NOAA's 1981–2010 U.S. Climate Normals: Monthly Precipitation, Snowfall, and Snow Depth

IMKE DURRE, MICHAEL F. SQUIRES, AND RUSSELL S. VOSE

NOAA/National Climatic Data Center, Asheville, North Carolina

XUNGANG YIN

ERT, Inc., Asheville, North Carolina

ANTHONY ARGUEZ AND SCOTT APPLEQUIST

NOAA/National Climatic Data Center, Asheville, North Carolina

(Manuscript received 30 January 2013, in final form 15 July 2013)

ABSTRACT

The 1981–2010 ''U.S. Climate Normals'' released by the National Oceanic and Atmospheric Administration's (NOAA) National Climatic Data Center include a suite of monthly, seasonal, and annual statistics that are based on precipitation, snowfall, and snow-depth measurements. This paper describes the procedures used to calculate the average totals, frequencies of occurrence, and percentiles that constitute these normals. All parameters were calculated from a single, state-of-the-art dataset of daily observations, taking care to produce normals that were as representative as possible of the full 1981–2010 period, even when the underlying data records were incomplete. In the resulting product, average precipitation totals are available at approximately 9300 stations across the United States and parts of the Caribbean Sea and Pacific Ocean islands. Snowfall and snow-depth statistics are provided for approximately 5300 of those stations, as compared with several hundred stations in the 1971–2000 normals. The 1981–2010 statistics exhibit the familiar climatological patterns across the contiguous United States. When compared with the same calculations for 1971–2000, the later period is characterized by a smaller number of days with snow on the ground and less total annual snowfall across much of the contiguous United States; wetter conditions over much of the Great Plains, Midwest, and northern California; and drier conditions over much of the Southeast and Pacific Northwest. These differences are a reflection of the removal of the 1970s and the addition of the 2000s to the 30-yr-normals period as part of this latest revision of the normals.

1. Introduction

Every decade, the National Oceanic and Atmospheric Administration's (NOAA) National Climatic Data Center (NCDC) releases a suite of climatological statistics that are collectively referred to as the ''U.S. Climate Normals'' (e.g., Heim 1996; Owen and Whitehurst 2002; Arguez et al. 2012). These products typically consist of climatological measures of central tendency, variability, and frequency of occurrence for temperature, precipitation, and other variables that were measured at stations operated by NOAA. They are used by industry, government agencies, and the general public for a wide range of purposes, such as water resources management, the determination of insurance and utility rates, the scheduling of street-repair projects, the allocation of resources for snow removal, and the planning of trips and weddings, to name a few. The purpose of each release is to update the climatological statistics such that they represent the most recent three complete decades, to account for changes in the station network, and to take advantage of the latest datasets and computational techniques. The latest update covers the period 1981–2010. As in the recent past, it includes stations located in the United States as well as various U.S.-operated sites in the Caribbean Sea and Pacific Ocean (Arguez et al. 2012).

The purpose of this paper is to document the procedures used to produce the monthly, seasonal, and annual

Corresponding author address: Imke Durre, NOAA/NCDC Rm. 504, 151 Patton Ave., Asheville, NC 28801.
E-mail: imke.durre@noaa.gov

DOI: 10.1175/JAMC-D-13-051.1

precipitation- and snow-related statistics in the product, to quantify some uncertainties associated with these procedures, to present updates to some of the most familiar climatological patterns of amounts and frequencies, and to compare some of these patterns with those for the previous normals period of 1971–2000. The parameters calculated included climatological averages of monthly, seasonal, and annual precipitation (hereinafter PRCP) and snowfall (hereinafter SNOW) totals; medians and quartiles of monthly PRCP and SNOW; and average frequencies of occurrence for various PRCP, SNOW, and snow-depth (hereinafter SNWD) events. The method involved the selection of stations on the basis of record completeness and data quality as well as the computation of the various statistics from data records that were frequently not complete. Relative to the 1971–2000 U.S. Climate Normals, which were generated from multiple datasets with different quality characteristics and contained separate products for PRCP and SNOW/SNWD, three major improvements were made. First, the 1981–2010 normals utilized a single data source that contained uniformly quality-assured data from all relevant observing networks. Second, precipitation- and snow-related normals were calculated together, thus achieving greater consistency between them. Third, state-of-the-art methods that had recently been implemented in other NCDC products were employed for producing average monthly PRCP totals that were as representative as possible of the full 30-yr period even when a station's record did not cover all 30 years.

The remainder of the paper is organized as follows. The data and station selection criteria are described in section 2. In sections 3–5, the methods employed to compute the various precipitation-related normals parameters are explained and selected results are presented. Section 6 contains a brief overview of climatological differences between the current and previous normals periods: 1981–2010 and 1971–2000. A summary follows in section 7. Three appendixes provide some additional details.

2. Data

Most U.S.-operated stations take three kinds of precipitation-related observations once per day: precipitation, which consists of rainfall and the liquid equivalent of any frozen precipitation; snowfall, which is the amount of new snow (and other frozen types of precipitation) that has fallen in the past 24 h; and snow depth, which is the total depth of snow (and other frozen types of precipitation) on the ground at the time of observation. PRCP is measured to the nearest hundredth of an inch (0.254 mm), SNOW is measured to the nearest tenth of an inch (2.54 mm), and SNWD is measured to the nearest whole inch (25.4 mm). Climatological statistics on these variables have traditionally been reported to the same precision in the United States, and this practice has been continued in the 1981–2010 climate normals as well as in this paper.

The observations used for the 1981–2010 climate normals originated from the National Weather Service's (NWS) U.S. Cooperative Observer Program (hereinafter "Coop"), the NWS Automated Surface Observing System (ASOS), the Federal Aviation Administration's Automated Weather Observing System (AWOS), and the Climate Reference Network (CRN). Coop observations from around 8000 stations accounted for nearly all of the data before the mid-1990s. Since then, ASOS equipment has replaced human observers at several hundred of those stations, and another few hundred new ASOS/AWOS and 125 CRN stations have been commissioned. Precipitation observations were taken manually at Coop sites and recorded automatically elsewhere. The rain gauges employed included unshielded standard nonrecording gauges at most Coop stations, shielded Geonor A/S weighing-bucket gauges at CRN stations, and a variety of tipping and weighing buckets at ASOS/AWOS stations. The accuracies and biases of these measurements depend on many factors, including gauge siting, the presence of a windshield, the presence of frozen precipitation, and observer accuracy (Woolhiser and Roldán 1986; Groisman and Legates 1994; Daly et al. 2007; Tokay et al. 2010; Diamond et al. 2013). Observations of snowfall and snow depth were all taken manually and were not available at CRN stations or at many ASOS and AWOS stations. The characteristics and uncertainties of snow measurements are described in Robinson (1989), Doesken and Judson (1997), Changnon (2006), Kunkel et al. (2007), and Doesken and Robinson (2009).

The data used for the 1981–2010 normals were taken from the Global Historical Climatology Network-Daily (GHCN-Daily) dataset (Menne et al. 2012). The U.S. component of GHCN-Daily is an integrated version of 14 source datasets, including NCDC's various holdings of daily surface observations. It thus is a single data source for stations from multiple networks. GHCN-Daily data are routinely processed through a uniform and comprehensive set of quality-assurance procedures (Durre et al. 2010), and values identified as erroneous in GHCN-Daily were excluded from the computations. No attempt was made, however, either in GHCN-Daily or as part of the calculations of the precipitation-related 1981–2010 normals, to control for inhomogeneities that may arise from changes in station location, instrumentation, or observing practice since the available methods

(Wijngaard et al. 2003; Mekis and Vincent 2011) required manual intervention and/or auxiliary information that rendered them impractical for the large network of stations considered herein. For documentation of the effects of these factors on precipitation and snow statistics, the reader is referred to Woolhiser and Roldán (1986), Groisman and Legates (1994), Kunkel et al. (2007), Doesken and Robinson (2009), and Christy (2012).

Normals parameters were calculated for stations within the 50 U.S. states, Puerto Rico, the Virgin Islands, and various islands in the central and western Pacific. In addition to these geographical criteria, stations were required to meet certain data-completeness requirements. Two categories of requirements were established, one for "traditional normals" and one for "quasi normals." A station was included in the traditional normals if its 1981–2010 PRCP record met the following two completeness criteria:

1) For each calendar month, there were at least 10 years in which the month was complete with daily precipitation totals.
2) For each day of the year except 29 February, there were at least 10 years in which 15 or more values were available within ±14 days of that day.

