Recent Changes in Cloud-Type Frequency and Inferred Increases in Convection over the United States and the Former USSR

BOMIN SUN

Department of Geosciences, Morrill Science Center, University of Massachusetts, Amherst, Massachussetts

PAVEL YA. GROISMAN

UCAR Project Scientist at National Climatic Data Center, Asheville, North Carolina

IGOR I. MOKHOV

A. M. Oboukhov Institute of Atmospheric Physics, Russian Academy of Sciences, Moscow, Russia

(Manuscript received 29 February 2000, in final form 15 July 2000)

ABSTRACT

Significant changes and a general redistribution in the frequencies of various cloud types have been observed during the past 40–50 years over the midlatitude land areas of the Northern Hemisphere. This is evident for North America and northern Eurasia in the daytime synoptic data of the United States and the former Soviet Union (FUSSR). An abrupt increase prior to the 1960s largely contributed to the upward trend in the frequency of convective clouds over both regions, particularly in the warm season. However, over both regions during the intermediate seasons and during the winter season over the FUSSR, the frequencies of convective clouds still showed gradual increase after the 1960s. The increase in the frequency of convective clouds has been accompanied by increases in the frequency of observation of high-level cloudiness (at elevations above 6 km) and heavy precipitation. Low cloudiness (stratiform types) has decreased over the FUSSR but increased over the contiguous United States. The latter increase was due to an increase in the frequency of stratocumulus clouds, while the frequency of stratus clouds has decreased. Generally, it appears that during the post-World War II period over the FUSSR high cloud-type frequencies increased and low cloudiness decreased with a relatively small change (increase) in total cloud cover, while over the United States cloud cover has increased at both low and high levels. The analyses of cloudiness information from the United States and the FUSSR reveal noticeable differences in definitions and observational practices that affect the estimates of climatology and interpretation of the results presented here in terms of changes of convective activity and its relation to precipitation in these two regions of Eurasia and North America.

1. Introduction

The cause of contemporary climate changes is highly debatable, but the fact that changes have indeed occurred has become evident (Houghton et al. 1996). One of the most often-cited changes, an increase in global surface air temperature, is manifested more prominently in the Northern Hemisphere than in the Southern Hemisphere, in high and midlatitudes more than in the Tropics, over land more than the oceans, and (in the Northern Hemisphere extratropics) over Eurasia more than North America (Jones 1994; Houghton et al. 1996; Serreze et al. 2000). Accompanying this widespread change in surface air temperature in midlatitude land areas over the past several decades, significant changes in land surface meteorological processes (Peterson et al. 1995; Vinnikov and Robock 1996; Groisman et al. 1999b), precipitation (Bradley et al.1987; Groisman and Legates 1995; Dai et al. 1997b), tropospheric precipitable water (Ross and Elliot 1996), and total cloudiness (Angell 1990; Henderson-Sellers 1992; Kaiser 1998; Dai et al. 1997a, 1999; Sun and Groisman 2000; Sun et al. 2000) have been observed. Whatever the reasons for the recent changes, these changes indicate a significant modification on a large spatial scale in atmospheric circulation patterns and in energy exchange processes. This paper adds an additional facet to the picture of these changes. It describes changes in the frequency of occurrence of cloud types during the past 40–50 yr over two large midlatitude regions in the Northern Hemisphere: the former Soviet Union (FUSSR) and the contiguous United States. Due to the limitation of long records of in situ cloud-type observations, few studies have been conducted to investigate their large-scale interdecadal var-

Corresponding author address: Pavel Ya. Groisman, UCAR Project Scientist at National Climatic Data Center, Federal Building, 151 Patton Avenue, Asheville, NC 28801.
E-mail: pgroisma@ncdc.noaa.gov

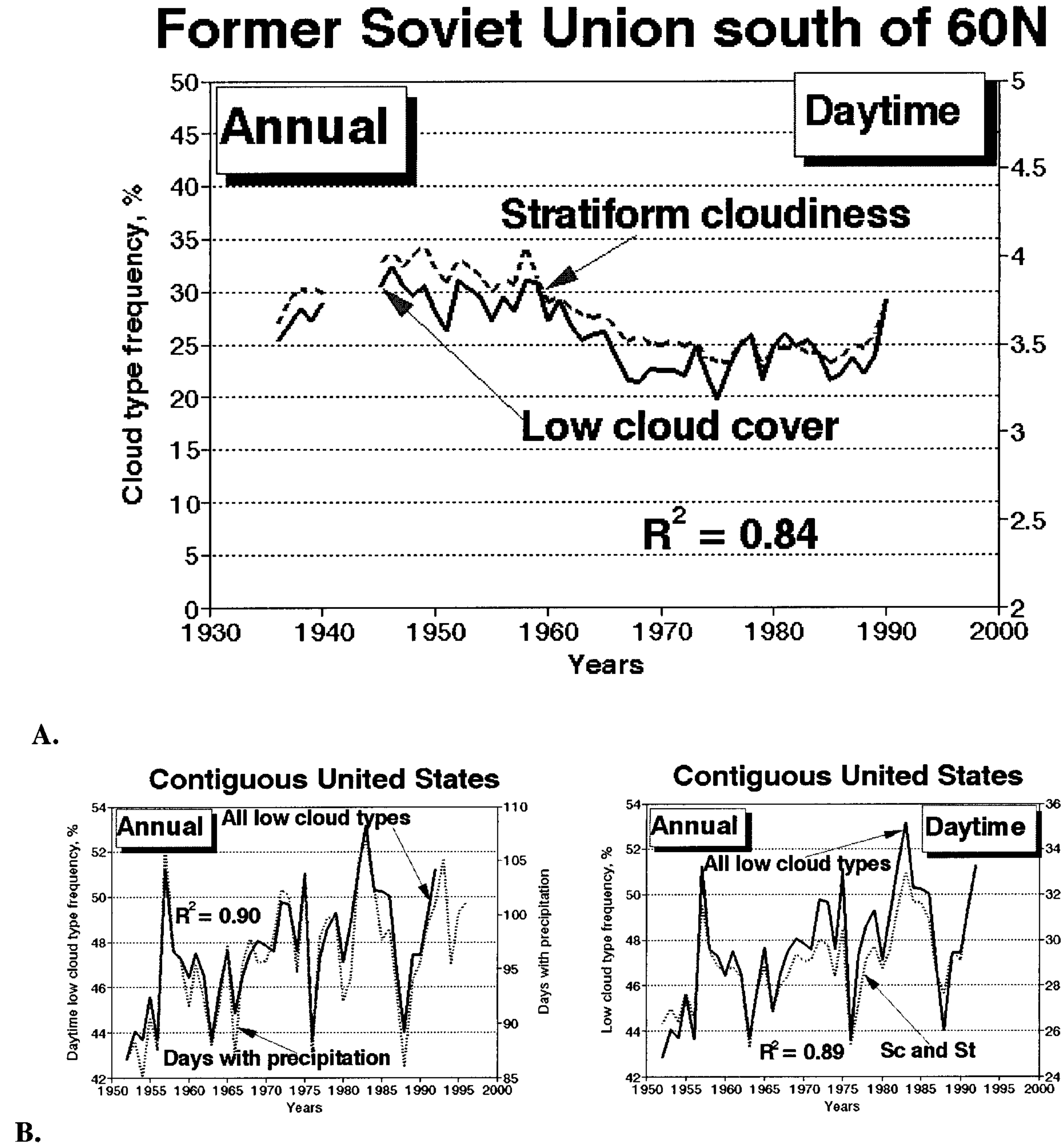


FIG. 1. Relationships between low cloud-cover amount and frequencies of low cloud type and precipitation reports. (a) Annual variations of low cloud-cover amount and frequency of the daytime (1300 LT only) stratiform low cloud types area-averaged over the FUSSR south of 60°N (from archive of Sun and Groisman 2000). (b) Annual variations of the daytime low cloud-cover-types frequency and the number of days with precipitation at the same locations area-averaged over the contiguous United States using the data of 127 serially complete stations shown in Fig. 2. *R* is the correlation coefficient.

iations, particularly over land areas (see, however, Kaiser and Razuvaev 1995; Sun and Groisman 2000). In the last paper a close relationship between the variations of low cloud-cover amounts and frequencies of low-level stratiform cloud types was found (Fig. 1a). For the United States we found a similar relationship (not shown) and relate an increase in the frequency of precipitation days to total increase in occurrence of low cloudiness (Fig. 1b). Linear trends of all three time series shown in Fig. 1b for the 1952–92 period are statistically significant at the 0.01 level and are equal to 1.9 days $(10\ \mathrm{yr})^{-1}$, 1.1% $(10\ \mathrm{yr})^{-1}$, and 0.9% $(10\ \mathrm{yr})^{-1}$, respectively.

The present paper focuses on the convective type of

TABLE 1. Seasonal frequency of daytime Cb cloudiness at U.S. airports area averaged over the contiguous United States and its changes with time. All linear trend estimates are statistically significant at the 0.01 level (except winter where it is significant at the 0.02 level). In the summer season, linear trend is a poor approximation of the increase in the Cb frequency that occurred jumpwise in the late 1950s, after which this frequency remained nearly unchanged.

	Winter	Spring	Summer	Autumn
Average Cb frequency, %, 1961–90 period	0.37	4.2	14.3	3.5
Linear trend of Cb frequency, % (10 yr)$^{-1}$, 1949–94 period	0.03	0.49	0.70	0.29
The same, but in % of average frequency	7.5	11.5	4.9	8.4
Variance R^2, ascribed to the linear trend	0.13	0.48	0.26	0.29

clouds often associated with heavy precipitation. Recent findings of changes in heavy precipitation over the United States (Karl and Knight 1998; Groisman et al. 2001) and Russia (Groisman et al. 1999a; Sun and Groisman 2000) can be also related to changes in convective cloudiness.

Cloudiness is composed of a variety of types that are generated by different dynamical and thermodynamical processes (Arking 1991; Houze 1993; Norris and Leovy 1994). On the other hand, different cloud types have different radiative effects and climatic impact (Hartmann et al. 1992; Fu et al. 1996; Wang and Rossow 1998). For example, high clouds are more effective in trapping longwave radiation than low clouds, while the latter are more effective in reflecting shortwave radiation than the former (Klein and Hartmann 1993). Boundary layer stratiform cloud types tend to shift to convective cloud types as sea surface temperature rises in the eastern equatorial Pacific (Fu et al. 1996). So, the use of individual cloud type in climate studies, instead of total cloudiness, may help identify the physical process (or processes) responsible for cloudiness variations, and the knowledge of changes of cloud type and/or vertical cloud distribution based on observational data can deepen our understanding of the large-scale interaction between clouds and climate in ongoing climatic changes. This information can also be used to validate global climate models, in which cloud processes and their effects still constitute one of the largest uncertainties (Weare and Mokhov 1995; Cess et al. 1996; Groisman et al. 2000).

