Cloud Characteristics and Radiation Forcing in the Global Land Monsoon Region From Multisource Satellite Data Sets

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Abstract The global land monsoon region has the highest land cloud amount in the world affecting two thirds of the world’s population. Understanding the characteristics of cloud-radiation relies heavily on satellite data set, while few studies have addressed the advantages and weaknesses of current existing satellite data sets in estimating the cloud-radiation characteristics over global land monsoon regions. Multisource satellite data sets are used in this study to show the cloud characteristics in different monsoon regions. We find that all satellite data sets consistently show a peak of cloud fraction, cloud top height and cloud radiation forcing during summer over the global land monsoon regions. A regional difference in cloud characteristics is observed from multisource data sets. The seasonal cycle of cloud amount in the North American monsoon region is relatively smaller than that of the other monsoon regions. High-level clouds dominate the North African monsoon, while Low-level clouds dominate the Asian monsoon. The cloud properties and their radiative forcings revealed by four cloud-parameter data sets with multispectral imagers, that is, International Satellite Cloud Climatology Project (ISCCP)-D2, ISCCP-H, Moderate Resolution Imaging Spectroradiometer (MODIS)-MYD, and MODIS-MOD, are similar to one another, except stronger short-wave cloud radiative forcing in ISCCP-FD. Multidata comparison confirmed the climate and seasonal cycles of cloud characteristics in this study, demonstrating a better representation of cloud vertical structure in CloudSat over global land monsoon region.

1. Introduction

The global land monsoon region, with the highest precipitation variability over land, affects two thirds of the world’s population (Wang et al., 2012). The global monsoon region includes six submonsoon regions: North American (N_Am), South American (S_Am), North African (N_Af), South African (S_Af), Asian (As), and Australian (Au) monsoons (Wang & Ding, 2008). The global monsoon is characterized by high annual total precipitation and a large seasonal cycle in precipitation. All global monsoon regions are connected to each other because of global mass conservation (Trenberth et al., 2000). Understanding the characteristics of cloud and radiation processes is an essential component of the energy and water cycle in the global monsoon region.

Compared to the study of precipitation changes over the monsoon region (Zhang & Zhou, 2011; Zhou, Yu et al., 2008; Zhou, Zhang, & Li, 2008), less attention has been devoted to cloud-radiation processes because of the limitations of observational data. Since the 1980s, the availability of satellite data has provided new opportunities for understanding the cloud and radiation characteristics over the global monsoon region. Considering the large impact of land monsoon precipitation changes on local social life and different cloud characteristics of land cloud from ocean cloud, this study mainly focuses on the cloud and radiation features over the global land monsoon region.

The distributions of High-, Middle-, and Low-level clouds are not exactly the same in submonsoon regions in the Northern Hemisphere, although High-level clouds have the highest occurrence frequency in all
monsoon regions. The amount of middle-level clouds is smaller in the North America monsoon region than that in other monsoon regions (Das et al., 2017). Previous studies found the seasonal cycle of clouds follows that of precipitation with the highest (lowest) cloud amount during summer (winter) in the Asian monsoon region and noted the difference between cloud amount in the East Asian monsoon compared to that of the South Asian monsoon (Luo et al., 2009; Wonsick et al., 2009). During winter, because of the friction effect of the Qinghai-Tibet Plateau and downdraft in the middle and upper atmosphere, a large area of stratus is seen in the East Asian monsoon region (Li & Gu, 2006; Luo et al., 2009; Yu et al., 2004; Zhang & Li, 2013; Zhang et al., 2014). In terms of cloud vertical structure, modulated by the development of the Asian summer monsoon, the cloud amount increases and develops into the upper levels during summer in the East Asian and South Asian monsoons. However, because of the downdraft in the middle and upper atmosphere during the East Asian monsoon region, low clouds dominate the East Asian monsoon (Luo et al., 2009). The net cloud radiative forcing in the Asian monsoon region is higher during summer and lower during winter, where the long-wave cloud radiative forcing (LWCRF) and short-wave cloud radiative forcing (SWCRF) offset each other at the top of the atmosphere (Rajeevan & Srinivasan, 2000).

