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ABSTRACT

In this paper, the global distribution of cloud water based on International Satellite Cloud Climatology Project (ISCCP), Moderate Resolution Imaging Spectroradiometer (MODIS), CloudSat Cloud Profiling Radar (CPR), European Center for Medium-Range Weather Forecasts Interim Re-Analysis (ERA-Interim), and Climate Forecast System Reanalysis (CFSR) datasets is presented, and the variability of cloud water from ISCCP, the Special Sensor Microwave Imager (SSM/I), ERA-Interim, and CFSR data over the time period of 1995 through 2009 is discussed. The results show noticeable differences in cloud water over land and over ocean, as well as latitudinal variations. Large values of cloud water are mainly distributed over the North Pacific and Atlantic Oceans, eastern ITCZ, regions off the west coast of the continents as well as tropical rain forest. Cloud water path (CWP), liquid water path (LWP), and ice water path (IWP) from these datasets show a relatively good agreement in distributions and zonal means. The results of trend analyzing show an increasing trend in CWP, and also a significant increasing trend of LWP can be found in the dataset of ISCCP, ERA-Interim, and CFSR over the ocean. Besides the long-term variation trend, rises of cloud water are found when temperature and water vapor exhibit a positive anomaly. EOF analyses are also applied to the anomalies of cloud water, the first dominate mode of CWP and IWP are similar, and a phase change can be found in the LWP time coefficient around 1999 in ISCCP and CFSR and around 2002 in ERA-Interim.

1. Introduction

Clouds are broadly distributed in the lower part of the atmosphere, covering 68.6% of the global sky (Rossow and Schiffer 1999). The knowledge of clouds is of great
importance in the studies of weather and climate, because 
clouds are greatly related to the formation of rain and the 
circulation of water (Kidd 2001). Clouds are also the ad-
justors of the radiation budget (Ramanathan et al. 1989).
Latent heat released in the phase change of cloud particles 
is an important source of nonadiabatic heating in the at-
mosphere (Posselt and Martin 2004). Clouds provide a 
link among hydrometeors, radiative properties, and the 
energy budget of the atmosphere.

Cloud liquid water content (LWC) and ice water con-
tent (IWC) are key variables to describe cloud structure;
their vertical integrations are liquid water path (LWP) 
and ice water path (IWP), respectively. Cloud water 
content and its change are directly related to the 
cloud amount and cloud phase (Rossow and Schiffer 
1999) and furthermore affect the radiation characteris-
tics of clouds. For instance, the result from the earth 
radiation budget shows that an increase of 20%–35% in the 
clouds of climate. For instance, the result from the earth 
radiation budget shows that an increase of 20%–35% in the 
canopy can be obtained from ground-based or air-orne measurements (Hayasaka et al. 1995; Turner et al. 
2007), and various satellite measurements, such as cloud 
products of the International Satellite Cloud Climatology 
Project (ISCCP) (Lin and Rossow 1996; Rossow and 
Schiffer 1999), Special Sensor Microwave Imager (SSM/I) 
(Weng et al. 1997), and Moderate Resolution Imaging 
Spectroradiometer (MODIS) (Wood and Hartmann 
2006), as well as the active sensor of the Cloud Profiling 
Radar (CPR) on board CloudSat (Stephens et al. 2002). 
These datasets offer capabilities in advancing the knowl-
edge of clouds. Furthermore, with a new parameterization 
method integrated into the forecast model, cloud water 
is provided as a prognostic parameter in reanalysis 
recently, including the European Center for Medium-
Range Weather Forecasts (ECMWF) Interim Re-Analysis 
(ERA-Interim) (Dee et al. 2011) and the Climate Fore-
cast System Reanalysis (CFSR) (Saha et al. 2010) con-
ducted under the National Centers for Environmental 
Prediction (NCEP). Compared to the free simulations of 
climate models, reanalysis data are generated by using a 
data assimilation system and are strongly constrained by 
various observations; they offer an encouraging data source 
in the climate diagnosis. So far, properties of precipitation, 
radiation flux, and cloud amount have been studied based 
on the reanalysis (Weare 2000; Chevallier et al. 2005; 
Griggs and Bamber 2008). A good performance of repre-
sent the observed distribution patterns of cloud water in 
reanalysis data has been found in the studies of Li et al. 
(2012). Based on these various datasets from satellite ob-
servations and models, the long-term variability could be 
investigated.

