RESEARCH ARTICLE

Why is there a tilted cloud vertical structure associated with the northward advance of the East Asian summer monsoon

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Abstract
The cloud fraction demonstrates an obvious northward-tilting structure associated with the northward advance of the East Asian summer monsoon. As a follow-up study, this study explores the physical explanation of the tilted structure based on ERA-Interim data. The lower convergence center is located on the northern side of the convective center, and the upper divergence center is located on the southern side of the convective center. This specific atmospheric circulation promotes the formation of the tilted cloud vertical structure. Further study shows that the convective instability layer is thinner, and the convective available potential energy is smaller on the northern side of the convective center, favoring the formation of cumulus and altocumulus clouds in the lower troposphere. Condensation from cumulus convection releases latent heat, enhancing convective activity and generating an abundance of deep convective clouds. As the cloud anvils after deep convective clouds collapse, high clouds accumulate in the upper troposphere and are transported to the southern side of the convective center. Therefore, the observed clouds demonstrate a tilted structure. This study can be used to validate cloud vertical structure simulated by climate and weather models.

KEYWORDS
East Asian summer monsoon, northward advance, tilted cloud vertical structure

1 | INTRODUCTION

Cloud vertical structure (CVS) reveals thermal, dynamic and microphysical processes in clouds and plays a prominent role in climate and weather (Weare, 2000). CVS can directly affect the radiation balance of the Earth–atmosphere system because of high and low clouds with different radiation effects (Hill et al., 2018). CVS may also significantly change the vertical distribution of the atmospheric heating and cooling rate (Mcfarlane et al., 2008; Turner et al., 2018), which directly affects atmospheric circulation and the hydrological cycle (Cao and Zhang, 2017). Additionally, CVS particularly affects the microphysical processes of clouds, influencing the intensity and occurrence of precipitation (Yan et al., 2018). In recent years, with more detailed observation data, the description and physical explanation of CVS have received more attention in climate studies (Jiang et al., 2012; Klein et al., 2013; Xie et al., 2017; Yamauchi et al., 2018).

The East Asian summer monsoon (EASM) usually advances stepwise from south to north (Ding and Chan, 2005). During the northward advance of the EASM, Sun et al. (2019) found that high clouds (HCs) occur in the upper troposphere and are located behind the convective center by...
approximately four degrees of latitude based on the CloudSat 2B-CLDCLASS-LIDAR product. Deep convective (DC) clouds are located near the convective center and can be considered as a reference for the precipitation center. Cumulus (Cu) and altocumulus (Ac) clouds mostly appear in the lower troposphere and guide the convective center by nearly three degrees of latitude. Thus, the clouds demonstrate an obvious tilted structure in the vertical direction. However, the physical explanation of this tilted structure is still an open question. Determining this physical explanation can improve the forecasting abilities of the EASM and precipitation and may guide researchers to further study the relationship between clouds and the EASM. Therefore, the purpose of this study focuses on the physical explanation of the tilted CVS.

2 | DATA AND METHODS

ERA-Interim dataset is used in this study, which is a global atmospheric reanalysis data released by the European Centre for Medium-Range Weather Forecasts (Dee et al., 2011). ERA-Interim dataset can describe the temperature, wind, humidity and their diurnal variations in East Asia better than other reanalysis data in terms of the representativeness of the atmospheric background (Bao and Zhang, 2013; Chen et al., 2014). Considering the golden period of the CloudSat dataset, ERA-Interim dataset from May to September 2007–2010 is used in this study and includes these variables: cloud fraction, geopotential height, wind vector, vertical velocity, specific humidity, relative humidity and air temperature.