Previous studies of cloud characteristics in the monsoon region have mainly focused on one or two submonsoon regions; the similarities and differences across different monsoon regions need to be summarized. In addition, the existing studies generally used one or a limited number of satellite data sets; the assessment of satellite cloud data sets is typically for global clouds. Thus, the data dependence is poorly understood in global monsoon regions. In the global monsoon regions with great cloud seasonal variability, a comprehensive comparison of the existing satellite data sets is an urgent need. In this study, we aim to answer the following questions: (1) What are the similarities and differences in the cloud features, including annual mean cloud amount, CRF, seasonal variability, and cloud vertical structure, over different land monsoon regions? (2) What are the differences among currently widely used satellite data sets?

The remainder of the study is organized as follows. Section 2 provides a brief introduction to the satellite data sets and method used in this study. In section 3, we provide the mean states, seasonal cycle, and vertical structure of clouds in individual land monsoon regions and compare the differences across multisatellite cloud data sets. Finally, section 4 summarizes the results of the study.

2. Data and Method

2.1. Data Description

There are two types of widely used cloud satellite data sets. The first type is cloud parameter data provided by a cloud sensor on-board satellite, such as multiple versions of the International Satellite Cloud Climatology Project (ISCCP), the Moderate Resolution Imaging Spectroradiometer (MODIS) carried by Terra (originally called EOS AM-1) and Aqua (originally called EOS PM-1), and a variety of standard data sets provided by CloudSat, which is a cloud-only satellite in the A-Train satellite observation group. There are several sensor types for retrieving cloud properties. Multispectral imagers are widely used in satellite data sets such as ISCCP and MODIS. An infrared (IR) sounder was originally designed for retrieval of atmospheric temperature and humidity profiles. One can use IR channels, such as ARIS (Atmospheric Infrared Sounder), to obtain cloud top pressure and cloud optical depth by using CO₂ absorption band. Lidar and radar from the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) and CloudSat can provide cloud vertical profiles (Stubenrauch et al., 2013). The second type is cloud radiation data provided by the Earth Radiation Budget satellite, such as the CRF data provided by Clouds and the Earth’s Radiant Energy System (CERES), Earth Radiation Budget Experiment, and other projects. In previously completed work, there are numerous studies regarding the differences in satellite data sets. In this analysis, we select several representative satellite data sets based on the difference in sensor types. Several satellite cloud data sets are used as follows:

1. Cloud amount from six cloud parameter data sets:

   a. Monthly mean cloud amount data sets provided by ISCCP D2 (ISCCP-D2) (Doutriaux-Boucher & Sèze, 1998) and ISCCP monthly H Gridded Monthly (ISCCP-HGM) (Young et al., 2018), in a 2.5° × 2.5° grid from July 1983 to June 2007 and a 1° × 1° grid from July 1983 to June 2015. ISCCP-H is an improved...
product of ISCCP-D2 issued in 2017 using the same inversion algorithm. We also use the top of the atmosphere CRF data from ISCCP Radiative Flux Data (ISCCP-FD), with the same latitude-longitude resolution and time span as that of ISCCP-D2 (Zhang et al., 2004).

b Monthly mean cloud amount data sets from the three-level atmospheric grid data MOD08_M3 (data from the Terra platform; MODIS_MOD) and MYD08_M3 (data from the Aqua platform; MODIS_MYD) from the MODIS (Salomonson et al., 1989). Both data sets are mapped onto a 2.5° grid. The time periods of MODIS_MOD and MODIS_MYD are from January 2000 to December 2010 and from January 2002 to December 2010, respectively.

c Monthly mean cloud occurrence frequency from the two-level CloudSat 2B-GEOprof (Cloud Geometrical Profile) 94-GHz cloud profiling radar with a horizontal resolution of 1.5 km and a vertical resolution of 240 m. The sensitivity of the radar is −30 dBZ (Marchand et al., 2009). Cloud mask, derived from 2B-GEOprof, is applied to calculate the cloud occurrence frequency. For example, in a certain level, when cloud mask is 0, a clear sky is detected. Otherwise, cloud fraction is set to 100% when cloud mask is larger than 20. If cloud mask is less than 20, the cloud fraction from 2B-GEOPROF-lidar should be taken into account. Therefore, the cloud occurrence frequency is actually a ratio of the number of times when the cloud is detected to the total number of satellite observations. The cloud occurrence frequency was mapped onto a 1° × 1° grid from July 2006 to June 2011. The cloud occurrence frequency may not be exactly comparable in magnitude with cloud fraction from ISCCP and MODIS; however, its spatial distributions and time evolutions are still quotable. CloudSat-CALIPSO is widely used to investigate the vertical structure of clouds (Luo et al., 2009; Yan et al., 2018).