Atmospheric convection plays an important role in vertical energy transport and surface heat and water balances [Global Energy and Water Cycle Experiment (GEWEX) 1990]. The contemporary in situ meteorological observational system lacks appropriate tools for a direct long-term monitoring of atmospheric convective processes. A surface observed cloud type is generally related to a particular atmospheric boundary layer structure (Norris 1998a,b), and therefore, the human identification of cloud types according to their corresponding morphological characteristics can allow us to trace the long-term changes in atmospheric processes and circulation patterns where clouds form and develop. The presence of convective clouds such as cumulus (Cu) and cumulonimbus (Cb) generally indicates a relatively strong vertical exchange of atmospheric heat and water vapor, and their penetration into a higher-tropospheric level can partly be identified by the presence of high-level clouds (Cirrus, Ci; Cirrocumulus, Cc; and Cirrostratus, Cs).[1] Stratiform clouds including stratocumulus (Sc) and stratus (St) clouds often reflect a relatively stable stratification of the lower troposphere. So, changes in frequency of occurrence of these types of clouds may signify intensification/weakening or, at least, more/less ‘‘visibility’’ of appropriate atmospheric processes. This paper presents our estimates of these changes during past 40–50 yr over the FUSSR and the United States.

2. Data and their preprocessing

The in situ cloud observations from the first order station networks in the contiguous United States (225 stations with manual 3-hourly/hourly cloudiness observations for the period from 1948 to 1994)[2] and the FUSSR (Razuvaev et al. 1995, updated; 223 stations with manual 3-/6-h cloudiness observations for the period from 1936 to 1990)[3] have been used in this study.[4]

The FUSSR dataset contains information about total and low cloud-cover amount measured in tenths) and

---

[1] The formation of high-level clouds over midlatitude land areas can be also caused by strong atmospheric baroclinic activities associated with frontal systems and jet streams. Besides, high-level atmospheric instability and the spreading of jet contrails can also lead to the formation of high-level clouds.

[2] See online at http://www4.ncdc.noaa.gov/ol/documentlibrary/datasets.html#TD3280.

[3] See online at http://cdiac.esd.ornl.gov/newsletr/fall98/ndp48.htm.

[4] There are two different reasons for not including the most current U.S. and FUSSR cloud-type observations in our analyses. The FUSSR synoptic data are still available from the Global Telecommunication System (GTS), but we prefer to work only with a much more carefully preprocessed, quality controlled, and serially complete national archive data source (Razuvaev et al. 1995, updated). The Russian Meteorological Service routinely updates this archive. Thus in the future, the FUSSR cloud-type information for the 1990s will also become available for scientific use. On the contrary, the U.S. National Weather Service has practically eliminated the cloud-type observations at most of its First Order Network since the introduction of the Automated Surface Observation System (ASOS) in the early 1990s. Currently ASOS does not report high-level cloud-over and cloud-type information at all and thus irreversibly breaks the homogeneity of time series of cloudiness characteristics.

five cloud-type groups, but no cloud-type sky coverage information is included in this dataset. In this dataset, low-level cloud types with a base height below 2000 m were separated into three groups: CLD1, CLD2, and CLD3.[5] CLD1 includes Cu and Cb clouds; CLD2 includes Sc and St clouds; and CLD3 includes nimbostratus (Ns), fractostratus (Fs), and fractocumulus (Fc) clouds. The midlevel cloud-type group (CLDM) with a base height between 2000 and 6000 m includes altocumulus (Ac) and altostratus (As) clouds. The high-level cloud-type group includes Ci, Cc, and Cs, which are associated with a cloud base higher than 6000 m. This partition and the cloud-type definitions are similar to those used in the International Cloud Atlas [World Meteorological Organization (WMO) 1975] with one exception: Ns cloud type is included in low cloudiness (rather than in midlevel cloudiness as suggested by the atlas) and combined with two other low cloud types (Fs and Fc). To be consistent, we preserve this exception in our analysis of the U.S. cloud types.

In the U.S. dataset (TD-3280), at each station manned by observers for each of the cloud layers,[6] one of 19 individual types of clouds were reported. We combine these 19 types into the following seven groups: 1) Cb (including cumulonimbus and cumulonimbus mammatus); 2) Cu (including cumulus and towering cumulus);[7] 3) Sc; 4) St; 5) Ns + Fs + Fc (to mimic the partition CLD3 used in Razuvaev et al. 1995); 6) midlevel cloud types (including altostratus, altocumulus, altocumulus lenticularis, altocumulus castellanus, and altocumulus mammatus); and 7) high-level cloud types (including cirrus, cirrocumulus lenticularis, cirrostratus, and cirrocumulus). Total cloud cover (measured in tenths until July 1996), and cloud amount and height by layer are also present in TD-3280. However, this information is practically not used in this study, because (a) changes in total cloud cover over the contiguous United States have already been reported by Sun et al. (2000) using the same database; (b) changes in the observing practice of the lowest layers of thin clouds in 1951 and 1988 compromise an attempt to estimate the low-level cloud amount from the cloud-layer information (see the appendix); and (c) a close correlation of low-level stratiform cloud-type frequencies with low-level cloud amount (Fig. 1a) makes unnecessary the attempt to estimate low-level cloud cover from the U.S. dataset for the entire period of record. In both countries' datasets, fog is not included in the cloud types but is listed separately as an independent weather phenomenon.

The nighttime cloud detection bias due to inappropriate illumination of clouds (Hahn et al. 1995) affects the climatology of high- and midlevel cloudiness (frequency and amount). In this study we present only daytime results. The hourly observation data from the U.S. First Order stations were not completely digitized for part of the study period: from January 1965 through August 1981 only each third hour (0000, 0300 UTC, etc.) was digitized. In the FUSSR meteorological network, in 1966 the daily observational time schedule was switched from four times per day with the daytime observation made always at 1300 and the nighttime observation made always at 0100 local standard time (LST) to eight times per day with observations made according to UTC at 0000, 0300 UTC, etc. This switch made the hours of observation incomparable over some time zones of that country between the pre- and the post-1966 periods. These temporal inconsistencies in cloud datasets could cause serious biases in the trend analyses of cloud-type frequency due to the strong diurnal cycle in the occurrence of some of the cloud types in the daytime, especially convective types of clouds. In the United States, this temporal inhomogeneity was eliminated by the selection and use of the subset of eight per day observations that were digitized throughout the entire study period (1948–94). Thus, to represent the daytime cloud cover in the United States, we select from this subset only the observations with local standard time between 0700 and 1800 LST. In the FUSSR dataset (except in the Table 3 calculations), we select for our analysis one daytime observation only (1300 LST that was always available before 1966 and in some time zones after 1966). In other time zones after 1966 we used two measurements (mostly at 1200 and 1500 LST) to estimate the 1300 LST values of cloud types and amounts using the interpolation procedure developed by Sun and Groisman (2000). It was found that the area-averaged daytime cloud-type frequency variations over the FUSSR are parallel to those at 1300 LST although the values of these frequencies are very different (cf. Fig. 6b).

Bajuk and Leovy (1998) and Norris (1998a) calculated the occurrence of frequency of each oceanic cloud type, which was reported based on a hierarchy set up by the synoptic code (WMO 1975). The use of some type of hierarchy is necessary with the data based upon the International Code for Radio Weather Reports from

---

[5] Within each group, a special code indicates a particular cloud type that is present at a given hour. But, for the CLD1 and CLD2 groups, we found that too often the two major cloud types (i.e., Cb and Cu or Sc and St) were present and reported simultaneously. Moreover, we found an inconsistency in reporting of this special code for the CLD1 group with time at some of the FUSSR stations. Therefore, throughout this paper (except in the Table 3 calculations) we do not further separate cloud types over the FUSSR and analyze only the five groups indicated above.

[6] Before 1984 up to four cloud layers were digitized in TD-3280. From 1984 to the ASOS introduction around the early 1990s, Microcomputer-Aided Paperless Surface Observations (MAPSO; see the appendix) allows an ''infinite'' number of cloud layers, but the situations when more than four cloud layers are visible from the ground are quite rare. For example, in Charleston, South Carolina, from 1984 up to the ASOS introduction in autumn 1995, the 5th cloud layer was reported only during 15 h and the 6th cloud layer was never reported.

[7] It would be beneficial to separate towering Cu in an independent group and/or join it with Cb but this cloud type has been reported separately in the U.S. dataset only since 1984.

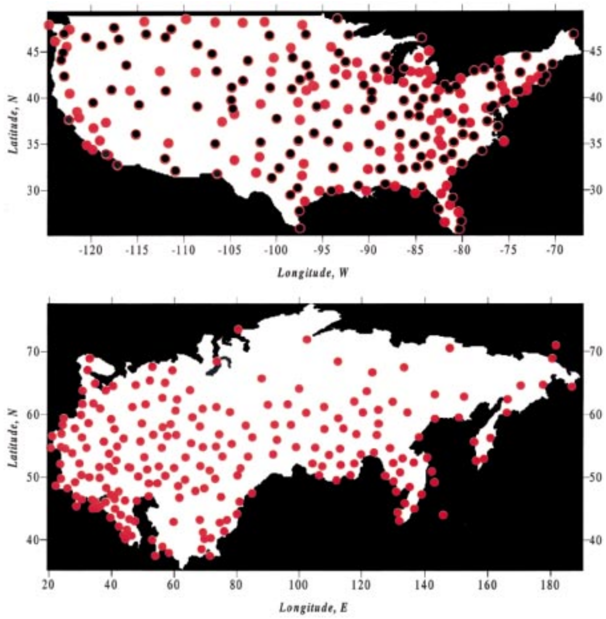


Fig. 2. Maps of the United States and the FUSSR stations used in this study. The U.S. stations marked with black dots in the middle represent a subset of the sites with serially complete cloud type and precipitation records for the period from 1952–92 used to construct the plot in Fig. 1b.

the Ships (U.S. Dept. of Commerce 1948), because only a predominant single cloud type is allowed to be reported for each of low, middle, and high layers. In this paper, we use an alternative method to calculate the occurrence of the frequency of cloud-type groups (5 in the FUSSR and 7 in the United States), because the digitized observers' logbooks used in both the U.S. and USSR archives deliver a much less restricted list of cloud types at the time of each observation (cf. the appendix). Therefore, if more than one group of cloud types was reported during the time of observation, each group is counted equally in the frequency calculation. This approach can (and does) generate different climatological values of cloud-type frequency compared to those based on the synoptic code (Warren et al. 1986). For example, Sun and Groisman (2000) report over the former USSR an up to 70% countrywide average summer daytime frequency of the presence of convective cloud types (Cb and Cu). This high value most probably is due to frequent reports of cumulus available in the comprehensive national archive (Razuvaev et al. 1995) but often omitted in abridged synoptic reports used to compile the Cu climatology in Warren et al. (1986). The typical summer Cu and Cb frequencies in Warren et al. (1986) over the FUSSR are about 15% and less than 25%, respectively. Thus, the underreporting of Cu in Warren et al. (1986) is threefold (if we assume that Cu frequency does not overlap with Cb frequency) or even higher (our estimates show that in 20% of situations with the presence of Cb observers in the FUSSR also reported the presence of Cu).

We define the monthly percentage of a cloud-type category at a given hour of the day as a ratio (×100) of the number of days/observations with a given cloud-type group to the total number of days/observations with available cloud information including fog and clear sky. Over the FUSSR, the daytime cloud-type frequency we present in this paper is thus calculated from the observation or the interpolation at 1300 LST (in Fig. 6b, we show an example of differences between the daytime and 1300 LST cloud-type frequency values in this country). Over the United States, the daytime hourly values in each month are averaged to produce the daytime monthly cloud-type frequency. If the cloud is obscured by lower clouds and is not reported, we consider it absent. Thus, we choose not to simulate and/or correct our estimates of cloud-type frequencies for possible (and inevitable) biases due to the surface position of observers.

