Time-Varying Biases in U.S. Total Cloud Cover Data

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ABSTRACT

This paper presents evidence of significant discontinuities in U.S. cloud cover data from the Integrated Surface Database (ISD) and its predecessor datasets. While long-term U.S. cloud records have some well-known homogeneity problems related to the introduction of the Automated Surface Observing System (ASOS) in the 1990s, the change to the international standard reporting format [aviation routine weather report (METAR)] in the United States in July 1996 introduces an additional inhomogeneity at many of the stations where humans still make or supplement cloud observations. This change is associated with an upward shift in total cloud of 0.1%–10%, statistically significant at 95 of 172 stations. The shift occurs at both National Weather Service and military weather stations, producing a mean increase in total cloud of 2%–3%. This suggests that the positive trends in U.S. cloud cover reported by other researchers for recent time periods may be exaggerated, a conclusion that is supported by comparisons with precipitation and diurnal temperature range data.

Additional discontinuities exist at other times in the frequency distributions of fractional cloud cover at the majority of stations, many of which may be explained by changes in the sources and types of data included in ISD. Some of these result in noticeable changes in monthly-mean total cloud. The current U.S. cloud cover database needs thorough homogeneity testing and adjustment before it can be used with confidence for trend assessment or satellite product validation.

1. Introduction

Long-term changes in cloudiness have important implications for climate feedbacks and provide a potentially useful test for evaluation of climate models. Uncertainties in cloud feedbacks are a major source of differences between climate sensitivities given by different GCMs (Pachauri and Reisinger 2007). Most GCMs predict decreasing cloud cover outside of the high latitudes as a result of increases in greenhouse gases, and this decrease could be an important factor in future climate change (Trenberth and Fasullo 2009). In addition, because clouds are a major determinant of surface solar radiation, cloudiness changes could affect the future availability of solar energy. Despite the importance of clouds, we cannot determine clearly whether cloudiness has increased or decreased globally in recent years. Long-term cloud cover data products from satellites have the advantage of global coverage, but changes in viewing angle (Campbell 2004; Evan et al. 2007), satellite calibration differences, and orbital drifts (Jacobowitz et al. 2003) may introduce artificial shifts in cloud cover time series. Observations of cloud cover made at ground-based weather stations are therefore an important source of climate information, but they may also be subject to artificial shifts because of changes in observing or reporting procedures.

Few studies have examined the temporal homogeneity of cloud cover information from U.S. weather stations. Karl and Steurer (1990) pointed out problems with continuity of U.S. ground-based cloud observations before 1950 but found no similar issues with the data after that time. More recently, the discontinuity resulting from the introduction of the Automated Surface Observing System (ASOS) in the mid-1990s has received

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attention (e.g., Warren et al. 1991; Sun et al. 2001; Sun and Groisman 2004; Dai et al. 2006). ASOS does not observe cloud above ~3.6 km, so the automation of most of the U.S. National Weather Service (NWS) network in the 1990s introduced a fundamental inhomogeneity in total cloud cover in the United States for most stations (Sun and Groisman 2004). However, military stations continued to make visual cloud observations until very recently, and a subset of NWS stations continued to supplement the automated reports with visual cloud observations. Dai et al. (2006) found a significant upward trend in total cloud for 1976–2004 from U.S. military station data, but they did not thoroughly examine their homogeneity. Data from the NWS human-augmented stations for the period since the introduction of ASOS have not to our knowledge been used for trend studies. The purpose of this paper is to assess the temporal homogeneity of total cloud cover data since 1949 at those U.S. military and NWS stations that continued to make visual observations after the introduction of ASOS in the mid-1990s.

2. Datasets

The Integrated Surface Database (ISD) archive (DS3505; NCDC 2011; Lott et al. 2001, 2008; Smith et al. 2011) at the National Climatic Data Center (NCDC) is the primary dataset that we evaluate for homogeneity. To help understand issues in ISD, we also analyze two predecessor datasets that have been discontinued: DATSAV3 (NCDC 2003) and DSI-3280 (NCDC 2005). Before the creation of ISD, U.S. cloud data from NWS stations were archived at NCDC in DSI-3280, formerly known as TD-3280 (Steurer and Bodosky 2000). Data in the 3280 dataset end in 2005; NCDC no longer updates this dataset, and it is not available online. Military station data were previously found in DATSAV3 (DSI-9956), a U.S. Air Force archive. All were kindly provided by NCDC. The appendix gives details about the characteristics of each of these sources of cloud data. Although the Extended Edited Synoptic Cloud Reports Archive land station dataset (Warren et al. 2007) contains quality-controlled cloud data starting at 1973 for many stations, it does not include most U.S. stations after the early 1990s, and so is not suitable for our purposes.

To validate cloud cover time series, we also used NWS Cooperative Observer Program weather station daily precipitation data, kindly provided by Pasha Groisman at NCDC. For this paper, we computed from that dataset the number of days with precipitation greater than 0.5 mm day^{-1} for each station and month. By using a uniform cutoff for minimum amount of precipitation, we minimize the effect of changes in gauges and thus reduce inhomogeneities in the rainfall data. We also used temperature data from the ISD for our chosen stations to calculate the diurnal temperature range, in addition to the Historical Climatology Network (HCN), monthly, version 3, adjusted maximum and minimum temperature data (Lawrimore et al. 2011).

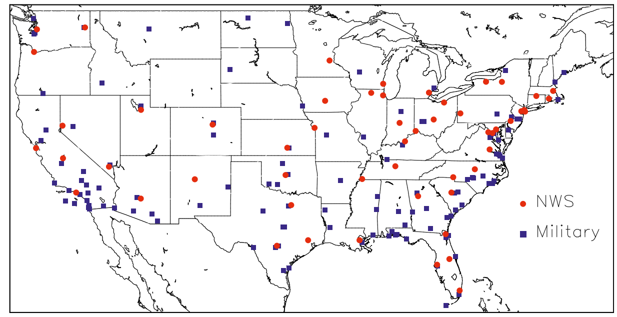

FIG. 1. Locations of stations used for this study.

To avoid the discontinuity between earlier human observations and those from ASOS, we have selected 55 NWS stations [now operated jointly with the Federal Aviation Administration (FAA)] that supplement ASOS with human observations, and 118 military stations in the contiguous United States that did not adopt ASOS in the 1990s. At these NWS stations, human observers provide backup of ASOS elements in the event of an ASOS malfunction or an unrepresentative ASOS report, and also add to ("augment") the automated observation when necessary with cloud cover information above 3.6 km. Figure 1 shows the locations of the stations used in this paper.