d The annual mean cloud amount from the Atmospheric Infrared Sounder (AIRS). AIRS is mounted on the Aqua satellite. It can detect the atmosphere through infrared and visible light. Because of the feature of the IR sounder, AIRS data are widely used to observe atmospheric water vapor and temperature (Aumann et al., 2003). The level 3 annual mean cloud amount which is also defined as the frequency of cloud occurrence is mapped onto a 1° × 1° grid from 2002 to 2018.

2. Cloud radiation from two Earth Radiation Budget satellite data sets

a Monthly radiation data from the CERES-Energy Balance and Filled V3.0 (Loeb et al., 2009) is used from March 2000 to June 2014 by mapping original data sets onto a 1° × 1° grid. The input data originate from multiple sets of products such as CloudSat, MODIS, and GEOS-4 (Goddard Earth Observing System-4). b Monthly radiation data from the Global Energy and Water Cycle Experiment Surface Radiation Budget (GEWEX SRB) from July 1983 to December 2007 (Stackhouse et al., 2004). The input data sets include multiple sets of cloud radiation products from ISCCP, OMI, and TOVS. The data set is mapped onto a 1° grid.

3. Circulations from ERA-Interim

The vertical motion (ω) was derived from ERA-Interim atmospheric reanalysis monthly data from 1979 to 2013 at a 1.5° × 1.5° latitude-longitude resolution at standard pressure levels. The spatial resolution of the data set is approximately 80 km (T255 spectral) with 60 vertical levels from the surface up to 0.1 hPa (Dee et al., 2011).

2.2. Monsoon Cloud Amount Index

Following Wang and Ding (2008), the global monsoon region is defined as the area where the monsoon precipitation index (MPI) is greater than 0.5 and the annual range exceeds 300 mm. MPI is defined as the ratio of the seasonal mean precipitation difference between the wet and dry seasons to the total annual precipitation. Similar to the MPI, a monsoon cloud amount index (MCI) is defined here to measure the seasonality of cloud amount. MCI is the ratio of the total cloud amount difference between the wet and dry seasons to the total annual mean cloud amount. The larger the MCI, the larger the seasonal variation in the cloud amount. Notably, the annual mean of the cloud amount is not the cumulative value of the monthly mean; thus, the MCI can be greater than 1. In this study, we only focus on the global land monsoon region.
3. Results

3.1. Seasonal Cycle of Cloud Characteristics

The distributions of total cloud amount derived from multiple satellite data sets are compared as shown in Figure 1. All data sets show similar spatial distributions of the annual mean total cloud amount in the global land monsoon region, with a decrease from the tropics to the poles. A quantitative comparison is listed in Table 1. The cloud amount in the global land monsoon domains derived from ISCCP and MODIS products are comparable to each other (Figures 1a–1d and Table 1). They all show that the annual mean cloud fraction of the monsoon regions exceeds 50% except for that of the Au region where the annual mean cloud fraction is approximately 40%.

The vertical averaged frequency of cloud occurrence revealed by AIRS and CloudSat is further shown in Figure 2 to confirm the spatial distribution of cloud fraction over the global land monsoon region (Figure 2). The cloud occurrence frequency measured by AIRS with an IR sounder is similar to that in

![Figure 1](https://example.com/figure1.png)

**Figure 1.** Spatial distributions of annual mean total cloud amount (unit: %) defined by the fraction of the sky covered by clouds in the global land monsoon region derived from (a) ISCCP_D2, (b) ISCCP_HGM, (c) MODIS_MOD, and (d) MODIS_MYD averaged over the available data set period.