In this study, we focus on the global distribution and 
long-term variability of cloud water based on the datasets 
of ISCCP and SSM/I, ERA-Interim and CFSR from 1995 
to 2009, and the climatology of cloud water path based on 
CPR and MODIS products. The rest of the paper is or-
ganized as follows: Sections 2 describes datasets and the 
method used in this study. Sections 3 and 4 present the 
distribution and variability of cloud water. Finally, we 
conclude the study in section 5.

2. Data and method

a. ISCCP data

ISCCP was established in 1982 under the World Cli-

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b. SSM/I data

Cloud products from the Defense Meteorological Satellite Program (DMSP) F13 SSM/I are also involved in this study. The retrieval algorithm is developed by Remote Sensing Systems (RSS) (Wentz 1997; Wentz and Spencer 1998), which simultaneously retrieves ocean wind speed, water vapor, LWP, and rain rate from multichannel brightness temperatures of SSM/I. A preliminary value of LWP is derived from 37-GHz observations first, assuming no rain exists in the atmospheric column. When LWP exceeds a rain threshold of 180 g m$^{-2}$, a LWP is adjusted as a function of rain rate $R$ and the rain column height $H$:

$$L = 180(1 + \sqrt{HR}).$$

The 0.25° grid from SSM/I version 7 (V7) monthly means of LWP through the time period of May 1995–November 2009 are remapped into 2.5° grid box for the convenience of comparing with ISCCP data.

c. CloudSat and CPR data

CloudSat was launched in 2006 and joined the A-Train satellites constellation. It carries a 94-GHz nadir-looking CPR, focusing on the observations of cloud distribution, structure, and radiative properties (Stephens et al. 2002). CPR provides the most advanced measurement of clouds at present. It measures vertical profiles of the power backscattered by clouds, has a vertical resolution of 500 m, and a horizontal footprint of about 1.4 km. In this study, the CloudSat radar-only cloud water content product (2B-CWC-RO) version 008 is used in the survey of the climatological distribution of cloud water path. This product contains profiles of cloud liquid and ice water content. Retrievals of cloud water content are based on a priori size distribution parameters of liquid and ice cloud particles and the radar measurements. First, the cloud water content profiles are retrieved for liquid and ice cloud separately. And then, based on the temperature data from the ECMWF model, composite profiles are created by using the retrieved ice water content at temperatures colder than $-20^\circ$C, the retrieved liquid properties at temperatures warmer than 0°C, and a linear combination of ice and liquid at intermediate temperatures. Additional details about the algorithm can be found in the work of Austin et al. (2009).

Since CPR measurements are sensitive to a large range of particle size, precipitating particles are also included in the total LWP and IWP in the CPR 2B-CWC-RO dataset, thus LWP and IWP in CPR data are likely overestimated. And this treatment in the retrieve method is one of the major uncertainties. For a more meaningful comparison between CPR and reanalysis data, the “flag method” described in the work of Waliser et al. (2009) and Li et al. (2012) is used. That is, based on the CloudSat cloud classification product (2B-CLDCLASS), we remove values in any profiles of LWC and IWC that are flagged as precipitating or the cloud type is classified as “deep convection” or “cumulus,” and then vertically integrated LWP and IWP data in the time range from 2007 to 2010 are gridded into seasonal 2.5° × 2.5° data.

Meanwhile, some validation studies show that CPR retrieval error is within 50%, compared with in situ measurements (Austin et al. 2009; Waliser et al. 2009). Jiang et al. (2012) addressed that LWC and IWC also have uncertainty because of the particle size distribution assumption and estimate CPR LWP/IWP uncertainty to be about a factor of 2. In our work, the factor of 2 is used as the uncertainty of CPR LWP/IWP. We use the value of LWP/IWP multiplied by 0.5 as the lower end and multiplied by 2.0 as the higher end. For CPR, we sum LWP and IWP, as well as the uncertainty limit.