3. Relevant recent history of U.S. cloud-observing practices

Between the early 1950s and the introduction of ASOS, we are not aware of any changes in NWS rules directly affecting reporting of total cloud cover. However, several changes in archiving and processing of weather reports occurred. For example, in 1965 NCDC began digitizing only reports made at times divisible by 3 (3-hourly reports) for most NWS stations, and it continued that practice until 1981 (NCDC 2005). Before July 1996, U.S. NWS stations reported total cloud cover in hourly reports as a number from 0 to 10 representing tenths of sky cover (Steurer and Bodosky 2000), and this and other cloud and weather information is collected in DSI-3280. From the early 1970s to July 1996, observers converted these data into eighths of sky cover to conform to the synoptic format for transmission over the Global Telecommunications System (GTS), which uses eighths as its standard for cloud amount information. After 1984,

TABLE 1. Summary of total cloud cover reporting formats for augmented NWS stations. Asterisk means including cloud less than 1/8 but greater than 0.

Time period	Values reported	Definition
Before ASOS	0/10–10/10	Fractional sky cover
ASOS introduction	CLR	0/10
to July 1996	SCT	1/10–5/10
	BKN	6/10–9/10
	OVC	10/10
July 1996–present	CLR	0/8
(METAR)	FEW	1/8–2/8*
	SCT	3/8–4/8
	BKN	5/8–7/8
	OVC	8/8

translation to eighths was done by software at the observing station rather than manually [see the appendix in Sun et al. (2001) for details]. That change was part of a general revision of the processing system for hourly data.

A major change in the cloud reporting format for NWS stations occurred with the introduction of ASOS, even at stations that continued to use human observers. The timing of the shift to ASOS varies between stations, beginning in or after 1992. After ASOS and before the aviation routine weather report (METAR), NWS stations, including those with human augmentation of cloud observations, reported only four broad categories of sky condition (clear, scattered, broken, and overcast), defined in terms of tenths. On 1 July 1996, the United States began using the international format (METAR) for internal reporting, introducing another change. In METAR, cloud information is reported as one of five, rather than four, sky condition categories, which are defined in terms of eighths of sky cover rather than tenths. Table 1 summarizes the formats used at NWS augmented stations for reporting total cloud amounts during the relevant time periods. The appendix gives a detailed discussion of the characteristics of cloud data found in each of the data sources we examined.

In addition, the definitions of *clear* and *overcast*, as distinguished from 1/8 and 7/8 or few and broken, may have changed over time for at least some types of data. Current rules clearly state that *clear* means no cloud cover at all (FAA 2001, sections 12.17b and 16-25; U.S. Air Force 2009, section 9.2.13). However, the NWS Handbook 7 for manual observations as of 1994 defined *clear* to include any cloud cover less than 1/10 (NWS 1994, 9-4). On the other hand, the Federal Meteorological Handbook for synoptic observations has consistently defined clear skies as those with no cloud cover at all (NOAA 1988, 4–7), and 1/8 to include any cloud cover less than 1/8. A shift from one definition to the other would affect the reported frequency of clear sky. Similar changes in definition may have occurred for overcast.

The transition to the METAR format affected both military and NWS weather stations. We are not aware of any further major changes in cloud observing practices since 1 July 1996 at NWS stations. At military stations, however, human observers have been replaced with an automated system at many stations starting in the mid-2000s.

Beyond these changes that affect most or all stations, changes over time in the source or type of data found in the archives for individual stations may affect total cloud cover values. The types of cloud reports found in these archives are described in the appendix. Each hourly record in ISD contains information on the source and type of data, but often the data are described as "merged" from two sources or types, so that the exact origin of the cloud cover data is not always clear.

4. Methods used

We evaluated the ISD cloud cover time series for both frequency of occurrence of individual fractional values and total cloud cover and for both NWS-augmented ASOS stations and military weather stations. To diagnose inhomogeneities, we calculated the frequency of occurrence of each fractional value of sky cover from 0/8 to 8/8 in each dataset as well as monthly means of total cloud cover. Since the ISD dataset does not discriminate clearly between data derived from nonnumeric sky condition reports and those that represent direct numeric evaluations of fractional cloud cover, we treated all total cloud data from ISD similarly. We selected observations made on or near the hour to focus on regular hourly observations made at uniform times as opposed to observation types or times that occur only sporadically. For most analyses, we used only the hours 1500, 1800, and 2100 UTC to avoid night observation biases and because fewer observations were digitized for some other observation times for some years. We calculated monthly means for each hour and then combined the 3-hourly means into one monthly mean. To make interannual changes clearer, for some plots we removed the seasonal cycle by subtracting climatological monthly means from the data using the period 1973–93.

The practice of reporting fog, other obscuring phenomena, and associated cloud cover changed several times since the early 1950s (for more details, see Steurer and Bodosky 2000; Sun et al. 2001). In this analysis, to avoid inhomogeneity of cloud cover information due to those changes, and to facilitate comparison, we treated

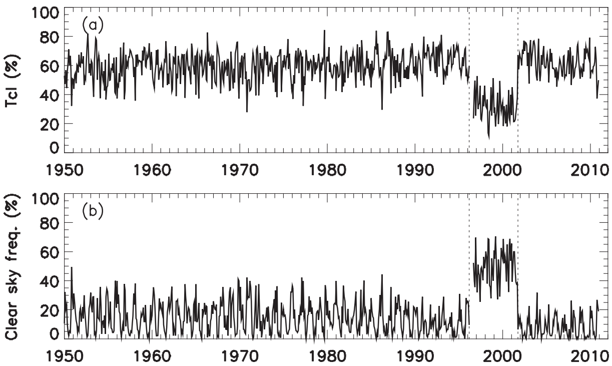

FIG. 2. (a) Total cloud cover at Jacksonville, FL, NWS station. (b) Frequency of clear sky at Jacksonville, FL. Both plots are from ISD. The two dashed vertical lines denote the time period when cloud observations are contaminated by ASOS.

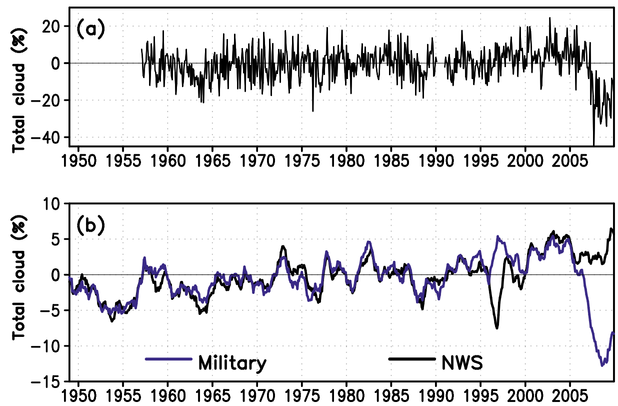

FIG. 3. (a) Total cloud anomaly at WMO station 724037 (Davison Army Airfield) showing the drop around 2006 due to the shift to automated systems. (b) The 12-month running means of U.S. mean of total cloud anomalies for military and NWS-augmented stations from ISD.

full obscuration of any type as overcast in all datasets. Results are generally similar if obscured sky is not included with overcast.