| Table 1 | Climatic Annual Mean Total Cloud Amount (Unit: %) Defined by Cloud Fraction in Different Global Land Monsoon Derived From ISCCP_D2, ISCCP_HGM, MODIS_MOD, and MODIS_MYD |
|---------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|         | N_Am       | S_Am       | N_Af       | S_Af       | As      | Au      |
| ISCCP_D2 | 59(57-61)  | 63(56-65)  | 54(50-57)  | 52(49-55)  | 60(58-63) | 45(39-51) |
| ISCCP_HGM| 61(57-63)  | 63(60-65)  | 56(54-59)  | 53(51-56)  | 61(58-63) | 47(42-53) |
| MODIS_MOD| 59(56-60)  | 62(57-73)  | 48(29-56)  | 51(46-70)  | 59(53-62) | 45(38-62) |
| MODIS_MYD| 63(62-64)  | 68(66-70)  | 57(55-57)  | 52(50-55)  | 65(63-66) | 46(44-48) |
| AIRS     | 42(40-44)  | 46(44-48)  | 34(32-36)  | 40(38-43)  | 46(43-47) | 32(26-40) |
| CloudSat | 40(39-40)  | 39(36-41)  | 36(34-38)  | 31(29-33)  | 44(43-45) | 28(2-32)  |

*Note. Climatic annual mean total frequency of cloud occurrence (unit: %) in AIRS and CloudSat. The numbers in brackets are the ranges from the minimum to maximum annual mean during the available period in each data set.*
CloudSat measured by cloud profile radar (Figure 2 and Table 1). The frequency of cloud occurrence is generally less than 50%, with the maximum over the South American monsoon region and minimum over the Australia monsoon region. This regional dependence is consistent with ISCCP and MODIS products, although with different magnitude due to the different definition in cloud amount (detail in 2.1).

To better investigate the cloud features in different satellite data sets, the distributions of High- (the cloud top is higher than 440 hPa), Middle- (the cloud top is higher than 680 hPa and lower than 440 hPa), and Low- (the cloud top is lower than 680 hPa) level cloud fractions are shown in Figure 2. Because the two versions of ISCCP use the same inversion algorithm and MODIS-MOD and MODI-MYD originate from the same sensor in different satellites (Terra and Aqua), we only show the results of ISCCP-D2 and the combined results of MODIS in Figure 3.

Generally, the patterns of clouds derived from ISCCP are similar to those from MODIS that cloud centers appear at the equator sides of most monsoon regions. In addition, both ISCCP and MODIS agree that high-cloud dominates most of monsoon regions, which is consistent with Das et al. (2017). Cloud fraction over global land monsoon region decreases from high level to low level, partly because that ISCCP and MODIS are good at observing the upper layers of clouds. An exception is Asian Monsoon region where the middle-cloud is prevailing (Figures 3b and 3e), that is because the friction effect of the Qinghai-Tibet Plateau.

The dominant role of High-level cloud in the global land monsoon can also be seen in CloudSat, as shown in Figure 4. Moreover, CloudSat observes the prevailing of Middle-cloud over Asian Monsoon region. Seeing from the cloud occurrence revealed by CloudSat which can well observe the vertical structure of cloud; however, the decrease of cloud amount from high to low levels in ISCCP and MODIS is not obvious in the cloud occurrence. More Low-cloud in CloudSat is partly because it has a strong penetrating power.

The CRF on the top of the atmosphere can reflect the impact of clouds on the radiation budget of the Earth-atmosphere system. If the NET CRF is dominated by SWCRF, clouds cool the atmosphere and vice versa. The distributions of annual mean CRF derived from different data sets are compared as shown in Figure 5 and a quantitative comparison is listed in Table 2. A consistency can be seen between the SWCRF and LWCRI over the global land monsoon regions, that is, a region with a strong SWCRF tends to be a region with a strong LWCRI. In addition, SWCRF is typically larger than LWCRI over these regions, producing a radiative cooling effect. For example, the South American monsoon region has the highest annual mean cloud fraction of the global monsoon areas, and its annual mean LWCRI and SWCRF are also stronger than that of the other submonsoons. The East Asian monsoon region, as an exception, is dominated by SWCRF because of the prevailing middle-level stratiform clouds. The Asian monsoon region, therefore, shows the second strongest SWCRF but has the weakest LWCRI (approximately 30 W/m²) of the global land monsoon regions (Table 2). The distributions of CRF derived from different satellite data sets are similar, but the SWCRF in ISCCP is stronger than that in the other data sets. This feature is more obvious in the South American monsoon region with the SWCRF being 10 W/m² stronger than that of the other two data sets.
Figure 6 shows the seasonal cycle of total cloud fraction in each global monsoon region from multiple satellite data sets and precipitation from GPCP. Generally, the cloud amount in each land monsoon region increases from winter to summer and decreases thereafter, peaking during summer. This result is consistent with the seasonal precipitation cycle. The month with the peak precipitation usually shows the peak in clouds, such as July in As and August in N_Af. An exception is shown in N_Am (Figure 6a). Unlike precipitation, clouds over N_Am do not show a significant seasonal cycle. In most satellite data sets, the difference in cloud amount in the North American monsoon region between winter and summer is less than 10%. The cloud amount from MODIS and CloudSat in the North American monsoon region presents a “double-peak” structure during winter and summer. All satellite data sets show a similar seasonal variation in the total cloud amount in the monsoon regions. Same as the spatial distribution in Figure 1, the annual cycle in cloud amounts from ISCCP and MODIS are comparable, and the cloud frequency in CloudSat is close to AIRS, which is about 20% lower than the cloud amounts in ISCCP and MODIS. We also notice a relative larger difference between CloudSat and AIRS in the southern monsoon regions during its winter season.