d. MODIS data

The MODIS is a downward-looking passive sensor on board both the Terra and Aqua satellites; it has 36 channels, and the horizontal resolution is about 1 km. Similar to that from ISCCP, the retrieval of cloud water path from MODIS is indirectly estimated from cloud optical thickness and effective radius at 1-km resolution (level 2 MYD06 product), based on measurements from visible and infrared channels (King et al. 1997). In this study, we focus on the 1° × 1° monthly cloud water path data from Aqua (MYD08_M3, collection 051), as this satellite is collocated with CloudSat, and the time series covers from 2006 to 2011. Cloud water path presented in all of the previously described datasets are gridbox means, while LWP and IWP in MYD08 products are averaged from the MYD06 product under cloud-only conditions. To get full-sky means, we multiply the monthly retrieved LWP and IWP by the monthly gridbox-mean cloud fraction, as in the work of Waliser et al. (2009) and Seethala and Horváth (2010), and then regrid into 2.5° × 2.5° data.

e. ERA-Interim data

ERA-Interim is a newly released ECMWF global atmospheric reanalysis. It is produced by using the ECMWF Integrated Forecast Model (IFS Cy31r2). Cloud water is described by prognostic equations:

$$\frac{\partial l}{\partial t} = A(l) + S_{\text{conv}} + S_{\text{strat}} - E_{\text{cld}} - G_{\text{prec}},$$

where $A(l)$ represents the transport of cloud water through the boundaries of the grid volume. The terms $S_{\text{conv}}$ and $S_{\text{strat}}$ stand for the cloud water formed by
convective and stratiform condensation processes, respectively. The value \( E_{\text{id}} \) indicates the rate of the evaporation of cloud water, and \( G_{\text{prec}} \) is the generation of precipitation from cloud. The phase of the cloud water is classified as a function of temperature. That is, the cloud is completely in the liquid phase if the temperature of the isobaric level is above 273.16 K and completely ice if below 250.16 K. For those with temperature in between, the fraction of liquid water \( \alpha \) in the total condensate is described as

\[
\alpha = \left( \frac{T - T_{\text{ice}}}{T_0 - T_{\text{ice}}} \right)^2,
\]

where \( T \) is temperature in kelvins, \( T_{\text{ice}} = 250.16 \) K, and \( T_0 = 273.16 \) K. A detailed description of the prognostic cloud scheme could be found in IFS documentation (http://www.ecmwf.int/research/ifsdocs/CY31r1/index.html).

The monthly means of cloud water variables used in this study are remapped to 2.5° × 2.5° using local area averaging from their original 0.75° × 0.75° grid. All the data are obtained from ECMWF data server (http://data-portal.ecmwf.int).

\( f. \) CFSR data

CFSR is a global reanalysis dataset (http://cfs.ncep.noaa.gov/cfsr/) provided by NCEP (Saha et al. 2010). The first guess field for the CFSR is generated by a coupled atmosphere–land–ocean model, and the atmospheric component is run at a spectral truncation of T382 in the horizontal with 64 hybrid vertical layers (a horizontal resolution of about 38 km). The cloud water content of CFSR is a prognostic variable in the atmosphere model (Moorthi et al. 2001) based on a simple cloud microphysics parameterization scheme (Sundqvist et al. 1989; Zhao and Carr 1997), that is,

\[
\frac{\partial q_c}{\partial t} = -\mathbf{V} \cdot \mathbf{q}_c - \sigma \frac{\partial q_c}{\partial \sigma} + S_c + S_g - P - E + F_{qc}.
\]

The term \( q_c \) is the cloud condensate mixing ratio, \( \sigma \) is an isobaric vertical coordinate, \( S_c \) is the formation of cloud water through convective processes, \( S_g \) is the formation of cloud water through grid-scale condensation, \( P \) is the rate of conversion from cloud to precipitation, \( E \) is the evaporation, and \( F_{qc} \) presents the horizontal and vertical diffusion (http://rda.ucar.edu/datasets/ds093.0/#docs/484.pdf). The phase of cloud water has not been distinguished in CFSR in advance. Since the relative humidity in CFSR is computed with respect to water when the temperature is greater than 273 K, with respect to ice when temperature is less than 273 K, and a mix of water and ice in between (http://rda.ucar.edu/datasets/ds093.0/#docs), we treated the phase of the cloud water in the same way.

