Article ID: 1006-8775(2013) 02-0171-10

VARIATIONS OF CLOUD FRACTION OVER EAST ASIA UNDER GLOBAL WARMING CONDITIONS IN THE PAST 20 YEARS

WU Jian (吴　涧)[1], LIU Jia (刘　佳)[2]

(1. Department of Atmospheric Science, Yunnan University, Kunming 650091 China; 2. Honghe Meteorological Office, Mengzi, Yunnan 661100 China)

Abstract: Based on the variation of cloud fraction revealed by D2 Cloud Climatic Data of the International Satellite Cloud Climatology Project and trend analysis methods, the trend of different types of cloud fraction over East Asia during 1984–2006 is obtained. The analysis focuses on the relationship between temperature and different cloud fraction under the background of globe warming. The result shows a fluctuating decreasing tendency in the total cloud fraction, high-level cloud and low-level cloud over East Asia with the decrement being 2.24%, 1.65% and 1.68%, respectively, while the mid-level cloud increases by 1.07%. In addition, there are great regional differences in cloud fraction. Temperature and water-vapor content variation caused by the greenhouse effects over East Asia is the primary reason for the variation of cloud fraction. Over the Tibetan Plateau, the Bay of Bengal and the Intertropical Convergence Zone, the temperature is negatively correlated with high-level cloud, but positively correlated with mid- and low-level cloud. However, over the West Pacific and the ocean east and north of Japan, the temperature is negatively correlated with low-level cloud but positively correlated with high-level cloud.

Key words: cloud fraction; greenhouse effect; East Asia; trend analysis

CLC number: P426.5 **Document code:** A

1 INTRODUCTION

As an important factor influencing climate change, cloud plays a vital role in weather, climate and global changes. Cloud adjusts the radiation energy and water balance of the earth-atmosphere system. Changes in cloud properties may impact on the global climate change while in turn climate change would also lead to the adjustment of cloud properties. For this reason, study on cloud climatology attracted early, great attention [1, 2].

Because of the important role that cloud plays in the climate system, the change in cloud fraction in different regions and time scales has been extensively studied. Ground-based observation showed that the total cloud fraction across many continents has shown an increasing trend since the mid-1950s[3], such as in most parts of the United States[4, 5], former USSR[6], Antarctic[7], as well as Western Europe, Canada (mid-latitude region) and Australia, etc[4]. However, the total cloud fraction decreases in some other areas. For example, in most areas of China, the total cloud fraction in day and night has reduced by 1% to 2% during 1951–1994[8, 9]. Besides, the total cloud fraction also decreases across Italy[10] and Central Europe[11]. These results revealed that the changing trend of cloud fraction is not the same in different parts of the world.

Liu et al. analyzed the total cloud fraction across the sky of China[12]. Wei and Zhong[13] believed that the distribution of total cloud fraction over the Tibetan Plateau is different from summer to winter. Chen et al.[14] claimed that the total cloud fraction declines from southeast to northwest of the Plateau but is more stable in summer than in winter. Besides, it is steadier in the east than in the west part. Moreover, the interannual and seasonal variation of total cloud fraction declines evidently. Different cloud types play different roles in the global climate system. For lack of different kinds of cloud data in climatology, most study about the cloud distribution only concentrated on the total cloud fraction. Now it is possible to carry out the analysis of different cloud types with further development of the International Satellite Cloud Climatology Project (ISCCP). Ding et al.[15] analyzed the global cloud fraction changes in the past 20 years with the ISCCP D2 data and attempted to explore its

Received 2012-01-18; **Revised** 2013-01-30; **Accepted** 2013-04-15

Foundation item: National Key Program for Developing Fundamental Sciences of China (2011CB952003); Natural Science Foundation of China (40975092, 41275162)

Biography: WU Jian, Ph.D., primarily undertaking research on aerosol and climate change.

Corresponding author: WU Jian, e-mail: wujian@ynu.edu.cn

possible influence on climate change.

The previous studies mostly focused on the temporal and spatial distribution of total cloud cover in specific regions. Presently, we need more research on the cloud fraction changes in East Asia, especially with regard to the relationship between the changes of cloud fraction and global warming and water vapor content variation. With its unique geographical location, East Asia is the major area of Asian monsoon activities. Climate change shows significantly over the East Asia, a continent with dense population and frequent human activities. Therefore, study on the basic features of changes in cloud fraction in East Asia has a great scientific implication. Especially, in the context of recent global warming, it is necessary to have a comprehensive understanding of the changes of cloud fraction over East Asia and to discuss the potential impact of global warming on cloud fraction.

2 DATA AND METHODS

The International Satellite Cloud Climatology Project (ISCCP) is a subordinate program of the World Climatology Research Project (WCRP). The observation data of cloud are the radiation measured by four geosynchronous satellites (GMS, METEOSAT, GOES, INSAT) and at least one sun-synchronous polar-orbiting satellite (NOAA). The D2 Cloud Climatology Data used in this paper is issued by ISCCP recently and much improved[16]. Researchers described the cloud detection method of ISCCP and the basic statistical features in detail[16, 17]. Presently, the maximal error in this dataset is estimated at 5% for cloud fraction and 10% for optic thickness[16]. Comparing with other data (including earth-based observation data, satellite data with higher spatial resolution and other cloud climatological data), Rossow and Garder[18], Rossow et al.[19], and Hahn et al.[20] also showed that the cloud fraction data of ISCCP fit other cloud data highly with global deviation at about 4%. Generally speaking, cloud observation data of ISCCP can truly reflect the cloud distribution all over the world and at present it is the best cloud climatology data covering every corner of the world. Its good applicability in China was also recognized in Wei et al.[21], Weng and Han[22], and Wang et al.[23].

