# Changes in Low Cloudiness over China between 1971 and 1996

NOBUHIKO ENDO

*Frontier Research Center for Global Change, JAMSTEC, Yokohama, Kanagawa, Japan*

TETSUZO YASUNARI

*Frontier Research Center for Global Change, JAMSTEC, Yokohama, Kanagawa, and Hydrospheric Atmospheric Research Center, Nagoya University, Nagoya, Aichi, Japan*

(Manuscript received 13 November 2004, in final form 5 September 2005)

## ABSTRACT

The climatology and long-term trends of low-cloud conditions over China were examined using the Extended Edited Cloud Report Archive data from 1971 to 1996. Linear regression analysis was applied to time series of clear-sky frequencies and low-cloud frequencies, and low-cloud amounts when present. Over the 26-yr study period, the clear-sky frequency increased over northern China. During summer, the frequency of cumuliform clouds decreased over almost all of China. A significant decrease characterized the trend in cumulonimbus (Cb) frequency; however, the Cb cloud amount when present increased over the Yangtze River basin and southern China. Increasing trends in stratocumulus (Sc) cloud amount when present were also observed over much of China.

## 1. Introduction

The global climate has changed during the last century (Houghton et al. 2001). Clouds are a key component of the global climate system because they strongly interact with radiative processes and the hydrological cycle. Thus, a thorough description of temporal and spatial variations in cloud conditions will facilitate a deeper understanding of changes in radiative processes and the hydrological cycle. Conventional surface-based visual cloud observations have been ongoing for decades worldwide, and cloud datasets based on such visual observations have been compiled in several countries over recent decades. Long-term cloud studies over the former United Soviet Socialist Republic (Sun and Groisman 2000), the United States (Angell 1990), Europe (Henderson-Sellers 1986), and Australia (Jones and Henderson-Sellers 1992) have found evidence of increasing total cloud amounts. In contrast, a decreasing trend in the annual-mean total cloud amount has been found over much of China (Kaiser 1998; 2000).

Total cloud amount is defined as "the amount of sky estimated to be covered by all cloud types" (WMO 1975). Thus, changes in several cloud types may constitute or be included in a change in the total cloud amount. Cumuliform, stratiform, and cirriform clouds can change in different ways. Such variations complicate investigations of relationships between trends in total cloud amount and other climate parameters. Each cloud type forms under different dynamic and/or thermodynamic conditions. A change in a specific cloud type may reflect changes in a specific atmospheric condition. Descriptions of long-term changes for specific cloud types are thus important.

Li et al. (2004) discussed the spatial distribution and seasonal cycle of clouds over China using a visual cloud observation dataset and a cloud dataset based on satellite observations from 1990 to 1998. However, they did not analyze long-term changes in low-cloud amounts. The present paper describes the climatological distribution of low clouds over China and presents trends in low-cloud frequencies and cloud "amounts when present" ("AWP"). Section 2 describes the data and methods. Section 3 presents the climatological features of low clouds and trends in low-cloud amount and frequency at individual stations and regionally. The discussion in Section 4 is followed by a summary.

## 2. Data and methods

This study used data from the Extended Edited Cloud Report Archive (EECRA). Hahn and Warren

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*Corresponding author address:* Dr. Nobuhiko Endo, Frontier Research Center for Global Change, JAMSTEC, 3173-25, Syowa-machi, Kanazawa-ku, Yokohama City, Kanagawa 236-0001, Japan.
E-mail: nobu@jamstec.go.jp

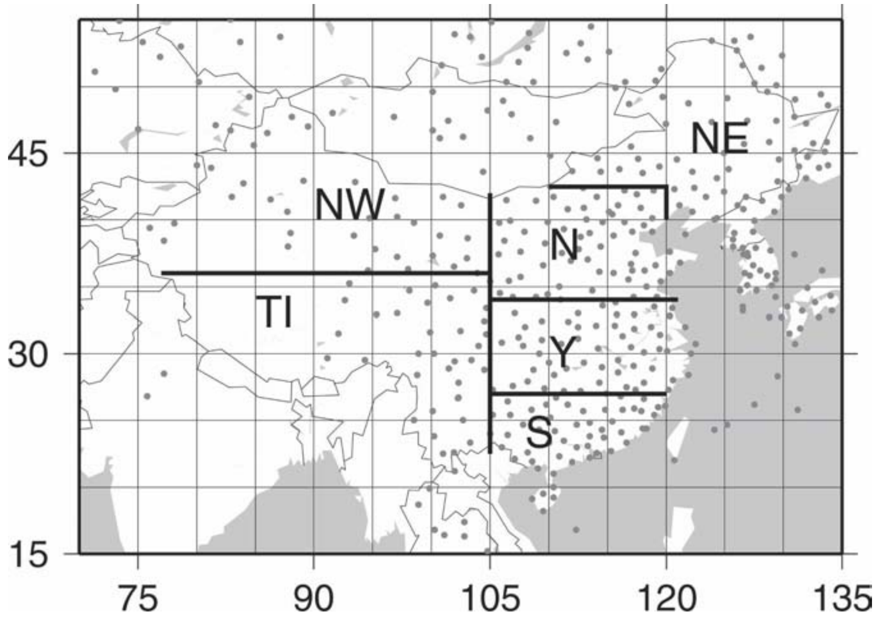

FIG. 1. Observation stations and geographic divisions used for the regional time series; N: northern China, TI: Tibet, NE: northeastern China, S: southern China, NW: northwest China, and Y: the Yangtze River basin.