As a large-scale circulation system, the EASM affects the amount and intensity of summer precipitation in the EASM region (110°–120°E, 22–40°N). An important characteristic of the EASM is that it advances from south to north. Each northward-advancing EASM is called a northward-advancing EASM event, which lasts approximately 5 days. Sun et al. (2019) characterized the EASM by precipitation and identified 22 northward-advancing EASM events using the extended empirical orthogonal function method. Then, these 22 events were composited into one event in time. In addition, the northward advance of the EASM is usually accompanied by a stronger convective weather system, and the corresponding precipitation is dominated by convective precipitation (Chen et al., 2017). Thus, the location of maximum precipitation averaged between 110°E and 120°E is regarded as the convective center.

Vorticity (vor) and divergence (div) can well describe the dynamic characteristics of the atmosphere. Atmospheric diabatic heating and moisture can be diagnosed using the apparent heat source \( Q_1 \) and apparent moisture sink \( Q_2 \) (Yanai et al., 1973), which can be calculated as:

\[
\text{vor} = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} \\
\text{div} = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\\
Q_1 = C_p \left( \frac{\partial T}{\partial t} + u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} + \omega \frac{\partial T}{\partial p} - \kappa \omega T \right), \\
Q_2 = -L \left( \frac{\partial q}{\partial t} + u \frac{\partial q}{\partial x} + v \frac{\partial q}{\partial y} + \omega \frac{\partial q}{\partial p} \right),
\]

where \( u \) and \( v \) represent horizontal winds, \( \omega \) represents vertical pressure velocity (Pa/s), \( T \) represents temperature, \( q \) represents specific humidity, \( t \) represents time, \( p \) represents air pressure, \( \kappa \) is a constant (0.286), \( C_p \) represents the air specific heat capacity at a constant pressure and \( L \) represents the latent heat of water condensation.

Each variable (e.g., div and \( Q_1 \)) in every three-dimensional grid is calculated using daily ERA-Interim data first, and the daily anomaly in every grid is obtained by subtracting the climatic average from the original value. Next, the daily composite anomaly in every grid is composited in time based on the 22 northward-advancing EASM events identified by Sun et al. (2019), and the daily composite anomaly in each grid during strong periods of the northward advance of the EASM (i.e., from the northward-advancing day to the third day after the advance) is composited again in space based on the location of the daily convective center.

![Composite cloudiness anomalies of ERA-Interim (shaded; unit: %) and CloudSat (contours; unit: %) based on the daily convective centers during the strong periods of the northward advance of the EASM. The values of the x-axis represent the relative distance to the convective center in degrees of latitude, where negative values represent distances south of the convective center and positive values represent distances north of the convective center.](image-url)
Finally, the anomaly relative to the convective center is obtained by averaging the composited anomalies along the zonal direction between 110°E and 120°E. The distribution of cloudiness anomaly is shown in Figure 1, and the cloudiness anomaly of CloudSat is also shown in Figure 1 using contours. Both CloudSat and ERA-Interim show that there is a belt of cloudiness extending northward at an altitude of 10 km (Figure 1). Most importantly, despite some differences in the lower atmosphere below 3 km, the cloudiness anomaly of ERA-Interim is roughly consistent with that of CloudSat, both of which exhibit an obvious tilted structure in the vertical direction. Therefore, ERA-Interim data can be used reliably to explain the tilted CVS associated with the northward advance of the EASM.

3 | DYNAMIC EXPLANATION

Associated with the northward advance of the EASM, the meridional winds converge in the lower troposphere, and the convergence center is located approximately 4°N of the convective center (Figure 2a). Water vapor originating from the South China Sea and Bay of Bengal humidifies the atmosphere in the southern part of the EASM region. The high level of relative humidity and strong convergent airflow in the lower troposphere create circulation conditions for the formation of clouds and rain. The meridional winds diverge in the upper troposphere, and the divergence center in the upper troposphere lags behind the convergence center in the lower troposphere, as shown in Figure 2a. The larger positive meridional wind anomalies in the lower troposphere promote the advance of the northward-advancing EASM, and the larger negative meridional wind anomalies in the upper troposphere convey the HC clouds southward. Therefore, vertical shear of the meridional wind is conducive to the formation of the tilted CVS. The large value area of vertical velocity connects the lower convergence center with the upper divergence center and presents a tilted structure in the vertical direction (Figure 2b). The maximum vertical velocity is located in the middle troposphere above the convective center, with a maximum value of more than $1.2 \times 10^{-2}$ m/s. The strong upward motion near the convective center is conducive to the formation of DC clouds. Therefore, an abundance of DC clouds appears in the convective center.