The D2 cloud climatology data collects 130 parameters about the total cloud fraction, air pressure of cloud top, temperature of the cloud top (of high-level, medium and low-level cloud), optic thickness of cloud, cloud water path, etc. This paper primarily uses the cloud fraction data from July 1983 to December 2006 and the spatial resolution is 2.5 °×2.5 °. The cloud is divided into three categories based on the pressure of cloud top, including low-level cloud (with cloud top pressure higher than 680 hPa), mid-level cloud (with cloud top pressure between 680 hPa and 440 hPa) and high-level cloud (with cloud top pressure lower than 440 hPa)[20]. Cloud fraction ranges from 0 to 100 (%), with clear sky expressed by 0 and full cloud fraction expressed by 100%. The temperature and specific humidity data are gained from the NCEP reanalysis dataset during the same period with similar spatial resolution. Analytic techniques used in this paper include trend analysis[24], the Mann-kendall catastrophe test method[25], correlation analysis, etc.

The linear regression coefficients is calculated as in

$$a = \frac{\sum_{i=1}^{n} t_i y_i - \frac{1}{n}(\sum_{i=1}^{n} t_i)(\sum_{i=1}^{n} y_i)}{\sum_{i=1}^{n} t_i^2 - \frac{1}{n}(\sum_{i=1}^{n} t_i)^2} \tag{1}$$

in which y_i, t_i and n represent the value for each year, the appropriate year for y_i, and the length of sample, respectively.

The linear trend coefficient r_{ty} is also calculated, where s_t and s_y represent variances of the serials of the year and analyzed observation variable respectively, as in

$$r_{ty} = \frac{s_t}{s_y} \bullet a\ . \tag{2}$$

Then, the deviation of temperature and specific humidity is standardized,

$$y' = \frac{y - \bar{y}}{s}, s = \sqrt{\sum_{i=1}^{n} (y - \bar{y})^2}\ . \tag{3}$$

The water-vapor content (w) of the whole layer in the atmosphere can be expressed as

$$w = \frac{1}{\rho g} \int_{p}^{p_0} q \, \mathrm{d}\, p \tag{4}$$

in which q stands for specific humidity, p for pressure, ρ for liquid water density, g for acceleration of gravity, and p_0 for sea level pressure, respectively.

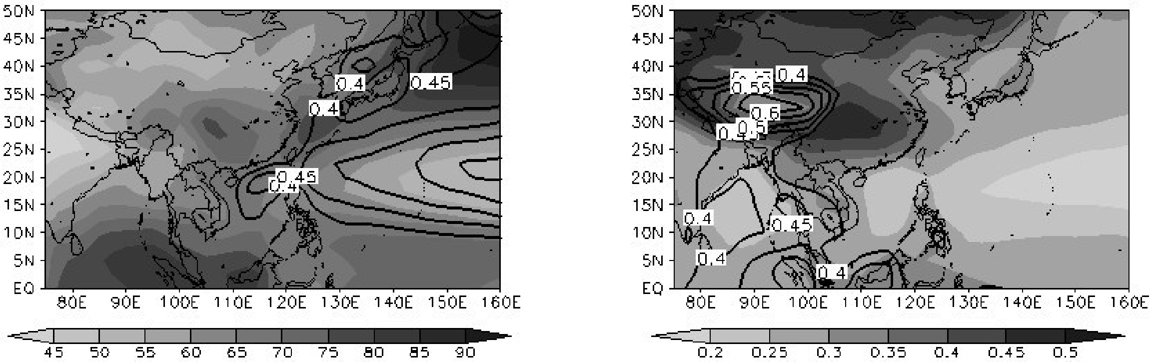
3 RESULTS AND ANALYSIS

3.1 *Distribution features of average cloud fraction*

Figure 1 shows the average distribution features of different kinds of cloud fraction over East Asia for the 23 years.

Total cloud fraction is the largest in the following three regions: the ocean to the east and north of Japan, the Bay of Bengal and its eastern region, and the western Pacific in the tropical convergence zone (ITCZ). The second highest cloud fraction occurs in Northeast China and the area along Yangtze River, while the least cloud fraction is over the Northwest

China, the Indian Ocean and the central Pacific. Low-level cloud mainly distributes over the ocean, especially the ocean to the east and north of Japan, central Pacific and South China Sea. Particularly, low-level cloud over the central Pacific takes up more than 60% whereas the mid- and high-level cloud in this area only account for 20% and 25% of the total amount, respectively. Mid-level cloud is generally in the northern areas of the land. Specifically, the highest mid-level cloud fraction is along Yangtze River while the Tibetan Plateau is the second highest, and the lowest one is over the Bay of Bengal, South China Sea and central Pacific. Nevertheless, the high-level cloud is mainly located over the high-altitude Tibetan Plateau, as well as the Bay of Bengal and ITCZ with frequent convective activities. This is in accordance with the results of Kang et al.[26]. The Tibetan Plateau has the most high-level cloud cover, taking up 60% of the total cloud fraction, followed by the Bay of Bengal and ITCZ, 50% and 40%, respectively. However, there is less high-level cloud in Northeast China, the oceans east and north of Japan and southeastern part of the South China Sea.