Nearly the entire station network was already in place over the United States in 1948 and over the FUSSR in 1936 (Fig. 2). So, there were no drifts in area coverage during the periods we analyzed. The U.S. First Order stations are well distributed over the contiguous land area with a higher density over the coasts. Currently

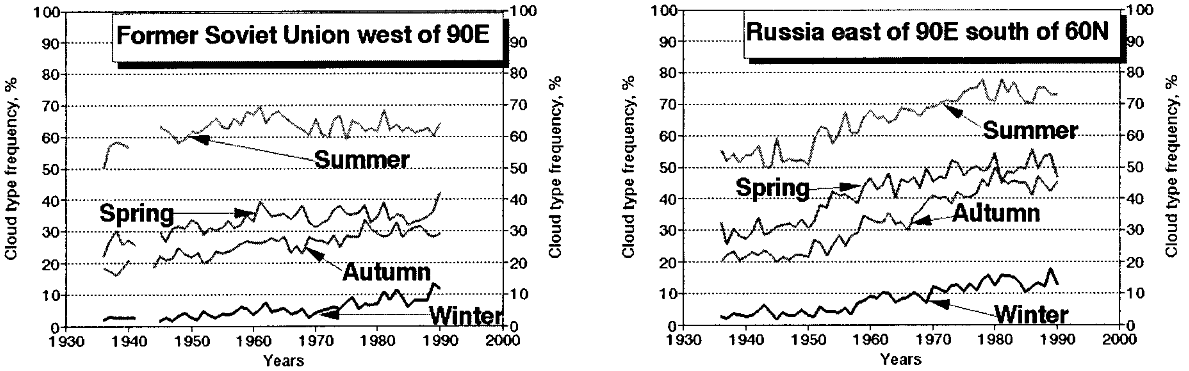


FIG. 3. Seasonal frequency of occurrence of daytime Cb and Cu and the western former Soviet Union (west of 90°E) area averaged over the Asian part of Russia (south of 60°N).

Table 2. Seasonal frequency of daytime Cb and/or Cu cloudiness area averaged over the USSR territory south of 60°N and its changes with time. All linear trend estimates are statistically significant at the 0.01 level.

	Winter	Spring	Summer	Autumn
Average Cb and Cu frequency, %, 1961–90 period	7.8	39.7	65.5	30.9
Linear trend of Cu and Cb frequency, % (10 yr)$^{-1}$, 1945–90 period	1.7	1.9	1.1	2.8
The same, but in % of average frequency	22.2	4.9	1.7	9.0
Variance R^2, ascribed to the linear trend	0.77	0.65	0.25	0.82

96% of the U.S. stations are at airports. A few of them (20) have been transferred from downtown to airports after 1948. The data from the downtown locations of these stations have been excluded from consideration in our analyses. This is considered important, because a recent intercomparison of cloud information from the airports and downtowns in Europe (Raino Heino, Finnish Meteorological Service 1999, personal communication) clearly show that ''century-long'' composite cloud-cover time series may contain spurious trends due to this change in station locations.[8] Cloud-type information from approximately 10 (in 1993) and 20 (in 1994) stations became unavailable after the introduction of the ASOS at these stations.

During the past decade several changes related to small clouds of the low layer were introduced in the U.S. network (the appendix) in 1984 and 1988, respectively. This reporting modification made it difficult to secure homogeneity of time series of the low cloud-layer amount and could cause artificial trends in the frequency of some cloud types. In order to avoid this mishap in our analysis of the U.S. cloud-type data, we counted only those cloud types that were reported with the total cloud cover greater than two-tenths (i.e., when at least 30% of the sky dome has clouds). Thus, we exclude cases with total cloud cover equal to or less than two-tenths from the numerator but not from the denominator in our frequency calculation. However, our results (see, e.g., Fig. 4) indicated that the use of two units of total cloud cover in selecting sample cases did not affect significantly the trend estimates of cloud-type frequency for the major low cloud types analyzed (Cb, Sc, and St), but lowers the absolute value of their cloud-type frequency. The U.S. observers are allowed to report ''obscuring phenomena other than fog'' (e.g., haze, heavy precipitation, drizzle, blowing sand/snow/dust) that prevent them from accurate determination of a cloud-layer's height and type with (or instead of) the lowest cloud-type reporting. The rules of this reporting changed several times prior to the early 1990s (in 1951, 1984, and 1988). In 1988, the new set of instructions ordered the observer to discontinue all cloud-type and amount reporting when more than half of the sky dome is obscured. To avoid inhomogeneity in the U.S. cloud-type frequency time series, we excluded from our analysis all cases when ''obscurations other than fog'' were reported. This is a small fraction of daytime hours with valid cloud-type/obstruction information (less than 2%), but thus about 10% of hours with precipitation were excluded from consideration.

The list of 223 long-term high quality synoptic stations for public distribution and international exchange (Razuvaev et al. 1995) was selected in the late 1950s from approximately 4000 USSR stations by the USSR Hydrometeorological Service (but synoptic data from only 109 stations from this list were transmitted abroad via the Global Telecommunication System). The historical data for the period from 1936 to 1990 from this list (the 6-h observations for 1936–65 and 3-h observations thereafter) are now available for the international community via the Department of Energy Carbon Dioxide Information Analysis Center at Oak Ridge, Tennessee (see footnote 3). The massive relocation of meteorological stations from downtowns to the outskirts of the cities occurred in the late 1930s. But some of the 223 stations (e.g., in Moscow and St. Petersburg) have remained in an urban environment, where they were throughout the entire study period. Over northern Siberia (north of 60°N) of the FUSSR, this station network is relatively sparse, so we do not include this region in our analyses. In the European part of the FUSSR a lot of missing values during World War II make it impossible to analyze cloudiness information, so this region during the period from the summer of 1941 to the autumn of 1944 is omitted in this study. Over the FUSSR south of 60°N, the station network has the best continuous coverage of 78% during the post-World War II period (most of the missing values are in the nighttime). Also, in the period of the data overlap (1971–90) this network has on average 20% more cloudiness information records for the same stations than the recent release of the Hahn and Warren (1999) global cloudiness archive.

To avoid any spurious trends in area-averaged time series due to temporal and spatial inhomogeneity of stations' valid data distribution in both countries, we used a standard approach in our averaging procedure (cf. Jones et al. 1986; Kagan 1979). First, for each station and each cloud characteristic, we calculated the mean value for the reference period (1961–90), which has the

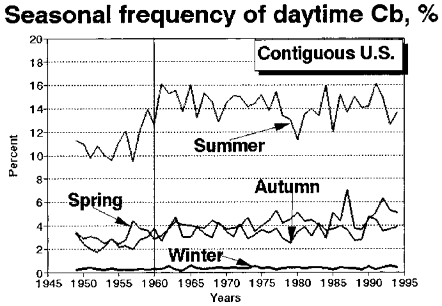
---

[8] The reason for this inhomogeneity is most clearly seen in the fog (ground cloud) frequency. In rural areas (the airports are often beyond the city limits), foggy conditions are still as frequent as they were 50–100 yr ago. In the downtowns, however, if we put aside air contamination and smog, foggy mornings are practically absent.

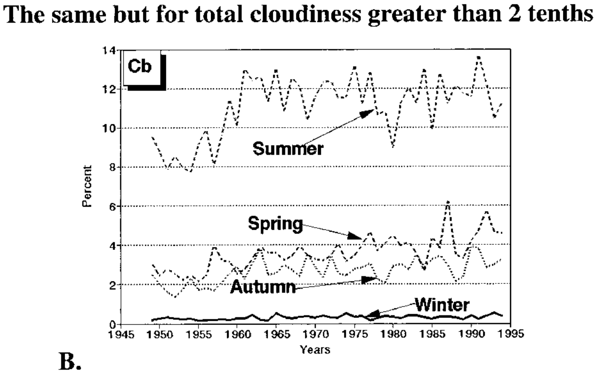
best data coverage at most of the stations. The stations that did not have at least 25 yr of data for this period (several new airports in the United States) were discarded from all further analyses. Thus, over the contiguous United States, the number of stations used in area averaging gradually increases from about 150 in the 1950s to about 190 in the 1980s. Then, we calculated the anomalies from these means and areally averaged the anomalies and means over the contiguous United States and the FUSSR south of 60°N using the Thiessen polygon method (Thiessen 1911; Kagan 1979).[9] For averaging over several large regions of the FUSSR and the United States, arithmetic area averaging was used. Finally, the area-averaged values of cloudiness characteristics are created by adding the area-averaged anomalies with the area-averaged mean values. Thus derived regional and countrywide time series of monthly cloud-type frequencies are converted into seasonal means: December–February for winter; March–May for spring; June–August for summer; and September–November for autumn.

As an additional precaution against spurious trends due to temporal and spatial inhomogeneity of stations' valid data distribution in both countries we compared our area-averaged time series of cloudiness-type frequencies with those derived from the ‘‘frozen'' network. The frozen network approach demands that those and only those stations that have valid data during the entire study period participate in the area averaging and the following trend analysis. The resulting area-averaged time series are ‘‘noisier,'' because they are constructed with a lesser amount of information available from the frozen network. But, we found that these time series reproduce the same tendencies that our major time series have. One of the results based on the frozen network of 127 U.S. stations with serially complete daily precipitation *and* cloud-type information for the 1952–92 period is shown in Fig. 1b.

The next section presents our estimates of recent changes in cloud-type frequency with the focus on cloud types generally connected with vertical atmospheric convection processes, Cu and Cb. As stated before, over the former Soviet Union only cumulative reliable information about the presence of Cb and/or Cu is available in our dataset while over the United States we are able to consider these two cloud types in all combinations, separately and together. For the United States we are also able to consider separately the St and Sc frequencies. Daily precipitation data from the same station networks are also used to investigate the connection of precipitation frequency and intensity with the occurrence of different cloud types.



A.



B.

FIG. 4. (a) Seasonal frequency of occurrence of daytime Cb area averaged over the contiguous United States; (b) same as (a), except only those occurrences were counted when total cloud cover is greater than two-tenths. The comparison of (a) and (b) indicates that the selection of different thresholds of total cloudiness does not affect the trend of this cloud-type frequency.

3. Results

Our analyses show a statistically significant increase in the frequency of convective cloudiness over the regions under consideration in all seasons (Tables 1 and 2, Figs. 3 and 4). This increase has been accompanied by an increase in the frequency of high cloudiness with a base above 6000 m (Fig. 5) and by an increase in convective-type precipitation events in the warm season (i.e., in precipitation events in the top-range percentiles that are usually associated with thunderstorms, cf. Fig. 6 and 7, Table 3, Sun and Groisman 2000). The relative changes in convective cloud-type frequencies are most prominent in intermediate seasons and in winter (cf. a 22% (10 yr)$^{-1}$ relative increase over the former USSR in winter in Table 2). In these seasons the changes have been mostly monotonic and gradual during the post-World War II period. On the contrary, most of the observed summer increase in Cu and Cb (over the FUSSR) and Cb (over the United States) had occurred prior to 1960 and then the summer frequency of convective cloudiness remained relatively stable (‘‘saturated,''

---

[9] The averaging weight of the valid datum at a given point in the Thiessen polygon method is proportional to the area of the region nearest to this point. The Thiessen area-averaged routine increases the contribution of the neighboring stations with available data into the area mean field anomaly value by covering/expanding the anomaly from these stations toward the point with missing datum. This averaging routine is simple and shows decent results for a wide variety of meteorological fields (Kagan 1979).

