Changes in Cloud-Ceiling Heights and Frequencies over the United States since the Early 1950s

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ABSTRACT

U.S. weather stations operated by NOAA's National Weather Service (NWS) have undergone significant changes in reporting and measuring cloud ceilings. Stations operated by the Department of Defense have maintained more consistent reporting practices. By comparing cloud-ceiling data from 223 NWS first-order stations with those from 117 military stations, and by further comparison with changes in physically related parameters, inhomogeneous records, including all NWS records based only on automated observing systems and the military records prior to the early 1960s, were identified and discarded. Data from the two networks were then used to determine changes in daytime ceiling height (the above-ground height of the lowest sky-cover layer that is more than half opaque) and ceiling occurrence frequency (percentage of total observations that have ceilings) over the contiguous United States since the 1950s.

Cloud-ceiling height in the surface–3.6-km layer generally increased during 1951–2003, with more significant changes in the period after the early 1970s and in the surface–2-km layer. These increases were mostly over the western United States and in the coastal regions. No significant change was found in surface–3.6-km ceiling occurrence during 1951–2003, but during the period since the early 1970s, there is a tendency for a decrease in frequency of ceilings with height below 3.6 km. Cloud-ceiling heights above 3.6 km have shown no significant changes in the past 30 yr, but there has been an increase in frequency, consistent with the increase in ceiling height below 3.6 km. For the surface–3.6-km layer, physically consistent changes were identified as related to changes in ceiling height and frequency of occurrence. This included reductions in precipitation frequency related to low ceiling frequency, and surface warming and decreasing relative humidity accompanying increasing ceiling heights during the past 30 yr.

1. Introduction

Clouds reflect solar radiation, trap thermal energy, and produce precipitation. Because of the complexity of feedbacks among these and other processes, their role in climate change is difficult to quantify (Potter and Cess 2004). Large discrepancies remain among global climate models related to the simulation of cloud properties (e.g., cloud amount, cloud albedo, and cloud height) and statistics, including their feedback effects on global temperature (Moore et al. 2001). Analysis of past cloudiness variability and its relation to other climatic parameters can provide constraints on model simulations.

Two primary sources of cloudiness observations are satellites and surface weather stations. Satellite cloud datasets are derived from radiance measurements and include cloud amount, cloud optical thickness, cloud-top pressure, and other radiative information. The International Satellite Cloud Climatology Project (ISCCP; Rossow and Schiffer 1999) dataset starts in 1983 and offers near-global coverage but has time-dependent inhomogeneities arising from changes in sat-

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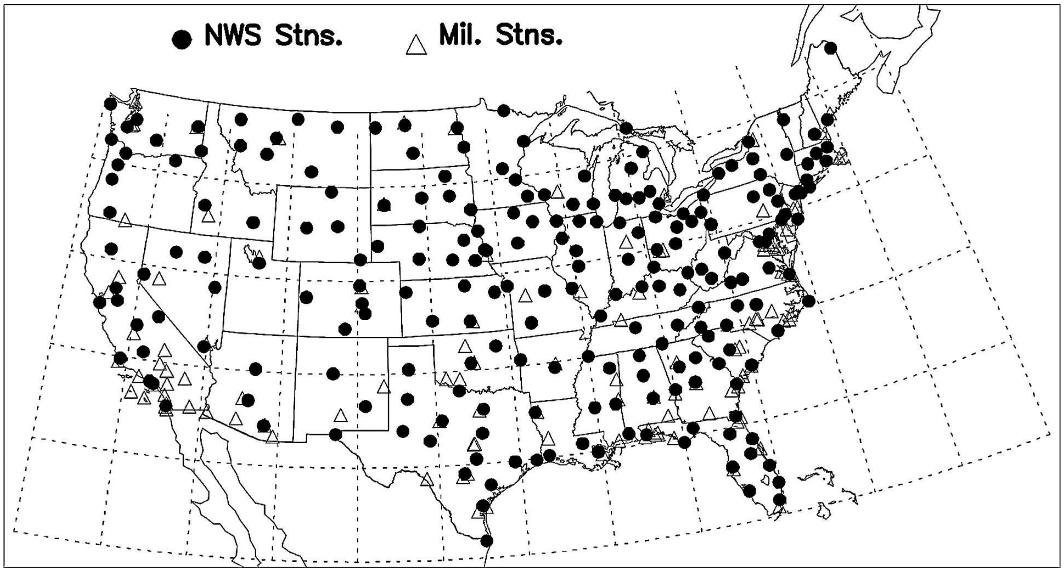

Fig. 1. Networks of 223 NWS first-order stations (black dots) and 117 military weather stations (triangles).

ellite view angle (Campbell 2004) and other problems (e.g., Klein and Hartmann 1993b).

Therefore, despite irregular and incomplete spatial sampling and lack of quantitative radiative information, the existing collection of cloud measurements made by surface observers is a valuable source of long-term information for the evaluation and diagnosis of cloud radiative interactions. Routine cloud observations from surface synoptic weather stations generally include total cloud cover, cloud opacity, cloud-layer amount and height, cloud type, and cloud-ceiling height. Due to a variety of issues, particularly those related to changes in reporting practices (Hahn and Warren 1999; Norris 1999; Sun et al. 2001; Dai et al. 2006), not all cloud information in national archives is suitable for climate change detection. Because of their general interest and simplicity, however, visual cloud observations have become the focus of many analyses (e.g., Angell 1990; Karl and Steurer 1990; Henderson-Sellers 1992; Norris 1999; Kaiser 2000; Sun 2003; Sun and Groisman 2004; Dai et al. 2006; Warren et al. 2007). To gain insight into detailed cloudiness changes, recent studies (Sun et al. 2001; Sun and Groisman 2004; Norris 2005) have focused on trends in cloud-type frequency and cloud layer amount.

Cloud-base height has important implications for climate change. Its variations directly impact cloud physical thickness and optical properties and reflect variations in surface heating conditions, planetary boundary layer structure, and atmospheric circulation (Doran and Zhong 1995; Norris 1998; Del Genio and Wolf 2000). However, compared to other cloud properties, cloud-base height observed at surface weather stations has had more changes related to the manner in which it has been reported (see section 2). This varies from station to station and network to network.

In U.S. weather observing practice, cloud-ceiling height is defined as the base height of the lowest cloud layer when it is reported as broken or overcast and not classified as "thin." Cloud-ceiling height differs from cloud-base height in that the former term is used only in reference to broken and overcast skies. When the sky is completely hidden by surface-based phenomena such as fog or precipitation, the height ascribed to the surface-based layer is the vertical visibility into the layer. The ceiling is otherwise termed unlimited when the preceding conditions are not met. So ceilings are reported as unlimited for scattered and clear skies.

Figure 1 shows the locations of 223 National Weather Service (NWS) first-order stations (sites that report a complete range of weather parameters either by trained personnel or automated equipment) and 117 military weather stations, located primarily at major airports. Data from these locations were used to calculate changes in cloud-ceiling occurrence frequency and ceiling height during the period 1951–2003 over the contiguous United States.

In section 2 we describe the historical observing practices for U.S. cloud-ceiling reports in the periods of human and Automated Surface Observing System (ASOS; NWS 1998) observations. ASOS was gradually implemented after the early 1990s to replace human observers. In section 3 we describe the cloud-ceiling datasets and the method used to generate national time series from station data. As shown in Fig. 1, NWS stations are densely distributed over the eastern United States but are sparse in the west. Most of the military stations are located along the Atlantic, the Gulf of Mexico, and the southern California coasts. To obtain spatially representative national cloud-ceiling information, we combined data from these two networks, but homogenous cloud-ceiling observations were a precondition for inclusion in our climate change detection analysis. Cloud-ceiling comparisons between the military and NWS networks are described in section 4, which indicates some discrepancies between NWS and military networks. In section 5, by examining changes in physically related independent parameters, spurious records are identified and removed. Finally, section 6 presents the climatology and climate change detection analysis in the resultant cloud-ceiling data and related climatic variables.