That is, the cloud water is completely in liquid phase if the air temperature of the isobaric level is above 273 K and completely in ice phase if the temperature is below 253 K. Between 273 and 253 K, the liquid water portion is linearly decreased with the decrease of temperature. The LWC and IWC are calculated from 6-houly CFSR data. Then, spatially and temporally averaged results are calculated every month for the global 2.5° × 2.5° grid.

In this study, the mean distributions of liquid and ice cloud water paths are analyzed first, and trend analysis and empirical orthogonal function (EOF) analysis are applied to the cloud water of the four datasets.

### 3. Distribution of cloud water

\( a. \) Cloud water path

For a general picture of the total CWP, which equals the sum of LWP and IWP, Fig. 1 presents the spatial distribution of CWP retrieved from ISCCP D2, ERA-Interim, and CFSR over the period 1995–2009, MODIS from 2006 to 2011, and CPR data from 2007 to 2010 for boreal winter [December–February (DJF)] and summer [June–August (JJA)]. From the first sight of the CWP in boreal winter (Figs. 1a–e), CWP has great latitudinal gradients and differences over land and over ocean. For oceanic clouds, large values of CWP are mainly distributed over the North Pacific and Atlantic Oceans, intertropical convergence zone (ITCZ), South Pacific convergence zone (SPCZ), and latitudinal band of westerlies around 30°–60°, both in the Northern and Southern Hemispheres. In these areas, CWP can reach up to 100 g m⁻² in ISCCP and CPR data and reach up to 200 g m⁻² in MODIS, ERA-Interim, and CFSR data. CWP over the land also shows significant spatial discontinuities, higher values concentrate over Congo River basin in central Africa, Southeast Asia, and the Amazon basin. Around areas dominated by the subtropical high, such as North Africa and West Australia, CWP values are lower than 10 g m⁻². Generally, the CWP from all the selected datasets show similar global distribution patterns, but the magnitudes are different from each other.

Comparing CWPs in boreal winter (Figs. 1a–e) with those in boreal summer (Figs. 1f–j), seasonal variability can be found over most of the globe, and the variability is more obvious over the land. From winter to summer, CWP over India and South China increases by about 100 g m⁻² in all the datasets, reflecting the increasing of cloud and rain during the summer monsoon. Locations of CWP maximums over the tropical areas also show the advance from south to north. Over the ocean, although CWP shows change in magnitudes and distribution areas, peak locations over westerlies show little change.
This indicates the relative stability of the cloud band in these regions.

Figure 2 presents zonal means of CWP during winter and summer for ISCCP, MODIS, CPR, ERA-Interim, and CFSR data. And the uncertainty interval of CPR data is indicated by the gray shaded area, estimated by a factor of 2. Generally speaking, zonal means mainly reflect the latitudinal inhomogeneity, CWP is concentrated
over tropical and midlatitude areas, and CWP over subtropical and polar regions is relatively lower than others, which are dominated by the large-scale circulation of the atmosphere. In wintertime, zonal means of CWP over the land (Fig. 2a) show maximums over 70°S, around the equator near 10°S, and 50°N. When summer comes, these peaks show a shift of 10° toward the Northern Hemisphere. Over the ocean (Figs. 2b,d), peaks of CWPs show some change in the magnitudes, but concentration centers only show a few moving along the latitude band.

As seen in Fig. 2, there are differences among all the data surveyed; CWPs from different datasets show different values, which could be attributed to the satellite instrument, retrieve method, and the different parameterization used in models. Zonal means of CWP from CFSR and ERA-Interim appear to have higher values in most of the latitude band, especially over land (Figs. 2a,c), while ISCCP has low CWP values, compared to the other datasets. Notably, CWPs from ISCCP, MODIS, ERA-Interim, and CFSR appear to be in good agreement with CPR data in the tropics. But large biases can be found around high-latitude regions.

b. Liquid water path and ice water path

Previously, we consider liquid and ice cloud water as a whole. In the following, we will show the distributions of LWP and IWP separately, as LWP mainly reflects characteristic of warm clouds, while IWP reflects clouds above the frozen height.