Figure 3. Spatial distributions of annual mean High- (cloud top higher than 440 hPa), Middle- (cloud top higher than 680 hPa and lower than 440 hPa), and Low- (cloud top lower than 680 hPa) level cloud fraction (unit: %) in the global land monsoon region derived from (a–c) ISCCP_D2, (d–f) MODIS (combining versions of MYD and MOD) averaged over the available data set period.
(June–August) than summer (December–February) (Figure 6h), especially in South Africa and South American monsoon region (Figures 6b and 6d).

Given the difference observation methods across the data sets used in this study, it is desirable to define a metric to measure the seasonality of cloud amount over the global land monsoon region. Thus, we defined and calculated MCI based on different data sets to quantify the intensity of the seasonal cycle as shown in Figure 7. Table 3 lists the climate mean MCI in the global land monsoon region. Except for the North American monsoon region, the MCI in all monsoon regions mostly ranges from 0.5 to 1, and South Africa

**Figure 4.** Same as Figure 3 but for the frequency of cloud occurrence (unit: %) in CloudSat averaged over the available data set period.
has the highest MCI which is near 1. Because of the small difference in cloud amount between the winter and summer in the North American monsoon region as shown in Figure 6a, the MCI of the North American monsoon region is only approximately 0.2 (Table 3). Notably, this seasonal variation is unevenly distributed in the Asian monsoon region. The MCI along the Yangtze River Basin in the East Asian monsoon region is near zero, and the MCI in the South Asian monsoon region is greater than 1.5. This result implies that the East Asian monsoon region has a weak seasonal difference in cloud fraction because of the large-scale stratus clouds in the East Asian monsoon region during winter.

Different from the low climate mean of cloud amount in CloudSat and AIRS, the distributions and magnitudes of MCI given by these two data sets are near those of the other products (Table 3). It can be concluded that even if the satellite data such as that of CloudSat and AIRS have a large gap in climatic mean cloud amount compared to the other products, in some monsoon regions these data sets can still provide a reasonable seasonal variation in cloud response to the monsoon.

Figure 5. Spatial distributions of climatologically annual mean SWCRF (left) LWCRF (middle) and NETCRF (right) at the TOA (unit: W m⁻²) in the global land monsoon region derived from (a, b) ISCCP_FD, (c, d) EBAF, and (e, f) SRB during the available data set period.

Table 2

| Data sets | CRF   | N_Am       | S_Am       | N_Af       | S_Af       | As        | Au        |
|-----------|-------|------------|------------|------------|------------|-----------|-----------|
| ISCCP     | SWCRF | −50(−52−47)| −60(−64−57)| −41(−44−38)| −49(−52−43)| −56(−59−53)| −37.4(−43.8−30.2) |
|           | LWCRF | 33(30–35)  | 37(33–40)  | 35(32–37)  | 31(28–31)  | 29(26–31)  | 28(24–31)  |
| EBAF      | SWCRF | −42(−44−40)| −50(−52−47)| −34(−36−33)| −34(−45−40)| −52(−54−51)| −34(−40−30) |
|           | LWCRF | 32(31–33)  | 36(34–38)  | 35(34–36)  | 30(28–31)  | 30(29–32)  | 28(24–33)  |
| SRB       | SWCRF | −43(−45−40)| −51(−55−46)| −30(−33−26)| −39(−42−34)| −54(−56−51)| −29(−35−25) |
|           | LWCRF | 34(31–36)  | 38(33–42)  | 36(33–38)  | 32(30–35)  | 31(30–33)  | 27(23–30)  |

