An evaluation of cloud vertical structure in three reanalyses against CloudSat/cloud-aerosol lidar and infrared pathfinder satellite observations

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Abstract
Cloud fraction is a great source of uncertainty in current models. By utilizing cloudiness fields from CloudSat/cloud-aerosol lidar and infrared pathfinder satellite observations (CALIPSO), the three widely used reanalyses including the Interim ECWMF Re-Analysis (ERA-Interim), Japanese 55-yr Reanalysis (JRA-55), and the Modern-Era Retrospective Analysis for Research and Applications (MERRA-2) are assessed for their representation of cloudiness. Results show all three reanalyses can basically capture the cloud horizontal pattern and vertical structure as in CloudSat/CALIPSO, yet the magnitude is markedly underestimated, in particular for JRA-55 and MERRA-2. Besides, all reanalyses struggle to simulate the mid-level clouds at low latitudes. In addition to these common deficiencies, the three reanalyses have their own distinctive behaviors and differ from one another. While ERA-Interim and JRA-55 show better performance for low-level clouds in the tropics, they exhibit remarkable underestimation for high-level clouds. On the contrary, MERRA-2 succeeds in representing high-level clouds but dramatically underestimates the low and mid-level clouds at low latitudes. As a measure of subgrid-scale variability of moisture, the derived “critical relative humidity ($RH_c$)” from CloudSat/CALIPSO exhibits distinctive vertical structures at different latitudes, it is thus speculated that poor specification or parameterization of $RH_c$ is responsible for these bias behaviors.

KEYWORDS
cloud fraction, cloud vertical structure, cloudiness parameterization, CloudSat/CALIPSO, reanalysis products

1 INTRODUCTION
Clouds are of fundamental importance in modulating Earth’s energy budget and hydrological cycle (Stephens, 2005). Over the past decades, great efforts have been devoted to improving cloud simulations in weather and climate models, yet its parameterization still remains a vast challenge and contributes to one of the largest uncertainties in climate projections (Andrews et al., 2012). Clouds typically stratify in the vertical, and different structures can lead to striking distinctions in cloud-radiative forcing (Weare, 2000). Low-level clouds have a net cooling effect via enhanced solar...
reflection, while high-level clouds commonly have a net warming effect by preventing thermal emission from outgoing. Cloud microphysical processes such as collision and sedimentation are affected by cloud vertical structure as well, which can then cause an influence on precipitation (Jakob and Klein, 1999). Therefore, the knowledge of cloud vertical structure is important for both cloud radiative transfer and microphysical processes.

However, such data of global average is unavailable prior to the launch of NASA CloudSat/CALIPSO, which joined the A-Train in April 2006. Passive sensors such as those utilized by the International Satellite Cloud Climatology Project (ISCCP) detect clouds based on the integrated effect of properties of the whole atmospheric column, thus making it impossible to retrieve clouds layer by layer (Rossow and Schiffer, 1999). Field campaigns with active sensors such as surface cloud profiling radar (CPR) can provide cloud vertical structure (Dong et al., 2006), yet they cannot fully sample the global variability in clouds, especially over the oceans. By carrying a 94 GHz cloud-profiling radar on board, CloudSat can provide vast amounts of unprecedented information of cloud vertical properties on a global scale. While the radar on CloudSat can penetrate into thick clouds, the lidar on CALIPSO is capable of detecting weak vapor condensation and thus optically thin cirrus clouds (Stephens et al., 2002). Thence, a combination of radar and lidar instruments can make full use of their complementary capabilities for better cloud detection. Over the past decade, CloudSat/CALIPSO have been widely used for cloud investigation and model evaluation (Luo et al., 2011; Yan et al., 2016; Yan et al., 2017; Yamauchi et al., 2018). In the cloud modeling community, a great challenge remains on how to well represent subgrid-scale cloud condensation and fractional cloudiness (Quaas, 2012; Wang et al., 2015). Almost all climate models suffer from the poor cloudiness simulation (Zhang et al., 2005). The situation is not getting much better for numerical weather models in spite of finer resolution and advanced assimilation system. For example, Stengel et al., (2018) points out that the total cloud cover in ERA-Interim is generally too low nearly everywhere on the globe except in polar-regions. Naud et al., (2014) found cloud fraction is slightly underestimated over the southern oceans for ERA-Interim, but severely underestimated for MERRA. In this study, we utilize CloudSat/CALIPSO to comprehensively evaluate cloudiness fields in three widely used reanalysis products, with the aim to point out their common deficiency as well as distinct behaviors. By diagnosing the so-called “critical relative humidity ($RH_c$)” from CloudSat/CALIPSO and auxiliary ECMWF products, it explains why cloudiness biases occur and sheds lights on potential improvement. The paper is organized as follows. Section 2 describes the data and method. These are followed by a critical evaluation of cloud fraction in reanalyses against CloudSat/CALIPSO. Section 4 discusses the possible cause of cloudiness biases and potential way for future improvement. The last section gives a summary.