Quasi normals were computed for active stations whose PRCP records were too short or incomplete to qualify for traditional normals so as to provide a rudimentary estimate of the climatological characteristics at those stations. A station qualified for the quasi-normals category if it

1) did not meet the traditional-normals criteria,
2) had a minimum of two years of precipitation observations for each calendar month, and
3) reported in 2010.

For PRCP, the traditional normals included averages, medians, and quartiles of monthly totals as well as frequencies of occurrence. The same suite of statistics was calculated for SNOW when a station's SNOW data also met the two traditional-normals completeness requirements. At stations where, in addition to PRCP and SNOW, the SNWD record qualified for traditional normals, frequencies of occurrence for SNWD were also computed. Quasi normals, on the other hand, were made available only in the form of estimated average totals of PRCP (see section 3a).

The data requirements for traditional normals were established following the recommendations and findings of the World Meteorological Organization (WMO 1989, 2007), which suggest the use of a minimum of 10 years of data. The quasi-normals category was added to accommodate recently established stations whose record had not reached a length of 10 years by the end of 2010. This latter category included, for example, a number of ASOS/AWOS stations and all CRN stations.

TABLE 1. Numbers of stations with traditional normals and quasi normals for precipitation, snowfall, and snow depth in the 1981–2010 U.S. Climate Normals.

	PRCP	SNOW	SNWD
Traditional normals	7484	6377	5279
Quasinormals	1823	0	0
Total	9307	6377	5279

Table 1 shows the final numbers of stations with traditional and quasi normals, and their spatial distribution is displayed in Fig. 1. Across the contiguous United States, the spatial density is approximately 12 precipitation stations per 10 000 km^2 (Fig. 1a), although coverage is certainly not uniform across the country. Stations tend to be located in cities and towns, and thus density is generally higher in the eastern United States and lower in the West, particularly at higher elevations (e.g., Higgins and Kousky 2013). There are a total of 9307 stations with PRCP normals, including 1823 with quasi normals (Table 1). SNOW and SNWD normals are provided for 6377 and 5279 of the stations with traditional PRCP normals, respectively. Expressed another way, statistics are available for all three variables at 5279 stations (Fig. 1b), for PRCP and SNOW at another 1098 stations, and for PRCP alone at a further 2930 stations. The smaller number of SNOW/SNWD stations relative to PRCP stations can be attributed to the greater difficulty in measuring snow, which results in less-complete, lower-quality records for SNOW/SNWD than for PRCP (Doesken and Robinson 2009). There also were 258 PRCP and 578 SNOW/SNWD stations that met the traditional-normals requirements but were excluded from the final product because postprocessing quality assurance on their normals revealed potentially significant irregularities in their data (appendix A).

Several of the statistics included in the 1981–2010 climate normals were based on time series of monthly totals, that is, PRCP or SNOW totals for individual yearmonths. These totals were computed from the daily observations. By following the method in WMO (1989), a total was calculated for every month that was complete when daily values, 2-day accumulations, and 3-day accumulations were considered. Multiday accumulations that extended from the end of one month to the beginning of another were excluded. In leap years, 29 February was included in the totals for February.

3. Average monthly totals

Perhaps the most basic quantity in the precipitation-related normals is the average monthly total. Provided

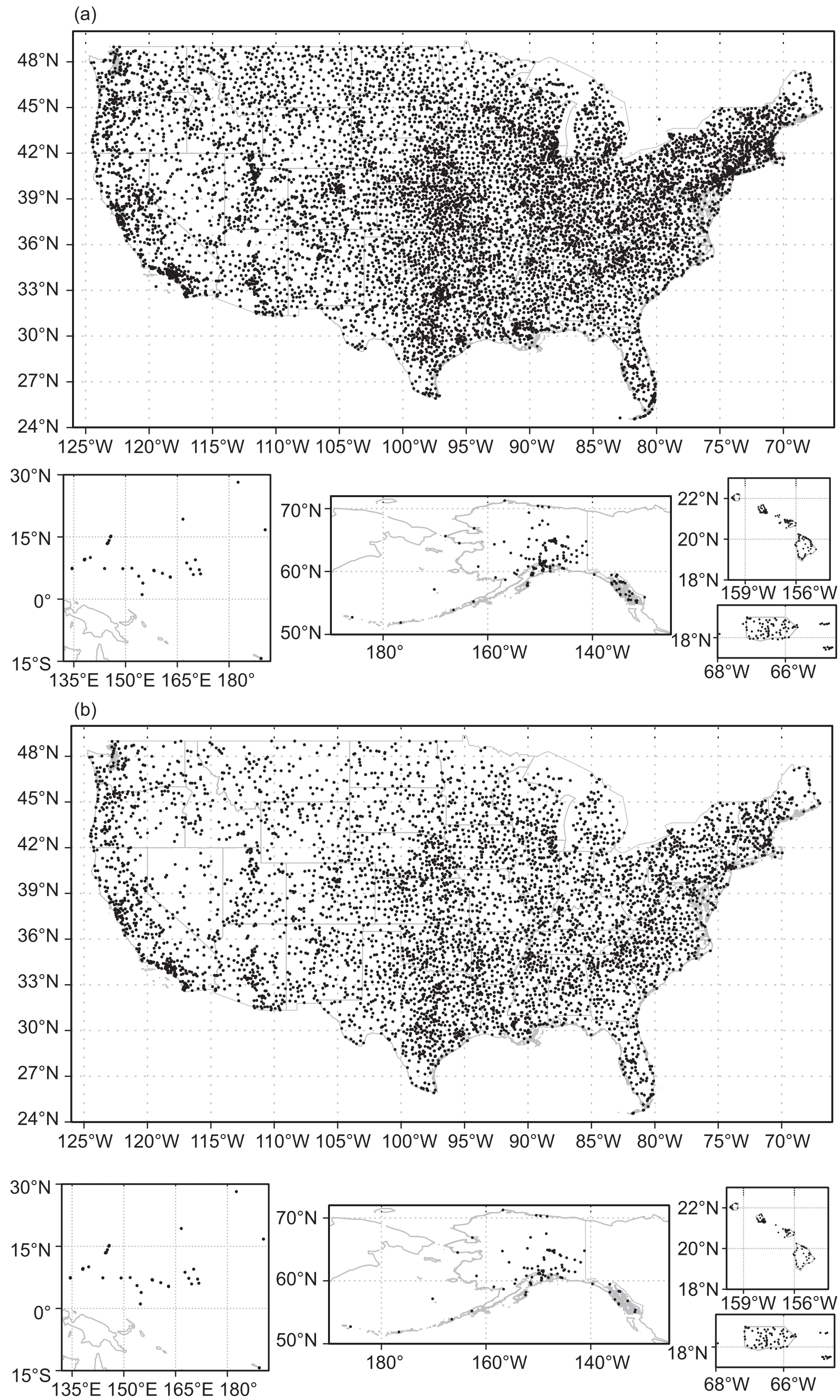

FIG. 1. Locations of (a) the 9307 stations with average monthly precipitation totals and (b) the 5279 stations with the full range of precipitation, snowfall, and snow-depth statistics in the 1981–2010 U.S. Climate Normals.

TABLE 2. Monthly, seasonal, and annual average totals of precipitation and snowfall at Fort Collins (GHCN-Daily station identifier USC00053005). In the row headings, months are abbreviated with the first three letters of their names. Spring is defined as March–May, summer is defined as June–August, autumn is defined as September–November, and winter is defined as December–February. For consistency with NOAA's official 1981–2010 climate normals product, PRCP and SNOW values are given in inches (1 in. = 25.4 mm). A trace of snowfall is indicated by 0.0*.