To test the significance of changes in total cloud cover at the times of changes in certain reporting practices, we applied a Student's *t* test to the difference between the mean of total cloud cover for periods before and after the relevant time. To test entire time series for the presence of multiple changes in mean, we used the standard normal homogeneity test as described in Reeves et al. (2007).

5. Data problems related to ASOS

The introduction of ASOS systems at NWS stations created a major inhomogeneity in the U.S. cloud record. We can avoid this problem to some extent by using only stations that continued to use human observers to augment the automated observations. However, some problems associated with ASOS occur even at those stations.

In the mid-1990s, many NWS stations that have human-augmented observations for most of the period after the introduction of ASOS nevertheless show temporary large reductions in total cloud coupled with large increases in frequency of clear-sky conditions. An example of such an effect is shown in Fig. 2, where total cloud cover between April 1996 and September 2001 at Jacksonville, Florida, drops by more than 40% of total cloud cover, while clear-sky frequency jumps suddenly. The decrease in low cloud cover in this time period (because of the misreporting of a portion of scattered clouds as clear skies; Sun and Groisman 2004) is much smaller than that for total cloud. These sudden changes suggest that the automated cloud reports were not augmented with human observations. Figure 3b shows a large temporary drop around 1996 in mean total cloud for the United States from NWS stations that may be attributable to such contamination. Examination of individual station time series for total cloud reveals that about 18 of the 55 NWS human-augmented stations in ISD have sudden declines on the order of 20% or more in total cloud in the mid- to late 1990s lasting up to several years, and another 10 have drops for a few months around 1996. These data are not designated as automated observations in the ISD reports. Similar drops are seen in total cloud time series before 2005 at only three military stations [World Meteorological Organization (WMO) stations 722909, 722080, and 724035] in ISD and only two of these in DATSAV3.

We identified data that were likely contaminated by ASOS reports in DSI-3280 by checking data for cloud cover amount above 3.6 km. If no cloud above 3.6 km was reported for any day in a month around the time of the introduction of ASOS, then we considered the total cloud data for that month to be ASOS rather than human augmented. All but 5 of the 55 NWS stations we examined had at least some such contamination in DSI-3280, indicating that more ASOS-contaminated data are included in DSI-3280 than in ISD. In DSI-3280, ASOS contamination occurs at some stations before as well as after the beginning of METAR in July 1996, while for ISD the contamination occurs only after July 1996.

Although military stations did not participate in the change to ASOS in the 1990s, data from those stations do show effects of transition to automated observing systems in more recent years. Starting in the mid-2000s, many military stations have introduced automated observing systems and discontinued reporting of human-augmented cloud fraction. The resulting large drop in reported total cloud is obvious in the record for individual stations (Fig. 3a) and produces a drop of more than 10% in the mean for all military stations (Fig. 3b). This change will make data from military stations less useful for monitoring cloud cover changes in the future.

6. Effects of the introduction of METAR

The transition to METAR in 1996 causes a reduced number of reported values for sky cover in ISD as reports of 1/8, 3/8, and 5/8 disappear and a corresponding increase in frequency of 4/8, 6/8, and 7/8. If the total cloud reports in ISD after METAR are averaged in the same way as those before METAR, then the transition coincides with increases in monthly-mean total cloud at 106 of the 118 military stations in ISD. The increases range from 0.1% to 10%, and 56 are statistically significant at the 95% level. The mean change in total cloud between the periods 1985–95 and 1997–2007 at ISD military stations is 2.2%, compared with a mean cloud cover between ~45% and 70%, and is obvious in U.S. mean time series (Fig. 3b). A similar increase happens in DATSAV3 total cloud in 1996 as reports of "4" are added to the previous 0, 2, 7, and 8. Many NWS stations also show an increase, but this is often masked by contamination with ASOS data around the same time (see section 5 above). If ASOS-contaminated data are included, then the increase at NWS stations is more prominent visually around 2000 than at 1996 (Fig. 3b). However, if obvious ASOS-contaminated data are removed, then the mean change in total cloud at our 55 NWS stations in 1996 is 3.6% in ISD, with a statistically significant upward shift at 39 stations.

To see whether the shifts at military stations could be caused by the METAR changes in reporting for partially cloudy conditions, we changed all occurrences of 4/8 to 2/8 in the ISD data starting at July 1996. The mean of total cloud for the modified data was less than that for the original data for July 1996–2009 by 3.75% of total sky cover, which is similar to, but slightly larger than, the mean shift in total cloud seen at that time in the military data. The resulting mean time series of total cloud (Fig. 4a) shows no apparent increase around 1996, in contrast to the original military data.

For NWS stations, we estimated the effect of the transition to METAR using the pre-METAR NWS data from DSI-3280 and applying the following changes: reports of 0 or 8/8 remain unchanged; reports of 1/8 and 2/8 are combined and recorded as 2/8; reports of 3/8 and 4/8 become 4/8; and 5/8, 6/8, and 7/8 become 7/8. When the results of this procedure are compared to the original data, they show a mean positive bias of 3.6% of total cloud cover. If 6/8 is used instead of 7/8 for reports of 5, 6, and 7/8, as is found in the ISD data coded as

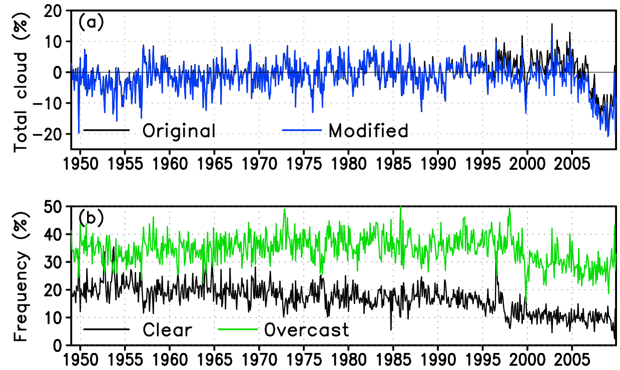

FIG. 4. (a) Monthly-mean anomalies of total cloud from military stations in ISD after changing fractional values of 4/8 to 2/8 in data for months after June 1996, compared to the original data. (b) Frequency of occurrence of clear ("0") and overcast ("8") averaged over 55 NWS stations from ISD.

synoptic, then the bias decreases to 0.7%. Because ISD includes some data that use 6 for broken and other data that use 7 instead, and the proportion of these types changes over time, the bias in the combined dataset is likely to vary with time. In addition, the bias may depend on the relative frequencies of the various sky cover fractions, and so it may vary among stations, times, and datasets.