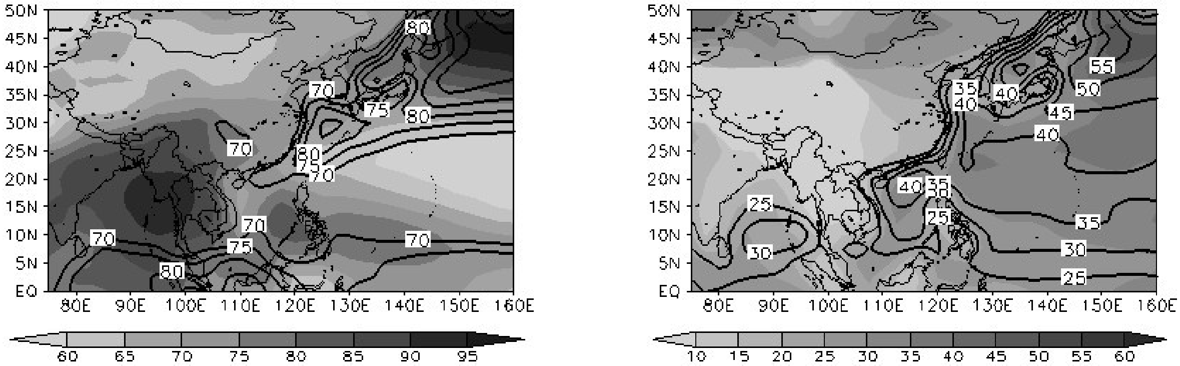


a. total cloud fraction and low cloud fraction b. middle cloud fraction and high cloud fraction

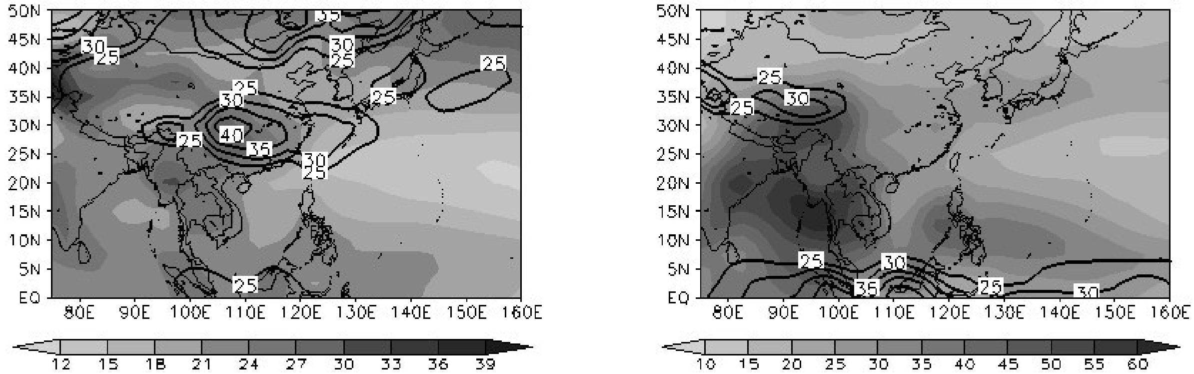
Figure 1. Annual average distributions of cloud fraction over East Asia for 1984-2006 (shading is for total cloud and middle cloud, contours are for the low and high-level cloud. Unit: %).

There is significant variation of cloud heights in the three high-value areas of total cloud fraction. The ocean east and north of Japan is mostly covered by low-level cloud because the high humidity over the ocean intrigues condensation at low levels. The Bay of Bengal and ITCZ are mainly covered by high-level cloud since strong solar radiation and rich water vapor trigger strong convection easily, which then forms more high cloud in low-latitude areas. As shown in Figure 1, total cloud fraction, mid-level cloud and high-level cloud are all small along 20°N, apparently because of the sinking of Hadley circulation over these areas.

Annual average distributions of total cloud fraction, high-level cloud, mid-level cloud and low-level cloud in summer and winter are shown in Figure 2. In summer, the total cloud fraction is highest over the ocean east and north of Japan, the Bay of Bengal and the ITCZ. Note that the total cloud fraction reaches a peak of 90% over the ocean east and north of Japan, with most cloud at the low level and some at the high level. However, the proportions over the Bay of Bengal and the ITCZ are 90% and 75%, respectively, with more high-level cloud than low-level cloud. In winter, the three high-value areas still exist, but the value over the ocean east and north of Japan increases and the high-value regions expand to the south till around 25°N. Meanwhile, the high-value regions over the Bay of Bengal and the ITCZ shrink to the equatorial zone and the percentages decrease to 85% and 70%, respectively.



a. total cloud fraction b. low-level cloud fraction



c. middle cloud fraction d. high-level cloud fraction

Figure 2. As in Figure 1 but for summer (shading) and winter (contour). Units: %.