(1999) compiled the EECRA based on global accumulated surface visual observations. Surface visual observations made at synoptic times and observational results were coded in accordance with World Meteorological Organization regulations (World Meteorological Organization 1988) and were sent to the global telecommunication systems. The EECRA includes cloud codes, as well as total and low-cloud amounts. EECRA data were collected from land stations from 1971 to 1996. The stations selected for the present study met the following two conditions: they were between 15° and 55°N, 70° and 135°E and had at least 100 observations for each month, with the exception of December and February, for every year. The requirements for December and February were less restrictive because data were frequently missing in those months during the early 1970s. There were 415 stations that met the above two conditions; this station network was fixed throughout the analysis period.

Regional time series of low-cloud conditions revealed regional characteristics for statistically robust trends. As described in a later section, the cumulonimbus frequency, which was closely associated with heavy rainfall, was climatologically larger in summer. Based on total precipitation distributions for summer, we defined six regions and examined trends in low-cloud conditions for each. Using the first-component spatial pattern produced by empirical orthogonal function (EOF) analysis of the summer rainfall total obtained by Nitta and Hu (1996), we divided the area east of 105°E into northern China (34°–42°N, 105°–120°E, including the Shandong Peninsula; 64 stations), the Yangtze River basin (27°–34°N, east of 105°E; 58 stations), and southern China (21°–27°N, east of 105°E; 47 stations). The area west of 105°E was divided into northwestern China (north of 36°N; 33 stations) and Tibet (south of 36°N; 39 stations). Northeastern China (north of 42°N) included 39 stations (Fig. 1). Stations south of 21°N were not included in the regional time series analyses. The arithmetic mean yielded the regional averages for low-cloud amounts.

The EECRA contains nine cloud codes for low-cloud conditions (World Meteorological Organization 1975) and two additional cloud types for obscured sky conditions. This study considered statistics for four types of low clouds [cumulus (Cu), $C_L$: types 1, 2; cumulonimbus (Cb), $C_L$: types 3, 9; stratocumulus (Sc), $C_L$: types 4, 5, 8; and stratus (St), $C_L$: types 6, 7]. The extended cloud-type code $C_L = 10$ in the EECRA also indicated cumulonimbus; however, that code was not included in this study because the code did not appear at any stations selected in the study. Low-cloud frequencies were calculated according to Norris (1998). Frequencies of clear sky ($\mathrm{FQ}_{\mathrm{clr}}$), sky-obscuring precipitation ($\mathrm{FQ}_{\mathrm{sop}}$), and sky-obscuring fog ($\mathrm{FQ}_{\mathrm{fog}}$) were calculated by

$$\mathrm{FQ}_{\mathrm{clr}} = \frac{N_{\mathrm{clr}}}{N_{\mathrm{all}}}, \quad \mathrm{FQ}_{\mathrm{sop}} = \frac{N_{\mathrm{sop}}}{N_{\mathrm{all}}}, \quad \mathrm{FQ}_{\mathrm{fog}} = \frac{N_{\mathrm{fog}}}{N_{\mathrm{all}}},$$