In this study, cloud ceilings were grouped into three height intervals: surface–2 km, 2–3.6 km, and above 3.6 km. The surface–2-km category is for low clouds, which are closely coupled to the lower atmospheric conditions. The 3.6-km level is used because it is the uppermost height the ASOS ceilometer can measure.

2. U.S. cloud-ceiling observations

Cloud ceilings at weather stations are determined based on sky condition and cloud height. Traditionally, sky conditions are visually estimated by human observers, who have used a variety of methods (e.g., more information available online at http://www.faa.gov/ats/ars/Directorates/Arw/section3-4.htm). The most common are the following.

- Pilot reports: These current weather reports can include cloud-layer height (estimated via pressure altimeter), in-flight visibility, and turbulence and are generally considered more reliable the closer the aircraft is to the cloud.
- Radar weather reports: These reports provide information regarding general areas of precipitation, type and intensity of precipitation, and direction and height of precipitation-bearing clouds.
- Radiosonde balloons: Observers compute the cloud height by multiplying the time it takes for the balloon to enter the cloud by the standard rise rate of the balloon. The accuracy of the height determined in this way is diminished when balloons do not enter a representative portion of the cloud base or during high winds or heavy precipitation.
- Convective cloud-base height diagrams: Based on this standard diagram, observers use temperature and dewpoint values to determine the cloud height. This method cannot be used in hilly terrain or to determine the height of noncumulus clouds.
- Ceiling lights: At night, observers use a theodolite to measure the angle formed by a distant surface-based light reflecting off of a cloud base, and determine cloud-base height via triangulation.
- Rotating beam ceilometers: These instruments use optical triangulation to measure the height to cloud base by sweeping a narrow beam of light at constant angular velocity in a vertical plane.
- Objects of known heights: Ceiling heights are estimated by using known heights of unobscured objects within 2.4 km of weather stations. This method is helpful in estimating low ceilings at airports with tall objects nearby.
- Visual estimation by experienced observers, if other options are lacking or are considered unreliable.

Each method applies a different principle to report ceiling height and their accuracies are not well documented, but it is likely that errors in estimated/measured ceiling height vary. Because the method used varies over time, among stations, and between networks (Lott et al. 2001), the homogeneity of cloud-ceiling time series is probably poorer than that of other cloud properties.

Starting in September 1992, ASOS gradually replaced human observers and has been the major source of cloud observations in the United States since 1995. ASOS was designed specifically to support aviation operations and forecast activities (NWS 1998) and the ceilometer measures clouds at or below 12 000 ft (3.6 km) and does not report cloud type or cloud opacity. The ASOS sky and ceiling information are automatically derived from ceilometer data. Ceiling height is estimated based on the height of clouds detected every 30 s during the previous 30 min (with the last 10 min of data doubly weighted). Unlike human observers, the ASOS ceilometer cannot distinguish between thin and opaque cloud layers.[1]

At some ASOS stations, the automatic observations are augmented and supported by human observers to include cloud conditions above 3.6 km, oversee operations, and flag unrepresentative observations. The allowable differences (from human observations) for ceil-

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[1] Using the sky condition and cloud-layer height information included in human observations from the NWS stations, we found for clouds below 3.6 km the daytime occurrence frequency of thin broken or overcast conditions is 3.0% of that for opaque sky conditions. We estimate that inclusion of thin sky conditions in ASOS ceiling reports could lower the ceiling height by 3.6%.

ing measurements varies with ceiling height: ±60 m for ceilings below 300 m, ±90 m for ceilings between 300 and 1500 m, ±150 m for ceilings between 1500 and 3000 m, and ±300 m for ceilings between 3000 and 3600 m (more information available online at http://www.nws.noaa.gov/asos/amscom.htm).

Of 223 NWS first-order stations, ~72% have been operated with only ASOS instruments, but the remainder have been augmented with human observations since 1995 (more information available online at http://www.avmet.com/awad/IndReportmain.cfm). Military stations also introduced the ASOS system at that time, but human observers augment ASOS observations at all military ASOS stations. Hence, observations from the military station network are probably more homogeneous than those from the NWS network for total cloud cover (Dai et al. 2006) and other cloud properties.

3. Data processing

Synoptic data from NWS first-order stations and military stations are collected in the Surface Airways Hourly Dataset (Steurer and Bodosky 2000) and the Integrated Surface Hourly Database (ISHD; Lott et al. 2001), respectively, both archived at the National Oceanic and Atmospheric Administration (NOAA) National Climatic Data Center. Military station data are available hourly. The NWS data are also hourly, except for January 1965–June 1981, when the digital archive was reduced to every third hour (viz. 0000, 0300, 0600, 0900, 1200, 1500, 1800, and 2100 UTC), and for consistency we used only eight observations per day for the full period of record. (Hourly NWS data have currently been digitized and included in ISHD.) Under conditions of poor illumination, human observers have difficulty identifying clouds (Hahn et al. 1995) and correctly reporting ceiling heights. Therefore, this analysis uses only observations made during daytime (between 0600 and 1800 LST).

When calculating monthly means from daily or hourly data, a minimum number of days per month is generally required to avoid sampling error. Over the contiguous United States, approximately 60% of ceiling reports come from low clouds. We found many stations, especially in arid areas of the western United States, with only a few cases of low-cloud-ceiling reports in a month for any hour. In summer during the daytime, 37% of the stations have fewer than five low-cloud-ceiling reports per month. To allow analysis of ceiling information from as many stations as possible, no minimum number of nonunlimited ceiling reports was required to create the monthly time series at individual stations. A disadvantage of this approach is the introduction of statistical noise from stations with only a few reports per month, but including more stations in spatial averages results in suppression of noise in national average time series.

To avoid spurious trends in area-averaged time series due to uneven spatiotemporal data distribution, we used the following procedure. First, monthly values of ceiling height or ceiling frequency were calculated at each station for each observation time. Daytime monthly values were averaged from monthly values at daytime hours, and a monthly anomaly time series for each station was calculated based on the reference period 1961–90. Second, station anomalies and means were averaged over 5° × 5° grid cells. The grid cell monthly anomaly time series and reference period monthly means were subsequently averaged to grid cell seasonal values. Finally, national anomalies and means were obtained via area-weighted averaging of values from all grid cells in the contiguous United States. To characterize changes in cloud ceiling and their relations to other climatic parameters, linear trends and correlations were assessed using the nonparametric median of pairwise slopes and Spearman rank-order correlation, respectively (Lanzante 1996), and statistical significance was tested using the Spearman test.

4. Comparison of cloud ceilings between NWS and military stations

This section compares mean values and temporal variations of cloud-ceiling frequency and height calculated from the two networks. The national average anomaly time series for the surface–2-km, 2–3.6-km, and surface–3.6-km layers (Figs. 2–4) show the best correspondence between NWS and military data from the early 1960s to the 1992 introduction of ASOS. Correlations between the two networks for the period 1962–91 are positive and statistically significant (at the 0.05 level) for all these cases (e.g., correlation coefficients are 0.96 and 0.78 for the surface–2-km ceiling frequency and height, respectively), with an exception of the 2–3.6-km ceiling height where the correlation coefficient is only 0.25. This poor correlation can be attributed to a noisy statistical sample in the 2–3.6-km ceiling layer due to the small sample size: the number of ceiling height samples in a month for the 2–3.6-km layer is only one-fourth that for the surface–2-km layer (see Table 1).