It can be seen in Figure 2 that the total cloud fraction is more in summer than in winter. The low-value area of cloud fraction near 20°N appears in winter but disappears and changes to a high-value area over the central Bay of Bengal with the maximum over 90%. There is more low-level cloud in winter than in summer. Take the area east of Japan for example. The low-level cloud takes up 45% of the total in summer but rises to over 55% in winter with the high-value areas expanding to the central Pacific. The mid-level cloud fraction in summer and winter are equal, as shown in Figure 2. In winter, low-value areas of mid-level cloud are around 20°N but they only appear over the ocean in summer. In the southeast of China where mid-level cloud is usually large in proportion, the value is higher in winter (with the maximum more than 40%) than in summer (with the maximum at 35%). Figure 2 also suggests that high cloud is more in summer than in winter. In summer, the high cloud fraction is large over the Bay of Bengal and the Tibetan Plateau with the highest percentage over 65% and the values over vast areas surrounding it are relatively high. The second highest value exists in the ITCZ with the highest value of 50%. In winter, the high-value area of high-level cloud moves southward, with the area of highest central value (40%) near the equator. The proportion of high-level cloud over the Tibetan Plateau is 35%. Low-value areas of total cloud fraction and mid- and high-level cloud fraction appear in the belt between 15–25°N in winter but disappear in summer. Apparently, the feature is induced by the southward (northward) movement of circulation in winter (summer). Water vapor forms cloud easily without deep convection. Therefore, the proportion of low-level cloud is relatively large. There is more low-level cloud over the ocean east and north of Japan in winter. This is related to weak convection and frequent cold air activities. Table 1 presents cloud variations in East Asia regardless of summer or winter, in which total cloud cover, and low- and high-level cloud all show a decreasing trend while mid-level cloud increases. The linear trend coefficients show that all kinds of cloud change evidently in these years. Both the rising trend of mid-level cloud and falling trend of high-level cloud are more significant in summer than in winter. In contrast, the falling trend of low-level cloud is more noticeable in winter than in summer (Table 1).

Table 1. Could amount changes in 1984-2006.

Cloud fraction	Summer		Winter		Annual mean		Total variation in 1984-2006(%)
	Average variability (% per year)	Linear trend coefficient	Average variability (% per year)	Linear trend coefficient	Average variability (% per year)	Linear trend coefficient	
Total cloud	–0.05	–0.22	–0.12	**–0.35**	–0.10	**–0.40**	–2.24
Low cloud	–0.03	–0.28	–0.12	**–0.70**	–0.07	**–0.66**	–1.68
Middle cloud	0.07	**0.78**	0.04	0.26	0.05	**0.48**	1.07
High cloud	–0.13	**–0.64**	–0.04	–0.20	–0.07	**–0.43**	–1.65

Notes: The linear trend coefficients defined by Eq. (2) passing the significance *t*-test at the 0.05 level are highlighted by the bold numerals.

The annual cycle of monthly cloud fraction also shows that total cloud fraction in summer is more than that in winter. In summer, high-level cloud is the most, followed by mid-level and low-level cloud, while the situation in winter is just the opposite (Figure 3). The total cloud fraction in February falls to the minimum at 60.2% and high-level cloud fraction reaches the lowest in January at 12.5%. In July, total cloud fraction and high-level cloud gradually increase and peak at 74% and 32%, respectively before declining. However, the low-level cloud shows another picture. Before falling to the bottom at 15.2% in July, it increases to 24%, the highest point in January, and then declines slightly. Mid-level cloud changes slightly from summer to winter keeping at 15.5%–20.5% in the year round, with the proportion falling to percentages between high-level and low-level cloud.

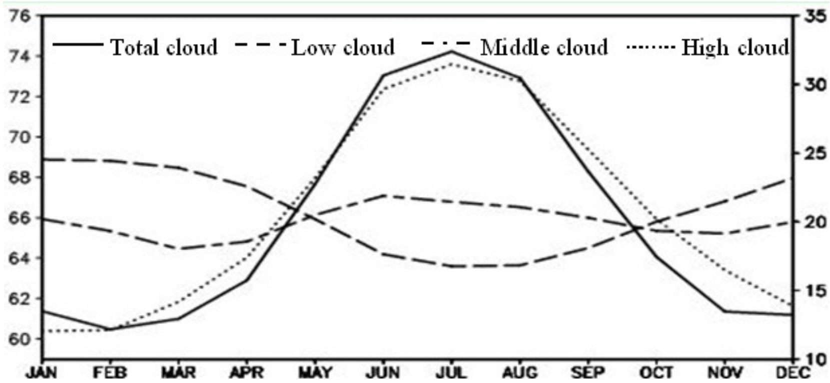
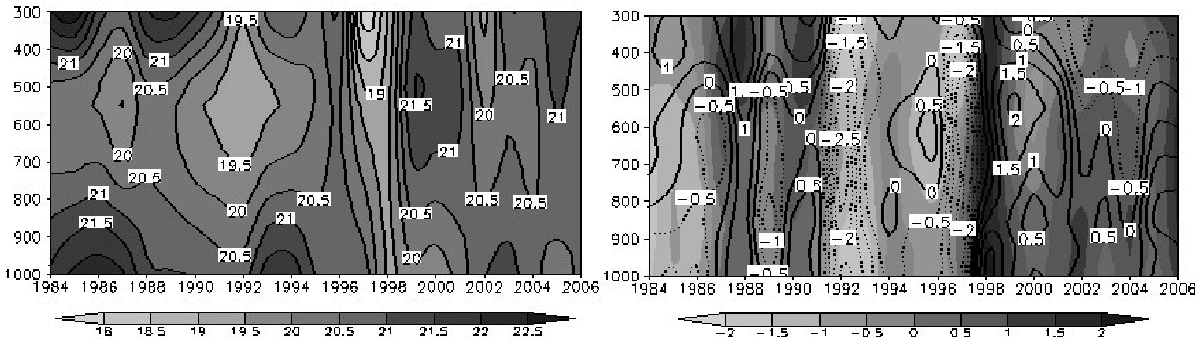


Figure 3. Time series of monthly cloud fraction in East Asia. The left coordinate is the change of total cloud fraction, and the right coordinate is the change of high-level cloud, middle cloud and low-level cloud. Units: %.