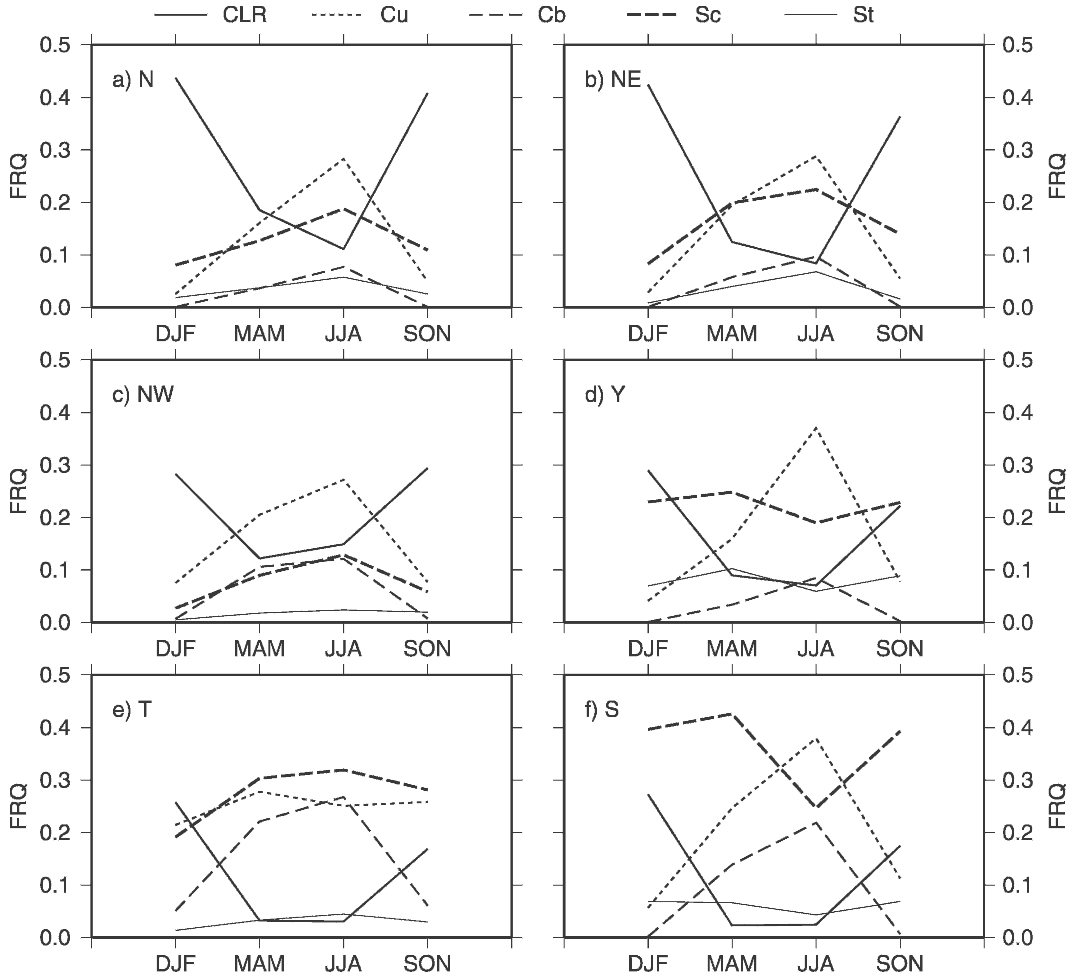

FIG. 2. Seasonal cycle of cloud and clear-sky frequency for the six study regions of China: clear-sky (thick line), Cu (short-dashed line), Cb (long-dashed line), Sc (long-dash–dotted line), and St (thin line) frequencies.

where $N_{\rm clr}$, $N_{\rm sop}$, and $N_{\rm fog}$ were the total number of observations reporting clear sky, sky-obscuring precipitation, and sky-obscuring fog, respectively, and $N_{\rm all}$ was the total number of all cloud observations, regardless of whether they were reported as low clouds. Occurrence frequencies of low-cloud types 1–9 ($\mathrm{FQ}_i$ where $C_L\ 1 \leq i \leq C_L\ 9$) were calculated by

$$\mathrm{FQ}_i = \frac{N_i}{N_{\rm low}}(1 - \mathrm{FQ}_{\rm clr} - \mathrm{FQ}_{\rm sop} - \mathrm{FQ}_{\rm fog}),$$

where $N_i$ was the total number of observations reporting cloud type $i$, and $N_{\rm low}$ was the total number of observations reporting low-cloud types when the sky was not clear. This study defined AWP as the sum of the low-cloud amount (Nh) divided by the number of low-cloud appearances. AWP statistics were prepared for each season.

Surface visual observations under dim light may hinder identification of cloud types (Hahn et al. 1995). The EECRA include data flags denoting sufficient light. Daytime statistics and nighttime statistics with good illumination were separately prepared for the four seasons (DJF, MAM, JJA, SON); daytime and nighttime statistics (hereafter DN) with good illumination were then averaged. Hahn and Warren (1999) noted several possibilities for biases, such as "day–night sampling bias" and "monthly sampling error." We also prepared statistics based on data collected at 0600 UTC (approximately 1400 local time in eastern China), and compared these results with DN statistics. The comparison showed that cumulus and cumulonimbus frequencies in the DN statistics were smaller than those in the 0600 UTC statistics. However, the climatological seasonal cycle of cloud frequencies was similar. Further time series of cloud frequencies also resembled each other. The DN statistics were more stable than the 0600 UTC statistics because of the large number of data used