	PRCP	SNOW
Jan	0.40	7.9
Feb	0.40	6.9
Mar	1.59	12.6
Apr	2.06	6.2
May	2.43	0.7
Jun	2.17	0.0*
Jul	1.71	0.0
Aug	1.60	0.0
Sep	1.33	0.9
Oct	1.15	3.6
Nov	0.76	8.6
Dec	0.50	8.4
Spring	6.08	19.5
Summer	5.48	0.0*
Autumn	3.24	13.1
Winter	1.30	23.2
Annual	16.10	55.8

for both PRCP and SNOW, this is the total amount of precipitation or snow that, on average during 1981–2010, fell during a specified calendar month at a particular location. As an example, consider the average monthly totals at Fort Collins, Colorado (Table 2)—a station that is used for illustrative purposes throughout this paper because of its relatively complete record in all relevant variables. During January, Fort Collins received an average of 0.40 in. (10.2 mm) of precipitation and 7.9 in. (200.7 mm) of snowfall. These amounts contribute to the average winter (December–February) and annual PRCP and SNOW totals also shown in Table 2. The following sections contain a description of how these parameters were calculated, document the results of two related sensitivity tests illustrating the accuracy of estimated average monthly PRCP totals, and present some spatial patterns of average monthly totals.

a. Computation

Starting from the yearmonth totals described at the end of section 2, each average monthly PRCP total was computed in one of four ways:

1) If an observed yearmonth total was available for each of the 30 years, the average was simply the arithmetic mean of all available observed yearmonth totals. This approach was used to produce 13.5% of the average monthly totals for PRCP.
2) If a PRCP record consisted of observed yearmonth totals in 10–29 of the 30 years, the missing yearmonth totals were first estimated using spatial median absolute deviation regression as described in appendix B, and the average monthly total was then calculated as the arithmetic mean of the combination of observed and estimated yearmonth totals. Approximately two-thirds of all average monthly PRCP totals were computed in this way.
3) If the record contained between 10 and 29 years of data and could not be filled in with estimated monthly totals, as was the case for 0.2% of the PRCP records (appendix B), the available (fewer than 30) observed monthly totals were averaged.
4) For PRCP records at quasi-normals stations (section 2), average monthly totals were estimated by closely following the method of Sun and Peterson (2005, 2006; see appendix C). The resulting quasi normals account for approximately 20% of all average monthly PRCP totals.

The first three methods described above apply to PRCP records at traditional-normals stations, for which the appropriate method was chosen for each calendar month separately. If fewer than 10 years of data were available for any one of the 12 average monthly PRCP totals at a particular station, then all average monthly PRCP totals for that station were computed by using the quasi-normals approach.

Since the estimation methods were not considered to be suitable for snowfall, average monthly SNOW totals were based purely on observed records using methods 1 and 3 above. They are therefore only available at traditional-normals stations. Approximately 15% of all SNOW averages were calculated from complete 30-yr records.

For both PRCP and SNOW, seasonal and annual average totals were produced by summing the appropriate average monthly totals. The seasons used were December–February, March–May, June–August, and September–November.

b. Sensitivity to estimation techniques

The purpose of either filling in missing yearmonth totals (method 2 above) or employing the quasi-normals approach (method 4) was to obtain estimated average monthly totals that were representative of local climatological conditions during the full 1981–2010 period, even when observations were not available in all 30 years. The use of such methods, however, also raises two questions: How well do the estimated average totals approximate the true 30-yr average, and how spatially consistent are average monthly totals that were computed using different methods?

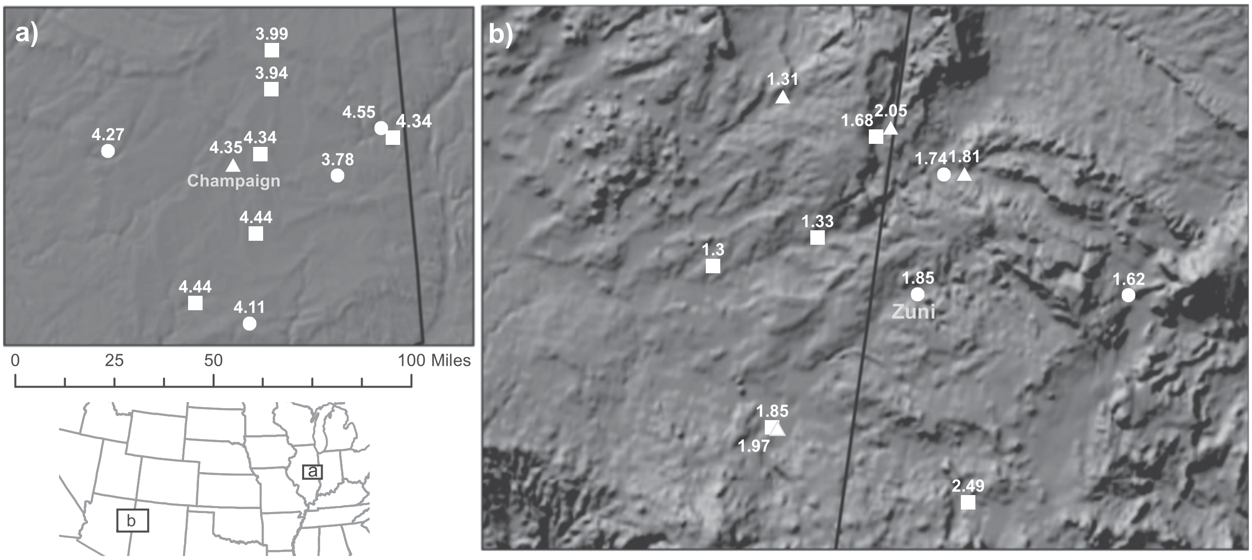

FIG. 2. Average July precipitation totals during 1981–2010 for stations with varying degrees of data completeness in two distinct regions: (a) Champaign 9 SW (GHCN-Daily station USW00054808; 40.0528°N, 88.3728°W) and its 10 nearest neighbors with average monthly PRCP totals and (b) all stations within 100 km of Zuni (USW00093044; 35.0706°N, 108.8389°W). Numbers indicate the average precipitation totals in inches. The symbols identify the locations of the stations, and their shapes indicate how the average monthly total was computed: from a complete record of 30 observed July totals between 1981 and 2010 (circles), from a combination of observed and estimated July totals (squares), or using the quasi-normals approach (triangles). For details on these methods, see section 3a.

To answer the first question, two sensitivity tests were performed by utilizing a subset of 175 stations whose 1981–2010 PRCP record was entirely complete. The first test assessed the average bias of quasi normals calculated from two years of data, the fewest number of years allowed in the quasi-normals computation, relative to the 30-yr climatological average. For each calendar month at each of the 175 stations, quasi normals were computed on the basis of the 2009 and 2010 data only, using neighbors drawn from the full set of traditional-normals stations. These quasi normals were then compared with the corresponding actual 30-yr average monthly PRCP totals. In this experiment, the quasi normals were, on average, 6.2% wetter than the corresponding complete-record normals, and this wet bias was present in the average error for each calendar month.

The second test simulated the most extreme case of incompleteness among the traditional normals, that is, the estimation of average monthly totals from a combination of 10 years of observed and 20 years of estimated yearmonth totals. At each of the same 175 complete-record stations, the last 10 years of observations were retained and the period from January 1981 through December 2000 was filled in using the regression-based estimates described in appendix B. The resulting average monthly totals were, on average, over all stations and months, 1.2% wetter than the corresponding normals that were based on 30 years of observed monthly totals, and the sign of the error varied from month to month.

To illustrate the degree of spatial consistency of average monthly totals that were based on records with different levels of completeness, the July average PRCP totals in two small, climatologically distinct regions are shown in Fig. 2. The area near Champaign, Illinois (Fig. 2a), represents an area in which precipitation is relatively high and is spatially homogeneous, whereas the 100-km radius around Zuni, New Mexico (Fig. 2b), is an example of a mostly dry region with complex terrain in which precipitation is more variable. In both cases, any spatial variability introduced by varying degrees of record completeness is indistinguishable from climatological station-to-station variability. In addition, the local patterns in Fig. 2 are consistent with the larger spatial pattern of July precipitation (Fig. 4). From both the quantitative and qualitative assessments above, it can be concluded that even the average monthly PRCP totals that are based on the shortest periods of record are generally consistent with the regional climate.

c. Large-scale spatial patterns

Figures 3 and 4 provide a large-scale view of the average precipitation and snowfall totals across all 50 states and relevant portions of the Caribbean and Pacific Islands during selected months. Included are January PRCP and SNOW (Fig. 3) as well as July PRCP (Fig. 4).