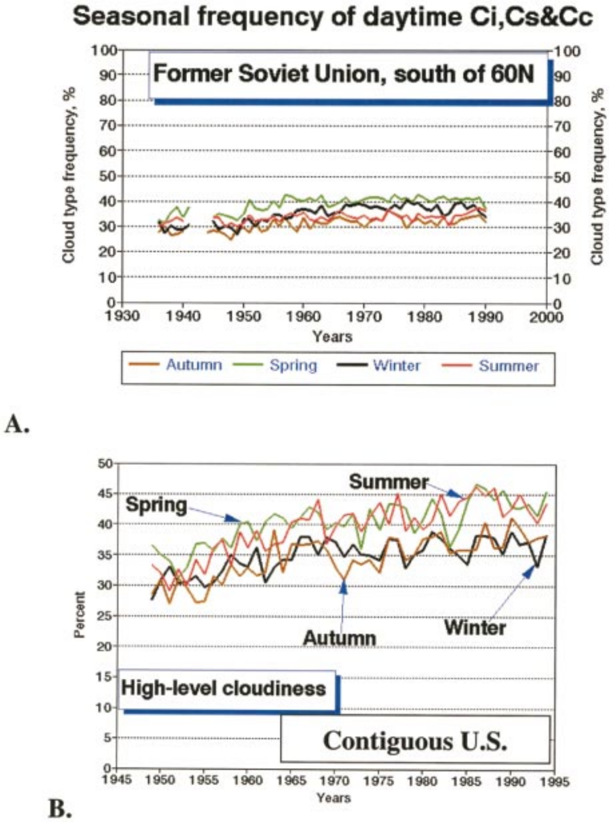


Fig. 5. Seasonal frequency of occurrence of daytime high-level clouds. (a) The former Soviet Union, south of 60°N, and (b) the contiguous United States when total cloud cover is greater than two-tenths.

probably, reached its upper limit).[10] Only over Siberia (the coldest region under consideration), had the increase in summer convective cloudiness continued up to the late 1970s, but then also remained unchanged.

Some of the observed changes in convective cloud-type frequencies are quite abrupt and require special assessments. The causes of the largest ‘‘jumps’’ in the time series of cloud-type frequency were first investigated for a possible change in observing and data processing practices and for a change in the number of stations with valid data. After verifying that the jumps were not caused by these factors, we studied the geographical pattern of changes and searched for supporting information from other meteorological variables (beginning with precipitation). Below we describe one such assessment. Figure 4 shows that over the contiguous United States a significant increase in summer and autumn Cb frequencies occurred around the year 1960. The assessment of the pattern of this abrupt change in Cb frequency shows that it is confined only to the southern half of the United States, while in the midwestern states the frequency of summer cumulonimbus was highest during the 1950s compared to the following decades. The southern regions indeed experienced drought in the 1950s (Karl and Koscielny 1982), which is consistent with less precipitation and streamflow (Groisman et al. 2001; cf. also Figs. 1 and 7) and frequent dust storms in Texas (the information about the dust storm frequency is available in the same U.S. archive TD-3280 used in this study; see also Greenberg et al. 1983). These independent evidences corroborate with the low countrywide Cb frequencies in the 1950s (associated with these regions only).

The sky coverage and the occurrence of frequency of high-level clouds can be biased if low-level clouds obscure the sky. One can argue that the decrease in stratiform cloud cover over the FUSSR itself makes it easier for surface-based observers to see the clouds in higher layers that otherwise are obscured by cloudiness at lower levels. Therefore, although it can be considered as supporting information for the increase in convective cloudiness, we refrain from such an interpretation of the increase in high-level cloudiness over this country. Over the United States an increase in convective cloudiness has been accompanied by an increase in high-level and stratiform low-level cloudiness, while midlevel cloud-cover frequency (not shown) remains nearly unchanged. As a result, total cloud cover has also increased. In such a situation it should be more difficult for surface-based observers to see the high-level clouds. If high-level cloudiness were not changed (but the low cloudiness increased), the U.S. observers would report *a decrease* in Ci, Cc, and Cs. But, actually they reported a continuous increase in high-level cloudiness during the past five decades. Thus, the increase in high-level cloud frequency leads to the conclusion that this observed increase over the United States was actually larger than reported in this paper. The observed increase in the frequency of high-level clouds shown in Fig. 5 may be caused by an increase in stronger convective processes as supported by the increase in low-level convective cloud types. Evidence supporting this speculation is that the frequencies of both convective clouds and high clouds showed rapid increases from the 1950s to the 1960s. However, other factors also can affect the formation of high-level clouds (see footnote 1). For example, some of the increase in high-level cloud frequency, especially over the U.S. airports and especially between 1950 and the early 1970s may be also due to an increase in the formation of Ci and/or Cs from the spreading of jet contrails (Changnon 1981).

Over the contiguous United States, the consistency of the increase between the Sc frequency (Fig. 8) and the number of days with precipitation (Karl and Knight 1998; Groisman et al. 1999a; Fig. 9) indicates that most precipitation events occur around (before/after) the time

---

[10] An autumn Cb time series over the contiguous United States (Fig. 4) shows both features: a strong increase prior to 1960 (as in the summer season) and a gradual increase thereafter (like in the spring and winter seasons).

TABLE 3a. Coincidence of Cu and Sc cloudiness with daytime 0700–1800 LST) and precipitation events of various intensity. Information from the present weather code is employed to determine a precipitation event and its intensity. Data of 225 U.S. and 223 FUSSR stations (Fig. 2) for the entire period of record were used to estimate the correlation between precipitation events and cloud types in 2 × 2 tables (examples are shown in Table 3b).

	Winter	Spring	Summer	Autumn	Annual
Contiguous United States					
Frequency of the presence (%) of Cb during the daytime hours when precipitation occurs					
All precipitation events	0.4	3	12	2	3
Moderate and heavy precipitation events	1	6	15	7	7
Heavy precipitation events only	3	14	23	8	13
Frequency of the presence (%) of Sc during the daytime hours when precipitation occurs					
All precipitation events	59	57	47	55	55
Moderate and heavy precipitation events	33	39	36	35	36
Heavy precipitation events only	33	35	30	31	32
Former Soviet Union					
Frequency of presence (%) of Cb during the daytime hours when precipitation occurs					
All precipitation events	19	51	70	45	49
Heavy precipitation events only	87	84	65	84	85
Frequency of the presence (%) of Sc during the daytime hours when precipitation occurs					
All precipitation events	30	32	33	39	34
Heavy precipitation events only	17	15	16	16	16

when Sc is present in the sky (Table 3). Over the FUSSR the increase in convective and high-level cloud cover has been accompanied by a decrease of low cloudiness, particularly of stratiform clouds (Fig. 1; Sun and Groisman 2000). This decrease also was accompanied by a decrease in the number of summer days with precipitation over eastern Russia, but there was no notable change in the precipitation frequency in the western part of the FUSSR (Groisman et al. 1999a). Figure 9 and Table 3, (cf. also Isaac and Stuart 1996) also suggest that the presence of Sc is a significant indicator of the precipitation events over the Northern Hemisphere midlatitude land areas. Due to the peculiarity of the cloud-type reporting in the United States (a high priority that is assigned to the Sc presence in the cloud layer) Sc clouds ‘‘indicate precipitation much better’’ than in the FUSSR.

Table 3 provides also two examples from the series of 2 × 2 tables of the relationship between coincident precipitation events and cloud-type frequencies over the United States and the FUSSR (the relationship is represented by the percentage of total hours with total/heavy precipitation). These 2 × 2 tables are constructed from all valid cloud types (Cb and Sc) and present weather code (precipitation of any kind, P_{all}, and moderate or heavy rain/snow/shower, P_{heavy})[11] data from all stations. Each of these tables shows significant correlations between Sc and Cb and precipitation of any kind.[12] Annually on average approximately 55% and 35% of precipitation events occurred in the presence of Sc clouds over the United States and the FUSSR, respectively. In the summer season more than 20% of heavy rainfalls originated from Cb over the United States. Over the FUSSR approximately 70% of heavy rainfall originated (or at least occurred in the presence of) Cb. Please note that definition of ‘‘moderate’’ and heavy precipitation in the U.S. observational practice is more restrictive than in the FUSSR (see footnote 11) and that it is optional for U.S. observers to report the ‘‘first cloud layer’’ obscured by precipitation [more than 40% of U.S. ‘‘heavy precipitation’’ cases occurred from skies ‘‘obscured by precipitation’’ and thus (a) nonclassified by cloud type and (b) excluded from consideration in Table 3].

Over the United States the occurrence of Cu cloudiness of ‘‘fair weather,’’ that is, unaccompanied by precipitation or by Cb and/or Sc cloud types, has decreased during the entire 1948–94 period (Fig. 10). We present only the frequency of Cu cloudiness of fair weather instead of the frequency of Cu themselves (that also have steadily decreased during the past five decades), because we found that in the last decade the decrease

---

[11] Moderate and heavy precipitation are defined in the U.S. present weather code as rainfall with intensity above 2.8 mm h^{-1} (>0.1 in. h^{-1}) and 7.6 mm h^{-1} (>0.3 in. h^{-1}), respectively, for liquid precipitation and snowfall that reduces visibility from 5/16 to 1/2 mile and to less than 1/4 mile, respectively, for frozen precipitation (National Climatic Data Center (NCDC) 1970). In the FUSSR ‘‘heavy’’ and ‘‘very heavy’’ precipitation intensities are defined subjectively at each station and season compared to the ‘‘ordinary’’ intensity in the given season (USSR State Committee on Hydrometeorology and Environmental Control 1985).

[12] Description of the χ^2 test used to estimate p in 2 × 2 tables can be found in the section titled ‘‘Categorized Data’’ of (Kendall and Stuart 1967). In the examples of Table 3, we present the statistic $X_c^2 = n(|ad - bc| - 0.5n)^2/[(a + b)(a + c)(b + d)(c + d)]$, where a, b, c, and d are elements of the 2 × 2 table and $n = a + b + c + d$. In the absence of a relationship between events (in our case between the occurrence of a particular cloud type and precipitation of a selected intensity), this statistic is supposed to have χ_1^2-distribution. High values of X_c^2 indicate that the probability of no relationship is miniscule.

TABLE 3b. Example of 2 × 2 tables used to examine correlations between daytime cloud type and precipitation occurrence: for the contiguous United States between annual Sc and all precipitation events; for the FUSSR between summer Cb and heavy precipitation events. In the absence of correlation in the 2 × 2 table, the χ_c^2 values should be sampled from a χ_1^2 distribution, which has an extremely low probability in these cases, because a 0.01-percent point of the χ_1^2 distribution is close to 20.