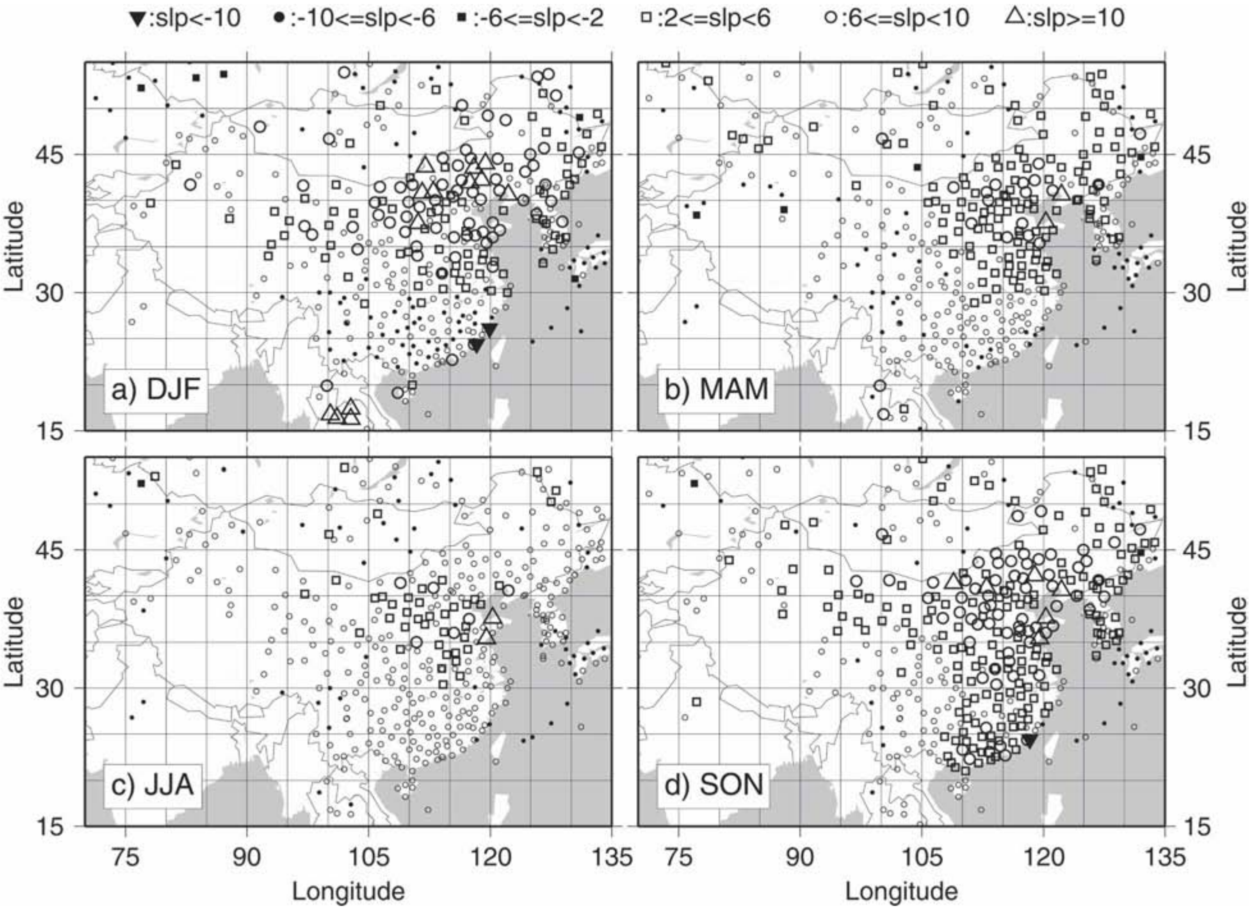

FIG. 3. Spatial distribution of trends in clear-sky frequency for each season. Trends with statistical significance at the 0.05 level are plotted by larger marks, trends without statistical significance are indicated by small circles, black and white marks indicate decreasing and increasing trends, respectively, and "slp" means trend of frequency.

in DN statistics. Therefore, we used the DN statistics in the following analysis.

Linear trends were calculated using linear regression techniques. A trend was defined as the linear regression coefficient. A significance level of 0.05 was used throughout the analysis.

## 3. Results

### a. Seasonal cycles of low-cloud frequencies

Figure 2 shows the seasonal changes in the clear-sky frequency and the cloud frequencies for four low-cloud types over six regions of China. The clear-sky frequency showed great seasonal variation. Clear skies occurred most frequently in winter and were also prevalent in autumn. The amplitude of seasonal change in cumulus frequency was large, showing a summer maximum in all regions. The maximum Cu frequency exceeded 30% in summer, except over the Tibetan Plateau. Cumulonimbus activity was also vigorous in summer. The frequency of Cb exceeded 20% in southern China and the Tibetan Plateau. The seasonal cycle of the stratocumulus frequency also exhibited a summer maximum and a winter minimum over northern, northeastern, and northwestern China and Tibet. In southern China and the Yangtze River basin, the frequency of Sc exceeded 20% throughout the year; the minimum Sc frequency was observed in summer. Regional differences in the seasonal cycle of Sc frequency were linked to regional differences in both atmospheric water vapor content and large-scale circulation. Nakata (1991) examined the occurrence of stratiform clouds over southern China during winter and found that stratiform clouds formed between low-level cold northeasterlies and warm southwesterlies south of the Tibetan Plateau. Klein and Hartman (1993) noted that downward motion caused by a local Hadley circulation helped support low-level stratiform cloud over southern China.

TABLE 1. Regional trends in clear-sky frequency, total cloud amounts, and three low cloud types during summer. Trend values are expressed as percent per decade. Asterisk indicates statistical significance at the 0.05 level.

| | Clear-sky frequency | Total cloud amount | Cumulus | | Cumulonimbus | | Stratocumulus | |
|---|---|---|---|---|---|---|---|---|
| | | | Frequency | AWP | Frequency | AWP | Frequency | AWP |
| Northeast China | 2.7* | −0.6 | −1.7* | 1.5 | 0.9 | 4.0* | 0.5 | 5.0* |
| Northwest China | 2.5* | −2.1 | −2.7* | 0.4* | 0.0 | 3.9* | 3.4* | 1.7 |
| North China | 3.6* | −1.6 | −3.0* | 0.8* | −0.3 | 5.1* | −0.5 | 4.3* |
| Yangtze River | 2.6* | 0.4 | −2.4* | 1.3* | −3.0* | 9.7* | −0.4 | 5.8* |
| South China | 1.6* | −2.8 | 1.0 | −0.9 | −6.3* | 5.7* | 3.4* | 4.3* |
| Tibetan Plateau | 0.6 | −0.5 | −1.8 | −0.9 | −1.2* | 1.6 | 2.5* | 2.3* |

### b. *Trends in clear-sky frequency and low cloudiness*

The clear-sky frequency showed an increasing trend over China throughout the year (Fig. 3). However, this trend was unequally distributed over the four seasons. During winter, the clear-sky frequency increased over the northern Yangtze River basin. The clear-sky frequency increased at a rate of 6.7% per decade in northern China. During summer, the largest increase, 3.6% per decade, occurred over northern China (Table 1). Although the number of stations with statistically significant trends was small, regional statistics showed increasing trends in clear-sky frequency over most of China, with the exception of the Tibetan Plateau. These increasing trends in the clear-sky frequency corresponded well with annual decreasing trends in total cloud amount over northern China (Kaiser 1998, 2000).