The configuration of the three-dimensional wind field gives rise to the lower troposphere north of the convective center a large positive vorticity anomaly (Figure 2c), where strong convergent airflow facilitates the condensation of water vapor into clouds (Figure 2d). A thicker layer of positive vertical velocity anomalies with strong upward motion facilitates the formation of DC clouds and transports water vapor into the upper troposphere (Figure 2b). In the upper...
troposphere and south of the convective center, with negative vorticity anomalies (Figure 2c), a strong divergent airflow (Figure 2d) results in the divergence and transport of clouds to the southern side of the convective center (Figure 2a). Overall, associated with the northward advance of the EASM, the lower convergence center is located on the northern side of the convective center, and the upper divergence center is located on the southern side of the convective center. This specific atmospheric circulation promotes the formation of the tilted CVS.

4 | THERMODYNAMIC EXPLANATION

The tilted CVS is composed of different spatial positions of various cloud types (Sun et al., 2019). Different cloud types are produced under different dynamic and thermodynamic conditions. The thermodynamic explanation can further analyze the generation environment for different cloud types. Since CVS tilts in the vertical direction, therefore, two points (6.5 degrees north and south of the convective center) were selected as the front and tail ends of clouds to explore the reason for the tilted CVS. Skew T–log P diagrams of these two points and the convective center are shown in Figure 3. The blue and black curves denote the vertical profiles of the dew point temperature and ambient temperature, respectively. The smaller the difference is between the two curves at a given altitude, the wetter the air. An air parcel near the surface may first undergo dry adiabatic rise followed by wet adiabatic rise until it reaches the lifting condensation level. The wet adiabatic motion takes into account condensation and rain processes. The red curves in Figure 3 describe the trajectories of an air parcel rising from the surface when the air parcel temperature is greater than the ambient temperature. At this time, the air parcel can move upward by buoyancy. The area enclosed by the red and black curves represents the convective available potential energy (CAPE). Associated with the northward advance of the EASM, the convective instability layer is thinner on the northern side of the convective center (Figure 3c). The relatively dry environment, with a smaller CAPE of 350 J, is not conducive to the formation of DC clouds, but it is conducive to the formation of shallow clouds, such as Cu and Ac clouds (Li and Zhang, 2016). In the convective center, the convective instability layer extends from near the surface up to 14 km, and the CAPE increases to 1824 J. The entire atmosphere is wet (Figure 3b), and DC clouds readily occur. On the southern side of the convective center, the surface is wet immediately after rainfall, dry and cold air may intrude into the middle troposphere (the difference between ambient temperature and dew point temperature is large), and the CAPE increases to 4,090 J (Figure 3a). Although the CAPE value is very large, there is no vertical velocity (Figure 2b), therefore, no convection occurs. The wetter air above 12 km is beneficial for HC cloud maintenance. Thus, an abundance of HC clouds exists in the upper troposphere on the southern side of the convective center.