Annual daytime precipitation/Sc occurrence over the contiguous United States; $X_c^2 = 1.8 \times 10^5$

	Hours with precipitation	Hours without precipitation	Total hours
Sc	788 426	3782 010	4570 436
No Sc	783 756	7744 016	8527 772
Total hours	1572 182	11526 026	13098 208

Summer daytime heavy precipitation/Cb occurrence hours over the FUSSR; $\chi_c^2 = 2.8 \times 10^3$

	Hours with heavy precipitation	Hours without heavy precipitation	Total hours
Cu	1179	513 666	514 845
No Cu	639	2420 108	2420 747
Total hours	1818	2933 774	2935 592

in the Cu frequency is overestimated due to the observation practice changes (the appendix). Over the FUSSR, we cannot separate the frequency of occurrence of Cu clouds of fair weather from heavy convective cloudiness, which is usually accompanied by thunderstorms and/or showers. An indirect evidence, increase in heavy (presumably convective type) precipitation and in the frequency of thunderstorm reports over Russia during the post-World War II period (Groisman et al. 1999a; Sun and Groisman 2000), indicates that the Cb clouds significantly contributed to the increase in convective-type cloudiness in this country.

Over the United States, we found an increase in most cloud types except Cu and St and a general increase in total and low cloudiness (Figs. 1b, 10, and 11; Sun et al. 2000; see also Dai et al. 2001). Over the FUSSR an increase in convective and high- and midlevel cloudiness has been accompanied by a decrease in low cloudiness, thus reducing trends in total cloud cover or even making these trends insignificant (e.g., in the winter season over the FUSSR, Sun and Groisman 2000). Here it should be noted that the choice of a different starting time can affect the long-term trend (Karl 1994). The above conclusions regarding cloudiness changes are drawn from the dataset during 1945–90 over the FUSSR and during 1949–94 over the contiguous United States.

4. Discussion and conclusions

Table 4 summarizes our findings of contemporary changes in cloudiness and cloud types over the United States and the FUSSR during the post-World War II period, including the results reported by Sun et al. (2000) and Sun and Groisman (2000). An increase in convective cloudiness has been observed in each season over these two countries, but most prominently in the intermediate seasons. In the summer season this increase had occurred solely prior to the 1960s. This increase has been accompanied by increases in the frequency of occurrence of high-level cloudiness and of heavy precipitation. Low stratiform cloudiness has decreased over the FUSSR but increased over the contiguous United States. The latter increase was due to an increase in Sc, while the frequency of St clouds has decreased. Generally, it appears that, during the post-World War II period, over the FUSSR the frequency of mid- and high-level cloudiness increased and low cloudiness decreased with a relatively small increase in total cloud cover (1945–90 period), while over the United States the cloud cover has increased at both low and high levels (1948–94 period).

Taking into account the seasonal cycle of convective cloudiness (the summer maximum), we conclude that a ‘‘summer-type’’ convective activity spread toward the intermediate seasons while during the summer season itself the frequency of its indicators (Cb and Cu) has become saturated. The qualitative character of the cloud-type frequency information does not allow direct conclusions about intensification of convective activity. We can only speculate that the increase in the frequency of occurrence of convective clouds over the United States and the FUSSR may indicate an enhanced upward moisture transport in the troposphere in the past 40–50 yr, which may contribute to the upward trend in tropospheric precipitable water over the Northern Hemisphere midlatitude land areas (Ross and Elliott 2001). On the other hand, the formation and development of clouds is related to several factors including the thermal structure of the atmosphere. The intensification of atmospheric convective processes, manifested by the increase in convective-type clouds, should be related to an increase in convective available potential energy (Ye et al. 1998), which can be caused by an increased atmospheric lapse rate and a moistening of the atmospheric boundary layer. According to empirical studies on the seasonal cycle and interannual variability (Mokhov 1983; Gulev et al. 1991), the lapse rate of the troposphere tends to show an increase (with an attendant decrease in static stability) as surface air temperature, especially over the continents, increases. Their finding is in agreement with our report of the increase in convective-type clouds over the United States and the FUSSR that have occurred in the period of a substantial increase of global surface air temperature with the largest warming over Northern Eurasia in winter (Jones 1994; Serreze et al. 2000). The warming over the Northern Hemisphere midlatitudes has been demonstrated also by an earlier retreat of snow cover in spring (Groisman et al. 1994, 2001). The decrease in static stability, in turn, may adversely affect stratiform cloud-type formation, particularly the St form. So, changes in cloud type revealed by this study suggest that significant

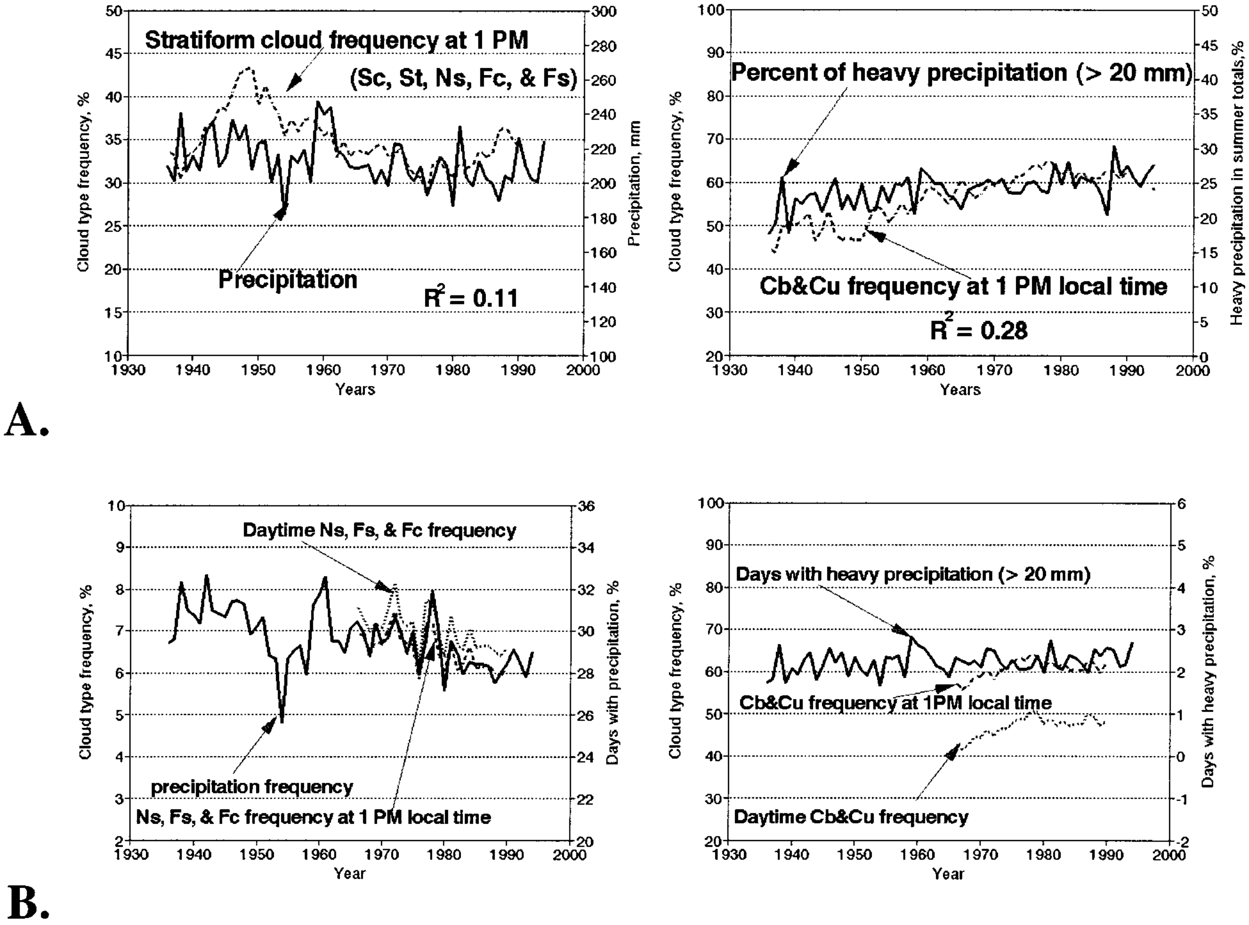


FIG. 6. Changes in summer (total and heavy, i.e., above 20 mm day^{-1}) precipitation and various low cloud types over the Asian part of Russia. (a) Comparison of the stratiform (convective) cloud-cover frequency at 1300 LST with precipitation and heavy precipitation summer totals; *R* is the correlation coefficient. (b) Comparison of stratiform (CLD3) and convective (CLD1) cloud-type frequency at 1300 LST during the daytime with precipitation and heavy precipitation frequency. All precipitation linear trends for the 1936–94 period in these four graphs are statistically significant at least at the 0.05 level. Precipitation frequency and totals decreased while heavy precipitation frequency and totals increased.

changes in the vertical profiles of temperature and humidity might have occurred in the past 40–50 yr. We believe that empirical data can provide a benchmark for verification of the reliability of these conclusions and the schemes used to reproduce cloudiness and its interactions with other meteorological variables in contemporary global climate models. Therefore, it would be instructive to compare our observed results to the model-simulated changes in cloudiness derived from transient runs of contemporary GCMs with external forcings (such as by the increase of atmospheric greenhouse gases) and/or with those "forced" by contemporary sea surface temperature changes, for example, the runs generated for the Atmospheric Model Intercomparison Project (AMIP; Gates et al. 1999). The results of these simulations so far show a wide range of conclusions regarding the changes in total cloudiness, its convective part, and the vertical distribution of clouds. For example, according to Mokhov and Love (1995) approximately one-third of the 30 GCMs participating in the AMIP-1 intercomparison show positive correlation between total cloudiness and surface air temperature over land in the Northern Hemisphere in the interannual variability, while others show an opposite sign of the correlation. However, the redistribution of cloudiness revealed in this study, such as (a) an increase in convective and high-level clouds; (b) a decrease in low-level clouds at high latitudes (cf. the FUSSR); and (c) an increase in low-level clouds in mid-latitudes (cf. the contiguous United States) is seen in some model-simulated warm climates (e.g., Roads 1978; Mitchell 1989; Kattenberg et al. 1996; Yao and Del Genio 1999; Dai et al. 2001).