Note. The numbers in brackets are the ranges from the minimum to maximum annual mean during the available period for each data set.
Figure 6. Climate mean annual cycle of total cloud amount (lines, right y axis, unit: %) and precipitation (bars, left y axis, unit: mm) in individual submonsoon regions derived from different satellite data sets. The yellow bars represent climatologically monthly mean precipitation from GPCP, and the lines represent monthly mean total cloud amounts from different data sets. (a) North American monsoon (N_Am), (b) South American monsoon (S_Am), (c) North African monsoon (N_Af), (d) South African monsoon (S_Af), (e) Asian monsoon (As), (f) Australian monsoon (Au), (g) Northern Hemisphere, and (h) Southern Hemisphere. The cloud amounts in ISCCP and MODIS products are defined by cloud fraction and defined by frequency of cloud occurrence in AIRS and CloudSat.
3.2. Cloud Vertical Structure in Different Monsoon Regions

Figure 8 shows the cloud vertical structures in each monsoon region from three satellite data sets. Same as Figure 6, we only provide the results of ISCCP‐D2 and MODIS (combining versions of MODIS_MYD and MODIS_MOD). A clear seasonal cycle in cloud vertical structure is seen from the vertical structure, with an increase in high-level clouds from winter to summer and a decrease thereafter in all monsoon regions (Figure 8), except for N_Af where high-level clouds dominate during the winter. Monsoon regions show a similar feature that clouds begin to more commonly develop during May in the Northern (November in the Southern) Hemisphere monsoon region and begin to dissipate during October in the Northern (April in the Southern) Hemisphere monsoon region except for Au, where the cloud level increases from December to February, which is shorter than that of other monsoon regions. CloudSat shows more detail of

Table 3

|       | N_Am | S_Am | N_Af | S_Af | As  | Au  |
|-------|------|------|------|------|-----|-----|
| ISCCP_D2 | 0.14 | 0.48 | 0.68 | 0.89 | 0.54 | 0.75 |
| ISCCP_HGM | 0.13 | 0.49 | 0.64 | 0.85 | 0.53 | 0.74 |
| MODIS_MOD | 0.09 | 0.55 | 0.95 | 0.99 | 0.53 | 0.88 |
| MODIS_MYD | 0.08 | 0.42 | 0.80 | 0.91 | 0.44 | 0.82 |
| AIRS    | 0.06 | 0.50 | 1.04 | 0.82 | 0.70 | 0.75 |
| CloudSat | 0.26 | 0.88 | 0.97 | 1.32 | 0.74 | 1.07 |
Figure 8. Vertical distributions of climatological mean cloud fraction (unit: %) in the global land monsoon regions from (a–f) ISCCP D2, (g–l) MODIS, and (m–r) CloudSat. The panels from top to bottom show N_Am, S_Am, N_Af, S_Af, As, and Au, respectively.
the vertical structure because the cloud profile radar of CloudSat is sensitive and the lidar of CALIPSO has a strong penetrating power. In contrast, because the sensor types of the other two data are multispectral imagers that can only obtain the spectral bands from the top class of the cloud, only the highest parts of the clouds can be scanned in these two data sets. Cloud levels in ISCCP are more widely distributed in profile than those in MODIS.

To understand the differences in cloud vertical structure between different monsoon regions, the mean vertical motion ($\omega$) of the monsoon regions is shown in Figure 9. The updraft correlates very well with cloud growth. In most monsoonal regions, with the development of the summer monsoon, the updraft dominates the whole level, leading to cloud growth. In N_Am, the updraft is weaker than that of other monsoon regions, which may be the reason for its weaker seasonal variability in clouds. In N_Af, even during the winter, the updraft is dominant at the high level (above 400 hPa), causing high-level clouds to dominate during winter.