3.2 *Interannual variability of cloud fraction, temperature and humidity in East Asia*

Spatial and temporal variations of cloud fraction in East Asia from 1984 to 2006 are shown in Figure 4a. In recent years, total cloud fraction, low-level and high-level cloud all show a decreasing trend, while mid-level cloud shows an increasing one. The distribution is in accordance with the trend of global cloud change[15, 27]. Maximum (22.5%) of high-level cloud fraction appeared in 1985 and the minimum (18%) was in 1997, while the counterparts of low-level cloud fraction appeared in 1986 and 1998 at 22% and 19.5%, respectively. Mid-level cloud kept rising and peaked in 1999 at 21.5% and bottomed in 1992 at 19.5%. Before 1998, both low-level and high-level cloud exceeded mid-level cloud and the minimum of high-level cloud and low-level cloud both appeared in 1997. After 1998, mid-level cloud increased noticeably with the maximum 21.5% in 1999. In order to further understand the temporal evolution of clouds changing features, a catastrophe test by applying the Mann-Kendall (M-K for short) approach is carried out. The result showed that 1986 is the year in which the catastrophe point occurred for total cloud fraction and high-level cloud. Before and after 1986, the average values of total cloud fraction are 68.6% and 66.0% respectively and those of high-level cloud are 22.2% and 20.6%. As mentioned above, the highest value of total cloud fraction and high-level cloud existed in 1985, followed by a noticeable decrease. However, the catastrophe point of low-level cloud is in 1989, and before and after that year, the low-level cloud fraction is 21.7% and 20.7%, respectively. The catastrophe points of mid-level cloud are in 1998, 2001, and 2003, respectively.



a. cloud fraction b. temperature (shade) and water vapor (contour)

Figure 4. Temporal and spatial variation of cloud fraction, temperature and water vapor standard deviation in East Asia. Vertical axis is the pressure (Units: hPa).

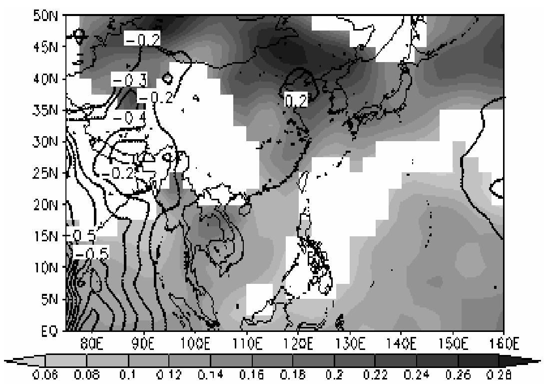
The relationship between cloud fraction changes and temperatures and humidity over East Asia is also explored. Figure 4b shows the spatial and temporal distribution of standard deviation of temperatures and humidity calculated with Eq. (3). The changes in the standard deviation of temperatures and humidity along with time and height are quite similar and they are closely related with the cloud fraction change. After 1986, air-column temperatures rose substantially with the centers at the middle and high levels. Air humidity increased as well. The standard deviations of temperature and water vapor between 1991 and 1997 are almost negative but they are large positive values for 1998 and after that, both temperature and water vapor are positive at mid- and lower-level but negative at higher levels. From 1986 to 1990, a noticeable rise in temperature led to a declining trend of mid-level cloud, and then in 1992, relatively low humidity contributed to small fractions of mid-level cloud and high-level cloud. In 1998 temperature rose quickly almost through the entire troposphere, and at the same time, high-level cloud, mid-level cloud and low-level cloud fractions all fell to their lowest points in recent years. It is found that abrupt temperature change happened in 1987, 1997 and 2002 according to the M-K mutation test. Temperature increased remarkably after 1998. Almost simultaneously, abrupt changes in total water content took place in 1987, 1997 and 2001, in accordance with the abrupt changes in different kinds of cloud. The general trend of temperature over East Asia is increasing with the annual variability at 0.14 °C/year, or specifically, 0.14 °C/year in winter but 0.13 °C/year in summer, respectively. However, the changes in total cloud fraction are opposite to the temperature variation, showing a general decreasing trend with the annual variation at –0.1%, or specifically, –0.12%/year in winter and –0.05%/year in summer, respectively. Then Eq. (1) is used to achieve the linear regression coefficient of cloud fraction, mass-weighted temperature, and humidity in height ranges of different kinds of clouds (Table 2). Total cloud fraction, high-level and low-level cloud are all reduced except for the increased mid-level cloud. Temperatures at all layers are significantly rising, particularly at the middle layer, whereas humidity increases considerably at the low level and slightly at mid-level, but reduces slightly at the high level. As shown in Figures 4a and 4b and Table 2, rising temperature and falling humidity will lead to large reduction of cloud fraction, and vise versa.