Figure 4 shows trends in the stratocumulus frequency. Statistically significant increasing trends were observed in southern China, while statistically signifi-

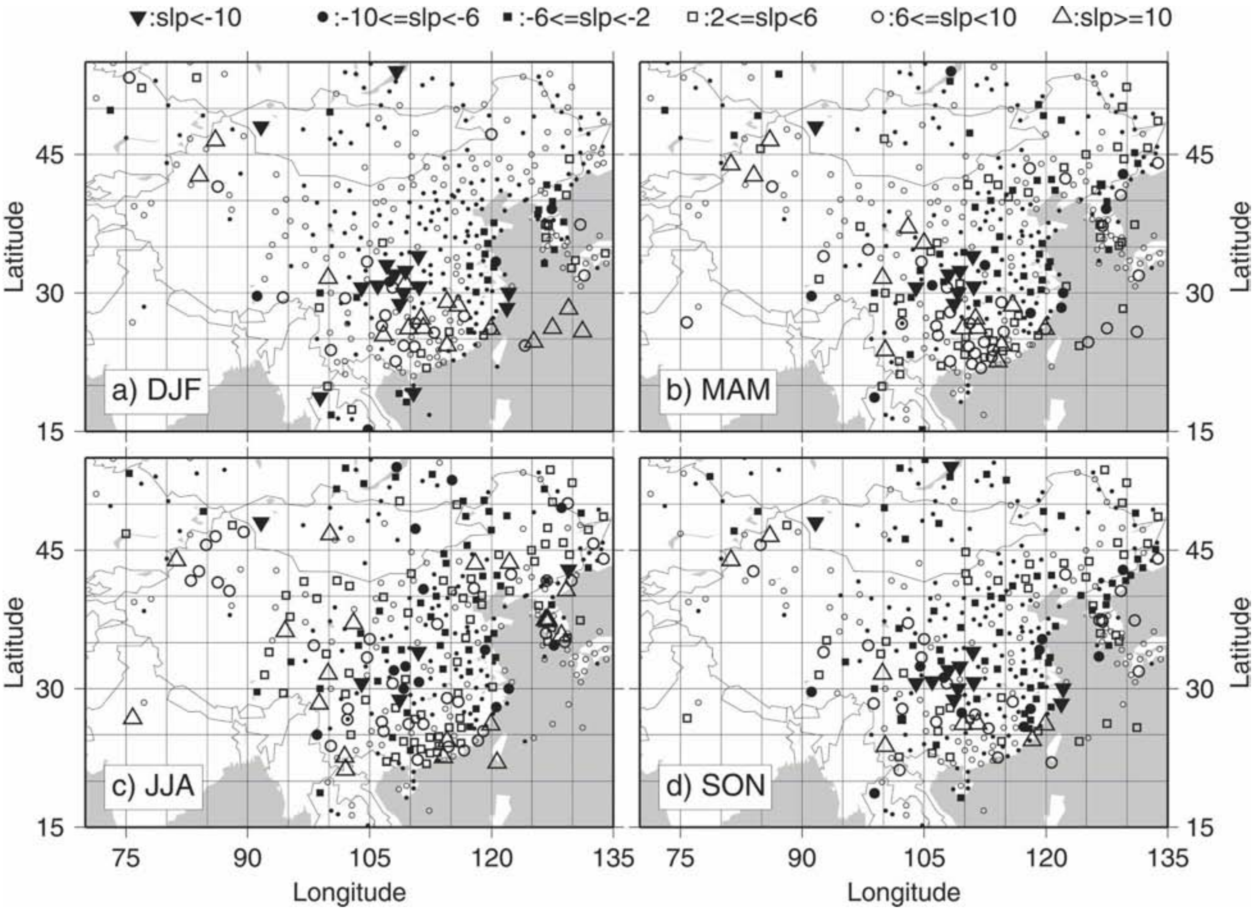

FIG. 4. As in Fig. 3 but for the trend in stratocumulus frequency in each season.