The mean differences in ceiling heights between the two networks (NWS-minus-military) for 1962–91 are −7 m for the surface–2-km layer and 19 m for the 2–3.6-km layer, neither of which is statistically significantly

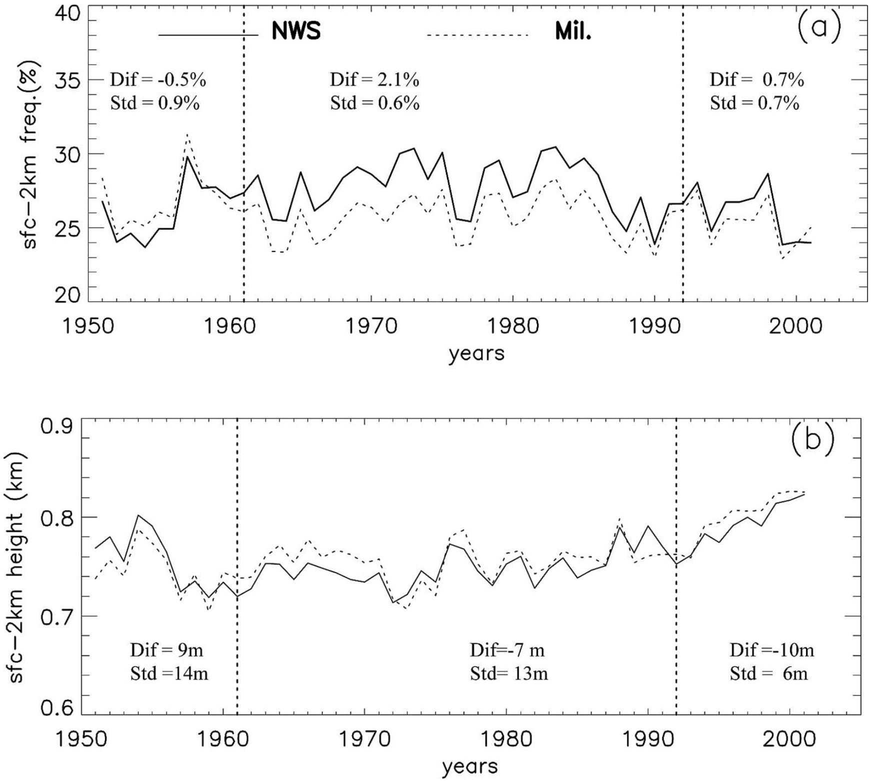

FIG. 2. Comparison of NWS and military network daytime annual-mean surface–2-km (a) ceiling frequency and (b) ceiling height. Station values were converted into 5° × 5° grid cell values, which were then averaged across the contiguous United States, where both networks have observations (see text for details). Vertical dashed lines in 1961 and 1992 demark spurious records in one of the datasets prior to 1961 and after the ASOS introduction in the early 1990s. "Dif" and "std" represent the mean NWS-minus-military difference and its std dev, respectively, for the period 1951–61, 1962–91, or 1992–2001.

different from 0 at the 0.05 level. However, the NWS ceiling frequencies in the period 1962–91 are 2.1% higher for the surface–2-km layer and 0.6% lower for the 2–3.6-km layer, both statistically significant. Even though the 1962–91 ceiling heights are similar for the surface–2-km and the 2–3.6-km layers, the greater surface–2-km ceiling frequency and smaller 2–3.6-km ceiling frequency in NWS data (cf. military data) cause the NWS surface–3.6-km ceiling height to be significantly lower than in the military network by 63 m (Fig. 4b).

Prior to the early 1960s and after the ASOS introduction in the early 1990s, data from the two networks appear inconsistent. For instance, compared to the 1962–91 surface-2-km ceiling frequency values, the military value is higher (by 1.1%) and the NWS value is lower (by 1.6%) in the period 1951–62 (Fig. 2a). During the transition from human to ASOS observation in the early 1990s, both the 2–3.6-km ceiling frequency and ceiling height at NWS stations drop to lower values, while no changes were found in military stations (Fig. 3). This contrast is still present if the cutoff height is changed from 3.6 to 3.4, 3.2, or 3.0 km. These inconsistencies cause discontinuities (around 1961 and at the time of the introduction of ASOS in the 1990s) in the NWS-minus-military difference time series, suggesting spurious signals in at least one of the datasets.

To determine the statistical significance of these discontinuities, we compared NWS-minus-military values prior to the early 1960s, after the early 1990s, and the period between using Student's *t* test. We find statistically significant differences, indicating a discontinuity in 1961–62 in the surface–2-km ceiling frequency and in the surface–3.6-km ceiling frequency and ceiling height. We also find a significant discontinuity beginning in 1995, but only for the 2–3.6-km ceiling frequency.

Comparison of ceilings above 3.6 km was limited to the period from the early 1970s to the early 1990s before the ASOS system was implemented, because from September 1956 to March 1970 the ceiling height was recorded as unlimited if the ceiling cloud was cirriform. Mean differences between the NWS and military networks are insignificantly different from 0 (−0.9% for

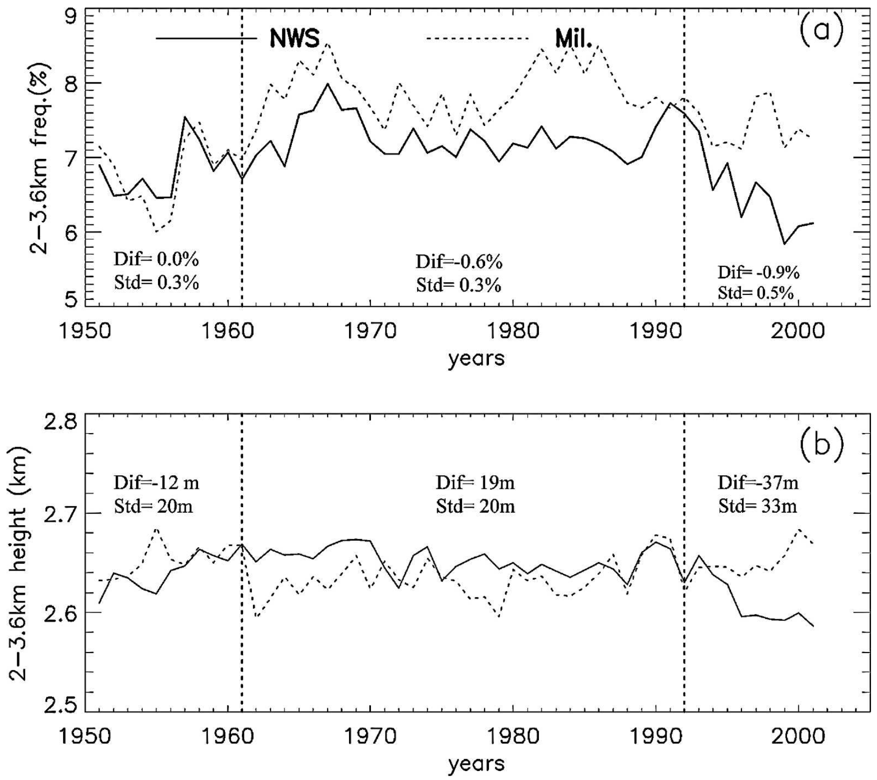

FIG. 3. Same as in Fig. 2, but for (a) 2–3.6-km ceiling frequency and (b) ceiling height.