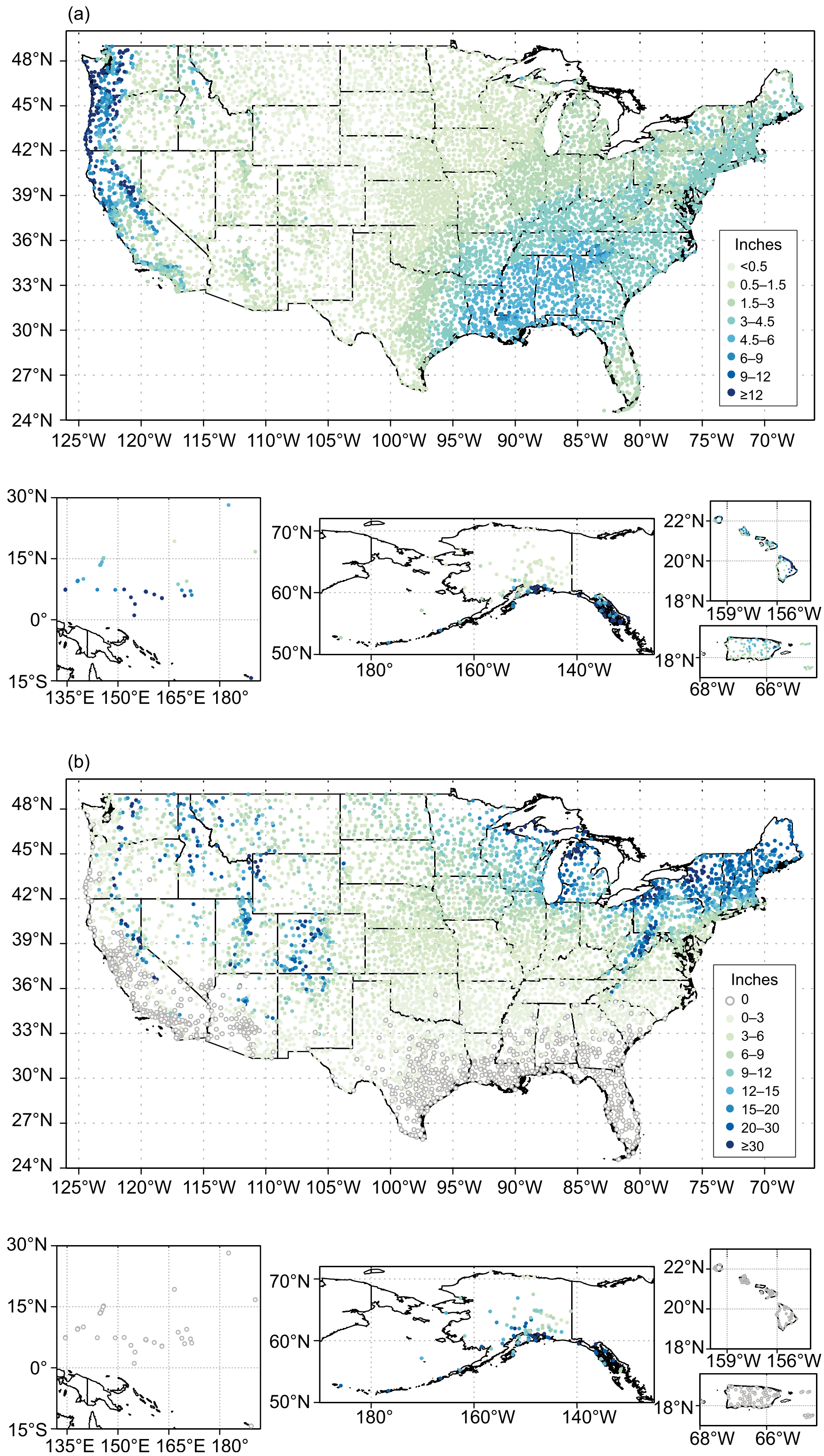

FIG. 3. Maps of 1981–2010 January average totals of (a) precipitation (in.) and (b) snowfall (in.) across the contiguous 48 states, Alaska, Hawaii, Puerto Rico, the Virgin Islands, and various islands in the central and western Pacific (including American Samoa, Guam, Johnston Atoll, Marshall Islands, Northern Mariana Islands, Federated States of Micronesia, Midway Islands, Palau, and Wake Island).

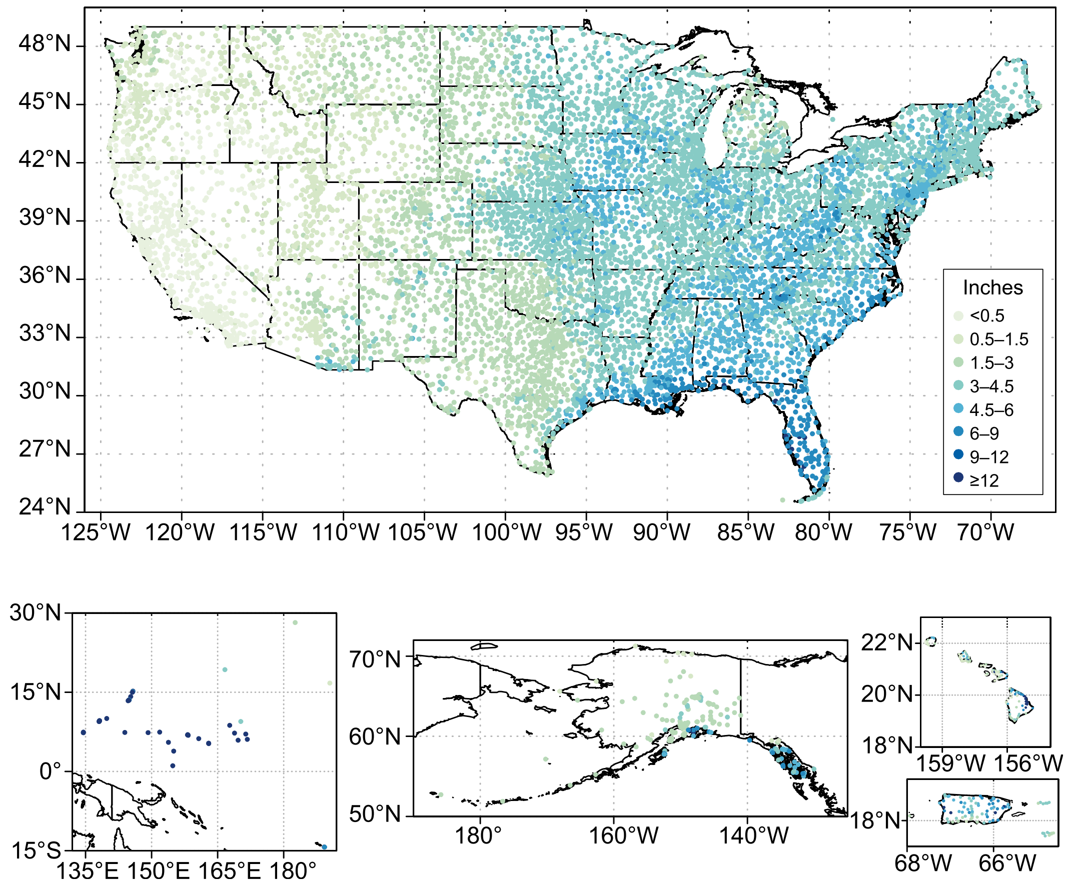

FIG. 4. As in Fig. 3, but for July average precipitation totals.

The January and July average PRCP totals reflect the combined effects of moisture availability and topography. The wettest areas are in regions where tropical moisture is plentiful or where moisture is advected across significant mountain ranges. These include locations in the U.S. Pacific Northwest in January as well as areas on the windward sides of the Hawaiian Islands, in parts of coastal Alaska, and on the islands in the tropical Pacific in both January and July. In addition, there are pronounced gradients in average PRCP over the central United States, between the relatively wetter areas to the south and east and the dry areas of the West. In January, this gradient is located north and west of a swath extending from eastern Texas to New England. In July, average PRCP decreases westward from Texas and the Great Plains.

Average snowfall totals reflect the combined effects of precipitation and temperature. In January (Fig. 3b), parts of the South, southwestern Arizona, lower elevations of California, and coastal Oregon are snow free. In July (not shown), nonzero average snowfall totals are found only at a few Alaskan and mountain locations. Average January snowfall exhibits a general north–south gradient over the eastern United States. Coastal Alaska and the higher elevations of the Pacific Northwest are among the snowiest areas in January, along with the leeward side of the Great Lakes and high elevations of the Appalachian Mountains. Relatively small average SNOW totals are found over much of the western half of the United States, with notable exceptions in mountain ranges.