4. Summary and Discussion

By using multiple sets of satellite products, we investigated the similarities and differences in cloud radiation, such as annual mean cloud amount, seasonal variability, and cloud vertical structure, in different
land monsoon regions of the world. We also compared these similarities and differences from multiple sets of satellite products. The main conclusions are summarized as follows:

1. Similar to precipitation, the global land monsoon regions also have a large cloud fraction and CRF and the cloud amount peak during summer. The annual mean cloud fraction over most of the monsoon region exceeds 50%, except for in the Australian monsoon region where the annual mean total cloud amount is around 40%. In addition, the seasonal variability in the cloud amount in the North American monsoon region is weaker than that in the other monsoon regions.

2. The vertical structure in different monsoonal regions shows some commonalities that during the development of the summer monsoon, clouds develop to a higher level during summer but are inhibited during winter. The high-level cloud is the most prevailing cloud type in all monsoon regions. N_Am and S_Am have less middle-level clouds when compared to those of the other monsoon regions. The evolutions of cloud vertical structure in different monsoon regions are probably related to the updraft of vertical monsoon circulations due to the adiabatic cooling. During the winter in N_Af, the updraft dominates at a high level resulting in a large cloud amount at a high level.

3. This study summarizes the similarities and differences in cloud-radiation characteristics across multiple data sets to improve the reliability of our conclusion in cloud-radiation variations. Two ISCCP data sets produce results essentially in agreement with MODIS data sets that the cloud fraction in these four data sets slightly varies. The frequency of cloud occurrence in CloudSat and AIRS are generally 20% lower than those in cloud fraction in ISCCP and MODIS due to different definitions and observation methods. A clearly decrease of cloud fraction from high to low levels in ISCCP and MODIS does not show in CloudSat. Moreover, ISCCP-FD, CERES-EBF, and GEWEX_SRB show high consistencies in representing cloud radiative forcing, including their climatological pattern and seasonal variabilities, although the SWCRF divided from ISCCP-FD is somewhat higher than that from SRB. The consistencies among multiple data sets ensure that the seasonal cycle in cloud radiation shown is robust.

References

Aumann, H. H., Chahine, M. T., Gautier, C., Goldberg, M. D., Kalnay, E., McMillin, L. M., & Strow, L. L. (2003). AIRS/AMSU/HSB on the Aqua mission: Design, science objectives, data products, and processing systems. IEEE Transactions on Geoscience and Remote Sensing, 41(2), 253–264. https://doi.org/10.1109/tgrs.2002.808356

Das, S. K., Golhait, R. B., & Uma, K. N. (2017). Clouds vertical properties over the Northern Hemisphere monsoon regions from CloudSat-CALIPSO measurements. Atmospheric Research, 183, 73–83. https://doi.org/10.1016/j.atmosres.2016.08.011

Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., et al. (2011). The ERA-Interim reanalysis: Configuration and performance of the data assimilation system. Quarterly Journal of the Royal Meteorological Society, 137(656), 553–597. https://doi.org/10.1002/qj.828

Douttiau Boucher, M., & Sée, G. (1998). Significant changes between the ISCCP C and D cloud climatologies. Geophysical Research Letters, 25(22), 4193–4196. https://doi.org/10.1029/98GL02098

Li, Y., & Gu, H. (2006). Relationship between middle stratiform clouds and large scale circulation over eastern China. Geophysical Research Letters, 33, L09T06. https://doi.org/10.1029/2005GL025615

Loeb, N. G., Wielicki, B. A., Doelling, D. R., Smith, G. L., Keyes, D. F., Kato, S., & Wong, T. (2009). Toward optimal closure of the Earth's atmosphere radiation budget. Journal of Climate, 22(3), 745–766. https://doi.org/10.1175/2008jcli2637.1

Luo, Y., Zhang, R., & Wang, H. (2009). Comparing occurrences and vertical structures of hydrometeors between eastern China and the Indian monsoon region using CloudSat/CALIPSO data. Journal of Climate, 22(4), 1052–1064. https://doi.org/10.1175/2008jcli2666.1

Marchand, R., Haynes, J., Mace, G. G., Ackerman, T., & Stephens, G. (2009). A comparison of simulated cloud radar output from the multiscale modeling framework global climate model with CloudSat cloud radar observations. Journal of Geophysical Research, 114, D00A20. https://doi.org/10.1029/2008JD009790