Other changes related to METAR besides the change in reporting of fractional cloud cover may also affect the homogeneity of cloud cover records. Mean frequency of occurrence of overcast and clear conditions go down by 6.3% and 5.0%, respectively, at NWS stations at or after 1996. Figure 4b shows the mean frequency of occurrence of clear- and overcast-sky reports from ISD for the 55 augmented NWS stations. For most of the record, the two quantities tend to be anticorrelated, so the roughly simultaneous declines in both in the late 1990s seem suspicious. A likely cause is a possible change in the definitions of sky condition categories, as described in section 3 above. However, the decline in overcast (also seen in DSI-3280), which is inconsistent with changes in precipitation (not shown), is not seen in data for low cloud. At military stations, overcast frequency declines in the late 1990s, but clear-sky frequency does not, in both ISD and DATSAV3 datasets. Thus, the effects of METAR on clear and overcast frequency do not appear consistent among variables and datasets.

DSI-3280 records five sky condition categories [clear (CLR), few scattered (FEW), scattered (SCT), broken (BKN), and overcast (OVC)] for the METAR period (see section 3 above and the appendix). We reconstructed these categories for the period from the early 1950s to June 1996 from fractional cloud cover values according to the category definitions used in METAR and found (figures not shown) that the frequencies of these categories shift in July 1996, with the shift direction varying with category: −2.0% for FEW, +10.4% for SCT, and +2.9% for BKN, in addition to the decrease in CLR and OVC described in the above paragraph. This analysis supports the conclusion that the definitions of sky conditions used in METAR, or their application in practice, are different from those for traditional cloud observations.

To summarize, the introduction of the METAR reporting format appears to produce major inhomogeneities in frequencies of reported sky conditions and in total cloud cover in ISD and also in the predecessor datasets DATSAV3 and DSI-3280.

7. Other problems

a. Problems with NWS data in ISD after 1996

At many NWS stations, the distribution of fractional cloud cover in ISD data changes suddenly at several points after 1996, as shown in Fig. 5. Some shifts reflect changes in the proportion of different data types included in ISD. For example, the sudden increase in 6/8 around 2000 is related at least in part to the increasing number of "merged synoptic and METAR" (SY-MT) reports and the further increase in 6/8 around 2005 is related to the inclusion of additional synoptic-only reports, while the sudden drop of 7/8 around 2005 is related to the reduced number of METAR reports included in ISD after that time. At stations with such shifts in distribution, total cloud amount is also affected. When NWS data in ISD are separated by data type, some shifts in distribution are still visible, particularly for SY-MT data (not shown). The occurrence frequencies for the sky condition categories in DSI-3280 after 1996 do not show similar changes. This problem is not evident in military station data from either archive.

b. Shifts in frequency distributions before ASOS at military stations

While the discontinuities at July 1996 are the most obvious problems in the U.S. total cloud record, some potential problems also exist in the data from earlier time periods, especially for the military stations. Figure 6a shows the frequency of occurrence of 2/8 sky cover averaged over all U.S. military stations in the ISD and DATSAV3 archives. In addition to the large drop in 1996, which coincides with an increase in frequency of 4/8 when METAR begins, the ISD results show several large shifts in frequency before 1996, particularly around 1973, 1978, 1980, and 1985. The DATSAV3 results have smaller shifts at similar times, but they still do not appear homogeneous. Figure 6b shows a similar analysis for 7/8

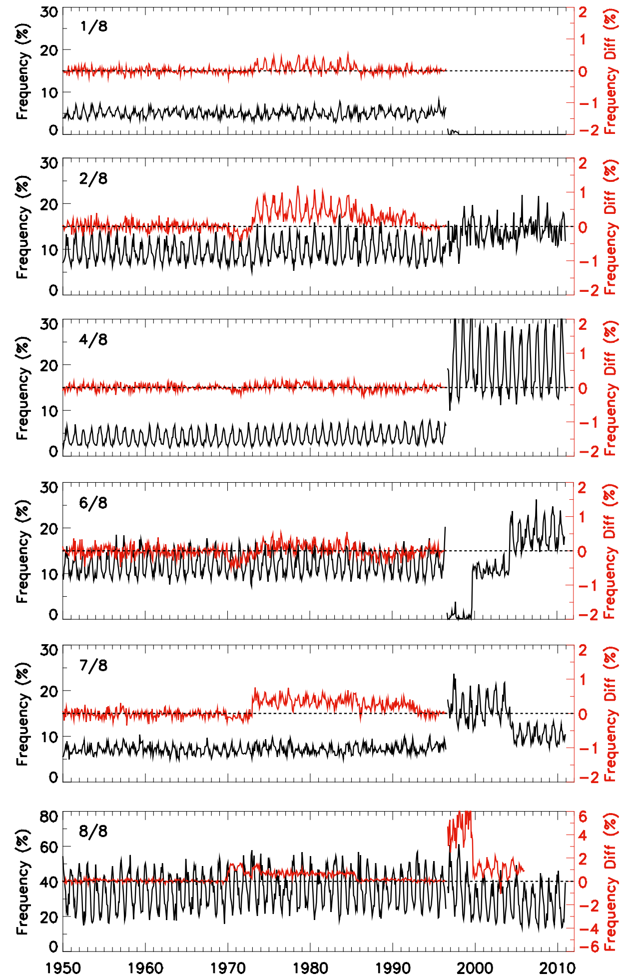

FIG. 5. Frequency of occurrence of selected fractional cloud cover values averaged from 55 human-augmented NWS/FAA ASOS stations from ISD data (black curves) and their differences from DSI-3280 frequencies (red curves). The ISD-minus-DSI-3280 frequencies for 8/8 end in December 2005 when the DSI-3280 data end and those for 1/8–7/8 end in July 1996 when METAR was implemented. ASOS-contaminated data have been removed. Seasonal cycle has not been removed. See text for details.

sky cover, where again the shifts are obviously much smaller for DATSAV3 than for ISD.