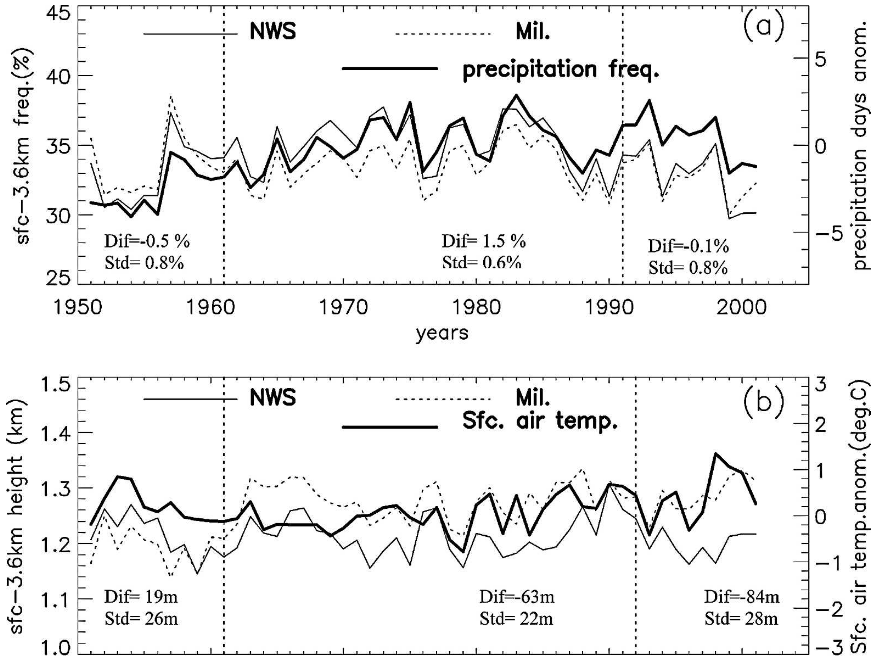

FIG. 4. Comparison of daytime annual surface–3.6-km (a) ceiling frequency and (b) ceiling height between NWS and military networks. Values were calculated in the same way as those in Fig. 2. Annual anomalies of precipitation days (%) and surface air temperature (°C) time series are included in (a) and (b), respectively.

TABLE 1. After exclusion of military data prior to 1961, and non-augmented NWS ASOS data after 1992, trends during 1951–2003 and 1971–2003 in (a) cloud ceiling height [m (10 yr)$^{-1}$] and (b) ceiling frequency [% (10 yr)$^{-1}$]. Time series of these parameters were averaged from all 5° × 5° grid cells across the contiguous United States. Trend estimates in boldface are statistically significant at the 0.05 level. Climatological mean (1961–90) values are also shown.

	Surface–2 km			2–3.6 km			Surface–3.6 km			>3.6 km	
		Trend [m (10 yr)$^{-1}$]			Trend [m (10 yr)$^{-1}$]			Trend [m (10 yr)$^{-1}$]			Trend [m (10 yr)$^{-1}$]
(a)	Mean (m)	1951–2003	1971–2003	Mean (m)	1951–2003	1971–2003	Mean (m)	1951–2003	1971–2003	Mean (m)	1971–2003
Winter	702	4.3	**24.5**	2647	5.4	**9.2**	1080	4.4	**27.7**	5564	13.1
Spring	849	**9.8**	**23.5**	2639	**5.0**	4.5	1233	**13.6**	**30.7**	5824	14.7
Summer	871	**8.0**	**20.1**	2713	**7.5**	**12.8**	1545	**11.1**	8.8	5685	−26.5
Fall	808	**8.6**	**30.8**	2661	−0.5	2.4	1270	4.7	**38.2**	5665	−3.1
Annual	772	**9.8**	**26.3**	2664	**2.2**	**7.3**	1282	7.6	**24.6**	5694	4.8

	Surface–2 km			2–3.6 km			Surface–3.6 km			>3.6 km	
		Trend [m (10 yr)$^{-1}$]			Trend [m (10 yr)$^{-1}$]			Trend [m (10 yr)$^{-1}$]			Trend [m (10 yr)$^{-1}$]
(b)	Mean (%)	1951–2003	1971–2003	Mean (%)	1951–2003	1971–2003	Mean (%)	1951–2003	1971–2003	Mean (%)	1971–2003
Winter	34	0.19	−0.52	7	0.01	0.12	41	0.17	−0.42	8	**1.65**
Spring	30	−0.31	−0.60	7	0.02	0.12	37	−0.24	−0.55	9	**2.08**
Summer	20	**−0.30**	−0.39	8	−0.00	−0.15	28	−0.34	−0.58	10	**2.32**
Fall	27	0.32	−0.87	7	0.03	−0.05	34	0.36	−0.91	8	**1.81**
Annual	28	0.04	**−0.60**	7	0.02	0.00	35	0.05	**−0.67**	9	**1.95**

ceiling frequency and 180 m for ceiling height), indicating the comparability of mean ceiling characteristics between the two networks. However, the time series are poorly correlated for both ceiling frequency and ceiling height, possibly related to real spatial differences between the two networks.

In summary, the consistency of ceiling variations between the two networks from the early 1960s to the early 1990s provides confidence in the reliability of the data for that time period. Discontinuities before and after lead to discrepancies in the annual time series that are present in all seasons, with smaller magnitudes in winter and larger ones in summer. The cloud discontinuities associated with introduction of ASOS reinforce earlier studies (McKee et al. 1994; Guttman and Baker 1996; Sun et al. 2005) showing the inhomogeneity introduced into the climate record at the time of the instrument change.

5. Validating cloud ceilings using physically related parameters

Lack of both station history on specific cloud-ceiling measurement methods used and information on possible biases associated with different methods prevents us from directly clarifying the conflicting ceiling information found in the two networks (Figs. 2–4). Therefore we seek other methods to identify a homogeneous climate record for ceilings.

Satellite data have been used to examine the interannual variability of cloud cover from surface observations (Sun 2003; Sun and Bradley 2004). However, satellite-based infrared and visible observations do not penetrate clouds and so do not yield cloud-base height information. Statistical characteristics of cloud vertical structure, including cloud-top and -base heights, can be inferred from radiosonde temperature and humidity profiles (Wang and Rossow 1995; Chernykh and Eskridge 1996; Naud et al. 2003; Chernykh and Alduchov 2004). However, due to changes over time in radiosonde vertical resolution, instrumentation, and observing practice, long-term changes in these cloud properties derived from radiosonde records (Chernykh et al. 2001) may be spurious (Seidel and Durre 2003; Chernykh et al. 2003) and inappropriate to validate observed cloudiness time series.

Changes in physically related parameters, for example, sunshine duration (Angell 1990; Karl and Steurer 1990) and diurnal temperature range (Dai et al. 2006), have been used to test the reliability of surface total cloud-cover observations. As will be discussed in the next section, there are limitations to the usefulness of physically or dynamically related parameters to conduct indirect data validation, but this approach appears to be our best option to reduce uncertainties in interpreting cloud-ceiling time series.

We used precipitation frequency time series to examine the homogeneity of ceiling frequency time series due to their high correlation with low cloud cover (Sun and Groisman 2004). The formation of low clouds is related to many parameters in the lower-tropospheric atmosphere, including, but not limited to, surface heating, low-level air convergence and advection, thermal profiles of the lower troposphere, and atmospheric circulation of different scales (e.g., Klein and Hartmann 1993a; Doran and Zhong 1995; Norris 1998; Wang and Rossow 1998; Del Genio and Wolf 2000). Surface air temperature (T_{sfc}) and relative humidity (RH_{sfc}) are closely associated with the condensation level of low clouds, which in most cases is their base height. We used long-term records of T_{sfc} and RH_{sfc} to examine the homogeneity of ceiling height information. Monthly T_{sfc} data (averages of monthly T_{max} and T_{min}) from the Global Historical Climatology Network (GHCN) dataset (Peterson and Vose 1997) have undergone homogeneity adjustment. However, RH_{sfc} measurements have experienced changes in instrumentation that could introduce inhomogeneity in long-term RH_{sfc} time series.