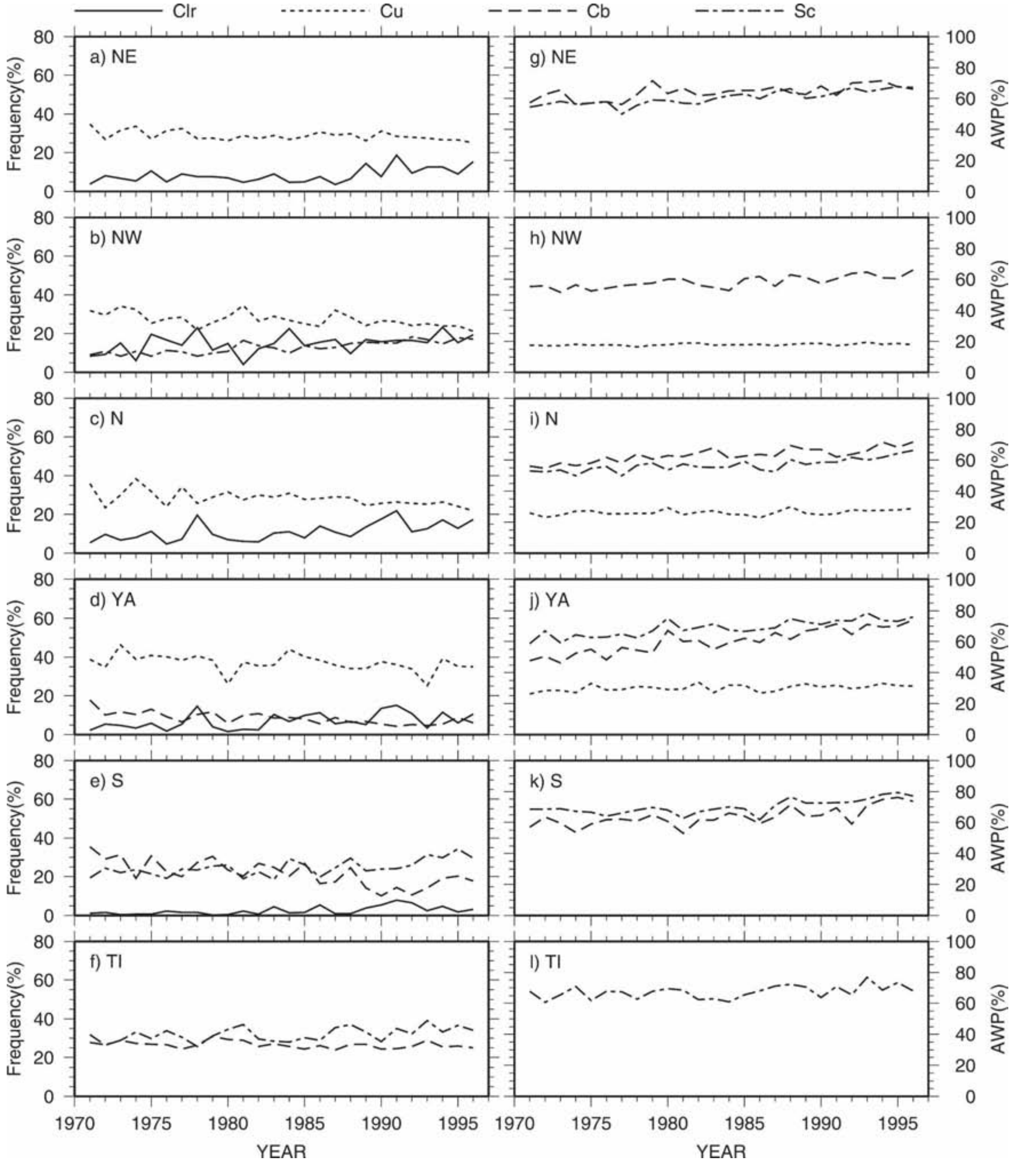

Fig. 5. Regional time series of clear-sky frequency, cloud frequency, and cloud amount when present (AWP). Only time series with statistical significance at the 0.05 level are plotted: N, TI, NE, S, NW, and Y as in Fig. 1.

cant decreasing trends occurred around the Sichuan basin during winter. In addition, the Sc frequency also increased in northwestern China. Similar spatial patterns in Sc frequency trends were also observed in other seasons. During summer, Sc frequency tended to increase in northeastern China. Interestingly, the AWP of Sc increased over China in summer (Figs. 5g–5k).

Trends in cumulus frequency are shown in Fig. 6. The Cu frequency trends tended to decrease over much of China. In winter, decreasing trends were observed over Tibet. Decreasing trends were dominant in southern China, the Yangtze River basin, and Tibet in spring. The trends were generally negative north of the Yangtze River basin, while the positive trends occurred in southern China during summer. The frequency of Cu decreased by 3.0% and 2.4% every 10 years in northern