Figure 6c showing the frequency of reporting of 2/8 sky cover at WMO station 724040 (Patuxent River Naval Air Station, Maryland) in ISD and in DATSAV3 is an example of a station with large shifts in distribution of sky cover. Since essentially all the data are described as "surface airways," the discontinuities should be related to changes in factors other than data type. Figure 6d shows the difference between total cloud at that station and at Reagan National Airport in Virgina (WMO station 724050), a nearby NWS/FAA station, for ISD and for DATSAV3. The merging process used to create ISD, along with changes in reporting practices at the station,

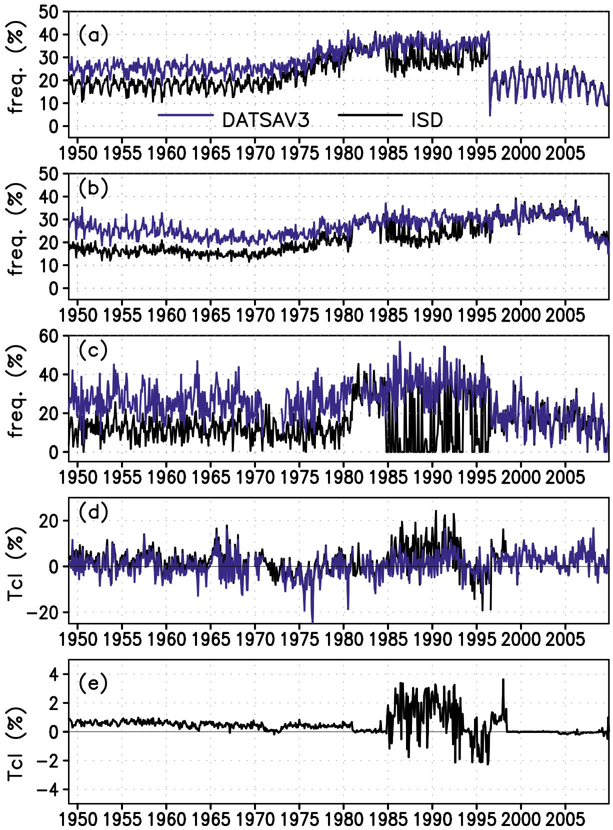

FIG. 6. (a) Frequency of occurrence of 2/8 sky cover at 1500, 1800, and 2100 UTC combined, averaged over all U.S. military stations in ISD (black) and DATSAV3 (blue). (b) As in (a), but for 7/8 sky cover. (c) Frequency of reporting of 2/8 sky cover at WMO station 724040 (Patuxent River Naval Air Station) from ISD (black) and DATSAV3 (blue) for 1500, 1800, and 2100 UTC combined. (d) Total cloud cover at Reagan National Airport from ISD minus that from WMO station 724040 (Patuxent) from ISD (black) and DATSAV3 (blue) at 1500, 1800, and 2100 UTC combined. (e) U.S. mean of monthly-mean total cloud from military stations in DATSAV3 minus that from ISD, in percent cloud cover. In (a)–(d), the seasonal cycle was removed using means from the period 1973–93.

affects the total reported cloud so as to make it less consistent with the record at Reagan National Airport than that from the DATSAV3 archive between 1985 and 1993. Shifts in the differences between total cloud cover at the two stations are obvious in both datasets at 1973 and 1996.

Figure 6e shows the difference between total cloud cover at U.S. military stations in the two datasets ISD and DATSAV3. For this figure, we used data only when it was present for a given month and station in both datasets. The difference is almost zero between 1981 and 1985 and after 1998, around a half percent before the early 1970s, but several percent cloud cover between 1985 and 1998. The differences in total cloud before the early 1970s and between 1980 and 1998 coincide with differences in cloud fraction distribution seen in Figs. 6a–c.

The distribution of observed sky cover fractions in DATSAV3 data show shifts that, while smaller than those in ISD for the same stations, are still suspicious. Since the DATSAV3 archive uses a consistent set of fractional sky cover values over time (before 1996), the large changes in frequency of the categories in the earlier record must reflect some other changes.

Using the standard normal homogeneity test, we located changepoints in the frequency time series for fractional cloud cover values at the military stations in ISD. The test compares the means of the time series before and after each possible changepoint and identifies points at which the shift is most significant. We examined only points with shifts in mean that were significant at the 95% level or better. We found all but two military stations had at least one changepoint in the frequency of 2/8 cloud cover before 1996, and at 85 of these stations, those shifts were larger than 10%. Considering all of the nine permissible reported cloud cover values, we found an average of 14 changepoints per station before 1996. Before 1995, the most common times of change were 1976, 1979, 1985, and 1980. However, these statistical changepoints in frequency distributions do not necessarily produce significant changes in total cloud because of the compensating effect of shifts in different fractions. For example, a jump in the frequency of 7/8 should cause an increase in total cloud, while an accompanying jump in the frequency of 2/8 may cause a decrease, which could lead to only a small, if any, net change in total cloud. Of the 118 military stations in ISD, 89 have changepoints in total cloud before the 1990s. However, this test alone cannot distinguish between natural and artificial shifts, so some of these changepoints may be the result of real climate variability. Since most of the changepoints in frequencies are coincident in time among different cloud fractions, as shown in Figs. 5 and 6, they are likely caused by data processing and observing problems. While some such problems are discussed in this paper, some still need verification from metadata.

c. Shifts in frequency distributions before ASOS at NWS stations

For the NWS stations we examined, if all observation times, or all daytime observations, are used, then the frequency of occurrence of some values in ISD, especially 2/8 and 7/8, shifts suddenly in the mid-1970s and the early 1980s (not shown). If only 3-hourly observations (taken at 0000, 0300, 0600 UTC, etc.) from ISD are used, then most of these shifts are not visible (see Fig. 5).

Between 1965 and 1981, NCDC digitized data from NWS stations for only every third hour, so the data source for other hours may differ from that for the 3-hourly data. In addition, clouds have systematic diurnal variability, particularly over land, so changes in observation times are likely to affect the homogeneity of the distribution of cloud observations. Users of the ISD archive should be aware of problems that may arise from the inconsistent reporting or archiving practices in the data for different hours of the day.

DSI-3280 has data only for the 3-hourly times from 1965 through 1981, and thus avoids inhomogeneity resulting from changes in data source, at the expense of less comprehensive coverage of the diurnal cycle. If ISD and DSI-3280 data from 3-hourly daytime observations are compared, then some differences in frequency of reporting of cloud fractions persist, primarily between 1973–84 and 1985–92 (Fig. 5). Those differences are primarily caused by the merging of different data sources (airways and synoptic reports) in ISD pointed out in the appendix. When data from 3-hourly observations are used, differences between total cloud cover from the two datasets are essentially zero prior to the early 1970s and between 1985 and 1995, and 1.2% for 1973–85.

NWS data shows fewer statistical changepoints in frequency distributions than military station data, with only 17 of 55 stations having changepoints in the frequency of occurrence of 2/8 cloud cover before 1996, and only one of those exceeding 10%. The proportion of NWS stations with statistical changepoints in total cloud in ISD before the 1990s (40%) is less than that for military stations (75%). The most common years for changepoints in total cloud at NWS stations were 1987, 1991, 1996, and 2000. Separating the NWS total cloud data into synoptic and airways types did not reduce the number of changepoints. Again, exactly how many of these changepoints represent artificial rather than real climate variability is not known, but it seems clear that NWS data before the 1990s show fewer likely homogeneity problems than the military data.