4. Medians and quartiles

Although climatological averages are commonly used in many applications, the median is a more appropriate measure of central tendency than the mean is for PRCP and SNOW, which have a positively skewed probability distribution (Wilks 2006). If—as, for example, in climate-monitoring applications—the average is used to define ‘‘normal’’ conditions, then the precipitation for a given month is more likely to be below normal than above normal (Kunkel and Court 1990). Therefore, the 1981–2010 U.S. Climate Normals include medians of monthly

TABLE 3. Lower quartiles (LQ), medians (Med), and upper quartiles (UQ) of monthly precipitation and snowfall totals at Fort Collins. Units and abbreviations are the same as in Table 2.

	PRCP			SNOW		
	LQ	Med	UQ	LQ	Med	UQ
Jan	0.16	0.37	0.59	3.5	8.1	10.1
Feb	0.16	0.33	0.57	3.7	5.6	11.2
Mar	0.5	1.32	1.8	6.9	9.8	15.6
Apr	0.98	1.91	2.74	1.9	5.2	8.3
May	1.45	2.16	2.89	0.0	0.0	0.1
Jun	1.14	2.06	2.97	0.0	0.0	0.0
Jul	0.89	1.30	1.98	0.0	0.0	0.0
Aug	0.65	1.19	2.14	0.0	0.0	0.0
Sep	0.67	1.13	2.07	0.0	0.0	0.7
Oct	0.51	0.84	1.70	0.0	1.3	5.3
Nov	0.34	0.65	1.23	3.3	7.1	11.8
Dec	0.17	0.38	0.53	2.6	7.0	11.5

totals in addition to averages. As indicators of variability, upper and lower quartiles are also provided.

Medians and quartiles of monthly PRCP and SNOW totals were calculated for each calendar month at all stations with traditional normals (Table 1). For PRCP, monthly totals missing from the observed record were filled in using the method described in appendix B, and the median and quartiles were computed from a combination of observed and estimated totals. For SNOW, only observations were used. As an example, Table 3 shows the resulting statistics for Fort Collins. In October at Fort Collins, for instance, the median monthly PRCP total is 0.84 in. (21.3 mm), implying that that month's precipitation exceeded this amount in one-half of the years between 1981 and 2010. The corresponding lower and upper quartiles indicate that PRCP was less than 0.51 in. (13.0 mm) in 25% of the years and greater than 1.70 in. (43.2 mm) during another 25%.

The aforementioned positive skewness of the frequency distribution of precipitation amounts is reflected in the median and average monthly precipitation totals for 1981–2010. At Fort Collins, for example, the average (Table 2) is greater than the median (Table 3) in all months, implying that monthly PRCP totals are below average more than one-half of the time. This positive skewness is widespread, as demonstrated by the map of January average-minus-median PRCP differences for the contiguous United States that is shown in Fig. 5. At 89% of the stations, the average January PRCP total is greater than the median, as in Fort Collins. There are, however, spatially coherent sets of stations in the Pacific Northwest and Southeast for which the reverse is true. In July (not shown), the distribution of average monthly PRCP totals is also positively skewed at approximately 90% of the stations, although the pattern of average-minus-median differences is less spatially coherent than in January and the magnitudes of the largest positive and negative differences are smaller. In summary, when an application requires a descriptor of the climatological precipitation, careful consideration is warranted as to whether the mean or the median is a more appropriate measure.

5. Frequencies of occurrence

The 1981–2010 normals also contain climatological frequencies of occurrence for various threshold exceedance events of PRCP, SNOW, and SNWD. During 1981–2010 at Fort Collins, for example, March was, on average, characterized by 6.5 days with PRCP $\geq$ 0.01 in. (0.254 mm), 5.5 days with SNOW $\geq$ 0.1 in. (2.54 mm), and 5.1 days with at least 1 in. (25.4 mm) of snow on the ground. For illustrative purposes, the full set of frequencies for this location is shown in Table 4.

The thresholds used were selected on the basis of requests from the NWS Climate Services Division and on the threshold exceedance events in the 1971–2000 U.S. Climate Normals (Owen and Whitehurst 2002). For each meteorological element, the lowest threshold reflects the lowest nonzero amount that can be measured with the equipment used at U.S. Coop stations. In the following sections, the method for computing the frequencies of occurrence is described and some spatial patterns of the resulting average frequencies of measurable amounts are presented.

a. Computation

A common means for quantifying average frequencies of occurrence is to determine the average number of days per month, season, or year on which a meteorological element exceeded a specified threshold during a predetermined set of years (WMO 1989; Owen and Whitehurst 2002). In this approach, the number of days on which the specified events occurred is counted for each year and month and then the climatological average for each month is obtained by averaging the appropriate yearmonth counts over the available years. This method is appropriate when a serially complete set of daily observations is available, but it can lead to underestimation if incomplete months are included.

For the 1981–2010 normals, the typical number of days per month on which an event occurs was therefore estimated not by the simple average, but as the product of the probability of occurrence of the event within available observations and the number of calendar days in the month. A step-by-step description of this calculation follows, using January for illustrative purposes:

1) All Januaries were identified in which the daily observations of the element of interest were missing

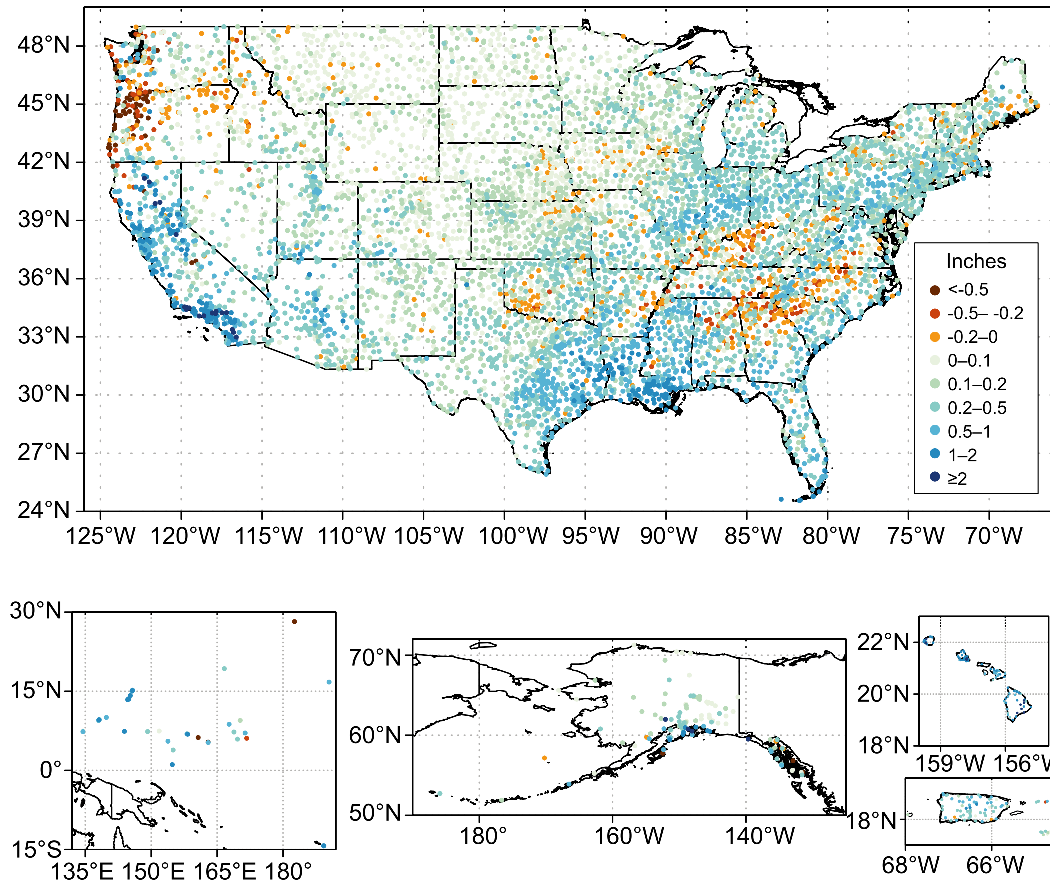

FIG. 5. Map of differences between the climatological average and median monthly precipitation totals for January during 1981–2010. Differences are shown in inches, and positive differences indicate that the average is greater than the median.

on nine or fewer days of the month. (Unlike in the calculation of monthly totals, all days that were part of multiday accumulations were counted as missing.)