Figure 3 presents the mean distribution of the mean LWP over the period 1995–2009 from cloud products of ISCCP, SSM/I, and the two reanalyses, as well as MODIS and CPR data. Generally, large LWP values mainly concentrate in midlatitudes over the ocean. It also shows a good correspondence between LWP and the regions with relatively low sea surface temperatures, where a large number of low clouds are observed (Weare 2000), such as the northeastern and southeastern Pacific and other areas off the west coast of the continents, especially in boreal summer. LWPs over land are mainly located around tropical rain forests.

Comparing LWPs from all of the six datasets, ISCCP (Figs. 3a,g) and MODIS (Figs. 3b,h) show relatively lower values around the ITZC, while the other two satellite datasets of CPR (Figs. 3c,i) and SSM/I (Figs. 3d,j) show an LWP center in the same region. Because both ISCCP and MODIS are passive nadir-view instruments and use visible and inferred channel signals to measure cloud properties, sensors on board cannot see the cloud at a lower level if the upper-level clouds are too thick. CPR uses the active, remote-sensing method to measure cloud characteristics, and SSM/I uses microwave channels, where the signals can penetrate the upper clouds. LWPs from ERA-Interim and CFSR show similar values and magnitudes to SSM/I data over the ocean; this result could be a benefit from the assimilations of satellite data.

Zonal means of LWP are presented in Fig. 4, focusing on the latitudinal gradient of cloud liquid water. Generally, LWPs over the land are lower than those over the ocean, and there are three peaks in the zonal means, corresponding to the ascending branch of the Hadley cell and the Ferrel cell. Locations of the peaks from the...
six datasets are almost the same, but some differences exist. LWP over the land (Figs. 4a,c) show large differences between the satellite and reanalysis data, and ERA-Interim has a high value of LWP (about 100 g m$^{-2}$) around the equator. Over the ocean, SSM/I data show the maximums in these six datasets, peaks can reach up to 140 g m$^{-2}$ in winter. Importantly, ISCCP shows good agreement with MODIS, but has smaller values outside the tropics and subtropics.

IWPs describe the mass of frozen water in the middle and high clouds. Compared with the warm clouds, the formation of ice clouds demands more harsh terms. In addition to sufficient water vapor, strong convective activities are also essential for the formation of cloud ice. Distributions of IWP from ISCCP, MODIS, CPR, ERA-Interim, and CFSR are illustrated in Fig. 5. Some concentration centers can be found over tropical forests, ITCZ, and SPCZ, as well as the regions of the mid-latitudes. In these areas, IWP can reach up to about 120 g m$^{-2}$ for ISCCP (Figs. 5a,i) and 150 g m$^{-2}$ for MODIS (Figs. 5b,g) and CFSR (Figs. 5e,j). While CPR (Figs. 5c,h) and ERA-Interim (Figs. 5d,i) show a lower value of 70 g m$^{-2}$.

Generally, all IWPs of these datasets show similar zonal distribution patterns, as illustrated in Fig. 6. During the boreal winter, zonal means over land (Fig. 6a) show maximums in the Southern Hemisphere around 60°S and in the Northern Hemisphere around 50°N; the maximum value of MODIS can exceed 140 g m$^{-2}$. Another peak is near the equator. Within the three datasets, the zonal mean of CFSR and MODIS exceeds 100 g m$^{-2}$, and CPR, ISCCP, and ERA-Interim are below 60 g m$^{-2}$. In between these latitude bands, IWPs reach the minimums below 20 g m$^{-2}$ around 10°N. Over the ocean (Fig. 6b), IWPs also exhibit three peaks, over midlatitudes around 60°S, 55°N, and near the equator. During the summer (Figs. 6c,d), peaks of IWP show a northward shift, reflecting the seasonal movement of the cloud band over the globe. Noticeably, IWP from ISCCP show a good agreement with that of CPR, but has larger values outside the tropics; this result is correspondent to the work of Eliasson et al. (2011).