3.3 *Correlation between cloud fraction and temperature, water vapor*

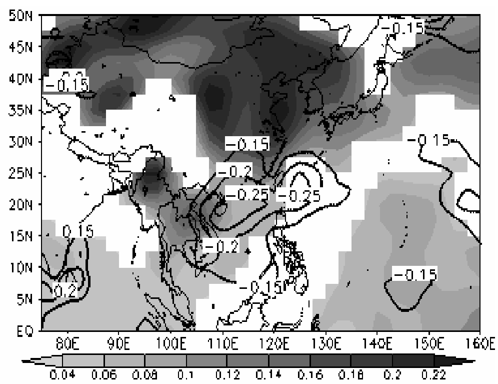
Using least squares analysis of the cloud and the related temperature trends in Eq. (1), we present the primary results in Figure 5, which shows the temperature field for high-level, mid-level and low-level cloud in which the height of their temperature ranges are obtained by taking a mass-weighted calculation.

Table 2. Linear regression coefficient of cloud fraction, temperature, and water vapor for each layer.

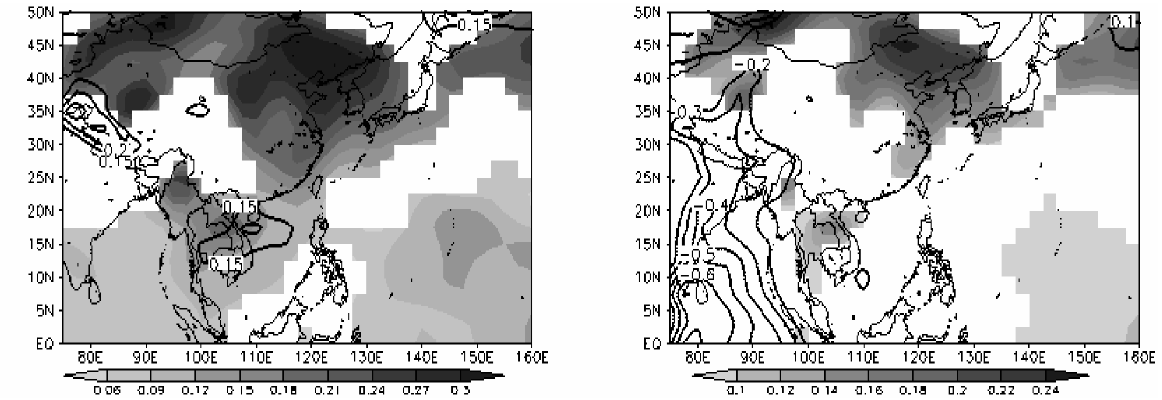
	Cloud fraction variability (% per year)	Temperature variability (℃ per year)	Water vapor variability (mm per year)
Corresponding level of high cloud	–0.07	0.07	-0.08×10^{-2}
Corresponding level of middle cloud	0.05	0.12	0.02×10^{-1}
Corresponding level of low cloud	–0.07	0.08	0.04
The whole layer	–0.10	0.11	0.05



a. Total cloud fraction and corresponding temperature field;



b. Low-level cloud and corresponding temperature field;



c. Middle cloud and corresponding temperature field; d. high-level cloud and corresponding temperature field.

Figure 5. Changing trends of all kinds of cloud fraction and corresponding temperature field in East Asia from 1984 to 2006. All of them pass the 95% significance test. Shading: temperature field (Units: °C/year); contour: cloud fraction (Units: %/year). The solid and dotted line shows the decrease and the increase, respectively.

Temperatures at different heights are relatively consistent in distribution. The trend is generally increasing, more significantly in the area north of 35°N than south of it. A weaker warming center exists in the lower latitudes of Indochina Peninsula; meanwhile the main cooling centers are located over the Tibetan Plateau, the Philippines and other places. Total cloud fraction over the Tibetan Plateau and the region from the Bay of Bengal tends to decrease, with the fastest reduction over the Bay of Bengal, reaching –0.7%/year. However, the total cloud fraction increases slightly at 100°E east of China, with the fastest growth over North China, as much as 0.3%/year. The fraction of total and low-level cloud over the western Pacific is mildly decreased, accompanied by a reduction center of low-level cloud over the South China Sea and the Philippines, with the center value reaching –0.3%/year. Low-level cloud increases slightly over mainland China, with the fastest growth over the Bay of Bengal and a central value at 0.3%/ year. Mid-level cloud tends to decrease mildly in recent years over the continent after keeping a large amount for many years. In the middle of the continent, the reduction is more evident, but there is an increasing trend of mid-level cloud over the Tibetan Plateau, with the center value at 0.3%/year. There is also a weak increment over the Indian subcontinent. The trend of high-level cloud is consistent with that of total cloud fraction, and the most significant area of high-level cloud reduction is the Bay of Bengal, with the central value at –0.5%/year, followed by the Tibetan Plateau. In general, the total cloud fraction in recent years reduces over the plateau and the proportion of high-level cloud shows a decreasing trend while the mid-level cloud increases. The total cloud and high-level cloud over the Bay of Bengal reduces but low-level cloud increases. The total cloud of West Pacific reduces whereas the low-level cloud has a mildly decreasing tendency but the high-level cloud slightly increases. The low-level cloud near the Philippines decreases but the mid-level cloud and high-level cloud increase. Because of the enhanced temperature and convection, more significant warming appears over the West Pacific, the South China Sea, the Philippine Islands, and the area north of 30°N, being conducive to generating more mid-level cloud and high-level cloud. Convection weakens as temperature decreases near the Tibetan Plateau, leading to decreased high-level cloud and increased mid-level and low-level cloud. This is a factor important for the entire region of East Asia: the high-level and low-level cloud decrease but the mid-level cloud increases. Figure 6 shows a changing trend of water vapor with respect to the ranges of different cloud altitude calculated with Eq. (4). Water vapor increases in almost the whole air column, especially over the southern Bay of Bengal, the southern part of the Philippines, and the area controlled by the subtropical high. However, it reduces over a few areas, such as the ITCZ over the ocean and southwest of Tibetan Plateau.