Rajeevan, M., & Srinivasan, J. (2000). Net cloud radiative forcing at the top of the atmosphere in the Asian monsoon region. Journal of Climate, 13(3), 650–657. https://doi.org/10.1175/1520-0442(2000)013<0650:ncrfat>2.0.co;2

Salomonson, V. V., Barnes, W. L., Maymon, P. W., Montgomery, H. E., & Ostrow, H. (1989). MODIS: Advanced facility instrument for studies of the Earth as a system. IEEE Transactions on Geoscience and Remote Sensing, 27(2), 145–153. https://doi.org/10.1109/36.20292

Stackhouse, P. W., Gupta, S. K., Cox, S. J., Mikowitz, J. C., Zhang, T., & Chiacchio, M. (2004). 12-year surface radiation budget data set GEWEX News.

Stubenrauch, C. J., Rossow, W. B., Kinne, S., Ackerman, S., Cesana, G., Chepfer, H., & Maddux, B. C. (2013). Assessment of global cloud datasets from satellites: Project and database initiated by the GEWEX radiation panel. Bulletin of the American Meteorological Society, 94(7), 1031–1049. https://doi.org/10.1175/bams-d-12-00117

Trenberth, K. E., Stepaniak, D. P., & Caron, J. M. (2000). The global monsoon as seen through the divergent atmospheric circulation. Journal of Climate, 13(22), 3969–3993. https://doi.org/10.1175/1520-0442(2000)013<3969:gdma>2.0.co;2

Wang, B., & Ding, Q. (2008). Global monsoon: Dominant mode of annual variation in the tropics. Dynamics of Atmospheres and Oceans, 44(3-4), 165–183. https://doi.org/10.1016/j.dynatmoce.2007.05.002

Wang, B., Liu, J., Kim, H. J., Webster, P. J., & Yim, S. Y. (2012). Recent change of the global monsoon precipitation (1979–2008). Climate Dynamics, 39(5), 1123–1135. https://doi.org/10.1007/s00382-011-1266-7

Wonsick, M. M., Pinker, R. T., & Govaerts, Y. (2009). Cloud variability over the Indian monsoon region as observed from satellites. Journal of Applied Meteorology and Climatology, 48(9), 1803–1821. https://doi.org/10.1175/2009jamc207.1
Yan, Y. F., Wang, X. C., & 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

Young, A. H., Knapp, K. R., Inamdar, A., Hankins, W., & Rossow, W. B. (2018). The International Satellite Cloud Climatology Project H-Series climate data record product. *Earth System Science Data*, 10(1), 583–593. https://doi.org/10.5194/essd-10-583-2018

Yu, R., Wang, B., & Zhou, T. (2004). Climate effects of the deep continental stratus clouds generated by the Tibetan Plateau. *Journal of Climate*, 17(13), 2702–2713. https://doi.org/10.1175/1520-0442(2004)017<2702:ceotdc>2.0.co;2

Zhang, L., & Zhou, T. (2011). An assessment of monsoon precipitation changes during 1901–2001. *Climate Dynamics*, 37(1-2), 279–296. https://doi.org/10.1007/s00382-011-1093-5

Zhang, Y., Chen, H., & Yu, R. (2014). Vertical structures and physical properties of the cold-season stratus clouds downstream of the Tibetan Plateau: Differences between daytime and nighttime. *Journal of Climate*, 27(18), 6857–6876. https://doi.org/10.1175/jcli-d-14-00063.1

Zhang, Y., & 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/s00376-013-1215-9

Zhang, Y., Rossow, W. B., Lacis, A. A., Oinas, V., & Mishchenko, M. I. (2004). Calculation of radiative fluxes from the surface to top of atmosphere based on ISCCP and other global data sets: Refinements of the radiative transfer model and the input data. *Journal of Geophysical Research*, 109, D19105. https://doi.org/10.1029/2003JD004457

Zhou, T., Yu, R., Li, H., & Wang, B. (2008). Ocean forcing to changes in global monsoon precipitation over the recent half-century. *Journal of Climate*, 21(15), 3833–3852. https://doi.org/10.1175/2008jcli2067.1

Zhou, T., Zhang, L., & Li, H. (2008). Changes in global land monsoon area and total rainfall accumulation over the last half century. *Geophysical Research Letters*, 35, L16707. https://doi.org/10.1029/2008GL034881