2 | DATA AND METHOD

CloudSat/CALIPSO generates 37,081 profiles along each orbit and 125 bins for each profile. To determine whether a pixel is cloudy or not, following Barker (2008), we use a combination of fields of $CPR\_Cloud\_mask$ and $Radar\_Reflectivity$ fields from 2B-GEOPROF and $CloudFraction$ from 2B-GEOPROF-LIDAR. The criteria are as follows. Each volume is classified as a cloud if one of the two conditions are satisfied: (a) $CPR\_Cloud\_mask \geq 20$ and $Radar\_Reflectivity \geq -30$ dBz or (b) $CloudFraction \geq 99\%$. We take the horizontal resolution of 2.5 × 2.5° and vertical resolution of 25 hPa as the standard grid size. The cloud fraction is then defined as the ratio of the number of cloudy pixels to that of total pixels within a grid at each layer. Similarly, the total cloud cover is determined in terms of the ratio of the number of cloudy columns that contain as least one cloudy pixel in the vertical dimension to that of the total columns within each grid. In addition to CloudSat/CALIPSO, the monthly ISCCP-D2 dataset is also used as a guiding reference (Rossow and Schiffer, 1999).

The three reanalyses to be assessed are ERA-Interim from the European Centre for Medium-Range Weather Forecasts (ECMWF) (Dee et al., 2011), Japanese 55-year Reanalysis (JRA-55) (Ebita et al., 2011), and the Modern-Era Retrospective Analysis for Research and Applications (MERRA-2) (Gelaro et al., 2017), which span the same period from 2007 to 2010 to accommodate CloudSat/CALIPSO missions. The cloudiness fields to be assessed are 3D cloud vertical structure ($CF_{3D}$), and total cloud cover ($CF_T$). These variables are processed to the same horizontal resolution as gridded CloudSat/CALIPSO. Auxiliary variables such as relative humidity ($RH$) from ECMWF products are used for $RH_c$ diagnosis purposes. For brevity, the main characteristics of all above data are listed in Table 1.