2) For each of the qualifying Januaries, the number of days on which the variable of interest was greater than or equal to the specified threshold was counted.
3) The counts for January in each year were summed, and the result was divided by the total number of January days with data in the qualifying years to obtain the probability of the threshold exceedance for January.
4) This empirical probability was then multiplied by the number of calendar days in the month to obtain the corresponding expected number of days per month on which the threshold was exceeded. [For February, the number of calendar days in the month was set to 28 + (7/30) to account for the seven leap years during 1981–2010.]

Assume, for example, that the expected number of days with PRCP ≥ 0.01 in. (0.254 mm) during January is to be calculated. If only 25 days are available in one of the years, another January is missing entirely, and January is complete in all other 28 years, the total number of days that are available is equal to (28 yr × 31 days) + 25 days = 893 days. If PRCP exceeds 0.01 in. on 308 of those days, then the probability of this event during January is 308/893, or 0.345, and the event is expected to occur on an average of 0.345 × 31, or 10.7, days during the month when rounded to the nearest tenth of a day.

This procedure was repeated for each month, variable, and threshold. The corresponding seasonal and annual values were obtained by summing the monthly expected numbers of days as appropriate. For example, summing the average frequencies for March, April, and May in Table 4 yields the corresponding spring frequencies.

More than two-thirds of the resulting average monthly frequencies were calculated from relatively complete records. For PRCP, approximately 35% of all average frequencies of occurrence are based on data from all 30 years. For SNOW and SNWD, 32% and 26% of the

TABLE 4. Monthly, seasonal, and annual average frequencies of occurrence (days) for several precipitation, snowfall, and snow-depth threshold exceedances at Fort Collins. Abbreviations for months and definitions of seasons are the same as in Table 2. Since the underlying observations are reported in English units, all thresholds are given in inches (1 in. = 25.4 mm). Frequencies of greater than zero and less than 0.5 days are shown as 0.0*.

	PRCP				SNOW					SNWD			
	≥0.01	≥0.10	≥0.50	≥1.00	≥0.1	≥0.5	≥1.0	≥3.0	≥10.0	≥1	≥3	≥5	≥10
Jan	4.2	1.7	0.0*	0.0	4.5	2.5	0.8	0.2	0.0*	13.8	7.6	3.2	1.1
Feb	4.9	1.2	0.0*	0.0	5.0	2.3	0.6	0.3	0.0	7.5	4.2	2.1	0.2
Mar	6.5	3.4	0.9	0.3	5.5	3.1	1.3	0.7	0.2	5.1	2.6	1.4	0.3
Apr	8.6	4.3	1.4	0.4	3.1	1.7	0.7	0.3	0.0*	1.5	0.6	0.4	0.0*
May	11.2	5.3	1.4	0.4	0.4	0.2	0.1	0.0	0.0	0.2	0.1	0.0	0.0
Jun	10.0	4.3	1.4	0.3	0.0*	0.0*	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Jul	9.0	3.3	0.8	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Aug	9.4	3.3	0.9	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Sep	7.6	3.3	0.8	0.1	0.4	0.2	0.1	0.1	0.0	0.1	0.1	0.0	0.0
Oct	6.3	2.9	0.6	0.1	1.4	0.9	0.4	0.1	0.1	1.0	0.5	0.3	0.1
Nov	5.2	2.5	0.3	0.0	4.1	2.3	1.2	0.5	0.0*	5.2	3.1	1.4	0.0*
Dec	4.5	1.4	0.2	0.1	4.7	2.3	0.8	0.4	0.1	12.2	7.7	3.4	0.8
Spring	26.3	13.0	3.7	1.1	9.0	5.0	2.1	1	0.2	6.8	3.3	1.8	0.3
Summer	28.4	10.9	3.1	0.9	0.0*	0.0*	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Autumn	19.1	8.7	1.7	0.2	5.9	3.4	1.7	0.7	0.1	6.3	3.7	1.7	0.1
Winter	13.6	4.3	0.2	0.1	14.2	7.1	2.2	0.9	0.1	33.5	19.5	8.7	2.1
Annual	87.4	36.9	8.7	2.3	29.1	15.5	6.0	2.6	0.4	46.6	26.5	12.2	2.5

frequencies fall into this category. Another 35% of the PRCP frequencies, 38% of the SNOW frequencies, and 43% of the SNWD frequencies are what WMO (1989) referred to as "standard" normals; that is, they were computed with between 25 and 29 years of data in which no more than three consecutive years were missing.

b. *Spatial patterns of average monthly frequencies*

To provide a sampling of the resulting frequencies of occurrence across all stations, Figs. 6 and 7 show maps of the expected numbers of days with measurable precipitation, snowfall, and snow depth for January and July, respectively. The corresponding patterns for higher exceedance thresholds (not shown) exhibit very similar features, although the frequencies of the events naturally decrease as the threshold increases.

The spatial patterns of the frequencies of days with PRCP ≥ 0.01 in. (0.254 mm) and SNOW ≥ 0.1 in. (2.54 mm) are similar to those for average totals (Figs. 3 and 4). During January, it precipitates on more than 25 days in the Pacific Northwest, on 15–25 days in the northern Appalachians and on the lee side of the Great Lakes, and on 7–15 days over much of the remainder of the eastern United States. Precipitation is much less frequent through the interior West and Great Plains. In Alaska, measurable precipitation falls on an average of more than 15 days in coastal areas as compared with 4–10 days at interior locations. In Puerto Rico and Hawaii, the frequency of rain days varies from 4–10 in the South to 10–20 on the northern windward sides of islands. Precipitation is less frequent in July (Fig. 7) than in January (Fig. 6a) throughout much of the West. There is little difference in precipitation frequency between the two months in the eastern United States, at the Caribbean stations, and in Hawaii.

In Figs. 6b and 6c, the eastern two-thirds of the United States is dominated by a south-to-north gradient in the number of January days with measurable SNOW and SNWD while the frequency of both snowfall and snow on the ground is highly variable across the West. East of the Rocky Mountains, the highest frequencies of SNOW ≥ 0.1 in. (2.54 mm) are 10 or more days along the Canadian border and on the leeward side of the Great Lakes. A snow depth of 1 in. (25.4 mm) is found during most of the month from North Dakota eastward to New England. At most locations in Alaska, it snows 0.1 in. (2.54 mm) on an average of 5–15 January days and snow cover with a depth of at least 1 in. (25.4 mm) is present on 25 or more days. July days with measurable snowfall or snow depth are observed only at Barrow, Alaska; Mount Washington, New Hampshire; and a few high-elevation stations in the western United States.

6. Climatological differences between 1981–2010 and 1971–2000

For readers interested in the practical implications of switching from the 1971–2000 normals to the 1981–2010 normals in their applications, all of the above calculations were repeated for the 30 years between 1971 and