The anomalies of \( Q_1 \) and \( Q_2 \) are shown in Figure 4. On the northern side of the convective center, the positive anomaly values of \( Q_1 \) are similar to those of \( Q_2 \), indicating that the atmosphere is warmed, and heat mainly originates from the condensation process. The maximum value of \( Q_2 \) is located in the lower troposphere, leading the convective center by nearly 3 degrees of latitude (Figure 4b), which is consistent with the location of maximum Cu and Ac clouds (Sun et al., 2019). The large value area of \( Q_2 \) is also consistent with those of Cu and Ac clouds, indicating that abundant water vapor condenses into Cu and Ac clouds and warms the lower atmosphere on the northern side of the convective center. The heated air parcel gains buoyancy and begins to move upward. Precipitation may occur due to more
water vapor condensing into clouds accompanied by ascending motion. The large value area of $Q_1$ corresponds to that of DC clouds (Figure 4a), which is a cloud type that is highly developed and prone to precipitation. Near the convective center, positive $Q_1$ and $Q_2$ anomalies occur throughout the troposphere. $Q_1$ is less than $Q_2$ in the lower troposphere and greater than $Q_2$ in the middle troposphere. This vertical distribution indicates that precipitation is dominated by convective precipitation and that most of the heat comes from the latent heat released by cumulus convective condensation. This distribution also indicates that convective activity is vigorous during this period (Johnson et al., 2016).

Another maximum $Q_1$ is located in the upper troposphere $4^\circ$S of the convective center (Figure 4a), corresponding to the location of maximum HC clouds. Similar to HC clouds, this large value area extends to $8^\circ$S of the convective center. HC is a cloud type with the greatest cloudiness anomaly, but the corresponding positive $Q_2$ anomaly is very small. When $Q_1$ is especially large and $Q_2$ is small enough to be negligible, a dry convection process is implied, and $Q_1$ originates from convective transport (Chen et al., 2015). In other words, HC clouds here are not completely generated from perturbation condensation but rather from the cloud anvils after DC clouds collapse.

The distinct vertical configuration of two maximum cores of $Q_1$ in the upper and lower atmospheres and one maximum core of $Q_2$ in the lower atmosphere correspond to different cloud types. This layout also describes the formation and development of clouds accompanied by the northward-advancing EASM. On the northern side of the convective center, water vapor condenses into Cu and Ac clouds in the lower troposphere and releases latent heat to warm the atmosphere. Clouds continue to develop in the vertical direction, and cumulus convection condensation releases more latent heat, enhancing convective activity. Abundant DC clouds is accompanied by strong convective activity. DC clouds bring more precipitation and correspond to the convective center. As the anvils after DC clouds collapse, HC clouds accumulate in the upper troposphere and are transported to the southern side of the convective center. These clouds undergo the processes of formation and development from the lower to upper troposphere, demonstrating a tilted structure.

5 CONCLUSIONS AND DISCUSSION

A marked tilted vertical structure of the cloud water content has been found associated with the northward propagation of the Indian summer monsoon (Jiang et al., 2011). This tilted structure also exists in the EASM region (Sun et al., 2019). Further study based on ERA-Interim data show that associated with the northward advance of the EASM, the lower convergence center is located on the northern side of the convective center, while the upper divergence center is located on the southern side of the convective center. This specific atmospheric circulation promotes the formation of the tilted CVS. The convective instability layer is thinner, and the CAPE is smaller on the northern side of the convective center, which is conducive to the formation of Cu and Ac clouds. The convective instability layer is thicker, and the entire atmosphere is wetter near the convective center, favoring the production of DC clouds. On the southern side of the convective center, wetter air above 12 km is beneficial to the maintenance of HC clouds. The water vapor condenses into Cu and Ac clouds and warms the lower atmosphere on the northern side of the convective center. Cumulus convection condensation releases more latent heat, enhancing convective activity. An abundance of DC clouds is accompanied by strong convective activity.

![FIGURE 4 Same as Figure 1 but for (a) Q1 and (b) Q2 anomalies (unit: J kg$^{-1}$ s$^{-1}$)](image-url)
the lower to upper troposphere, demonstrating a tilted structure.