The noted changes in cloudiness should be related to the changes in atmospheric circulation. In particular, a general intensification of the atmospheric "center of action," the Siberian high, during the winter months has been observed since the end of the nineteenth century. Model analysis by Mokhov and Petukhov (1999, 2000) shows that the increased lapse rate over Siberia may be

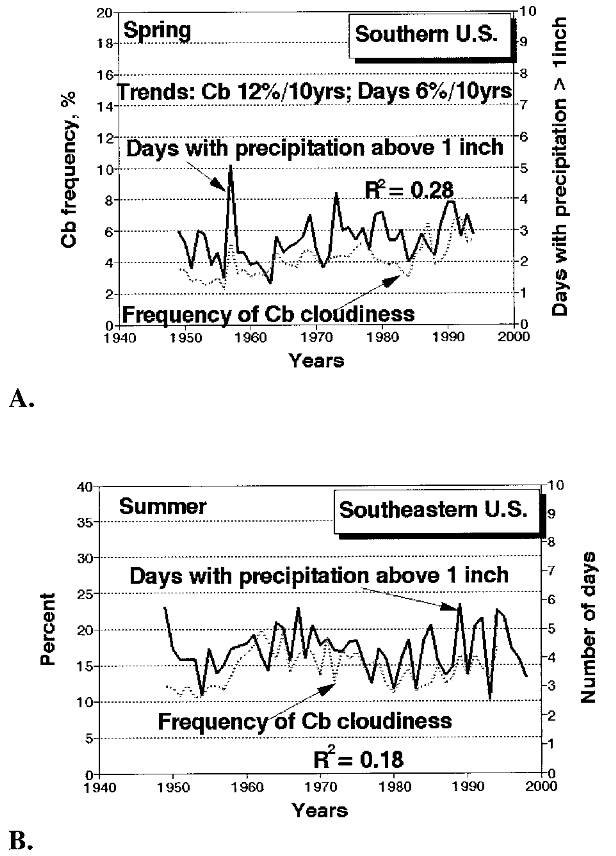


Fig. 7. (a) Change in frequency of spring days with heavy precipitation and Cb clouds over the southern United States (Texas, Louisiana, Mississippi, Arkansas, Oklahoma, and Kansas); (b) same, except for the summer period over the southeastern United States (Alabama, Georgia, Florida, the Carolinas, and Virginia). *R* is the correlation coefficient. Trends in Fig. 7a are expressed in percentage rate.

responsible for this enhancement. The general intensification of the Siberian high should be accompanied by a cloudiness decrease, particularly by a decrease in low cloudiness, because the geopotential anomaly associated with the Siberian high is spread up to the midtroposphere. This is in agreement with the estimates of the stratiform cloudiness changes over Eurasia during the last several decades (Fig. 1a; Sun and Groisman 2000).

Our analysis of the cloudiness data from two countries reveal noticeable differences in definitions and observational practices that affect the estimates of climatology of some of cloudiness characteristics and (to some extent) their relationship with precipitation. Among these differences are, for example, assignment of priorities to various cloud types in the U.S. observational practice that make invisible some precipitation clouds in the presence of others (e.g., Ns, Fs, and Fc in the presence of Sc at the same layer) and the provision of sky reports obscured by precipitation. Therefore, while the separate records (and the results based on them) for the United States and the FUSSR are internally consistent (with the caveats given in the appendix and section 2) the interpretation of these results in terms of changes of convective activity and precipitation would not be the same in these two areas. This can be illustrated on the analyses of precipitation–cloud-type relationships in both countries. Statocumulus most often are not precipitation-producing clouds but our analyses in Table 3 shows that they are strongly associated with precipitation over the contiguous United States (55% rainy hours from *nonobscured* skies annually are associated with Sc), while this number is much less over the FUSSR where Sc is reported without any preference, and a rainy day has a chance to be associated with precipitation-producing cloud such as Ns (Fig. 6b). The elimination of situations when skies are obscured by precipitation and the high priority of reporting of Sc and St compared to all other clouds (except of Cb and towering Cu) in the U.S. observational practice lead to the situation shown in Fig. 1b where Sc and St daytime variations define 90% of annual countrywide variations for the all daytime low cloud-type frequencies and 72% for the

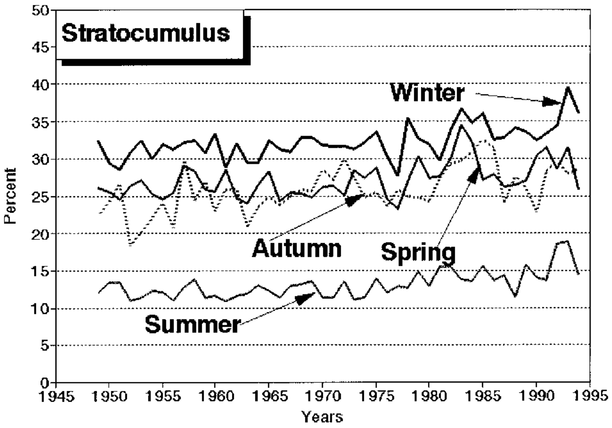


Fig. 8. Same as Fig. 4b for the contiguous United States except for Sc.

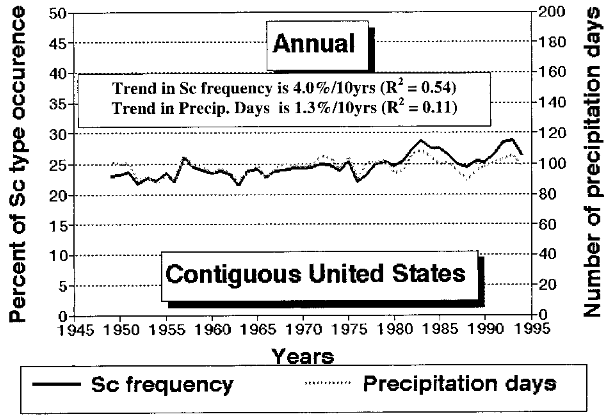


Fig. 9. Change in annual frequency of days with precipitation and stratocumulus area averaged over the contiguous United States. R^2 is the variance ascribed to the linear trend.

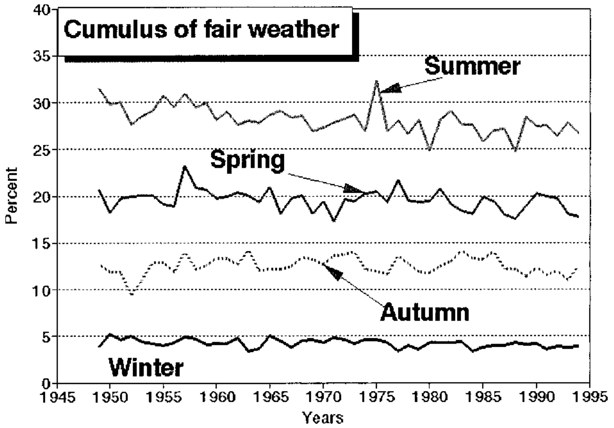


FIG. 10. Same as Fig. 4b for the contiguous United States except for cumulus of fair weather.

precipitation events frequency. For the FUSSR, on the contrary, we still can see (e.g., in Fig. 6) that precipitation is better associated with the CLD3 low cloud-type group (Ns, Fc, and Fs) than with Sc and St. Cumulonimbus were found to have a stronger relationship with heavy precipitation over the FUSSR than over the United States (Table 3). This was expected, because in the more continental climate of this country (compared to the United States), heavy precipitation more often has a local convective origin, instead of being produced by frontal storm systems. But, due to different definitions of heavy precipitation in synoptic reports of both countries (see footnote 11) and a significant portion of the U.S. heavy precipitation events (>40%) reported from obscured skies (and thus excluded from consideration), the empirical evidence of the "relative" strength of this relationship should not be taken as a final word. Furthermore, in our CLD1 time series for the FUSSR, we cannot separate Cb from much more frequently occurring Cu, most of which do not produce any precipitation (e.g., Cu of fair weather). Thus, the correlation with heavy precipitation of CLD1-frequencies over the FUSSR is less than that which we found over the contiguous United States for Cb and heavy precipitation.

Acknowledgments. We thank Drs. Vyacheslav N. Razuvaev (Russian Institute for Hydrometeorological Information), Stephen G. Warren (University of Washington), Aiguo Dai (U.S. National Center for Atmospheric Research), and two anonymous reviewers for thoughtful comments and recommendations. We are grateful to Mr. Frank T. Keimig (University of Massachusetts), Mr. Devoid S. Ezell, and Mr. Matthew W. Bodosky (U.S. National Climatic Data Center) for technical assistance and consultations. The U.S. NOAA Office for Global Programs, Russian Research Program on Global Change of Environment and Climate, U.S. National Science Foundation Grant ATM-9905399, U.S. Dept. of Energy Grant DE-FG02-98ER626604, and Russian Foundation for

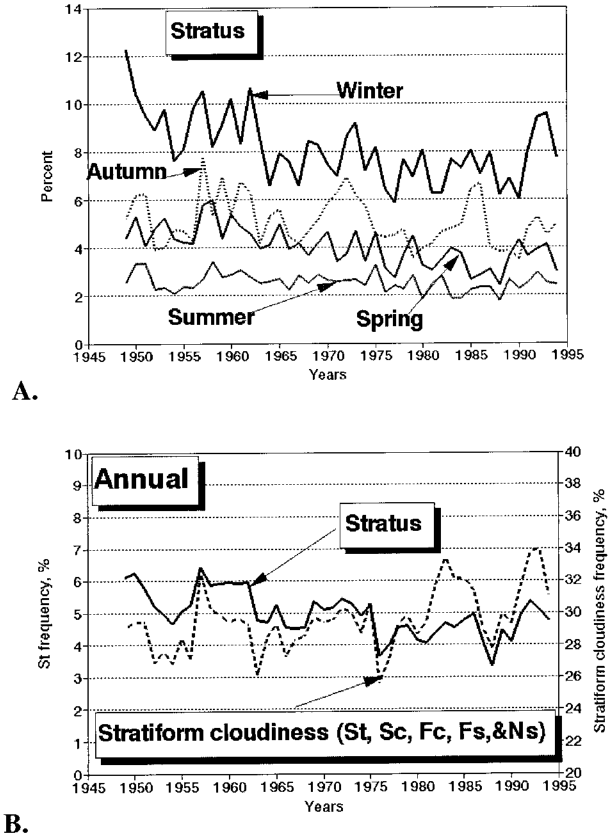


FIG. 11. (a) Same as Fig. 4b for the contiguous United States except for stratus. (b) Same as (a) but for annual stratus cloud-type frequency and for the annual frequency of all stratiform low cloudiness types (St, Sc, Fc, Fs, and Ns).

TABLE 4. Major changes in cloudiness during the post-World War II period over the United States and the former Soviet Union, including the results reported by Sun et al. (2000) and Sun and Groisman (2000). The linear trend estimate, "increase" or "decrease," is statistically significant above the 0.05 level.

Cloud characteristic	United States	FUSSR
Winter		
Total cloud amount	No change	No change
Low-level stratiform cloudiness	No change	Decrease
Convective cloudiness	Increase	Increase
Midlevel cloudiness	Uncertain	Increase
High-level cloudiness	Increase	Increase
Intermediate seasons		
Total cloud amount	Increase	Increase
Low-level stratiform cloudiness	Increase	Decrease
Convective cloudiness	Increase	Increase
Midlevel cloudiness	Uncertain	Increase
High-level cloudiness	Increase	Increase
Summer		
Total cloud amount	Increase	Increase
Low-level stratiform cloudiness	Increase	Decrease
Convective cloudiness	Increase*	Increase*
Midlevel cloudiness	Uncertain	Increase
High-level cloudiness	Increase	Increase

* The summer increase in convective cloudiness over both countries has occurred primarily prior to 1960.

Basic Research Grant 99-05-64551 provided support for this study.

APPENDIX

Homogeneity Issues and Specifics of the Cloudiness Information Used in This Study

a. National archives' data versus GTS synoptic information

Abridged synoptic reports available via GTS represent so far the single source for global assimilation of cloud information (Warren et al. 1986; Hahn and Warren 1999). The practices used in processing these GTS reports differ in several ways from those for the national archive data we used in this study. If inappropriately used, these GTS reports may adversely affect the trend estimates of cloud amount and cloud type. Therefore, below we compare the major features of the GTS cloudiness reports with those available from national archives of the United States and the FUSSR.

