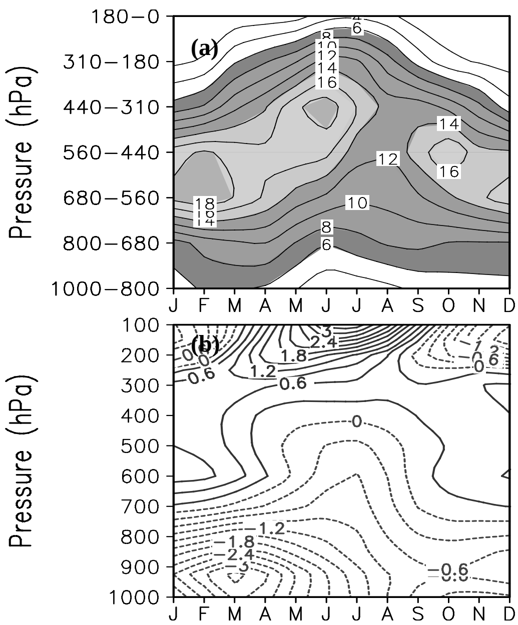


Figure 6. Pressure-seasonal section of (a) cloud cover (%) and (b) divergence (10^6 s^{-1}) averaged in the region 23–32ºN, 102–120ºE. Solid lines denote divergence and dashed lines denote convergence.

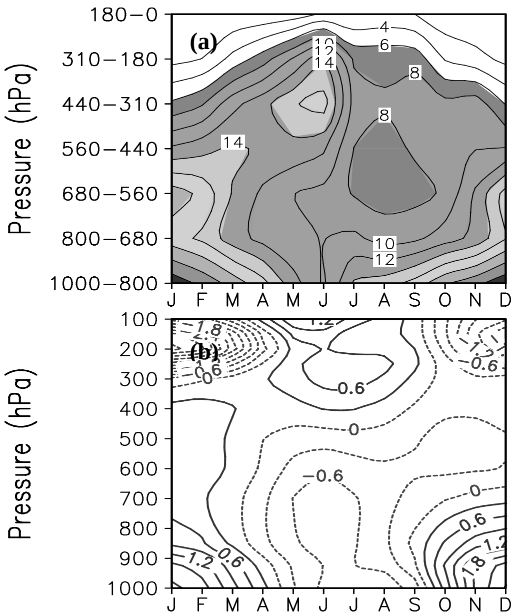


Figure 7. Same as Figure 6 but averaged in the region 23–32ºN, 120–130ºE.

Cloud thickness should not be neglected when describing vertical distribution. However, cloud-top height is difficult to observe from the surface, and satellites cannot retrieve cloud-bottom height because of shielding, especially when multilayer clouds occur. The middle-to-low clouds, especially low clouds, are underestimated in the ISCCP data, and this influences the description of the cloud vertical structure in our work. Fortunately, the CloudSat data (Stephen and Vane[27]), which is directly derived from Earth Science Enterprise (ESE) mission in the early 2000s, can describe the macro and micro parameters of clouds at each vertical level, and this data will be used to disclose more subtle cloud vertical structures in our future research.

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