3 | RESULTS AND ANALYSIS

Firstly, we compare the simulation of total cloud cover in reanalysis products against CloudSat/CALIPSO and ISCCP-D2. Figure 1 shows the global distribution of $CF_T$ for CloudSat/CALIPSO and the differences between CloudSat/CALIPSO and other datasets. Positive (negative) values mean that CloudSat/CALIPSO provides larger (smaller) $CF_T$ than a given dataset. From the top to the bottom are for CloudSat/CALIPSO, ISCCP-D2, ERA-Interim, JRA-55, and...
MERRA-2. Consistent with Luo et al. (2017), the CFT from CloudSat/CALIPSO is slightly larger than ISCCP-D2 at low latitudes, presumably because CloudSat/CALIPSO detects more broken cumulus clouds and high-level cirrus clouds (Sassen and Wang, 2008; Sassen et al., 2008). Overall, all three reanalyses can well reproduce the same spatial pattern as CloudSat/CALIPSO, for example, cloudiness centers along storm tracks, and in middle-high latitude of the southern hemisphere. The clouds do not show obvious seasonal change except in the tropics, which move in pace with the seasonal shift of the global monsoon systems and the Intertropical Convergence Zone (ITCZ). The biases in magnitude are however considerable. All reanalyses underestimate CFT in comparison with CloudSat/CALIPSO, especially for JRA-55 and MERRA-2, where the underestimation reaches as high as 30% over northern hemisphere lands. Overall, the ERA-Interim shows the most resemblance to CloudSat/CALIPSO among all three reanalyses, despite slight underestimations over land surfaces. As will be shown next, the bias in CFT to some extent can be attributed to the bias in 3D fractional cloudiness (CF$_{3D}$).

Figure 2 gives the zonally averaged cloud vertical structure from CloudSat/CALIPSO and the three reanalyses. For both summer and winter, CloudSat/CALIPSO exhibits pronounced cloudiness in lower troposphere in middle and high latitudes, which corresponds to large CFT in Figure 1. In the tropics, high-level clouds above 400 hPa shift across the equator from June-August (JJA) to December-February (DJF), in accordance with the seasonal moving of ITCZ. Meanwhile, due to the prevailing large-scale subsidence controlled by the descending branch of the Hadley cells, few clouds are found to maintain over subtropical zones, which is mainly composed of trade cumuli. Compared with CloudSat/CALIPSO, cloud fraction in all reanalyses is clearly underestimated in spite of similar vertical structures, which is in line with the underestimation in CFT. Moreover, all

**TABLE 1** List of datasets and variables

| Datasets         | Period       | Resolution             | Variables                                                          |
|------------------|--------------|------------------------|----------------------------------------------------------------------|
| CloudSat/CALIPSO | 2007/01–2010/12 | 2.5° × 2.5°, 40 levels | CF$_T$, CF$_{L}$, CF$_{H}$, CF$_{3D}$                               |
| ISCCP-D2         | 2007/01–2010/12 | 2.5° × 2.5°, —        | CFT                                                                |
| ERA-Interim      | 2007/01–2010/12 | 1° × 1°, 37 levels     | CF$_T$, CF$_{3D}$, RH                                               |
| JRA-55           | 2007/01–2010/12 | 1.25° × 1.25°, 27 levels | CF$_T$, CF$_{3D}$, RH                                               |
| MERRA-2          | 2007/01–2010/12 | 0.5° × 0.625°, 42 levels | CF$_T$, CF$_{3D}$, RH                                               |

**FIGURE 1** Global distribution of total cloud cover from (a–c) CloudSat/CALIPSO and the differences between CloudSat/CALIPSO and (d–f) ISCCP, (g–i) ERA-Interim, (j–l) JRA-55, and (m–o) MERRA-2 datasets at different seasons. Positive (negative) values mean that CloudSat/CALIPSO provides a larger (smaller) total cloud fraction than for a given dataset (unit: %)
reanalyses fail to reproduce vertical cloud structures in the tropics that extend from the surface up to 200 hPa. Again, ERA-Interim is closest to CloudSat/CALIPSO, although considerable biases are still observed. While JRA-55 exhibits comparable performance as ERA-Interim for low-level clouds in the tropics, it reveals apparent underestimation for high-level clouds. On the contrary, MERRA-2 succeeds in representing high-level clouds, but dramatically underestimates the low and mid-level clouds at low latitudes.