1) UNITS

Historically, two unit systems were used for quantitative characterization of cloud amounts: octas (eighths) were used in most European countries while tenths were used in the United States, Canada, the FUSSR, China, and several other countries. In 1947, the International Meteorological Organization (IMO) suggested the use of octas for marine ship observations in order to facilitate and unify the vital meteorological information exchange. Thus, from January 1949 all ships started to report cloud-cover amounts in octas (U.S. Dept. of Commerce 1948) while most of the countries (the United States and the FUSSR included) still preserved their previous observational practices. In the early 1970s, GTS, which uses octas as its standard for cloud-amount information, received the U.S. and the FUSSR cloud-amount data that were recalculated by observers (often far from the observation sites) from the data in tenths. The errors from these man-made recalculations can be considered minimal in the U.S. First Order station dataset. But starting in January 1984, all U.S. synoptic reports were automatically generated at the time of observation in the framework of MAPSO software and the cloud amounts in tenths were converted (rounded) to octas without any adjustments. This procedure *guarantees* systematic biases (i.e., inhomogeneity of the time series) of cloud-cover amounts reported via GTS in this country.

2) QUALITY CONTROL

In general, the non-real-time data from national archives contain many fewer errors because national data centers have performed all necessary quality control procedures and verifications before they release the data to the public. In extremely rare situations the synoptic information that left the station via GTS channels was compared/verified using the original source data. At the final destination point,[A1] although additional quality controls on the synoptic information are performed, there is still no verification from the origination source. These checks, however, cannot distinguish, for example, an erroneous value of total cloud cover of 0.7 from true value of 0.5. So, if someone tries to use the original online synoptic data, he/she must use robust statistical procedures at each step of his/her analyses: the data may contain from 1% (minimum) to 20% erroneous information. Also, we found the data directly received from the radio intercept, as is done over the FUSSR,[A2] can have substantial deviations from reality.

3) PECULIARITIES OF NATIONAL OBSERVATIONAL PRACTICE

National Weather Services of major countries have developed their own observational procedures independently (but with some IMO–WMO coordination) and these procedures also change with time to address evolving demands of society. Therefore, the observing practices from different countries or different time periods in the same country may make the cloud-type frequencies hard to compare. For example, there is a distinctive difference between the cloud-type reporting in the FUSSR and the United States. For the United States, since the 1930s, aviation applications have been the dominant driver of cloud data requirements, while climatic continuity was not a major consideration. In the FUSSR (and currently in Russia) cloud reports have always been a part of the observation routine at more than 4000 (~2000 in Russia) meteorological stations. Russian observers can list all cloud types present at a given hour in the sky (e.g., Cb, Cu, and Sc) without associating them to a specific layer height, while U.S. observers must first list the cloud layers and then assign to each of them a *predominant* cloud type using a hierarchy of cloud types. Thus, the U.S. observers may skip reporting the small cumuli and other cloud types that are low on the list of this hierarchy (e.g., Fc and Fs) that happen to be at the same height as widespread Sc and/or deep Cb. Furthermore, one would expect that the convective activity over the relatively humid contiguous United States is much higher than over the relatively dry FUSSR. But, our analyses of the national archives' data presents a different result: over Russia

---

[A1] Such as DATSAV* archives (USAFETAC 1986) where up to 400 quality checks are performed for the third version of this archive, DATSAV3 (N. Lott, NCDC 1999, personal communication).

[A2] For example, the Hahn and Warren (1999) database contains synoptic data of more than 2000 USSR stations for the 1970s and the 1980s, while only 109 stations were officially designated for international exchange by the USSR Hydrometeorological Service.

(along 55°N) the reported summer Cu and Cb frequencies, 60%, are much higher than the 50% over the eastern United States (along 35°N). The above-mentioned difference in reporting practices primarily explains this paradox: Cu have much less chance to be reported over the United States than over the FUSSR.

Only three cloud layers (low, middle, and high) and the associated predominant cloud types are allowed in GTS reports. Therefore, the cloud-type information in national archives of the United States and the FUSSR is much more comprehensive than in the GTS-based datasets. However, the GTS reports do have the advantage that a single reporting code is used in all countries worldwide, so analyses of GTS reports may be preferred if cloud-type frequencies of different countries are to be compared, as for example in the global climatology of Warren et al. (1986).

WMO (1975) provides a history of cloud-type definitions adopted worldwide, which preserves the major cloud types and their definitions from the versions of 1939 and 1956. Nevertheless, one major cloud type, Ns in the USSR/Russian observational practice is routinely assigned to the low-level (low étage) cloud-type general (USSR State Committee on Hydrometeorology and Environmental Control 1985), despite the WMO recommendation to put it into the midlevel étage (WMO 1975). Except for this peculiarity, we are not aware of any substantial deviations in the cloud-cover observational practice in the FUSSR throughout the post-World War II period. We, however, encountered an inconsistency of reporting with time of the code that partitions Cb and Cu in CLD1 data (see footnote 5) in Razuvaev et al. (1995). This was extremely unfortunate because it prevented us from considering the time series of Cb separately, especially in their relationship to heavy precipitation that appears to be intense (Table 3). The next section describes the specifics of information on various cloudiness characteristics contained in the U.S. national archive of the Surface Airways Hourly Data (TD-3280) used in this study. It indicates that careful attention to the homogeneity issues is needed before cloudiness changes in this country are analyzed.

b. *Cloudiness characteristics in the U.S. Surface Airways Hourly Data (TD-3280)*

1) TOTAL CLOUD COVER

Before the introduction of ASOS in the early 1990s total cloud cover was consistently estimated in tenths without accounting for the number of reported cloud layers. That means that the total cloud cover can be higher than the sum of cloud cover amounts of four (or six) cloud layers available in the digital archive. The ASOS introduction at the U.S. First Order stations irreversibly breaks the homogeneity of this characteristic, because automated stations no longer report high-level and part of the midlevel cloud cover above ~3600 m (12 000 ft). In the early 1990s, the NCDC specialists found a widespread coding error in total cloud-cover values in the digital data prior to 1978 in intermediate hours only (that means hours other than 0000, 0300, 0600 UTC, etc.) The code for missing values of total cloud cover in these hours coincided with the overcast value code (10). This is an additional reason for us to use the U.S. data only with a 3-h time step in this study.

2) OPACITY

During the past 50 yr opaque and/or thin clouds have been redefined three times (on 1 June 195l; on 1 June 1962; and on 1 April 1970). The changes in wording of this definition were not dramatic, but their implementation generated three homogeneity problems in the opaque cloud-cover time series that are difficult to fix. The ASOS does not distinguish thin from opaque cloud cover at all and this variable (amount of opaque cloud cover) became obsolete (absent) after the early 1990s.

3) CLOUD CEILING HEIGHT

This characteristic is a derivative of the lowest opaque cloud-layer information, and thus the homogeneity problems with opacity time series affect any time series that are constructed using the cloud ceiling height data. Additionally, before 1 April 1970 the ceiling for cirriform clouds was reported, but currently the cloud ceiling for these clouds is considered unlimited in observers' manuals.

4) CLOUD-LAYER INFORMATION

The cloud-layer amount reporting practice was changed completely in a set of instructions implemented on 1 June 1951 by the National Weather Service. The number of layers reported in the digitized part of the archive was changed in 1984 (instead of four an observer was allowed to report an infinite number of cloud layers) and in the early 1990s with the implementation of ASOS (automated stations reported up to three and those augmented by observers up to six cloud layers). We found that changes in the number of cloud layers itself did not significantly affect the homogeneity of time series of derived information (e.g., cloud amount by layer). But, the rules for reporting these layers were also substantially changed in June 1951 and then in April and June 1988 (when several changes related to reporting of the lowest cloud layer within an obscured ceiling and the lowest thin scattered cloud layer connected with the second layer were implemented). The above changes could affect the frequency of reporting of ‘‘insignificant’’ low-level cumuli, Fs, and Fc clouds in the presence of Cb, Sc and/or St.

5) Cloud-type information

The practice of reporting at least four cloud layers and predominant cloud types associated with these layers during most of the post-World War II period (except the ASOS epoch) keeps the major cloud-types information unaffected by observational practice changes. The only change was a separate reporting of towering Cu from Cu starting in 1984. After 1984 the fifth and above cloud layers were allowed to be digitized, but they were reported extremely rarely. The U.S. observers assign to each of the cloud layers a *predominant* cloud type. The level of underreporting of nonpredominant cloud types in the U.S. observational practice remained stable (and, therefore, did not create an inhomogeneity of the cloud-type frequency time series) until 1 January 1984, when the Microcomputer-Aided Paperless Surface Observations (MAPSO) were implemented at all U.S. First Order stations. MAPSO is software that allows observers to insert their observations directly on the digital media. During this process a set of consistency checks are conducted and interactively reported to observers. This quality control reinforces a strict following of manual instructions. In particular, it does not allow cloud layers at the same height, keeps their base heights inside the atmospheric boundaries specific for each cloud type, and ascribes only one cloud type (if present) to each cloud level. Thus, in the past, two different cloud types could be assigned to the same cloud level, now this deviation is corrected on the spot and observers need to further generalize their reports: low cloud layers become more extensive and their number decreases. This change, therefore, also could affect the frequency of reporting of insignificant low-level cumuli, Fs, and Fc clouds in the presence of Cb, Sc, and/or St.

The above indicates that the time series of total cloud cover and cloud-type frequencies of the major cloud types (Cb, Sc, St; alto- and cirriform cloudiness) are best suited for analyses of cloudiness changes during the Post-World War II period over the United States.

REFERENCES

Angell, J. K., 1990: Variations in the United States cloudiness and sunshine duration between 1950 and the drought year of 1988. *J. Climate,* **3,** 296–308.

Arking, A., 1991: The radiative effects of clouds and their impact on climate. *Bull. Amer. Meteor. Soc.,* **72,** 795–813.

Bajuk, L. J., and C. B. Leovy, 1998: Seasonal and interannual variations in stratiform and convective clouds over the tropical Pacific and Indian Oceans from ship observations. *J. Climate,* **11,** 2922–2941.

Bradley, R. S., H. F. Diaz, J. K. Escheid, P. D. Jones, P. M. Kelly, and C. M. Goodess, 1987: Precipitation fluctuations over Northern Hemisphere land areas since the mid-19th century. *Science,* **237,** 171–275.

Cess, R. D., and Coauthors, 1996: Cloud feedback in atmospheric general circulation models: An update. *J. Geophys. Res.,* **101,** 12 791–12 794.

Changnon, S. A., 1981: Midwestern cloud, sunshine, and temperature trends since 1901: Possible evidence of jet effects. *J. Appl. Meteor.,* **20,** 496–508.

Dai, A., A. D. Del Genio, and I. Fung, 1997a: Clouds, precipitation and temperature range. *Nature,* **386,** 665–666.

——, I. Fung, and A. D. Del Genio, 1997b: Surface observed global land precipitation variations during 1900–1988. *J. Climate,* **10,** 2943–2962.

——, K. E. Trenberth, and T. R. Karl, 1999: Effects of clouds, soil moisture, precipitation, and water vapor on diurnal temperature range. *J. Climate,* **12,** 2451–2473.