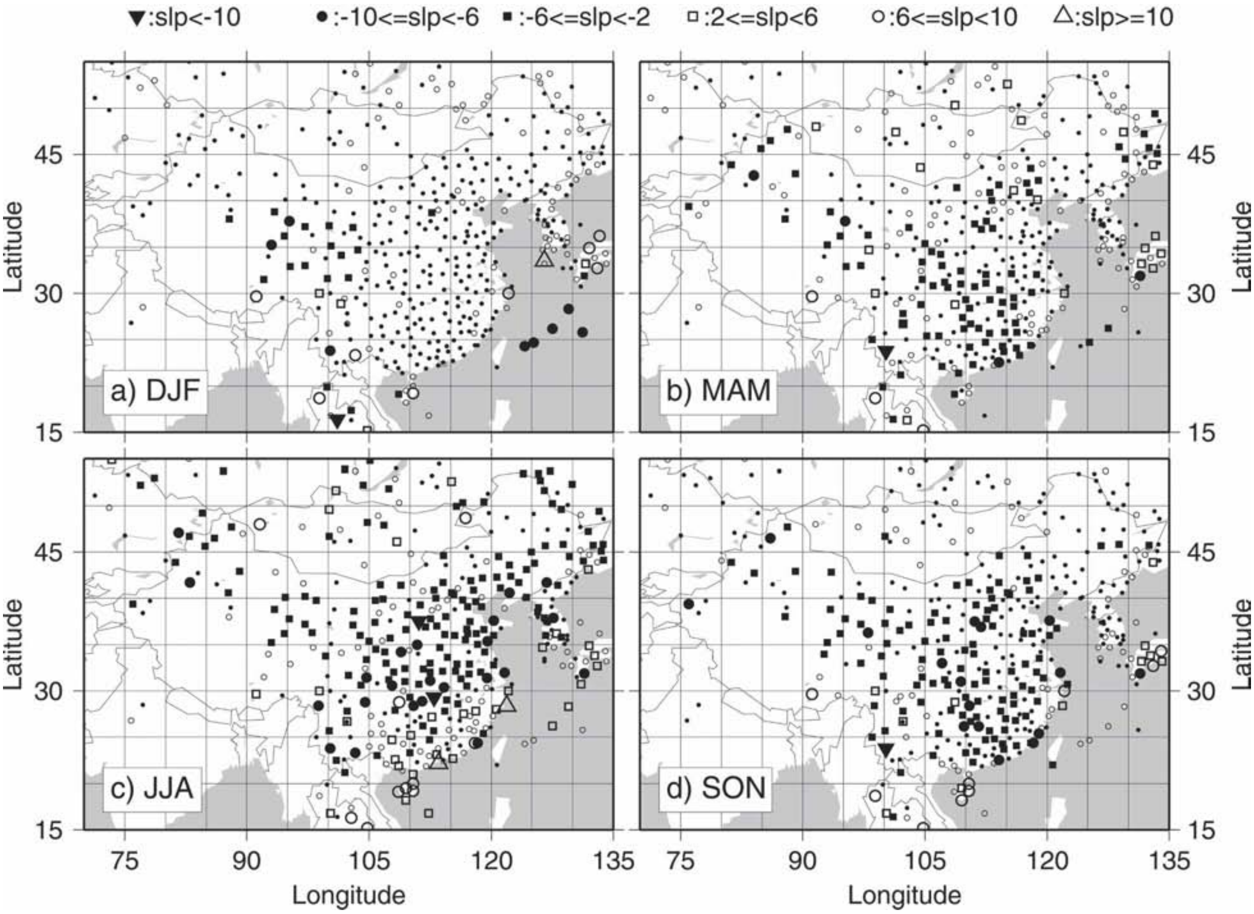

FIG. 6. As in Fig. 3 but for the trend in cumulus frequency in each season.

China and the Yangtze River basin, respectively, during summer (Figs. 5c–5d). Concurrently, the Cu AWP increased over northwestern and northern China and the Tibetan Plateau at a small, but statistically significant, rate (Figs. 5h–5j). In autumn, the trends generally tended to decrease over almost all of China.

Figure 7 shows trends in the frequency of cumulonimbus and the AWP of Cb in summer. The figure clearly illustrates a significant decrease in Cb frequency over southern China. The Cb frequency decreased by approximately 6.3% every 10 years and was statistically significant at the 0.05 level (Table 1). In contrast, the AWP of Cb increased at a rate of 5.7% per decade in southern China. Over southern China, Cb decreased, Sc increased, and Cu showed small changes. Increasing trends in Cb frequency and the AWP of Cb were evident over Inner Mongolia and southern Siberia. The trends in the AWP of Cb were positive over China; the largest such increase was 9.7% per decade over the Yangtze River basin (Table 1). A large decrease in the Cb frequency (−3.0% per decade) also occurred over the Yangtze River basin.

## 4. Discussion

During summer, the Cb frequency clearly decreased in southern China, especially along the coast of the South China Sea. The seasonal average of the Cb cloud amount (cloud amount = frequency × AWP) decreased from 17% in the early 1970s to 12% in the early 1990s, whereas the seasonal average of the Sc cloud amount increased from 17% to 26%. Because the EECRA included "coded" cloud reports, this change may indicate only a regional decrease in Cb in that cumulonimbus-type clouds were reported when Cb appeared, regardless of the existence of Sc (WMO 1975). Limitations in the coded cloud report must be considered. Recently, Lu and Dong (2001) and Lu (2001) found that the summer subtropical high over the northwestern Pacific has extended farther westward since 1979, frequently extending westward to cover parts of southern China. Downward motion generally dominates in an anticyclone, so any westward extension of the subtropical high would result in enhanced downward motion over southern China. In addition, as the