4. Variation of cloud water

To illustrate the variations of cloud water in the period from 1995 to 2009, we analyzed the time series of CWP anomalies first. Considering that data of ISCCP are less accurate over the polar regions, analyses are only conducted over 60°S–60°N. As shown in Fig. 7, CWP of ISCCP exhibits lower values over 1995–2002, and anomalies in this time period are about $-10$ g m$^{-2}$.
After 2002, CWP anomalies rise gradually, and by the end of 2009, the magnitude of the anomaly is near $18 \text{ g m}^{-2}$. Along with ISCCP data, CWP anomalies of ERA-Interim and CFSR are shown in Figs. 7b and 7c. Compared with ISCCP, the amplitudes of CWP anomalies of the two reanalyses data are smaller, only about half of ISCCP. It is noticeable that ERA-Interim and CFSR mainly show negative CWP anomalies before 2003, except for 1998. Generally, CWP anomalies of these data also show the influence of some climate events, such as the El Niño in 2009. In addition, both ERA-Interim and CFSR represent high positive anomalies in 1998, while...
ISCCP only shows a small negative value, since CWPs of ISCCP before 2002 are mainly lower than those after 2002.

We also conduct our analysis on the linear trend of CWP by the method of least squares. These datasets show significant increasing trend in the period 1995–2009. The annual linear change trend are 1.05 g m\(^{-2}\) for ISCCP, 0.13 g m\(^{-2}\) for ERA-Interim, and 0.18 g m\(^{-2}\) for CFSR, and all of them pass the significance test at the 95% level.

Anomalies and results of linear regression of LWPs are depicted in Fig. 8. Over the land, only ISCCP (Fig. 8a) shows an increasing trend, while ERA-Interim (Fig. 8c) and CFSR (Fig. 8e) exhibit no significant upward or downward linear trend. From the data over the ocean, it is evident that LWPs of ISCCP, ERA-Interim, and CFSR (Figs. 8b,d,f) increase in 1995–2009; the slope of the trend lines is 0.436, 0.199, and 0.362 g m\(^{-2}\) yr\(^{-1}\), respectively. LWPs of SSM/I data over the ocean shows a decreasing trend of 0.072 g m\(^{-2}\) yr\(^{-1}\), yet this result does not pass the significance test at the 95% level.

Anomalies of IWPAs of ISCCP, ERA-Interim, and CFSR are shown in Fig. 9. Generally, magnitudes of IWP anomalies over the land (Figs. 9a,c,e) are twice those over the ocean (Figs. 9b,d,f), reflecting the relatively stability of IWP over the ocean. The maximum anomaly of ISCCP, 12 g m\(^{-2}\) over the land and 6 g m\(^{-2}\) over the ocean, occurs in 2001. Compared to ISCCP, IWP anomalies of ERA-Interim and CFSR maintain smaller magnitudes, and the maximum anomaly amplitude is about 2 g m\(^{-2}\) in ERA-Interim and 3 g m\(^{-2}\) in CFSR. Furthermore, a significant increasing trend can be found in ISCCP data. The growth rate of IWP is 0.371 g m\(^{-2}\) yr\(^{-1}\) over the land and 0.461 g m\(^{-2}\) yr\(^{-1}\) over the ocean (exceeding the 95% confidence level). IWP of ERA-Interim show no significant change trend, and IWP of CFSR present a slight upward trend over the land (0.090 g m\(^{-2}\) yr\(^{-1}\)) and decreasing trend over the ocean (0.079 g m\(^{-2}\) yr\(^{-1}\)) during the time period.

EOFs are introduced into climate studies to discuss spatial patterns and how the patterns change with time. We conduct EOF analyses on the monthly anomalies of CWP, LWP, and IWP from 1995 to 2009. The first dominant eigenvectors and corresponding time coefficient series are illustrated in Figs. 10–12. Each of the modes is distinct from the nearest neighbor using the North et al. (1982) criterion.