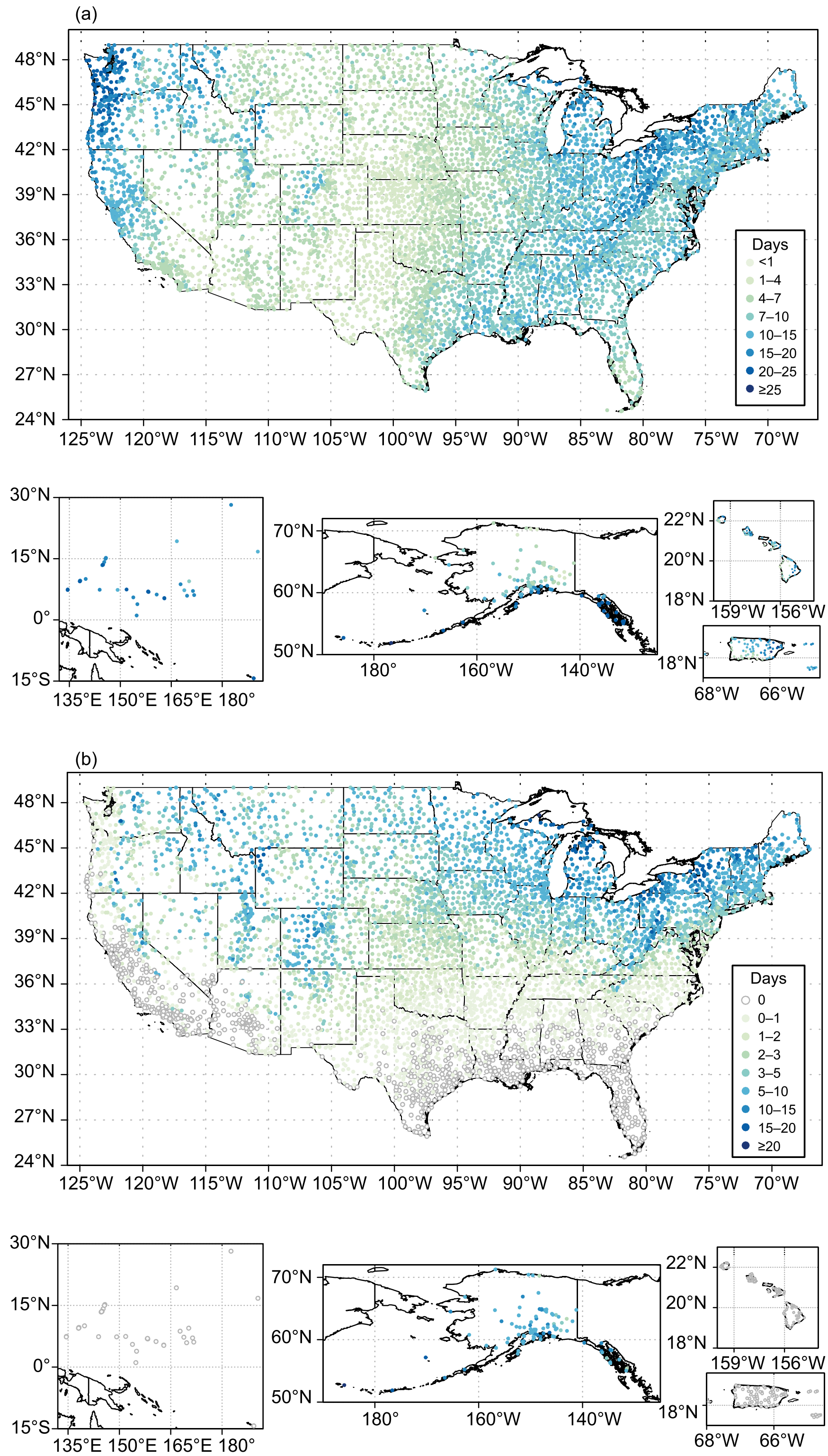

FIG. 6. Maps of the 1981–2010 average number of January days with (a) measurable precipitation (PRCP = 0.01 in. or 0.254 mm), (b) measurable snowfall (SNOW ≥ 0.1 in. or 2.54 mm), and (c) measurable snow depth (SNWD = 1 in. or 25.4 mm).

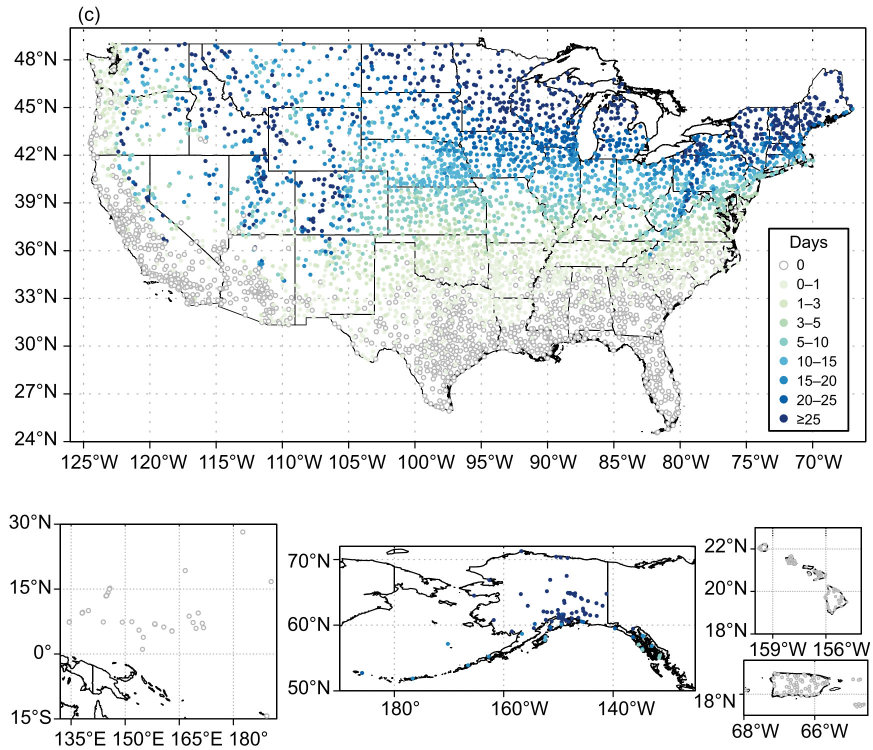

FIG. 6. (*Continued*)

2000; for stations with at least 25 yr of data in both 30-yr periods, the results were subtracted from the corresponding values for 1981–2010. Since the years of 1981–2000 are common to both periods, the differences between the climatological averages for 1981–2010 and 1971–2000 are entirely the result of differences between the 2001–10 and 1971–80 decades and therefore are not necessarily representative of linear 1971–2010 trends.

Figure 8 shows maps of the interperiod differences for a sample of annual statistics over the contiguous United States (Figs. 8b,d,f), along with the annual values of those parameters for the 1981–2010 period (Figs. 8a,c,e). The most spatially uniform interperiod differences are found in the frequency of measurable SNWD (Fig. 8f). Most of the northern two-thirds of the contiguous United States and Alaska exhibit a decrease of days with snow cover between the two periods. This pattern is qualitatively consistent with the generally slightly lower average annual snowfall totals (Fig. 8d) and warmer temperatures (Arguez et al. 2012) during 1981–2010 across much of the country. The lower annual number of days with measurable snow on the ground during the 2000s when compared with the 1970s also appears to be consistent with a shift toward earlier springtime snowmelt across North America over the past few decades that has been identified in other studies (Dyer and Mote 2006; Brown and Robinson 2011).

Figure 8b displays widespread positive differences in average annual totals across much of the Great Plains, Midwest, and northern California, implying that the 2000s were wetter than the 1970s in those areas. Differences of the opposite sign are found in the Southeast and Pacific Northwest. From studies of decadal precipitation variations, large-scale and regional dynamical forcings could be contributing to this pattern by affecting the position of the storm track and influencing the location and strength of the flow of moisture from the Gulf of Mexico into the central and eastern United States (Cayan et al. 1998; Jutla et al. 2006; Small and Islam 2008; Zhong et al. 2011).

7. Summary

In this paper, the methods for calculating the monthly, seasonal, and annual statistics for precipitation, snowfall, and snow depth that are part of NOAA's 1981–2010 U.S. Climate Normals were presented. The monthly statistics include averages, medians, and quartiles of monthly precipitation and snowfall as well as the frequencies of occurrence for various precipitation, snowfall, and snow-depth exceedances (Tables 2–4). Statistics on monthly SNOW totals as well as average frequencies of occurrence for all variables were computed directly from the GHCN-Daily dataset, whereas the statistics