——, T. M. L. Wigley, B. Boville, J. T. Kiehl, and L. Buja, 2001: Climates of the twentieth and twenty-first centuries simulated by the NCAR Climate System Model. *J. Climate,* **14,** 485–519.

Fu, R., W. T. Liu, and R. E. Dickinson, 1996: Response of tropical clouds to the interannual variation of sea surface temperature. *J. Climate,* **9,** 616–634.

Gates, W. L., and Coauthors, 1999: An overview of the results of the Atmospheric Model Intercomparison Project (AMIP 1). *Bull. Amer. Meteor. Soc.,* **80,** 29–55.

GEWEX, 1990: Scientific plan for the Global Energy and Water Cycle Experiment. World Meteorological Organization, Rep. WCRP-40 (WMO/TD 376), 83 pp.

Greenberg, J. H., J. Bromberg, C. M. Reed, T. L. Gustafson, and R. A. Beauchamp, 1983: The epidemiology of heat stress deaths, Texas—1950, 1970–75, and 1980. *Amer. J. Public Health,* **73,** 805–807.

Groisman, P. Ya., and D. R. Legates, 1995: Documenting and detecting long-term precipitation trends: Where we are and what should be done. *Climatic Change,* **31,** 601–622.

——, T. R. Karl, R. W. Knight, and G. L. Stenchikov, 1994: Changes of snow cover, temperature, and radiative heat balance over the Northern Hemisphere. *J. Climate,* **7,** 1633–1656.

——, and Coauthors, 1999a: Changes in the probability of heavy precipitation: Important indicators of climatic change. *Climatic Change,* **42,** 243–283.

——, E. L. Genikhovich. R. S. Bradley, and B. Sun, 1999b: Trends in turbulent heat fluxes over Northern Eurasia. *Interactions between the Cryosphere, Climate and Greenhouse Gases,* M. Tranter et al., Eds., IAHS Publ. No. 256, IAHS Press, 19–25.

——, R. S. Bradley, and B. Sun, 2000: The relationship of cloud cover to near-surface temperature and humidity: Comparison of GCM simulations with empirical data. *J. Climate,* **13,** 1858–1878.

——, R. W. Knight, and T. R. Karl, 2001: Heavy precipitation and streamflow in the United States: Trends in the twentieth century. *Bull. Amer. Meteor. Soc.,* **82,** 219–246.

Gulev, S. K., I. I. Zveryaev, and I. I. Mokhov, 1991: Tropospheric lapse rate as a function of surface temperature. *Izv. Acad. Sci. USSR, Atmos. Oceanic Phys.,* **27,** 287–294.

Hahn, C. J., and S. G. Warren, 1999: Extended edited synoptic reports from ships and land stations over the globe, 1952–1996. Environmental Science Division Publ. 4913, ORNL/CDIAC-123, NDP-026C, 71 pp. [Available from Carbon Dioxide Information Analysis Center, Oak Ridge, TN 37831; online at http://cdiac.esd.ornl.gov/ftp/ndp026c.]

——, ——, and J. London, 1995: The effect of moonlight on observation of cloud cover at night, and application to cloud climatology. *J. Climate,* **8,** 1429–1446.

Hartmann, D. L., M. E. Ockert-Bell, and M. L. Michelsen, 1992: The effect of cloud type on Earth's energy balance: Global analysis. *J. Climate,* **5,** 1281–1304.

Henderson-Sellers, A., 1992: Continental cloudiness changes this century. *GeoJournal,* **27.3,** 255–262.

Houghton, J. T., L. G. Meira Filho, B. A. Callander, N. Harris, A. Kattenberg, and K. Maskell, Eds. 1996: *Climate Change 1995: The Science of Climate Change.* Cambridge University Press, 572 pp.

Houze, R. A., 1993: *Cloud Dynamics.* Academic Press, 573 pp.

Isaac, G. A., and R. A. Stuart, 1996: Relationship between cloud type and amount, precipitation, and surface temperature in the Mackenzie River Valley—Beaufort Sea area. *J. Climate,* **9,** 1921–1941.

Jones, P. D., 1994: Hemispheric surface air temperature variations: A reanalysis and an update to 1993. *J. Climate,* **7,** 1794–1802.

——, S. C. B. Raper, R. S. Bradley, H. F. Diaz, P. M. Kelly, and T. M. L. Wigley, 1986: Northern Hemisphere surface air temperature variations, 1851–1984. *J. Climate Appl. Meteor.,* **25,** 161–179.

Kagan, R. L., 1979: *Averaging of Meteorological Fields* (in Russian). Gidrometeoizdat, 212 pp. (Reprinted by Kluwer Academic Publishers, 1997, L. S. Gandin and T. M. Smith, Eds., 279 pp.)

Kaiser, D. P., 1998: Analysis of total cloud amount over China: 1951–1994. *Geophys. Res. Lett.,* **25,** 3599–3602.

——, and V. N. Razuvaev, 1995: Cloud cover and type over the former USSR, 1936–83; Trends derived from the RIHMI-WDC 223-station 6- and 3-hourly meteorological data base. *Proc. Sixth Int. Meeting on Statistical Climatology,* Galway, Ireland, University College, 419–422.

Karl, T. R., 1994: Smudging the fingerprints. *Nature,* **371,** 380–381.

——, and A. J. Koscielny, 1982: Drought in the United States: 1895–1981. *J. Climatol.,* **2,** 313–329.

——, and R. W. Knight, 1998: Secular trends of precipitation amount, frequency, and intensity in the United States. *Bull. Amer. Meteor. Soc.,* **79,** 231–242.

Kattenberg, A., and Coauthors, 1996: Climate models—Projection of future climate. *Climate Change 1995: The IPCC Second Assessment,* J. T. Houghton et al., Eds., Cambridge University Press, 285–358.

Kendall, M. G., and A. Stuart, 1967: *Inference and Relationship.* Vol. 2, *The Advanced Theory of Statistics,* Charles Griffin, 690 pp.

Klein, S. A., and D. L. Hartmann, 1993: The seasonal cycle of low stratiform clouds. *J. Climate,* **6,** 1587–1606.

Mitchell, J. F. B., 1989: The ''greenhouse'' effect and climate change. *Rev. Geophys.,* **27,** 115–139.

Mokhov, I. I., 1983: Tropospheric lapse rate and its relationship to surface air temperature by observations. *Izv. Acad. Sci. USSR, Atmos. Oceanic Phys.,* **19,** 688–693.

——, and P. K. Love, 1995: Diagnostics of cloudiness evolution in the annual cycle and interannual variability in the AMIP (Cloudiness Diagnostics Subproject 13). *Proc. First Int. AMIP Sci. Conf.,* Monterrey, CA, U.S. Department of Energy and World Climate Programme, WMO/TD-752, 49–53.

——, and V. K. Petukhov, 1999: Sensitivity analysis of Atmospheric Centers of Action. *Geophys. Res. Abstr.,* **1,** p. 431.

——, and ——, 2000: Atmospheric Centers of Action and tendencies of their change. *Izv. Acad. Sci. USSR, Atmos. Oceanic Phys.,* **36,** 292–299.

National Climatic Data Center (NCDC), 1970: Reference manual to WBAN hourly surface observations. NCDC TD 144, 14 pp. [Available from NOAA/National Climatic Data Center, Federal Building, 151 Patton Avenue, Asheville, NC 28801.]

Norris, J. R., 1998a: Low cloud type over the ocean from surface observations. Part I: Relationship to surface meteorology and the vertical distribution of temperature and moisture. *J. Climate,* **11,** 369–382.

——, 1998b: Low cloud type over the ocean from surface observations. Part II: Geographical and seasonal variations. *J. Climate,* **11,** 383–403.

——, and C. B. Leovy, 1994: Interannual variability in stratiform cloudiness and sea surface temperature. *J. Climate,* **7,** 1915–1925.

Peterson, T. C., V. S. Golubev, and P. Ya. Groisman, 1995: Evaporation losing its strength. *Nature,* **377,** 687–688.

Razuvaev, V. N., E. G. Apasova, and R. A. Martuganov, 1995: Six- and three-hourly meteorological observation from 223 USSR stations. ORNL/CDIAC-66, NDP-048, 69 pp. + appendixes. [Available from Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge, TN 37831.]

Roads, J. O., 1978: Numerical experiments on the climatic sensitivity of an atmospheric hydrological cycle. *J. Atmos. Sci.,* **35,** 753–773.

Ross, R. J., and W. P. Elliott, 1996: Tropospheric water vapor climatology and trends over North America: 1973–93. *J. Climate,* **9,** 3561–3574.

——, and ——, 2001: Radiosonde-based Northern Hemisphere tropospheric water vapor trends. *J. Climate,* **14,** 1864–1880.

Serreze, M., and Coauthors, 2000: Observational evidence of recent changes in the northern high latitude environment. *Climatic Change,* **46,** 159–207.

Sun, B., and P. Ya. Groisman, 2000: Cloudiness variations over the former Soviet Union. *Int. J. Climatol.,* **20,** 1097–1111.

——, ——, R. S. Bradley, and F. Keimig, 2000: Temporal changes in the observed relationship between cloud cover and surface air temperature. *J. Climate,* **13,** 4341–4357.

Thiessen, A. H., 1911: Precipitation averages for large areas. *Mon. Wea. Rev.,* **39,** 1082–1084.

USAFETAC, 1986: DATSAV2 Surface USAFETAC Climatic Database. User Handbook No. 4, USAF Environmental Technical Application Center, Operating Location A, Federal Building, Asheville, NC, 6 pp. + appendices.

U.S. Dept. of Commerce, 1948: International code for radio weather reports from the ships. U.S. Weather Bureau, W.B. 1046 (revised), 24 pp.

USSR State Committee on Hydrometeorology and Environmental Control, 1985: *Nastavlenie Gidrometeorologicheskim Stantsiyam i Postam.* Vol. 3 (Part 1), Gidrometeoizdat, 300 pp.

Vinnikov, K. Y., and A. Robock, 1996: Scales of temporal and spatial variability of mid-latitude soil moisture. *J. Geophys. Res.,* **101,** 7163–7174.

Wang, J., and W. B. Rossow, 1998: Effects of cloud vertical structure on atmospheric circulation in the GISS GCM. *J. Climate,* **11,** 3010–3029.

Warren, S. G., C. J. Hahn, J. London, R. M. Chervin, and R. L. Jenne, 1986: Global distribution of total cloud cover and cloud type amounts over land. NCAR Tech. Note NCAR/TN-273 + STR, 29 pp. + 200 maps.

Weare, B. C., and I. I. Mokhov, 1995: Evaluation of total cloudiness and its variability in the Atmospheric Model Intercomparison Project. *J. Climate,* **8,** 2224–2238.

WMO, 1975: Manual on the observation of clouds and other meteors. WMO Publ. 407, 155 pp.

Yao, M.-S., and A. D. Del Genio, 1999: Effects of cloud parameterization on the simulations of climate changes in the GISS GCM. *J. Climate,* **12,** 761–779.

Ye, B., A. D. Del Genio, and K.-W Lo, 1998. CAPE variations in the current climate and in a climate change. *J. Climate,* **11,** 1997–2015.