The stratocumulus and shallow cumulus clouds have important implications on cloud feedbacks in climate models (Stephens, 2005; Zhang et al., 2013). The cloud transition, referring to the transition from stratocumulus to shallow cumulus and to deep convective clouds, remains the subject of numerous studies (Teixeira et al., 2011; Zhang et al., 2013). Cloud transitions along the Global Energy and Water Cycle Experiment Cloud System Study/Working Group on Numerical Experimentation (GCSS/WGNE) Pacific Cross-Section Intercomparison (GPCI) transect and seasonal evolutions over the southeastern equatorial Pacific (SEP) are two cases of such kind (Yu et al., 2017). Figure 3 presents cloud transition along the GPCI transect and seasonal evolution over the SEP region in three reanalyses and CloudSat/CALIPSO. The GPCI cross-section connects the two locations of 1°S, 173°W and 35°N, 125°W. Along the GPCI transect, low-level clouds decrease while high-level cloud increase with increasing sea surface temperature (SST) from the west coast of California to the equator. Similarly, over

**FIGURE 2** Zonally averaged cloud vertical structure from (a–c) CloudSat/CALIPSO, (d–f) ERA-Interim, (g–i) JRA-55, and (j–l) MERRA-2 datasets at different seasons (unit: %)
the SEP region, low-level clouds decrease while high-level cloud increases from JJA to DJF. In general, all three reanalyses can basically capture the cloud transition along the GPCI transect and over the SEP region, yet they show their own distinctive characteristics. Low-level clouds to the west of California are well reproduced in ERA-Interim, whereas only marginally found in JRA-55 and MERRA-2. High-level clouds in the tropics are well represented in MERRA-2 but remain significantly underestimated in ERA-Interim and JRA-55. For clouds over the SEP region, all reanalyses exhibit significant underestimation throughout the troposphere. The low and mid-level clouds in the tropics are dramatically underestimated in MERRA-2, and to a lesser degree in JRA-55 and ERA-Interim. High-level clouds in MERRA-2 are somewhat overestimated, whereas moderately underestimated in JRA-55 and ERA-Interim. The bias characteristics along GPCI transect and over the SEP region are in agreement with those found in Figure 2, suggesting these clouds are potentially representative of clouds globally.

Cloud simulation in East Asia has always been a great challenge (Wang et al., 2004; Zhang and Li, 2013). According to the underlying topography, we divide East Asia into three regions in Figure 4a: the Tibetan Plateau above 3 km (TP, 25°–35°N, 90°–103°E), East China (EC, 25°–35°N, 110°–120°E), and Western North Pacific (WNP, 20°–30°N, 125°–135°E). The monthly mean cloud fraction
over these regions from CloudSat/CALIPSO and the three reanalyses are shown in Figure 4b–m. Over the TP region, large cloudiness is mainly concentrated between 600 and 200 hPa and reaches its maximum in summer. Over the EC region, clouds spread throughout the troposphere and show clear seasonal variation, with more clouds produced in summer and less in winter. The vertical extension of clouds from lower troposphere to an upper high level with seasonal evolution is clearly observed. Over the WNP region, low-level clouds prevail in winter, while high-level clouds dominate in summer. When compared with CloudSat/CALIPSO, all reanalyses fail to reproduce clouds around 400–600 hPa over the TP region, with the location too low for ERA-Interim and JRA-55 whereas too high for MERRA-2. ERA-Interim and
JRA-55 basically capture the cloud seasonal variation over EC and WNP regions, yet the magnitude is significantly underestimated for JRA-55 and to a lesser degree for ERA-Interim. MERRA-2 underestimates low and mid-level clouds in winter but overestimates high-level clouds in summer. Moreover, MERRA-2 fails to reproduce the tilting structure of clouds from January to July.