Figure 4 indicates that from the early 1960s to the early 1990s ceiling-frequency and ceiling-height variations are closely associated with precipitation and T_{sfc}, respectively. Correlations, based on the 1961–92 period of homogeneous data, between ceiling frequency and precipitation are 0.77 and 0.83, for NWS and military data, respectively. Correlations between ceiling height and surface temperature are 0.41 and 0.35. All are statistically significant at the 0.05 level. This gives reassurance that the ceiling data from both networks are realistic for that period. Prior to the early 1960s, the surface–3.6-km ceiling frequency and ceiling height at NWS stations are highly consistent with precipitation frequency and T_{sfc} anomalies, respectively, but the military data are not. (For 1951–60 data, we obtain a T_{sfc}–NWS ceiling height correlation coefficient of 0.61 while the T_{sfc}–military data ceiling height correlation coefficient is 0.38.) In the ASOS period, the ceiling frequency and ceiling height at military stations are closer to anomalies of precipitation frequency and T_{sfc}, respectively, than the NWS data. This comparison suggests that prior to the early-1960s military ceiling frequency (ceiling height) is biased high (low), while the NWS ceiling frequency and ceiling height, particularly at altitudes higher than 2 km, in the ASOS period are biased low.

The causes of these biases are unknown and may be subtle. Surface observers may tend to overestimate the sky cover because gaps in clouds near the horizon may not be visible. Pilots also can make this kind of overestimation but with a magnitude greater than ground observers as they fly over the top of cloud decks at high speed. Cloud ceilings could have been reported more frequently at the military stations prior to the early 1960s, if most of the ceiling records at that period came from pilot reports.

The NWS–military differences in the ASOS period particularly after 1995 (Figs. 2–4) may indicate the difference between human and automatic observations, since many NWS stations used only ASOS at that time. Human observations are made from horizon to horizon and cover an area with a radius of ~30 km. In contrast, ASOS is designed to measure conditions within an ~8-km radius of the installation. ASOS sky-cover reports are also weighted to reflect the past 10-min observations. When cloud systems move rapidly and cloud heights rise and fall quickly, ASOS observations may miss some of this variability because of the averaging time used (more information available online at http://www.faa.gov/ats/ars), but it can be captured by an acute observer. Thus, trends derived from ceiling data containing nonaugmented ASOS observations (Richardson et al. 2003) could be biased toward increasing ceiling height.

Spurious ceiling data found in the comparison, including the military data prior to 1961 and the nonaugmented ASOS observations in NWS stations, were excluded from further analysis. Ceiling data combined from the two networks, analyzed in the next section, include only data from human observations and human-augmented ASOS observations. The latter include data from all military ASOS stations and 62 NWS human-augmented ASOS stations.

6. Climatology, trends, and variations in ceiling frequency and ceiling height

a. *Climatology*

Climatological (1961–90) mean ceiling heights for ceilings below 3.6 km are higher in the warm season and lower in the cold season (Table 1). This is particularly evident for the surface–2-km layer, where the summer height exceeds the winter by ~169 m. A different seasonality is observed for the above-3.6-km layer: spring ceiling height exceeds that of other seasons by 140–320 m.

Ceilings for the surface–3.6-km layer (Fig. 5a) in the eastern United States (east of 100°W) are generally lower than in the west, but there are smaller-scale regional differences. For example, ceilings in the West Coast are lower by 300–600 m compared to other regions in the west and ceilings in Florida, southern Louisiana, and coastal North Carolina and Virginia are higher by ~300 m than in many other areas in the eastern United States. These spatial patterns are consistent

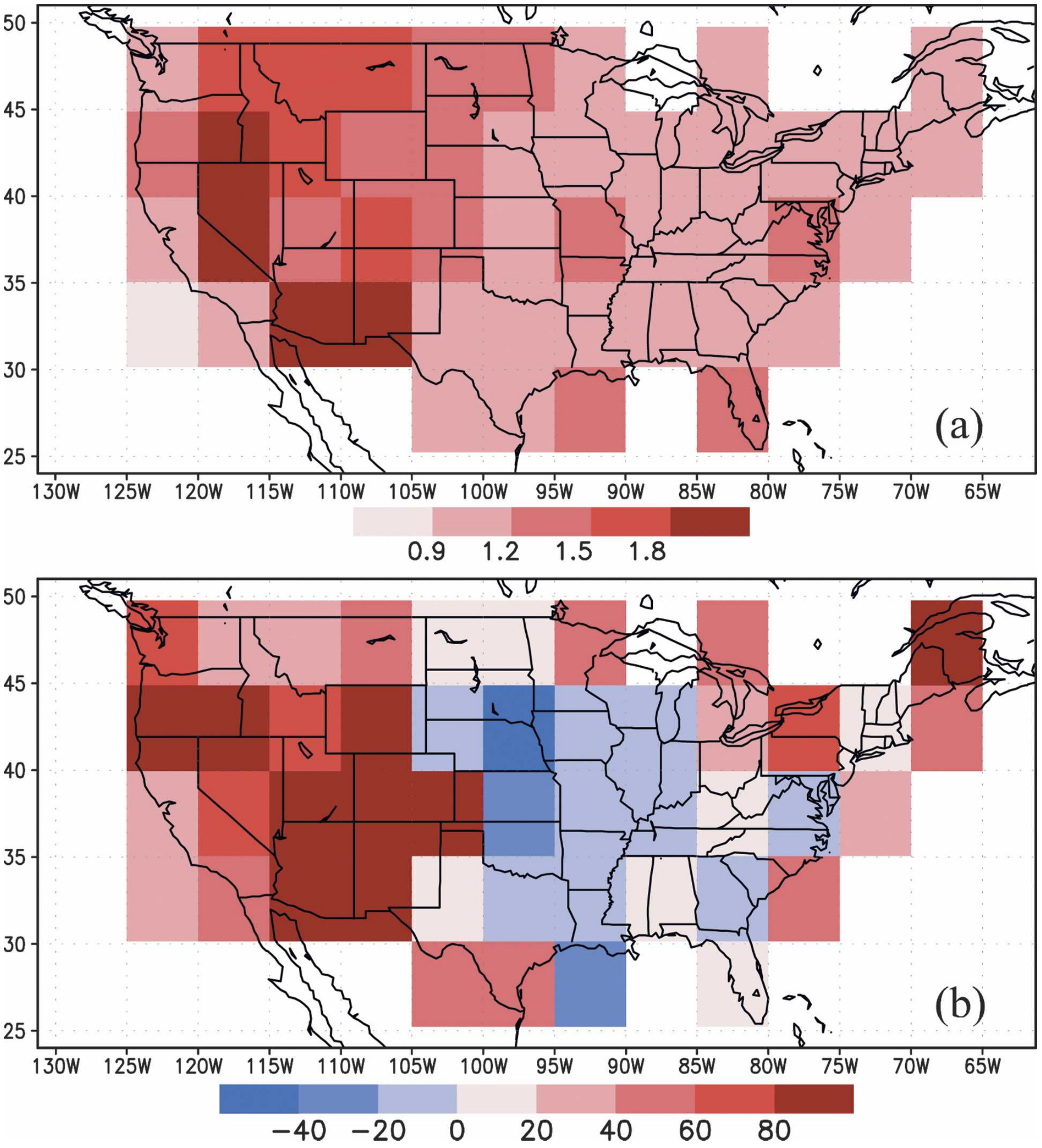

FIG. 5. (a) Climatological (1961–90) annual mean ceiling height (× 100 m) for the surface–3.6-km layer and (b) linear trends [m $(10\ \mathrm{yr})^{-1}$] in annual surface–3.6-km ceiling height during 1971–2003 in 5° × 5° grid cells.

with base heights of stratus (St) and stratocumulus (Sc) clouds reported by Warren et al. (1986), even though these two cloud types contribute only a portion of total ceiling cases.