8. Comparison with precipitation and diurnal temperature range

Time series of monthly means of the number of days with precipitation are typically well correlated with those of cloud cover, although the relation is stronger for low cloud than for total cloud (Wang et al. 1993; Sun et al. 2001). Despite the issues discussed above, time series of annual means of total cloud for our NWS stations from both ISD and DSI-3280 (Fig. 7a) correspond well with the number of days per year with precipitation from the same stations before 1996, with a correlation coefficient of 0.79 for 1949–94. Note that ASOS-contaminated cloud data were included in the DSI-3280 and ISD cloud time series shown in Fig. 7. As discussed in section 5, the contamination in DSI-3280 is more severe and widespread than in ISD, and that may explain the pronounced dip around 1996 in DSI-3280 cloud cover. After 1999, however, ISD appears to show too much cloud in comparison with the precipitation data, which is not true in the DSI-3280 cloud data.

Diurnal temperature range (DTR) tends to be inversely related to cloud cover (Dai et al. 1997); correlations using ISD and DSI-3280 NWS stations for 1949–94 are -0.78 and -0.81, respectively. Comparison of DTR at our NWS stations from the HCN-adjusted temperature dataset with total cloud from ISD and DSI-3280 without removing ASOS-contaminated data (Fig. 7b) shows that cloud cover from ISD is greater than expected after 1999, while cloud cover from DSI-3280 is consistent with DTR after 2000. This again indicates that ISD overestimates total cloud after METAR begins.

Figure 7c shows total cloud from military stations in ISD and DATSAV3 compared to DTR from two sources. DTR data from the HCN gridded adjusted dataset was subsampled to use the grid boxes corresponding to our military stations. (The HCN-adjusted station dataset did not include enough data from our military stations to be usable for our purposes.) Figure 7c also shows DTR from the unadjusted ISD temperature data from our military stations, which avoids problems of spatial sampling but uses data that may not be homogeneous in time. DTR from the unadjusted station data shows a negative trend not apparent in the HCN data. Although the timing and extent of the differences varies with dataset, the military station cloud cover is greater than expected from the DTR record for the period 1994–2003 using either DTR source. This comparison again suggests that the upward trend in ISD total cloud cover from military stations in the last 20 years as shown in Dai et al. (2006) may be largely artificial.

Surface solar radiation is also closely related to cloud cover. Data from the U.S. Surface Radiation Network (SURFRAD) shows an increase in solar radiation and a decrease in cloud since the late 1990s (Long et al. 2009). Unfortunately, SURFRAD is small and does not coincide with our station set. Nevertheless, the Long et al. results provide some additional evidence that the apparent increase in total cloud in the ISD data after 1996 is not real.

9. Conclusions

Many problems with the U.S. total cloud data discussed in this paper are related either to the introduction

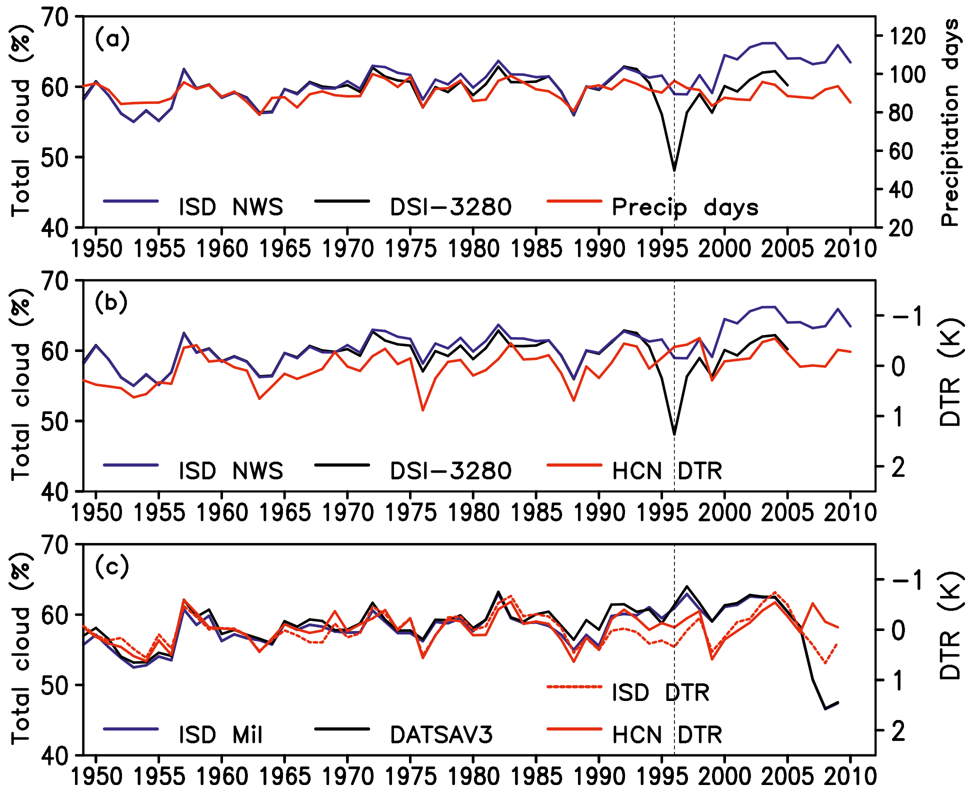

FIG. 7. (a).Total cloud cover for NWS stations from ISD and DSI-3280 with number of days with precipitation at the same stations. DSI-3280 data after the introduction of ASOS are reconstructed from sky condition reports using the method described in the text. ASOS-contaminated data are not removed. The dashed vertical line at 1996 indicates the start of METAR implementation. (b). As in (a), but for anomalies in diurnal temperature range calculated from GHCN-adjusted temperature data. (c). Total cloud cover for the United States from ISD and DATSAV3 military station data, with diurnal temperature range anomaly from ISD military station data and HCN gridded data subsampled at the locations of the military stations.

of automated observing systems or to the change to the METAR reporting system in 1996. The inhomogeneities created by ASOS may not be curable by homogeneity adjustment, because the ASOS measures a fundamentally different quantity than that reported by a human weather observer. It may be feasible to reconstruct total cloud using ASOS data as a source, but this would go beyond the normal limits of homogeneity adjustment. Thus, the data from NWS stations that did not continue human observations after ASOS was implemented, and those from military stations that now use only ASOS systems, cannot readily be used together with historical human observations for long-term trend detection.

The switch to METAR reporting is also a major problem. A mean increase in total cloud around 1996 of 2.2% sky cover at military stations and 3.6% at NWS human-augmented stations is probably at least in part the result of the introduction of METAR, the conversion of METAR reports to numeric cloud cover values, or related changes in data archiving. This change is likely to have a major effect on trends for recent decades. Precipitation and diurnal temperature range data do not appear to be consistent with such a large increase in U.S. cloud cover in the mid-1990s. Thus, the increase in total cloud shown in Dai et al. (2006) using military station data for 1976–2004 may be largely artificial.