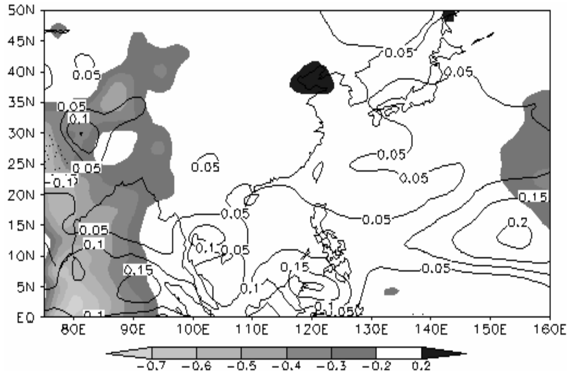
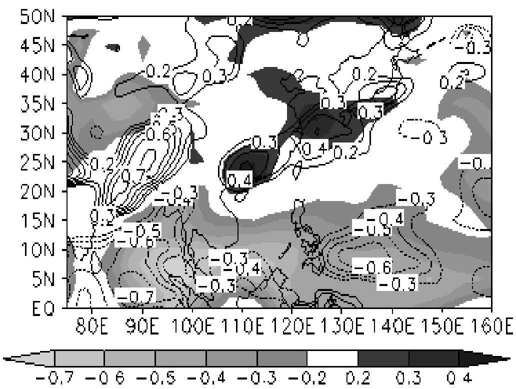
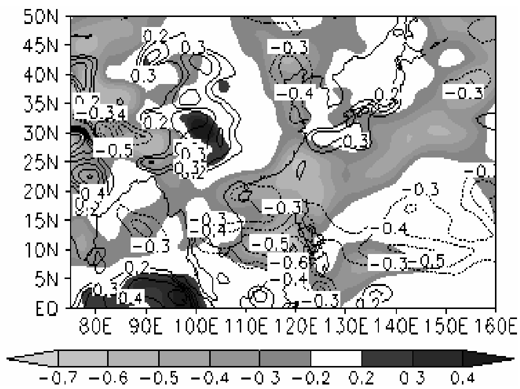


Figure 6. Changing trends of water vapor column content and cloud fraction in East Asia from 1984 to 2006. All of them pass the 95% significance test. Contours: change in water vapor column content (Units: mm/Year); shading: change in cloud fraction (Units: %/year).

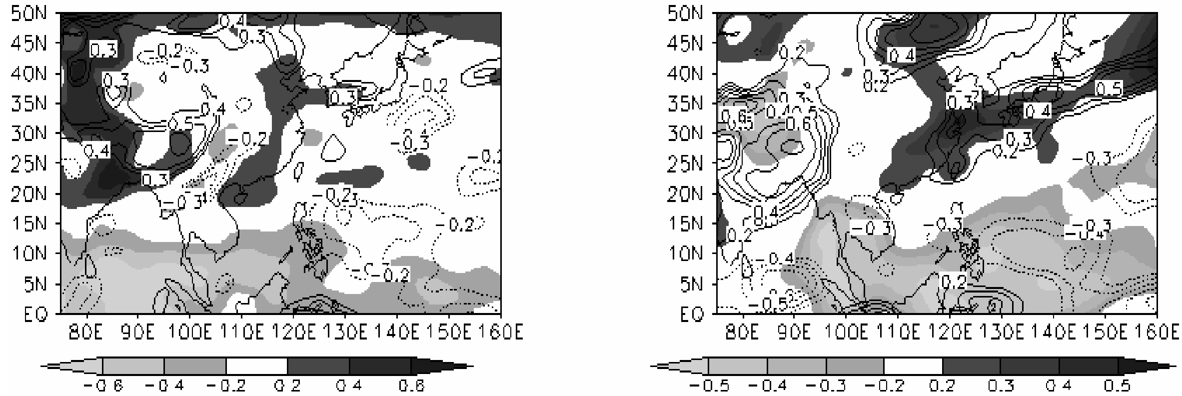
To further investigate the relationship between changes in cloud fraction and global warming, we calculated the correlation coefficient between the cloud fraction and the quality-weighted temperature at the same level as well as the water vapor content, respectively. Shading and contours in Figure 7 are for the correlation coefficients between cloud and temperature and between cloud and water vapor, respectively (both have passed the 95% significance test). Temperature and total cloud fraction over the Bay of Bengal, ITCZ and Tibetan Plateau are negatively correlated in a significant way and the maximum appears over the Bay of Bengal with the center more than –0.7, while a positive correlation is in the southeastern China. Low-level cloud over the West Pacific is negatively correlated with the temperature in a significant way, especially in the vicinity of the Philippines. In contrast, a positive correlation exists over the southern Bay of Bengal, with a weak positive correlation over the southwestern China. Mid-level cloud and temperatures over the Bay of Bengal are negatively correlated in a significant way but positive correlation is situated over the eastern China, with its center over the Tibetan Plateau. High-level cloud and temperatures over the Tibetan Plateau, Bay of Bengal, ITCZ and other areas exhibits a significant negative correlation, indicating that as global warming intensifies over these regions, high-level cloud reduces significantly but mid-level cloud increases over the Tibetan Plateau, with slightly increased low-level cloud over the Bay of Bengal. Positive correlation is over the eastern China, Japan, and the ocean to the east and north of Japan. It is clear that as the global warming is increasing, low-level cloud reduces significantly but mid-level and high-level cloud increases over these areas. The cloud fraction trend, concluded from the temperature warming and the correlation between temperature and cloud, is consistent with the cloud fraction mentioned above. Cloud fraction over the Tibetan Plateau is positively correlated with the water vapor, which reduces over the region, and all kinds of cloud fraction also tend to decrease. The positive correlation is most significant in high altitudes where the high-level cloud decreases most significantly. Over the central Tibetan Plateau, negative correlation between low-level cloud and water vapor is very weak, indicating that the low-level cloud is increasing while the water vapor reduces over this region. On the ocean surface east and north of Japan, water vapor is negatively correlated with low-level and mid-level cloud. The water vapor and cloud at high level has a more significant positive correlation. When water vapor is increasing over the region, there is a weak increase of high-level cloud and a reduction of low-level and mid-level cloud. Over the Bay of Bengal, low-level cloud and water vapor are positively correlated while high-level cloud and water vapor show a significant negative correlation. Over the South China Sea, water vapor is in significantly negative correlation with low-level cloud but in positive correlation with high-level cloud. That is, with the water vapor increasing over the region, low-level cloud decreases but high-level cloud increases. From the analysis above it can be found that with global warming and changes in water vapor content, each category of cloud has undergone significant variations. Low-level cloud accounts for more proportion in waters north and east of Japan, the Philippines and other places where temperatures and water vapor increase to cause a significant reduction in low-level cloud and a mild increase in mid-level and high-level cloud. However, over the Bay of Bengal, Tibetan Plateau and ITCZ, where high-level cloud accounts for more proportion, there is a significant reduction in high-level cloud and increase in mid-level and low-level cloud. Over the eastern China and the Yangtze River basin, where the mid-level cloud is more evident, high-level cloud increases significantly while low-level cloud decreases, resulting in significantly decreased low-level cloud and increased mid-level cloud, leading to the reduction of the total cloud fraction.