The first mode of CWP explains 14.4%, 5.0%, and 5.0% of the total variance for ISCCP, ERA-Interim, and CFSR, respectively. There are some noticeable features in the first EOFs. The modes of ISCCP (Fig. 10a) show a three-band zonal pattern over the western Pacific Ocean, the peak center occurs over the ITCZ and the valley center occurs over the westerlies. Furthermore, minimums also occur over the southern end of Africa and South America. From the time coefficient series of ISCCP (Fig. 10d) a significant sign reverse can be found around 2002. Before 2002, all the signs of the time coefficients are negative, reflecting the decreasing of CWP in the positive-phase regions, such as areas over the western Pacific ITCZ, while CWP mainly increases outside these areas. Time coefficients reach the minimum in 2001; after this time point, all sign of time coefficients is positive, and the amplitudes keep increasing, reflecting the increasing trend over ITCZ and the eastern Pacific Ocean regions. The first mode in ERA-Interim and CFSR (Figs. 10b,c) shows a similar pattern that is positive phase over South China, Southeast Asia, and the western Pacific along the coast line, while CWP exhibits negative phase over most of ITCZ, SPCZ, and midlatitude in land. Time coefficient series of the first mode for ERA-Interim (Fig. 10e) are also similar to CFSR (Fig. 10f). Generally, in 1998, 2003, 2005, 2007, and 2009, time coefficients are below zero, showing the relatively low CWPs over the western Pacific Oceans.
EOF modes of LWP over the globe are illustrated in Fig. 11. About 5% of the total variance is explained by the first EOF mode, corresponding to the most significant changing patterns of anomalies. The modes of ISCCP, ERA-Interim, and CFSR (Figs. 11a–c) show a north–south-oriented three-band zonal pattern, positive phase around the equator and negative phase in the midlatitudes. Also, the mode reflects an east–west contrast over the Pacific Ocean. Over land, the mode shows negative phase centers over northern Africa, southern China, most of the United States, and eastern Brazil. Compared to the mean LWP (Fig. 3), the EOF patterns show good agreement with the horizontal distribution of LWP. The time coefficients of ISCCP and CFSR show a significant reversal around 1999. Before 1999, all the signs of the time coefficients are negative, and the minimum come in 1998, reflecting the increasing of LWP around ITCZ over the western Pacific Ocean, while LWP's along the eastern Pacific coast lines are mainly decreasing in these years. The time series of ERA-Interim also exhibits a sign reversal, but the time point is around 2002. Over the oceans, EOF modes of ISCCP, ERA-Interim, CFSR, and SSM/I datasets are illustrated in Figs. 11g–n. Generally, EOF modes and time coefficients of ISCCP, ERA-Interim, and CFSR over the ocean are similar to those over the globe. The EOF mode of SSM/I data shows a similar pattern to that of CFSR. The time coefficients reach the minimum around 1998, after this year, the time coefficients mainly remain a positive value.

The EOF modes of the IWP anomalies (Fig. 12) are similar to the modes of CWP, showing a three-band zonal pattern over the Pacific, that is, a positive phase center over the ITCZ and negative centers over the westerlies. Time coefficients of IWP are also similar to that of CWP. These similarities reflect that the variations of IWP are the main contributor to the variations of CWP in ISCCP, ERA-Interim, and CFSR datasets.

To depict the relationship between the variation of cloud water and the variation of temperature and water
vapor, anomalies of temperature over the global surface, column-integrated water vapor (CWV), and temperature and specific humidity $Q$ at different isobaric levels are illustrated in Fig. 13. Here we only show the result of ERA-Interim, since the surface temperature (TS) is not analyzed in CFSR, and vertical distributions of temperature and specific humidity of CFSR show similar patterns to those of ERA-Interim. As shown in Figs. 13a, 13c, 13e, and 13g, there are some noticeable features in the anomalies of temperature and water vapor over the land. TS (Fig. 13a) reaches a minimum in 1996, 2001, and 2008, where the anomalies are less than 0.8 K, and reaches its peak in 1998 and 2002. From the monthly anomalies of temperature at different isobaric level we can see that maximum amplitudes (Fig. 13c) of anomalies always occur near the surface and above 700 hPa, and anomalies of temperature variations show a similar regularity to surface temperature. Furthermore,

![FIG. 9. As in Fig. 8, but for IWP.](image-url)

![FIG. 10. (a)–(c) Spatial distributions of the first mode of CWP, number above each panel reflects the percentage of total variance described by the first mode, and (d)–(f) the corresponding time coefficients.](image-url)
CWV and specific humidity also rise when the temperature is getting warmer, and the maximum anomaly of column-integrated water vapor occurs in 1998. Compared to land, temperature and water vapor over the ocean have followed a similar pattern, but the amplitudes of sea surface temperature and CWV is smaller; the maximum anomalies of TS are only 0.2 K. By comparing the variations of temperature, water vapor (Fig. 13), and cloud water (Figs. 7–9), some interesting features can be found. Generally, when temperatures rise,
CWP, LWP, and IWP also exhibit a rising anomaly, especially in the ERA-Interim, CFSR, and SSM/I data. This corresponds to the results in the work of Weng et al. (1997), because warmer air could hold water. Finally, the source of cloud condensation will become richer (Wentz et al. 2007).