The spatial distribution of the above-3.6-km ceiling height (not shown) is quite different from that of the surface–3.6-km layer (Fig. 5a). For the above-3.6-km layer, the ceilings are lower west of 105°W than in the east, with the lowest ceilings in the northwest and the highest in Florida and southern Texas.

Climatologically, ceilings with height below 2 km occur more frequently in winter (34%) than other seasons (20%–30%). Ceiling frequency is much lower for the 2–3.6-km layer (~7%) and above 3.6 km (~9%; Table 1), and in those layers, ceilings occur most frequently in summer. Spatial patterns (not shown) indicate ceilings for the surface–3.6-km layer occur more frequently in northeast, the Great Lakes region, and the state of Washington while less frequently in the Southwest. Above 3.6 km, ceilings occur more frequently in the Great Plains, Rocky Mountains, and southeast than in other areas of the country.

b. *Trends*

Table 1a shows seasonal and annual trends in ceiling height for the continental United States, averaged from all 5° × 5° grid cells across the country. Ceiling height increased for the surface–3.6-km layer in all seasons during 1951–2003, with statistically significant increases (at the 0.05 level) of 13.6 and 11.1 m $(10\ \mathrm{yr})^{-1}$ in spring and summer, respectively. Significant upward trends occur mostly in the period after 1971 and in the surface–2-km layer. For instance, the trend in annual surface–3.6-km ceiling height is 7.6 m $(10\ \mathrm{yr})^{-1}$ and is not statistically significant during 1951–2003, but is much larger [24.6 m $(10\ \mathrm{yr})^{-1}$] and statistically significant for the period 1971–2003. Trends for the surface–2-km layer for the two periods are 9.8 and 26.3 m $(10\ \mathrm{yr})^{-1}$, respectively, and both are statistically significant.

Spatially, the trend pattern for the ceiling height below 3.6 km during 1971–2003 varies by season and with height interval (not shown). But in most cases, as shown in Fig. 5, the upward trends occur mainly over the western United States and the coastal regions, and negative trends occur over the central United States. Ceiling heights above 3.6 km show 1971–2003 decreases in summer and autumn and increases in winter and spring, resulting in no significant annual change.

As shown in Table 1b, 1951–2003 ceiling frequency trends are not statistically significant, except for a significant decline in the summer surface–2-km ceiling occurrence. There is, however, a statistically significant frequency decrease of 0.67% $(10\ \mathrm{yr})^{-1}$ after 1971 for ceilings with height below 3.6 km. Increases in the above-3.6-km ceiling occurrence in the period 1971–2003 are due to upward jumps in the early 1990s and around 1995.

c. *Temporal relations with physically related parameters*

Seasonal relationships between the surface–3.6-km ceiling frequency and precipitation frequency during 1951–2002 are shown in Fig. 6. Correlations based on the unfiltered ceiling and precipitation frequency data are significant in all seasons, indicating the overall match between them. To separate the decadal changes from interannual variations, we filtered the ceiling and precipitation frequency datasets with a nine-point binomial filter and examined interannual correlations on both time scales. On interannual time scales, the surface–3.6-km ceiling frequencies are significantly correlated with precipitation frequencies in all seasons. On decadal time scales, the correlation is highly significant in winter and autumn, much weaker in spring, and statistically insignificant in summer. The low correlations on decadal time scales in summer is primarily due to their opposite trends: in summer, ceiling frequency decreased [0.45% $(10\ \mathrm{yr})^{-1}$], while precipitation frequency increased [0.49% $(10\ \mathrm{yr})^{-1}$].

To understand the different relationships between precipitation and cloud frequency in different seasons, we note that different cloud types are associated with winter versus summer precipitation. Heavy summer rain events have increased since the early 1950s (Karl and Knight 1998), consistent with observations of increased cumulonimbus (Cb) frequency (Sun et al. 2001). But Cb frequency accounts for only a small portion of low cloud frequency. The decrease in occurrence of other broken/overcast clouds including stratus (St) dominated the trend in ceiling frequency (Sun and Groisman 2004), which explains the apparent inconsistency in summertime trends (Fig. 6). In winter and autumn, most precipitation is from stratiform clouds, and the high correlation between precipitation and ceiling frequencies in both seasons on interannual and multidecadal time scales (Fig. 6) suggests that the time series of the below-3.6-km ceiling occurrence frequency are reliable.

Correlations between T_{sfc} and surface–3.6-km ceiling height based on the unfiltered datasets are significant in all seasons (Fig. 7). The smaller (relative to other seasons) summer correlation is related to behavior in the 1960s and the 1970s. On interannual time scales, the correlations between ceiling height and T_{sfc} are significant in all seasons except in winter. The lack of correlation in winter on interannual time scales is consistent with the findings of Warren et al. (2007), who found positive interannual correlations between low-cloud-base height and T_{sfc} in summer but no correlation in winter, and with findings of Del Genio and Wolf (2000), who found that bases of low clouds do not change much with surface temperature on diurnal and synoptic time scales.

Overall, the ceiling height–T_{sfc} correlations are lower than ceiling–precipitation frequency correlations (Figs. 6 and 7). This could be related to several factors. First, each variable represents an average over a different number of days per month; T_{sfc} is an average over all days with data available (generally >25), while the ceiling height value was averaged from available ceiling cases, around 9–12 days in a month (Table 1b), and the number of precipitation days may be even lower. Second, the physical linkage of the ceiling height with T_{sfc} is not as direct as the ceiling–precipitation frequency relation, since cloud formation is the consequence of interactions among many different processes and T_{sfc} can explain only a portion of the variance in ceiling height variability.

Nevertheless, the high consistency between ceiling height and T_{sfc} on decadal and long-term time scales in all seasons indicates that combined ceiling height time series are likely realistic. Multidecadal coupling also