Because the quantity reported in METAR (sky condition as one of five categories) is similar to the total cloud fraction as reported before METAR, it may be possible to create a continuous and reasonably consistent cloud cover record beyond 1996 at those stations that have human-augmented cloud observations. As in the tests described in section 6, it may be possible to convert the observations made under different systems to a consistent set of categories to reduce inhomogeneities. However, because the METAR change occurs at the same time at all U.S. stations, methods of adjustment that rely on comparison to neighbor stations will be difficult to apply. In this case, comparisons to related quantities like precipitation and DTR will be important.

Other less significant but common problems occur in the NWS data in ISD after 1996, because of changes in the approach used to convert sky condition reports to total cloud values, but do not happen to the corresponding data in DSI-3280. These problems can be avoided by using only data from the latter archive and applying a uniform method to convert sky conditions to numeric values. The shifts in frequency distributions seen in the military data before 1996 may require homogeneity adjustments if they significantly affect total cloud. These and other inhomogeneities that occur at different times at different stations may be susceptible to correction at least in part by automated or manual comparisons to neighbor stations.

Because ISD contains a mixture of information from different sources with differing characteristics integrated into a single cloud cover field, ISD cloud cover data for the United States must be used with great caution for trend analysis, even if data from ASOS are excluded. Previous archives such as DSI-3280 and DATSAV3, now discontinued at NCDC, generally appear to be more consistent over time than ISD, although DATSAV3 military station data also contain troubling changes in the distributions of fractional sky cover in the 1970s and 1980s. Some problems with ISD data may be avoided by using subsets of the available data, but at the price of reduced data sampling or length of record. We suggest that existing U.S. cloud data should not be used for trend analysis for periods extending across 1996 without homogeneity adjustment, and that before 1996, NWS data from DSI-3280 are the most reliable source of trend information. For analysis of short-term variability, the problems shown in this paper should be less troublesome. It is important to note that we have not examined the ISD data from outside the contiguous United States, and the inhomogeneities shown in this paper may not be relevant to cloud data from other countries, or to data from the United States that is of a consistent type and is derived from a consistent source.

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APPENDIX

Characteristics of Total Cloud Data in ISD, DSI-3280, and DATSAV3

a. Types of total cloud data

Total cloud cover data in the United States are derived from two main sources: hourly reports and synoptic reports. Hourly observations (often called airways observations before 1996 and METAR afterward) are normally made every hour according to rules determined by the nation that is making the observations (Steurer and Bodosky 2000). Synoptic observations are made every 3 or 6 h according to WMO standards for transmission over the global weather telecommunication system. NWS station synoptic reports may be derived from airways hourly or METAR observations. Both data types are included in ISD, and both have been used in the past to assess trends in U.S. cloud cover.

b. DSI-3280

Before the introduction of ASOS, this dataset contains only surface airways reports with all possible total cloud cover fractional values ranging from 0/10 to 10/10. Between the start of ASOS and the July 1996 METAR implementation, reports consist of one of the four sky condition categories clear (0/10), scattered (1–5/10), broken (6–9/10), and overcast or obscured (10/10). After July 1996, reports contain one of the five nonnumeric categories used in the METAR reporting system. The ASOS and METAR sky condition reports can be converted into fractional cloud cover to produce a continuous series for the whole period of record by assigning an equivalent cloud fraction to each category. For comparison with ISD cloud cover from NWS stations, we derived total cloud cover in eighths from the nonnumeric sky condition category data in DSI-3280 for the ASOS and METAR reports based on the methods used in Sun and Groisman (2004).

c. DATSAV3

The DATSAV3 total cloud cover is archived in eighths, and cloud cover information for military stations between 1949 and 1996 consists almost entirely of 0/8, 2/8, 7/8, and 8/8, as would be consistent with observations derived from the sky condition descriptions "clear," "scattered," "broken," and "overcast." After the introduction of METAR in 1996, reports contain the values 0/8, 2/8, 4/8, 7/8, and 8/8, corresponding to the revised descriptions "clear", "few scattered," "scattered," "broken," and "overcast." Reports for all daylight hours are present for most years, but some stations do not report at night during some periods.

d. ISD

ISD was developed to integrate multiple sources of surface weather observations into a single database, to better meet customer needs. Where several sources are available for the same observation, the merging procedure uses the source that is considered to have the highest data quality. This means that the source and type of data can vary over time and between stations. ISD reports cloud cover from the early 1950s up to the present as eighths of sky cover, and includes surface airways, synoptic, METAR, and merged data types in the same total cloud coverage field. According to the ISD metadata, when sky condition information is converted to numeric values, few (1/8–2/8) should become a value of 02, or 2/8; scattered (3/8–4/8) should become 04, or 4/8; and broken (5/8–7/8) should become 07, or 7/8; 7 can also denote a more precise observation of 7/8 sky cover from a synoptic or a numeric-valued airways report, and similarly for other values. In this sense the total sky cover information in ISD can be ambiguous unless the user refers to data type or source information or metadata to determine the origin of the data. [NCDC has acknowledged this weakness and plans to address it in the future (N. Lott 2012, personal communication).]

For the NWS first-order stations prior to the early 1970s, the eighths data in ISD are converted from tenths derived from airways dataset DSI-3280 (1/10 becomes 1/8, 2 or 3/10 becomes 2/8, etc.). For the period 1973 up to the ASOS implementation in the 1990s, cloud cover data in ISD also contain combined airways and synoptic reports, designated as ''merged synoptic and airways,'' occurring mostly at synoptic times (i.e., 0000, 0600, 1200, and 1800 UTC), while data for the other hours are airways. Both data types include all values from 0/8 to 8/8 during this period.

After the introduction of ASOS, fractional cloud cover in eighths is converted from the descriptive sky condition categories listed in Table 1. After July 1996, three data types are included in ISD for NWS stations: METAR reports that use the values 0, 2, 4, 7, and 8; ''merged synoptic and METAR'' reports that use the values 0, 2, 4, 6, and 8; and pure synoptic reports that also use only 0, 2, 4, 6, and 8. The result is that total cloud cover data for NWS stations in ISD after METAR begins contain the values 0, 2, 4, 6, 7, and 8.