5. Summary and conclusions

In this paper, we analyzed the climatology of CWP, LWP, and IWP from ISCCP, MODIS, CloudSat, SSM/I, ERA-Interim, and CFSR. We also show the long-term variability of CWP, LWP, and IWP from ISCCP, SSM/I, ERA-Interim, and CFSR in the time range between 1995 and 2009.

Generally, large values of CWP, LWP, and IWPs are mainly concentrated over the North Pacific and Atlantic Oceans, eastern ITCZ, areas off the west coast of the continents, and tropical rain forest, while clouds in the regions dominated by subtropical high are less than other regions. The distribution of cloud water is related with the atmospheric circulation, and cloud water centers show a latitudinal shift with the change of the seasons. The climatology of CWP, LWP, and IWP from
several independent datasets shows similar distributions and zonal means. Figure 2 shows a relatively good agreement among CPRs from the satellite data of ISCCP, MODIS, and CPR, as well as reanalysis datasets, and zonal means remain in the uncertainty intervals of CPR data. Furthermore, ISCCP appears to have good agreement with MODIS in terms of LWP and with CPR in IWP. This result indicates a relatively good data quality of ISCCP cloud water data in the use of climatology study.

By analyzing the anomalies of CWP, LWP, and IWP during 1995–2009, variations of cloud water are studied. The CWP anomalies show an increasing trend in ISCCP, ERA-Interim, and CFSR datasets in the time period considered, and a significant increasing trend of LWP has been found in ISCCP, ERA-Interim, and CFSR over the ocean too. But LWP in SSM/I data shows no significant trend. What is more, ISCCP also shows an increasing trend in IWP. The results from EOF analysis show a similar distribution of positive and negative centers between the dominant mode pattern of CWP and IWP for ISCCP, ERA-Interim, and CFSR datasets. And the time coefficients of the first mode of LWP in these three datasets show a sign reversal around 1999 (ISCCP and CFSR) and 2002 (ERA-Interim).

In terms of CWP, LWP, and IWP in ISCCP dataset, cloud water is calculated by multiplying cloud optical depth by a fixed coefficient [Eqs. (1) and (2)] for the 15 kinds of cloud types (Rossow and Schiffer 1999), so the increasing trend in the time period of 1995–2009 reflects an internally increasing cloud optical depth from 1995 to 2009. By using passive nadir-viewing sensors in visible and infrared channels, results from ISCCP mainly show the information at the top of clouds, while SSM/I, in the microwave channels, could get information from the whole cloud column (Wentz 1997; Wentz and Spencer 1998). As shown in Figs. 3 and 4, there is a large difference between LWP from ISCCP and SSM/I resulting from the different remote sensing methods, different instrument sensitivity, and different retrieval algorithms, and the long-term variability of LWP also shows a noticeable difference. Cloud water in ERA-Interim and CFSR are computed by some governing equations in the numerical models (Moorthi et al. 2001; Dee et al. 2011). The temperature and humidity of the air mass are some terms that determine the formation of the cloud in the models. As illustrated in Figs. 7–9 and 13, when temperature and humidity reach higher values, CWP, LWP, and IWP in the reanalysis datasets always show higher values. These reasons partially describe the differences among the long-term trends of cloud water in the four datasets, but more detailed diagnosis needs to be done on the change of cloud water and the water budget, as well as the uncertainties intrinsic to the SSM/I and ISCCP algorithms.

Additionally, since clouds have a significant effect on the radiative balance, changes of cloud water will lead to the change of radiative budget. As discussed previously, there are some differences in the change trend of CWP, LWP, and IWP among ISCCP, ERA-Interim, and CFSR. Further studies are needed to answer the question whether ERA-Interim and CFSR can represent a corrected radiative budget states of the current climate.

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REFERENCES