4 | DISCUSSIONS

The reason why cloudiness biases occur in reanalyses touches the basis of cloudiness parameterization in general circulation models (GCMs). For the majority of models at present, cloud fraction at each level is diagnosed either by an empirical RH-based formula, or a PDF-based statistical scheme. The key to cloudiness parameterization relies on how to properly account for the subgrid-scale variability of moisture (Tompkins, 2003), which is usually measured by “critical relative humidity ($RH_c$)” (Quaas, 2012) and expressed as

$$RH_c = 1 - \frac{1 - \overline{RH}}{(1 - CF_{3D})^2}$$

for $0 < CF_{3D} < 1$, where $\overline{RH}$ denotes grid-mean relative humidity. By utilizing $CF_{3D}$ from CloudSat/CALIPSO and $\overline{RH}$ from auxiliary ECMWF products, we derive the averaged $RH_c$ at different latitudes for the observation, which is shown in Figure 5, with its SD overlaid in each subplot. At low and middle latitudes, the observational $RH_c$ first decreases with altitude and then increases upward. At high latitude, the observed $RH_c$ decreases with altitude in the upper troposphere, producing a second peak around 300 hPa. It is thus inappropriate to use one fixed $RH_c$ profile everywhere as in many previous studies (Lohmann and Roeckner, 1996; Quaas, 2012). The specification or parameterization of $RH_c$ should accurately account for both horizontal and vertical variations. In Figure 5 we also overlay the $RH_c$ profiles for the three reanalyses, which to some extent measure the subgrid-scale variability of moisture in models. Overall, the $RH_c$ profiles in reanalyses are larger than the observation, especially at low and middle latitudes. The $RH_c$ profiles for ERA-Interim and JRA-55 show more resemblance to the observation from surface up to 300 hPa, while the $RH_c$ profiles for MERRA-2 exhibit comparable and even smaller value than the observed $RH_c$ in the upper atmosphere. Note the “observed” $RH_c$ is not perfect, as it relies on $\overline{RH}$ from ECMWF profiles. This also explains why $RH_c$ in ERA-Interim shares more resemblance to the observation. The biases in $RH_c$ profiles are consistent with the biases in cloud fraction. As implied in Equation (1), a large (small) value of $RH_c$ typically leads to an underestimation (overestimation) in cloud fraction, given that $\overline{RH}$ in reanalyses bear close resemblance to reality due to data assimilation. Alternatively, the overestimation (underestimation) of cloud fraction is presumably due to a small (large) specification of $RH_c$ in models. For climate models, the bias of $\overline{RH}$ adds one more uncertainty, in addition to the uncertainty of $RH_c$.

5 | CONCLUSIONS

By using the CloudSat/CALIPSO data, we evaluated cloud fraction in three reanalyses (ERA-Interim, JRA-55, and MERRA-2) to identify their quality and reliability for cloud simulation. It is found that while all reanalyses can basically capture the horizontal pattern and vertical structure as in CloudSat/CALIPSO, they show considerable biases against satellite retrievals and differ from one another as well.

The most pronounced feature is that all reanalyses more or less underestimated the total cloud cover against CloudSat/CALIPSO, especially for JRA-55 and MERRA-2, with the bias reaching as high as 30%. Further analysis demonstrates that these underestimations are tightly related with the underestimation in 3D cloud fraction. All reanalyses struggle to simulate the mid-level clouds at low latitudes. We further assessed the transition of clouds along GPCI
transect and seasonal evolution over the SEP region. While all reanalyses can generally reproduce the transition from stratocumulus to shallow cumulus and eventually to deep convective clouds, they exhibit considerable biases in comparison with CloudSat/CALIPSO. ERA-Interim and JRA-55 perform better for low and mid-level clouds, but exhibit apparent underestimation for high-level clouds, whereas MERRA-2 succeeds in representing high-level clouds but dramatically underestimates low and mid-level clouds. We also extended the analysis to East Asia and found similar bias characteristics as along GPCI and over SEP.