East Asia is the region with the greatest simulated errors in global climate models. These simulated errors come from the uncertainties of clouds in climate models. Nearly all Coupled Model Intercomparison Project Phase 5 (CMIP5) models cannot reproduce the characteristics of clouds in East Asia (Cesana and Chepfer, 2012; Zhang and Li, 2013). The EASM is the most important weather system in East Asia during the summer, and it inevitably affects CVS. Associated with the northward advance of the EASM, the clouds demonstrate a northward tilted structure (Sun et al., 2019). As a follow-up study, exploring the physical explanation of the tilted CVS can improve the understanding of CVS in East Asia. This study can be used to validate CVS simulated by climate and weather models and may guide researchers to further study the relationship between clouds and the EASM.

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REFERENCES

Bao, X. and Zhang, F. (2013) Evaluation of NCEP–CFSR, NCEP–NCAR, ERA-Interim, and ERA-40 reanalysis datasets against independent sounding observations over the Tibetan plateau. Journal of Climate, 26(1), 206–214. https://doi.org/10.1175/JCLI-D-12-00056.1.
Cao, G.Y. and Zhang, G.J. (2017) Role of vertical structure of convective heating in MJO simulation in NCAR CAM5.3. Journal of Climate, 30, 7423–7439. https://doi.org/10.1175/JCLI-D-16-0913.1.
Cesana, G. and Chepfer, H. (2012) How well do climate models simulate cloud vertical structure? A comparison between CALIPSO-GOCCP satellite observations and CMIP5 models. Geophysical Research Letters, 39, L20803. https://doi.org/10.1029/2012GL053153.
Chen, G., Iwasaki, T., Qin, H. and Sha, W. (2014) Evaluation of the warm-season diurnal variability over East Asia in recent reanalyses JRA-55, ERA-Interim, NCEP CFSR, and NASA MERRA. Journal of Climate, 27(14), 5517–5537. https://doi.org/10.1175/JCLI-D-14-00005.1.
Chen, J.H., Wu, X.Q., Yin, Y. and Xiao, H. (2015) Characteristics of heat sources and clouds over eastern China and the Tibetan plateau in boreal summer. Journal of Climate, 28(18), 7279–7296. https://doi.org/10.1175/JCLI-D-14-00859.1.
Chen, T.C., Tsay, J.D. and Matsumoto, J. (2017) Interannual variation of the summer rainfall center in the South China Sea. Journal of Climate, 30(19), 7909–7931. https://doi.org/10.1175/JCLI-D-16-0889.1.
Dee, D.P., Uppala, S.M., Simmons, A.J., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M.A., Balsamo, G., Bauer, P., Bechtold, P., Beljaars, A.C.M., van de Berg, L., Bidlot, J., Bormann, N., Delsol, C., Dragani, R., Fuentes, M., Geer, A.J., Haimberger, L., Healy, S.B., Hersbach, H., Hölm, E.V., Isaksen, L., Källberg, P., Köhler, M., Matricardi, M., McNally, A. P., Monge-Sanz, B.M., Morcrette, J.J., Park, B.K., Peubey, C., de Rosnay, P., Tavolato, C., Thépaut, J.N. and Vitart, F. (2011) The ERA-Interim reanalysis: configuration and performance of the data assimilation system. Quarterly Journal of the Royal Meteorological Society, 137, 553–597. https://doi.org/10.1002/qj.828.
Ding, Y.H. and Chan, J.C.L. (2005) The East Asia summer monsoon: an overview. Meteorology and Atmospheric Physics, 89, 117–142. https://doi.org/10.1007/s00703-005-0125-z.
Hill, P.G., Allan, R.P., Chiu, J.C., Bodosi-Salcendo, A. and Knippertz, P. (2018) Quantifying the contribution of different cloud types to the radiation budget in southern West Africa. Journal of Climate, 31(13), 5273–5291. https://doi.org/10.1175/JCLI-D-17-0586.1.
Jiang, J.H., Su, H., Zhai, C., Perun, V.S., del Genio, A., Nazarenko, L. S., Donner, L.J., Horowitz, L., Seman, C., Cole, J., Gettelman, A., Ringer, M.A., Rostamian, L., Jeffrey, S., Wu, T., Brient, F., Dufresne, J.-L., Kawash, H., Koshuro, T., Watanabe, M., Lécuyer, T. S., Volodin, E.M., Iversen, T., Drange, H., Esquiva, M.D.S., Read, W.G., Waters, J.W., Tian, B., Teixeira, J. and Stephens, G.L. (2012) Evaluation of cloud and water vapor simulations in CMIP5 climate models using NASA “A-Train” satellite observations. Journal of Geophysical Research, Atmospheres, 117, D14105. https://doi.org/10.1002/jgrd.50141. Johnson, R.H., Ciesielski, P.E. and Rickenbach, T.M. (2016) A further look at Q1 and Q2 from TOGA COARE. Geophysical Monographs, 156, 1.1–1.12. https://doi.org/10.1002/9781118639065.ch1.
Klein, S.A., Zhang, Y., Zelinka, M.D., Pincus, R., Boyle, J. and Gleckler, P.J. (2013) Are climate model simulations of clouds improving? An evaluation using the ISCCP simulator. Journal of Geophysical Research. Atmospheres, 118(10), 1329–1342. https://doi.org/10.1002/jgrd.50141.
Li, Y.Y. and Zhang, M.H. (2016) Cumulus over the Tibetan plateau in the summer based on CloudSat observations and ERA-Interim reanalysis. Climate Dynamics, 36, 2219–2232. https://doi.org/10.1007/s00382-010-0853-8.
Sun, G.R., Li, Y.Y. and Lu, J. (2019) Cloud vertical structures associated with northward advance of the East Asian summer monsoon. Atmospheric Research, 215, 317–325. https://doi.org/10.1016/j.atmosres.2018.09.013.
Turner, D.D., Shupe, M.D. and Zwink, A.B. (2018) Characteristic atmospheric radiative heating rate profiles in Arctic clouds as observed at Barrow, Alaska. *Journal of Applied Meteorology and Climatology*, 57(4), 953–968. https://doi.org/10.1175/JAMC-D-17-0252.1.