For many military stations, ISD data before 1973 contain all permissible values for total sky cover (0–8), but data after that date and before 1996 typically contain only the values 0, 2, 7, and 8, except for sporadic occurrences of 1, 3, and 5 between 1985 and 1992 at certain stations. With the exception of Charleston Air Force Base, more than 99% of records for military stations before 1996, including those before 1973, are designated in ISD as surface airways data. The appearance of the values 1, 3, and 5 for some periods and not others may be the result of combining data from differing sources with inconsistent formats, and introduces a potentially significant inhomogeneity in the record. In some cases the transition coincides with a change in the data source or type indicated in the ISD record, but in other cases there is no way to distinguish the incompatible records within ISD. In some cases ISD contains data from one archive for some hours and from a different archive for other hours of the same day, or for the same hour during different years. This is due to the merging process, which brings in all available sources of data, giving preference to the data source that is considered to have the best quality. The DATSAV3 total cloud cover information for military stations is more consistent, in that it uses only 0, 2, 7, and 8 before 1996 at all stations. After 1996, the military station data in ISD contain only the values 0, 2, 4, 7, and 8. Although the military reports in ISD are less consistent over time than those in DATSAV3, they include data before 1973 for about 24 stations that have no such data in DATSAV3, and so are more complete.

REFERENCES

Campbell, G., 2004: View angle dependence of cloudiness and the trend in ISCCP cloudiness. Preprints, *13th Conf. on Satellite Meteorology and Oceanography,* Norfolk, VA, Amer. Meteor. Soc., P6.7. [Available online at https://ams.confex.com/ams/13SATMET/techprogram/paper_79041.htm.]

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

——, T. R. Karl, B. Sun, and K. E. Trenberth, 2006: Recent trends in cloudiness over the United States: A tale of monitoring inadequacies. *Bull. Amer. Meteor. Soc.,* **87,** 597–606.

Evan, A. T., A. K. Heidinger, and D. J. Vimont, 2007: Arguments against a physical long-term trend in global ISCCP cloud amounts. *Geophys. Res. Lett.,* **34,** L04701, doi:10.1029/2006GL028083.

FAA, 2001: Surface weather observations. Order 7900.5B, Department of Transportation, Federal Aviation Administration, 267 pp. [Available online at http://www.faa.gov/air_traffic/publications/at_orders/media/SWO.pdf.]

Jacobowitz, H., L. L. Stowe, G. Ohring, A. Heidinger, K. Knapp, and N. R. Nalli, 2003: The Advanced Very High Resolution Radiometer Pathfinder Atmosphere (PATMOS) climate dataset. *Bull. Amer. Meteor. Soc.,* **84,** 785–793.

Karl, T. R., and P. M. Steurer, 1990: Increased cloudiness in the United States during the first half of the twentieth century: Fact or fiction? *Geophys. Res. Lett.,* **17,** 1925–1928.

Lawrimore, J. H., M. J. Menne, B. E. Gleason, C. N. Williams, D. B. Wuertz, R. S. Vose, and J. Rennie, 2011: An overview of the Global Historical Climatology Network monthly mean temperature dataset, version 3. *J. Geophys. Res.,* **116,** D19121, doi:10.1029/2011JD016187.

Long, C. N., E. G. Dutton, J. A. Augustine, W. Wiscombe, M. Wild, S. A. McFarlane, and C. J. Flynn, 2009: Significant decadal brightening of downwelling shortwave in the continental United States. *J. Geophys. Res.,* **114,** D00D06, doi:10.1029/2008JD011263.

Lott, N., R. Baldwin, and P. Jones, 2001: The FCC Integrated Surface Hourly database: A new resource of global climate data. National Climatic Data Center Tech. Rep. 2001-01, 42 pp.

——, R. S. Vose, S. A. Del Greco, T. F. Ross, S. Worley, and J. L. Comeaux, 2008: The Integrated Surface Database: Partnerships and progress. Preprints, *24th Conf. on Interactive Information Processing Systems,* New Orleans, LA, Amer. Meteor. Soc., 3B.5. [Available online at https://ams.confex.com/ams/88Annual/techprogram/paper_131387.htm.]

NCDC, 2003: Data documentation for data set 9956 (DSI-9956): DATSAV3 global surface hourly data. National Climatic Data Center, 52 pp. [Available online at ftp://ftp.ncdc.noaa.gov/pub/data/documentlibrary/tddoc/td9956.pdf.]

——, 2005: Data documentation for data set 3280 (DSI-3280): Surface airways hourly. National Climatic Data Center, 30 pp. [Available online at ftp://ftp.ncdc.noaa.gov/pub/data/documentlibrary/tddoc/td3280.pdf.]

——, 2011: Data documentation for Integrated Surface Data. Federal Climate Complex, National Climatic Data Center, 130 pp. [Available online at ftp://ftp.ncdc.noaa.gov/pub/data/noaa/ish-format-document.pdf.]

NOAA, 1988: Surface synoptic codes. Federal Meteorological Handbook 2, FCM-H2-1988, Office of the Federal Coordinator for Meteorology, 131 pp. [Available online at http://www.ofcm.gov/fmh2/fmh2.htm.]

NWS, 1994: Surface observations. Observing Handbook No. 7, U.S. Department of Commerce, 215 pp.

Pachauri, R. K., and A. Reisinger, Eds., 2007: *Climate Change 2007: Synthesis Report.* Cambridge University Press, 104 pp.

Reeves, J., J. Chen, X. L. Wang, R. Lund, and Q. Lu, 2007: A review and comparison of changepoint detection techniques for climate data. *J. Appl. Meteor. Climatol.,* **46,** 900–915.

Smith, A., N. Lott, and R. Vose, 2011: The Integrated Surface Database: Recent developments and partnerships. *Bull. Amer. Meteor. Soc.,* **92,** 705–708.

Steurer, P. M., and M. Bodosky, 2000: Surface airways hourly (TD-3280) and airways solar radiation (TD-3281). National Climatic Data Center, 50 pp.

Sun, B., and P. Ya. Groisman, 2004: Variations in low cloud cover over the United States during the second half of the twentieth century. *J. Climate,* **17,** 1883–1888.

——, ——, and I. I. Mokhov, 2001: Recent changes in cloud-type frequency and inferred increases in convection over the United States and the former USSR. *J. Climate,* **14,** 1864–1880.

Trenberth, K., and J. T. Fasullo, 2009: Global warming due to increasing absorbed solar radiation. *Geophys. Res. Lett.,* **36,** L07706, doi:10.1029/2009GL037527.

U.S. Air Force, 2009: Surface weather observations. U.S. Air Force Manual 15-111, 138 pp.

Wang, W.-C., Q.-Y. Zhang, D. R. Easterling, and T. R. Karl, 1993: Beijing cloudiness since 1875. *J. Climate,* **6,** 1921–1927.

Warren, S. G., J. London, and C. J. Hahn, 1991: Cloud hole over the United States? *Bull. Amer. Meteor. Soc.,* **72,** 237–238.

——, R. Eastman, and C. Hahn, 2007: A survey of changes in cloud cover and cloud types over land from surface observations: 1971–96. *J. Climate,* **20,** 717–738.