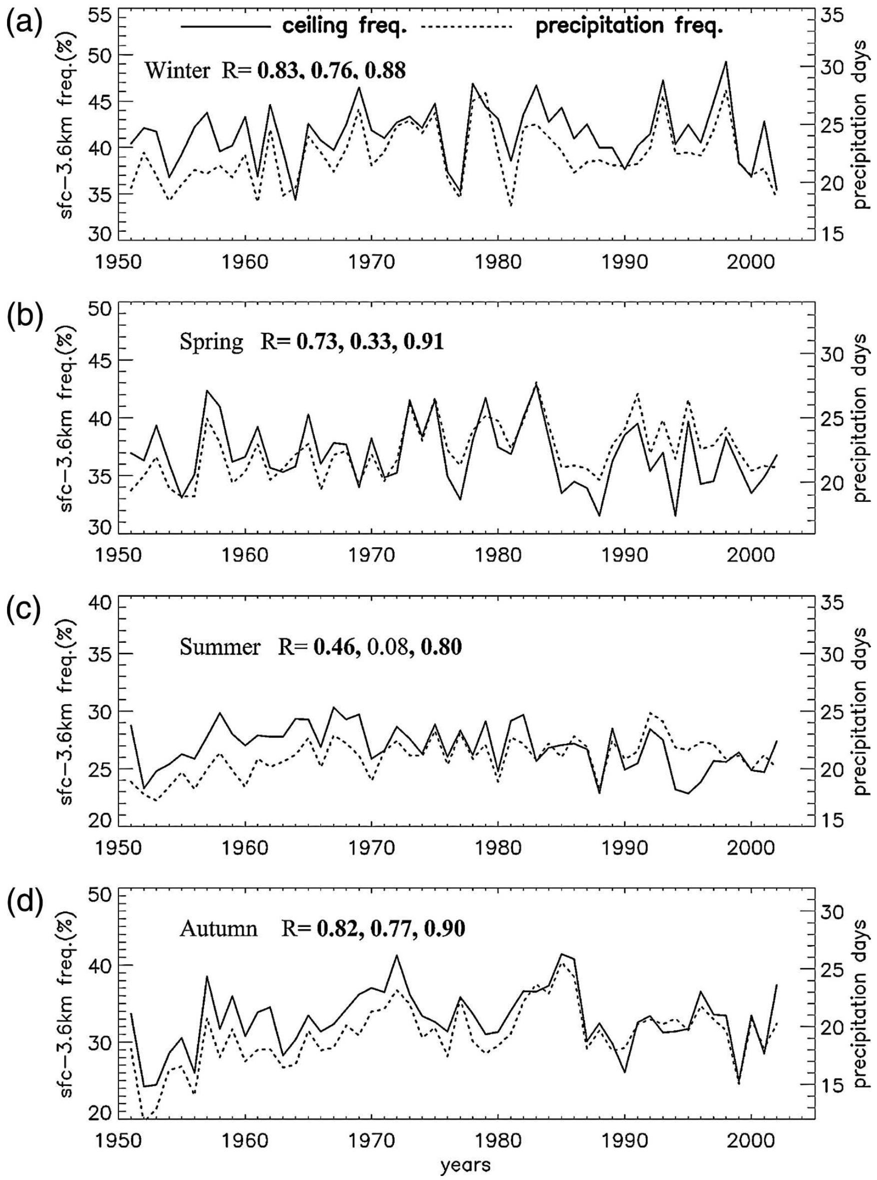

FIG. 6. Annual daytime surface–3.6-km ceiling frequency and number of days per season with precipitation averaged from all 5° × 5° grid cells across the contiguous United States. Also shown are the correlation coefficients (R) between the unfiltered datasets, the nine-point binomial filtered datasets, and the residuals after the nine-point binomial filtering. Correlations in boldface are significant at the 0.05 level.

suggests that changes in T_{sfc} are probably at least one of the causes of the long-term change in base height of lower-tropospheric clouds.

As shown in Fig. 8, prior to the early 1990s $\mathrm{RH}_{\mathrm{sfc}}$ is highly consistent with ceiling height on both interannual and decadal time scales: the drier the near-surface air, the higher the ceiling height. This consistency provides additional evidence of the reliability of ceiling height data. It also suggests changes in dewpoint observing methods, including the change from the use of sling psychrometers to hygrothermometers in the early 1960s, and from the latter to dewpoint hygrothermometers (model HO-83) in the mid-1980s (Gaffen and Ross 1999), did not introduce a notable discontinuity in $\mathrm{RH}_{\mathrm{sfc}}$ data.

We notice, however, higher $\mathrm{RH}_{\mathrm{sfc}}$ values beginning around the early 1990s (Fig. 8). This possible jump, most evident in spring, coincides with the modification of the ASOS HO-83 system beginning in 1991. A comparison of observations from ASOS sites with those

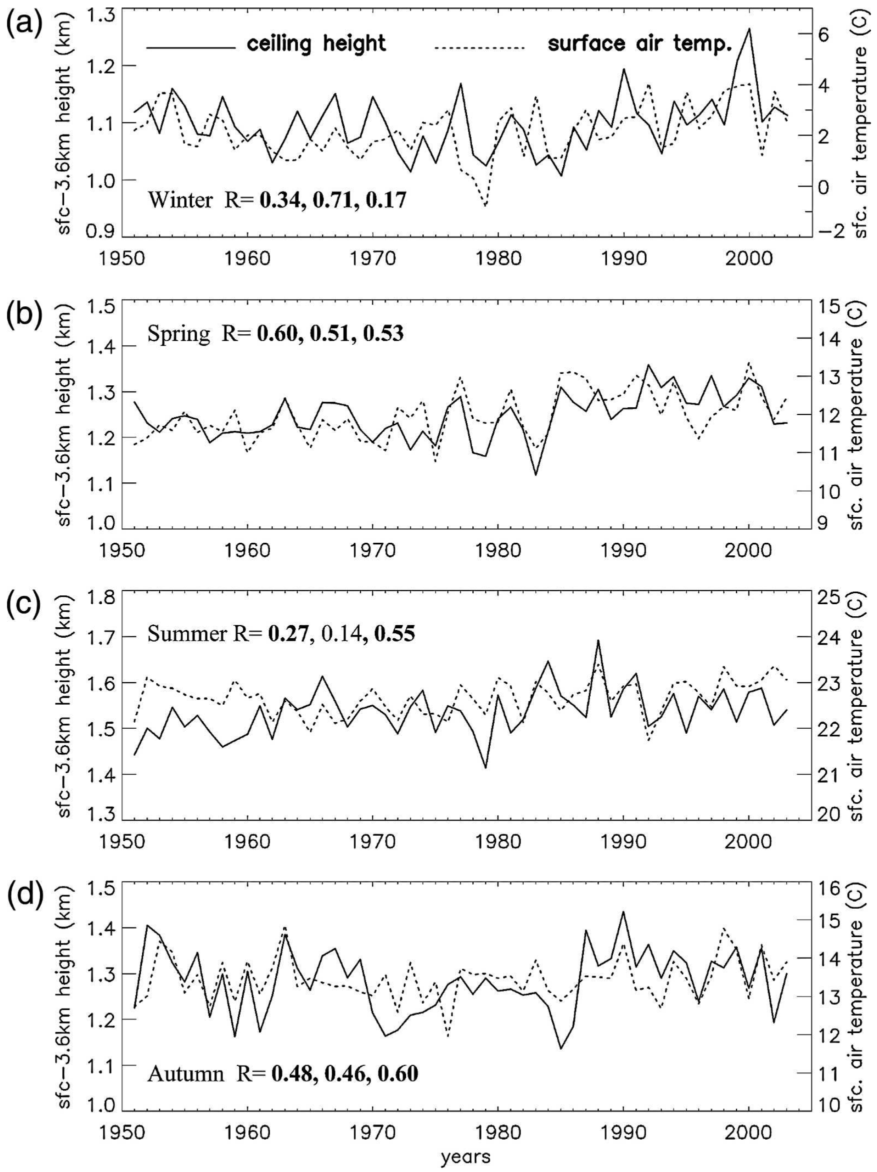

FIG. 7. Same as in Fig. 6, but for surface–3.6-km ceiling height and surface air temperature.

from pre-ASOS sites reveals that ASOS measures relatively lower temperatures and a few percent (1%–3%) higher RH_{sfc} (McKee et al. 1994). This finding, combined with the disruption of the ceiling height–RH_{sfc} relation, suggests a discontinuity in RH_{sfc} values after the early 1990s.