The derived “critical relative humidity ($RH_c$)” from CloudSat/CALIPSO exhibits distinctive vertical structures at different latitudes. The diagnosed $RH_c$ from reanalyses show variations in terms of latitudes, yet they do not well match the observation. Moreover, the value of $RH_c$ in all reanalyses are larger than the observation at lower troposphere, especially for MERRA-2. This explains why cloudiness biases occur in reanalyses. Thence, the subgrid-scale variability of moisture should be accurately specified or parameterized in models. Failing of this would yield bias in cloud fraction.

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**DATA AVAILABILITY**

All data used in this study are available to the public. The CloudSat/CALIPSO data can be downloaded from the website at cloudsat.atmos.colostate.edu/data.

The ISCCP data are available from https://isccp.giss.nasa.gov/products/products.html. ERA-Interim reanalysis is available from https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/ERA-Interim. JRA-55 reanalysis is available from http://jra.kishou.go.jp/JRA-55/index_en.html.

MERRA-2 reanalysis is available from https://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/data_access/.

**REFERENCES**

Andrews, T., Gregory, J.M., Webb, M.J. and Taylor, K.E. (2012) Forcing, feedbacks and climate sensitivity in CMIP5 coupled atmosphere-ocean climate models. Geophysical Research Letters, 39, L09712. https://doi.org/10.1029/2012GL051607.

Barker, H.W. (2008) Overlap of fractional cloud for radiation calculations in GCMs: a global analysis using CloudSat and CALIPSO data. Journal of Geophysical Research: Atmospheres, 113, D00A01. https://doi.org/10.1029/2007jd009677.

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., Holm, E.V., Isaksen, L., Kallberg, 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., Thepaut, 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.

Dong, X.Q., Xi, B.K. and Minnis, P. (2006) A climatology of midlatitude continental clouds from the ARM SGP central facility. Part II: Cloud fraction and surface radiative forcing. Journal of Climate, 19, 1765–1783. https://doi.org/10.1175/jcli3710.1.

Ebita, A., Kobayashi, S., Ota, Y., Moriya, K., Kumabe, K., Onogi, K., Harada, Y., Yasui, S., Miyaoka, K., Takahashi, K., Kamahori, H., Kobayashi, C., Endo, H., Soma, M., Oikawa, Y. and Ishimizu, T. (2011) The Japanese 55-year reanalysis “JRA-55”: an interim report. Sola, 7, 149–152. https://doi.org/10.2151/sola.2011-038.

Gelaro, R., McCarty, W., Suárez, M.J., Todling, R., Molod, A., Takacs, L., Randles, C.A., Darmenov, A., Bosilovich, M.G., Reichle, R., Wargan, K., Coy, L., Cullather, R., Draper, C., Akella, S., Buchard, V., Conaty, A., Silva, A.M.D., Gu, W., Kim, G.-K., Koster, R., Lucchesi, R., Merkova, D., Nielsen, J.E., Partyka, G., Pawson, S., Putman, W., Rienecker, M., Schubert, S. D., Sienkiewicz, M. and Zhao, B. (2017) The modern-era retrospective analysis for research and applications, version 2 (MERRA-2). Journal of Climate, 30, 5419–5454. https://gmao.gsfc.nasa.gov/pubs/docs/Bosilovich803.pdf.

Jakob, C. and Klein, A. (1999) The role of vertically varying cloud fraction in the parameterization of microphysical processes in the ECMWF model. Quarterly Journal of the Royal Meteorological Society, 125, 941–965.

Lohmann, U. and Roeckner, E. (1996) Design and performance of a new cloud microphysics scheme developed for the ECHAM general circulation model. Climate Dynamics, 12, 557–572.

Luo, Y.L., Zhang, R.H., Qian, W.M., Luo, Z.Z. and Hu, X. (2011) Intercomparison of deep convection over the Tibetan plateau-Asian monsoon region and subtropical North America in boreal summer using CloudSat/CALIPSO data. Journal of Climate, 24, 2164–2177. https://doi.org/10.1175/2010jcli4032.1.