Weare, B.C. (2000) Insights into the importance of cloud vertical structure in climate. *Geophysical Research Letters*, 27(6), 907–910. https://doi.org/10.1029/1999GL011214.

Xie, F., Xue, W., Li, L.J., Zhang, T., Wang, B. and Xu, S. (2017) Quantification of the responses of equatorial Pacific surface wind to uncertain cloud-related parameters in GAMIL2. *Atmospheric Science Letters*, 18, 458–465. https://doi.org/10.1002/asl.789.

Yamauchi, A., Kawamoto, K. and Okamoto, H. (2018) Differences in the fractions of ice clouds between eastern and western parts of Eurasian continent using CALIPSO in January 2007. *Atmospheric Science Letters*, 19(3), 807. https://doi.org/10.1002/asl.807.

Yan, Y.F., Wang, X.C. and Liu, Y.M. (2018) Cloud vertical structures associated with precipitation magnitudes over the Tibetan plateau and its neighboring regions. *Atmospheric and Oceanic Science Letters*, 11(1), 44–53. https://doi.org/10.1080/16742834.2018.1395680.

Yanai, M., Esbensen, S. and Chu, J.H. (1973) Determination of bulk properties of tropical cloud clusters from large-scale heat and moisture budgets. *Journal of the Atmospheric Sciences*, 30, 611–627. https://doi.org/10.1175/1520-0469(1973)030,0611:DOBPORT.2.0.CO;2.

Zhang, Y. and Li, J. (2013) Shortwave cloud radiative forcing on major stratus cloud regions in AMIP-type simulations of CMIP3 and CMIP5 models. *Advances in Atmospheric Sciences*, 30(3), 884–907. https://doi.org/10.1007/s00376-013-2153-9.

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