7. Summary and discussion

Through a comparison of ceiling data from NWS first-order stations with those from military stations, and through further comparisons with changes in physically related parameters, periods with inhomogeneous records were identified. Prior to the early 1960s, the surface–3.6-km ceiling frequency (ceiling height) in military stations appears to be spuriously large (low). After the ASOS introduction in the early 1990s, the surface–3.6-km ceiling frequency and ceiling height both appear to be too low in the NWS network. Ceiling data are consistent between the two networks from the early 1960s to the early 1990s and are consistent with physically related parameters, suggesting no significant artifacts were introduced in that time period from the use of different ceiling-observing methods. After discarding the apparently biased records, including the military data prior to 1961 and the nonaugmented

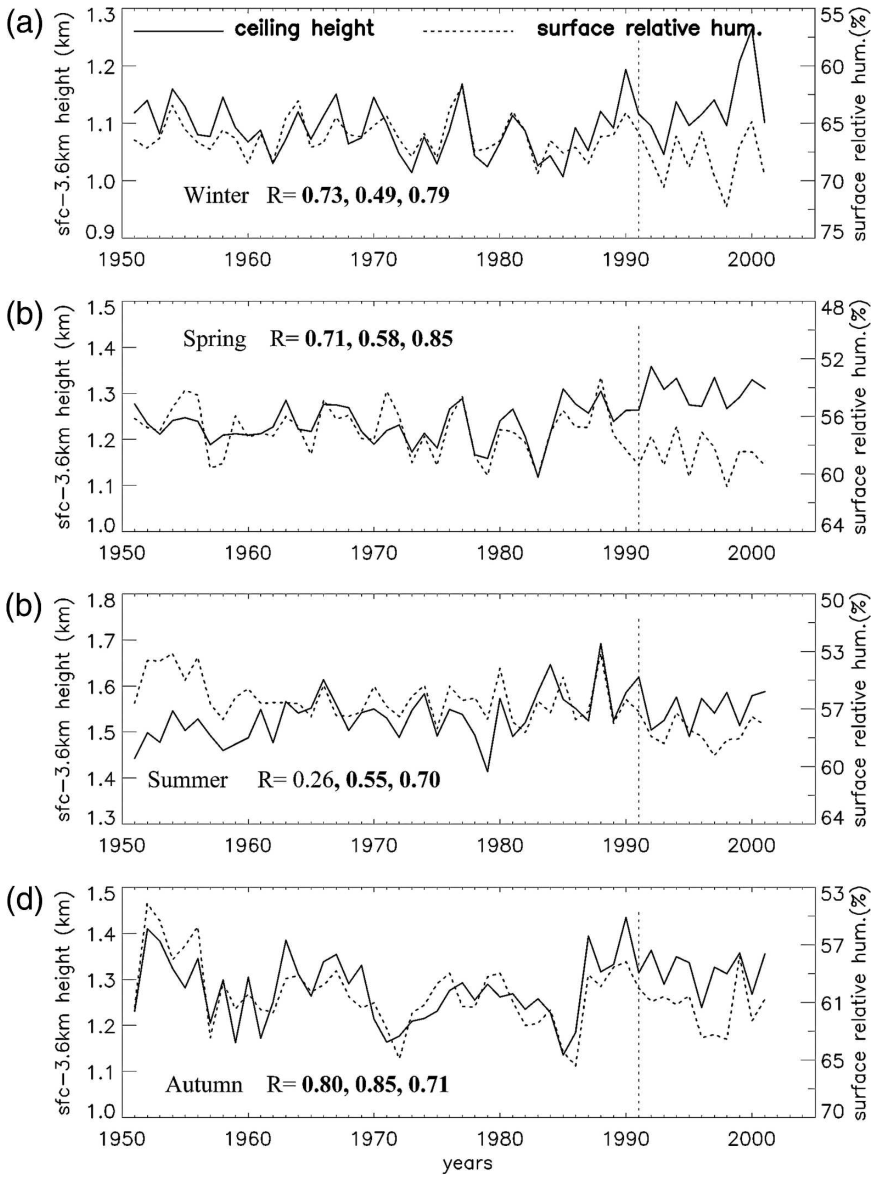

FIG. 8. Same as in Fig. 7, but for surface relative humidity. Correlations for 1951–91 as a possible artifact may be present in humidity data associated with the ASOS introduction in the early 1990s. Note the scale for relative humidity increases downward on the right ordinate.

ASOS observations in NWS stations (after 1992), a combined ceiling dataset was used consisting of data from the two networks, including human observations and human-augmented ASOS observations.

Results indicate a general increase in surface–3.6-km and surface–2-km ceiling height during 1951–2003, due mainly to increases after the early 1970s (Table 1a). No significant change was found in surface–3.6-km ceiling occurrence, but there is a tendency for a decrease in occurrence frequency of ceilings below 3.6 km since the early 1970s (Table 1b). The above-3.6-km ceiling height has remained stable in the past 30 yr, but its occurrence frequency increased (Table 1b). The consistency of the below-3.6-km ceiling time series with time series of precipitation frequency, T_{sfc}, and RH_{sfc} (Figs. 6, 7, and 8) suggests that the combined ceiling dataset is likely realistic.

Del Genio and Wolf (2000) found that on diurnal, synoptic, and seasonal time scales, surface warming and increasing surface dryness are associated with higher low clouds. The consistency of the surface–3.6-km ceiling height with T_{sfc} in the past 54 yr (Fig. 7) suggests that this relationship prevails on interannual and multidecadal time scales as well. We speculate that the rapidly increasing T_{sfc} since the early 1970s has reduced RH_{sfc} (not necessarily surface moisture content), contributing to rising lifting condensation levels and base heights of lower-tropospheric clouds. These changes might, in turn, prevent low cloud formation with large sky coverage (e.g., a cloud cover of 75%–100%), leading to decreasing low-cloud-ceiling frequency in recent decades (Fig. 6 and Table 1b). An increase in upward buoyancy force arising from increasing T_{sfc} might have caused more frequent low scattered clouds (with sky coverage of 10%–50%), but with smaller sky coverage per occurrence. However, Warren et al. (2007) find a slight increase in convective cloud types at the expense of stratiform clouds during 1971–96 for global land areas. Alternatively, reduced RH_{sfc} could allow an increase in T_{sfc} as solar energy is converted into sensible rather than latent heat.

Broken and overcast sky cover accounts for 70% of mean low cloud cover (Sun and Groisman 2004). The decreasing ceiling occurrence frequency since the early 1970s is reflected in the decreasing low cloud cover suggested by Sun and Groisman (2004). The decrease in low cloud cover and the increase in total cloud cover (Dai et al. 2006) in the past 30 yr requires an increase in sky coverage of high clouds (e.g., with the height above 3.6 km) with a rate greater than the decline rate of low cloud cover. The increase in high cloud cover appears consistent with increasing high cloud frequency (Table 1b; Sun et al. 2001), cirrus cloud cover (Minnis et al. 2004), and heavy precipitation events (Groisman et al. 2004).

The albedo of low clouds is generally greater than that of high clouds. Despite an increase in total cloud cover, a decrease in low cloud cover since the late 1980s could lead to an increase in the amount of solar radiation at the surface. This might be one of the factors leading to more sunlight reaching the ground in the last 20 yr, as suggested by surface- (Wild et al. 2005) and satellite-derived radiation data (Pinker et al. 2005). Results from this analysis and other related studies (e.g., Karl and Steurer 1990; Sun et al. 2001; Sun and Groisman 2004; Dai et al. 2006) tend to indicate that in the past several decades significant changes might have occurred over the United States in cloud characteristics and cloud vertical distribution. Radiative effects of these changes, and their linkage to changes in the atmospheric thermodynamics and circulation, are critical to improved understanding of contemporary climate change.

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