Luo, Z.J., Anderson, R.C., Rossow, W.B. and Takahashi, H. (2017) Tropical cloud and precipitation regimes as seen from near-simultaneous TRMM, CloudSat, and CALIPSO observations and comparison with ISCCP. Journal of Geophysical Research: Atmospheres, 122, 5988–6003. https://doi.org/10.1002/2017jd026569.

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Naud, C.M., Booth, J.F. and Del Genio, A.D. (2014) Evaluation of ERA-interim and MERRA cloudiness in the Southern Ocean. *J. Clim.*, 27, 2109–2124. https://doi.org/10.1175/jcli-d-13-00432.1.

Quaas, J. (2012) Evaluating the “critical relative humidity” as a measure of subgrid-scale variability of humidity in general circulation model cloud cover parameterizations using satellite data. *Journal of Geophysical Research: Atmospheres*, 117, D09208. https://doi.org/10.1029/2012jd017495.

Rozsos, W.B. and Schiffer, R.A. (1999) Advances in understanding clouds from ISCCP. *Bulletin of the American Meteorological Society*, 80, 2261–2287. https://doi.org/10.1175/1520-0477(1999)080<2261:acifi>2.0.co;2.

Sassen, K. and Wang, Z. (2008) Classifying clouds around the globe with the CloudSat radar: 1-year of results. *Geophysical Research Letters*, 35, L04805. https://doi.org/10.1029/2007gl032591.

Sassen, K., Wang, Z. and Liu, D. (2008) Global distribution of cirrus clouds from CloudSat/Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) measurements. *Journal of Geophysical Research: Atmospheres*, 113, D00A12. https://doi.org/10.1029/2007jd009972.

Stengel, M., Schlundt, C., Stapelberg, S., Sus, O., Eliasson, S., Willen, U. and Meirink, J.F. (2018) Comparing ERA-interim clouds with satellite observations using a simplified satellite simulator. *Atmospheric Chemistry and Physics*, 18, 17601–17614. https://doi.org/10.5194/acp-18-17601-2018.

Stephens, G.L. (2005) Cloud feedbacks in the climate system: a critical review. *Journal of Climate*, 18, 237–273. https://doi.org/10.1175/jcli-3243.1.

Stephens, G.L., Vane, D.G., Boain, R.J., Mace, G.G., Sassen, K., Wang, Z.E., Illingworth, A.J., O’Connor, E.J., Rossow, W.B., Rockel, B., Rossow, W.B., Ritter, B., Siebesma, A.P., Soares, P.M., Rockel, B., Rossw, W.B., Ritter, B., Siebesma, A.P., Soares, P.M. M., Turk, F.J., Vaillancourt, P.A., Von Engeln, A. and Zhao, M. (2013) CGILS: a new dimension of space-based observations of clouds and precipitation. *Bulletin of the American Meteorological Society*, 83, 1771–1790. https://doi.org/10.1175/bams-83-12-1771.

Teixeira, J., Cardoso, S., Bonazzola, M., Cole, J., Del Genio, A., DeMott, C., Franklin, C., Hannay, C., Jakob, C., Jiao, Y., Karlsson, J., Kitagawa, H., Kocherl, M., Kuwano-Yoshida, A., LeDrian, C., Li, J., Lock, A., Miller, M.J., Marquet, P., Martins, J., Mechoso, C.R., Meijgaard, E.V., Meinke, I., Miranda, P.M.A., Mirovon, D., Noggers, R., Pan, H.L., Randall, D.A., Rasch, P.J., Rockel, B., Rossw, W.B., Ritter, B., Siebesma, A.P., Soares, P.M. M., Turk, F.J., Vaillancourt, P.A., Von Engeln, A. and Zhao, M. (2011) Tropical and subtropical cloud transitions in weather and climate prediction models: the GCSS/WGNE Pacific Cross-Section Intercomparison (GPCI). *J. Clim.*, 24, 5223–5256. https://doi.org/10.1175/2011jcli-3672.1.