a. Total cloud fraction correlated with temperature and water vapor;



b. Low-level cloud and related temperature and water vapor;



c. Middle cloud and related temperature and water vapor; d. High-level cloud and related temperature and water vapor.

Figure 7. Coefficient distributions of cloud fraction and related temperature and water vapor. All of them pass the 95% significance test. Shading: cloud and significantly related temperature; contour: cloud and significantly related water vapor, respectively.

4 CONCLUSIONS AND DISCUSSION

According to the latest D2 cloud climate data set given by ISCCP, this paper studies the spatial and temporal evolution of cloud features from January 1984 to December 2006 over East Asia, focusing on the cloud fraction variation and its relationship with warming over East Asia under the global warming background.

(1) The distribution of cloud fraction is different from region to region. The low-level cloud is mainly over the ocean east and north of Japan. However, the high-level cloud is generally located over the Tibetan Plateau, east of the Bay of Bengal and the tropical western Pacific. Total cloud fraction, low-level cloud, and high-level cloud all tend to decrease in the past 23 years while the mid-level cloud tends to increase.

(2) The temperature increase helps reduce the cloud fraction corresponding to the height. The values of high-level, mid-level and low-level cloud are the lowest in 1998 with significantly increased temperatures for specific levels. A significant increase of temperatures in 1986–1990 also leads to a decreasing trend of the mid-level cloud. In addition, the reduction of moisture content also helps reduce the cloud fraction for the height. The significantly low water vapor content in 1992 resulted in the observed small fraction of mid-level cloud and high-level cloud.

(3) The coordination of global warming and the variation in water vapor content contribute to the significant changes in each category of cloud. The ocean to the east and north of Japan, the Philippines, etc., accounting for a larger proportion of low-level cloud, show a significant reduction in the low-level cloud but a mild increase in the mid-level and high-level cloud. However, a larger proportion of high-level cloud is situated over the Bay of Bengal, Tibetan plateau, and ITCZ, where the high-level cloud reduces significantly while the mid-level and low-level cloud increases. A larger proportion of mid-level cloud is over the eastern China and the Yangtze River basin, accompanied by a significant increase in high-level cloud and a reduction in low-level cloud. It also results in the overall trends of a significant reduction of high-level cloud and low-level cloud, as well as an increase of mid-level cloud over East Asia, causing a reduction of total cloud fraction.

According to the cloud distribution under the background of global warming and its possible effect on the cloud fraction via warming and changing cloud water vapor content, this paper obtains some meaningful results. Due to the lack of quantitative approaches and research on the climatic effects of cloud radiation, it is temporarily impossible to fully assess the interactions and feedback mechanisms between greenhouse effect and changes in cloud distribution over East Asia. Some more in-depth investigation is needed in the future.

Acknowledgement: The ISCCP D2 cloud data set used in this paper is provided by the NASA GISS. Air temperature and specific humidity data are provided by the NCEP.

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Citation: WU Jian and LIU Jia. Variations of cloud fraction over East Asia under global warming conditions in the past 20 years. *J. Trop. Meteor.*, 2013, 19(2): 171-180.