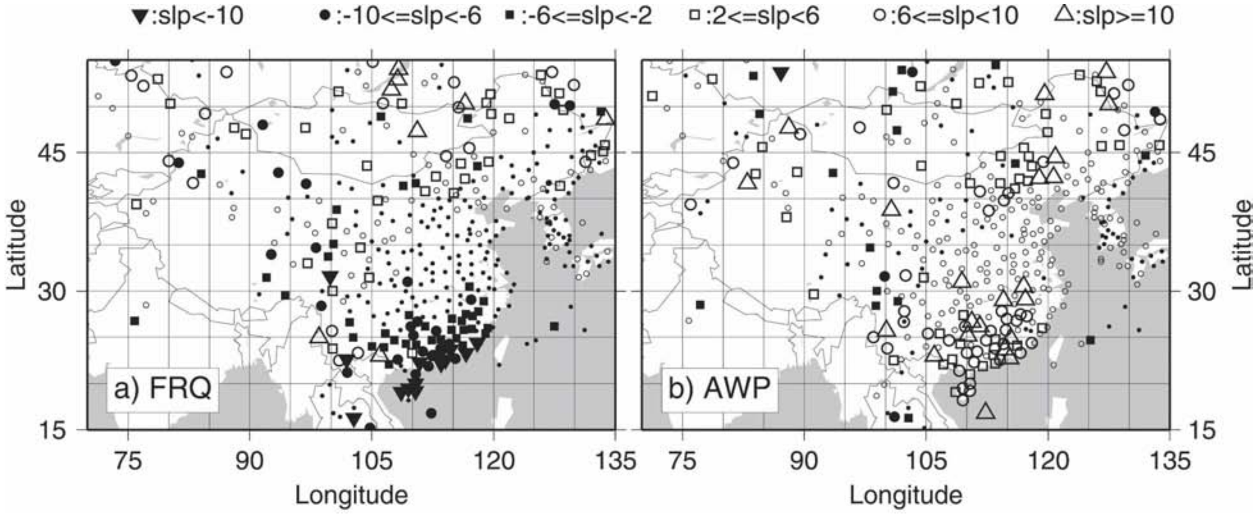

Fig. 7. Trends in (a) the frequency of Cb, and (b) Cb amount when present. Trends with statistical significance at the 0.05 level are plotted by larger marks, trends without statistical significance are indicated by small circles, black and white marks indicate decreasing and increasing trends, respectively, and "slp" means trend of frequency.

subtropical high builds to the west, water vapor transport from the Tropics to eastern China along the northwestern rim of the subtropical high would move westward, and the large-scale convergence zone may also move. Increasing amounts of Cb occurred over Yunnan Province in southwestern China (Fig. 7a). These changes in Cb may be related to the westward extension of a subtropical high over the northwestern Pacific.

The frequency of Cb in the Yangtze River basin decreased from about 13% in the early 1970s to 6% in the 1990s during summer. The frequency of Cu also tended to decrease over the Yangtze River basin. These changes suggest more stable atmospheric stratification over the Yangtze River basin. However, heavy rainfall events in summer have become more frequent in the Yangtze River basin in recent decades (Endo et al. 2005). The decrease in the Cb frequency, in conjunction with an increase in heavy rainfall events, at first seemed counterintuitive. However, a decrease of the number of days with precipitation (figure not shown) and an increase of the AWP of Cb (Table 1) were also found in the Yangtze River basin. Therefore, while Cb frequency declined, an increasing probability of heavy rainfall with larger AWP of Cb appeared during the study period.

Trenberth (1998) found that an increase in surface temperature increased the atmospheric water holding capacity and the atmospheric moisture content in a coupled atmosphere–ocean general climate model (AOGCM) climate change simulation. These changes imply that the number of stronger rainfall events will increase. In fact, researchers have found increased amounts of convective clouds (Sun et al. 2001), heavy rainfall events (Karl and Knight 1998; Groisman et al. 1999), and tropospheric water vapor content (Ross and Elliott 2001) in the United States. Although the tropospheric water vapor content also increased over eastern China (Zhai and Eskridge 1997; Ross and Elliott 2001), a different relationship between Cb and heavy rainfall trends is evident in the Yangtze River basin.

It is useful to consider differing relationships between trends in convective cloud frequency and heavy rainfall events for the Yangtze River basin and the Great Plains of the United States. Heavy rainfall is generally brought by organized convective clouds that appear near the mei-yu front over the Yangtze River basin (e.g., Akiyama 1973; Ninomiya 1984); such clouds also appear over the Great Plains (e.g., Carlson et al. 1983). Convective development over the Great Plains is typically accompanied by a strong capping inversion and a dry, warm midtroposphere above a mixed layer (e.g., Emanuel and Raymond 1993). The development of deep convective clouds in eastern China during summer is characterized by large evapotranspiration from paddy fields and a moist midtroposphere environment (Shinoda and Uyeda 2002). The environment that supports deep convective development is quite different for the two regions. The different relationships between convective cloud trends and heavy rainfall events in the two regions may be attributed, therefore, to the different environmental factors accompanying the development of deep convection.

## 5. Summary

The climatology and long-term trends of low-cloud conditions over China were examined based on the 26-yr Extended Edited Cloud Report Archive. The following observations are reported:

1) Clear-sky frequency increased over northern China throughout the year. Clear-sky frequency increased in northeastern China, except in summer. Clear-sky frequency also rose in northwestern and southern China in autumn.
2) Cumulus frequency decreased over eastern China in spring, summer, and autumn. A significant decrease in cumulonimbus frequency occurred, while the AWP of Cb showed a statistically significant increase over southern China and the Yangtze River basin during summer. Convective cloud amounts decreased over most of China. However, an increase of Cb frequency and an increase of the AWP of Cb occurred over Inner Mongolia during summer.
3) Stratocumulus frequency increased during summer over southern and northwestern China and the Tibetan Plateau. The AWP of Sc also increased over most of China. Stratocumulus frequency increased over southern China and Sc frequency declined north of the Yangtze River in other seasons.

This study used “coded” cloud reports. Surface observers can log several cloud types in the observation records, but the coded cloud report can describe a cloud type only for a single layer. In addition, data for land stations in EECRA covered only a limited period. Further analyses using surface-level visual observation data for longer periods, archived at meteorological agencies, are warranted.

*Acknowledgments.* The Extended Edited Cloud Report Archive was obtained from the Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy.

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