Tompkins, A.M. (2003) Impact of temperature and humidity variability on cloud cover assessed using aircraft data. *Quarterly Journal of the Royal Meteorological Society*, 129, 2151–2170. https://doi.org/10.1256/qj.02.190.

Wang, W.C., Gong, W., Kau, W.S., Chen, C.T., Hsu, H.H. and Tu, C. H. (2004) Characteristics of cloud radiation forcing over east China. *Journal of Climate*, 17, 845–853. https://doi.org/10.1175/1520-0442(2004)017<0845:Coocrf>2.0.co;2.

Wang, X.C., Liu, Y.M., Bao, Q. and Wu, G.X. (2015) Comparisons of GCM cloud cover parameterizations with cloud-resolving model explicit simulations. *Science China-Earth Sciences*, 58, 604–614. https://doi.org/10.1007/s11430-014-4989-y.

Weare, B.C. (2000) Insights into the importance of cloud vertical structure in climate. *Geophysical Research Letters*, 27, 907–910. https://doi.org/10.1029/1999gl011214.

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, e807. https://doi.org/10.1002/asl.807.

Yan, Y.F., Liu, Y.M. and Lu, J.H. (2016) Cloud vertical structure, precipitation, and cloud radiative effects over Tibetan Plateau and its neighboring regions. *Journal of Geophysical Research: Atmospheres*, 121, 5864–5877. https://doi.org/10.1002/2015jd024591.

Yan, Y.F., Wang, X.C. and Liu, Y.M. (2017) Cloud vertical structures associated with precipitation magnitudes over the Tibetan Plateau and its neighboring regions. *Atmospheric and Oceanic Science Letters*, 11, 44–53. https://doi.org/10.1080/16742834.2018.1395680.

Yu, H.Y., Zhang, M.H., Lin, W.Y. and Zhang, X.X. (2017) Cloud transitions: comparison of temporal variation in the southeastern Pacific with the spatial variation in the northeastern Pacific at low latitudes. *International Journal of Climatology*, 37, 2923–2933. https://doi.org/10.1002/joc.4889.

Zhang, M.H., Lin, W.Y., Klein, S.A., Bacmeister, J.T., Bony, S., Cederwall, R.T., Del Genio, A.D., Hack, J.J., Lohmann, U., Miniin, P., Musat, I., Pincus, R., Stier, P., Suarez, M.J., Webb, M.J., Wu, J.B., Xie, S.C., Yao, M.S. and Zhang, J.H. (2005) Comparing clouds and their seasonal variations in 10 atmospheric general circulation models with satellite measurements. *Journal of Geophysical Research: Atmospheres*, 110, D15S02. https://doi.org/10.1029/2004jd005021.

Zhang, M.H., Bretherton, C.S., Blossey, P.N., Austin, P.H., Bacmeister, J.T., Bony, S., Brient, F., Chezedela, S.K., Cheng, A., Del Genio, A.D., De Roode, S.R., Endo, S., Franklin, C.N., Golaz, J.C., Hannay, C., Heus, T., Isotta, F.A., Dufresne, J.-L., Kang, I.-S., Kawai, H., Koehler, M., Larson, V.E., Liu, Y., Lock, A.P., Lohmann, U., Kharoutdinov, M.F., Miodo, A.M., Noggers, R.A.J., Rasch, P., Sandu, I., Senkbeil, R., Siebesma, A.P., Siegenthaler-Le Drian, C., Stevens, B., Suarez, M.J., Xu, K.-M., von Salzen, K., Webb, M.J., Wolf, A. and Zhao, M. (2013) CGILS: results from the first phase of an international project to understand the physical mechanisms of low cloud feedbacks in single column models. *Journal of Advances in Modeling Earth Systems*, 5, 826–842. https://doi.org/10.1002/2013ms000246.

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, 884–907. https://doi.org/10.1007/s00376-013-2153-9.

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