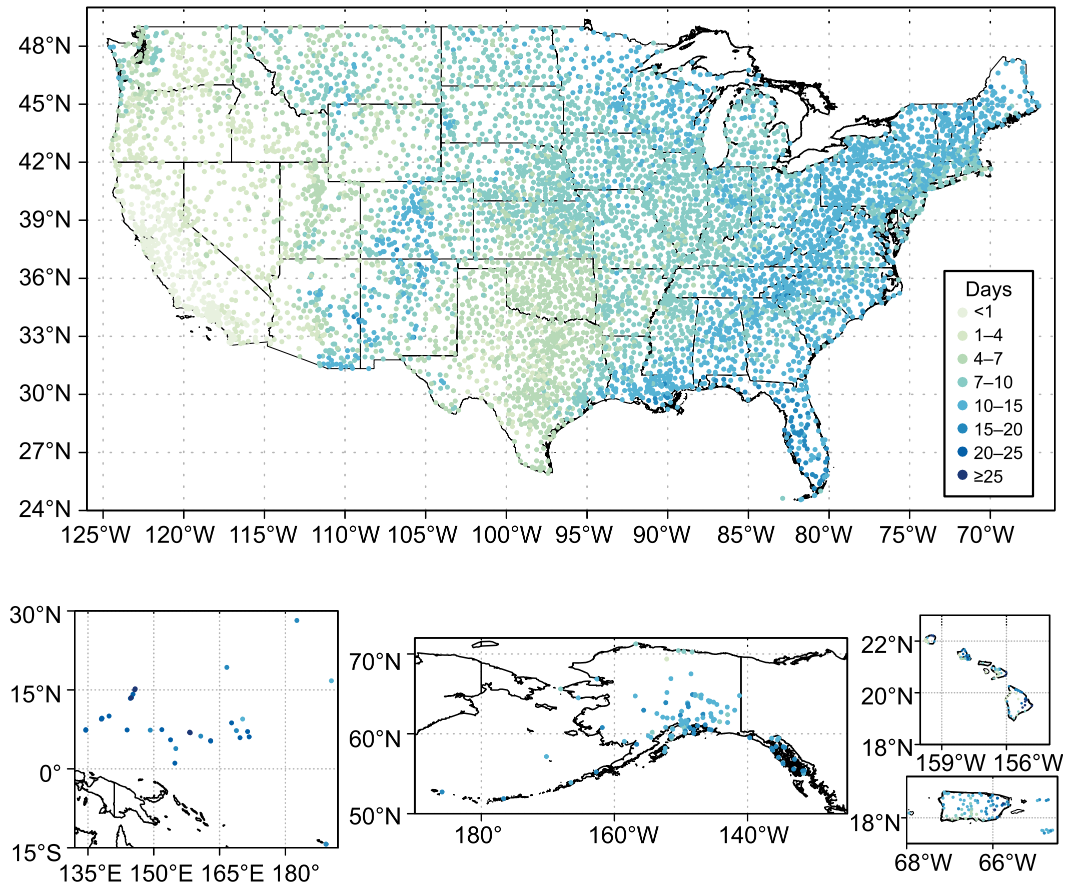

FIG. 7. As in Fig. 6, but for the average number of July days with measurable precipitation.

on monthly PRCP totals were enhanced by two state-of-the-art estimation methods: 1) median absolute deviation regression for filling in missing PRCP totals for individual yearmonths and 2) a slightly modified version of Sun and Peterson's (2006) approach for estimating average monthly PRCP totals at short-record stations.

The 1981–2010 normals that result exhibit the familiar climatological patterns. For example, the wettest areas include the coastal Pacific Northwest in January as well as areas on the windward sides of the Hawaiian Islands, in parts of coastal Alaska, and on the islands in the tropical Pacific in both January and July. Coastal Alaska and the higher elevations of the Pacific Northwest also are among the snowiest areas in January, along with the leeward side of the Great Lakes. Users switching from the 1971–2000 to the 1981–2010 U.S. Climate Normals will notice that average annual precipitation for 1981–2010 was higher over much of the Great Plains, Midwest, and northern California and was lower in the Pacific Northwest and Southeast. In addition, there were fewer days with snow on the ground throughout much of the country than in 1971–2000.

All of the statistics described in this paper can be accessed via NCDC's file transfer protocol and Climate Data Online user interfaces as well as through various third-party sources, including the local NWS offices and the Applied Climate Information System. In the files available directly from NCDC, each normals parameter is accompanied by an indicator that both classifies the underlying record according to the WMO (1989) completeness criteria and identifies the estimation technique (if any) that was used in the calculation.

With this latest installment of the U.S. climate normals, climatological parameters for SNOW and SNWD are, for the first time, provided alongside those for PRCP at all stations for which a sufficient amount of data is available. The full range of statistics is provided at 7484 stations for PRCP, at 6377 stations for SNOW, and at 5279 stations for SNWD (Table 1). Estimated average monthly PRCP totals are supplied for an additional 1823 active short-record observing sites. For snowfall and snow depth in particular, these numbers represent a significant increase in the number of normals stations when compared with previous releases of this product.

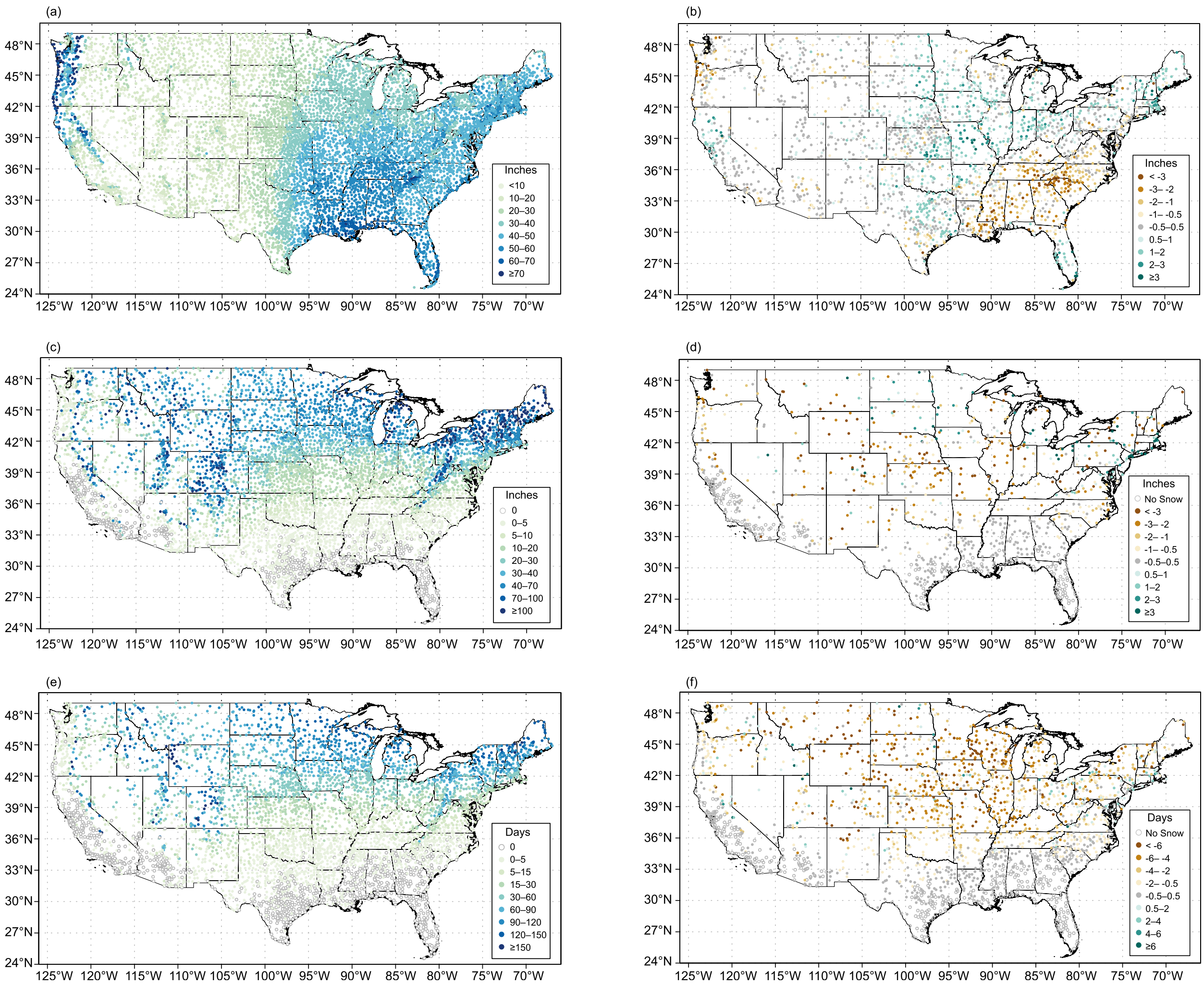

FIG. 8. (left) Annual averages of selected parameters for 1981–2010, and (right) differences with corresponding values for 1971–2000 for (a),(b) annual precipitation totals (in.), (c),(d) annual snowfall totals (in.), and (e),(f) annual number of days with measurable (≥1 in. or 25.4 mm) snow depth. On the difference maps, only those stations are plotted whose underlying record for the parameter in question consisted of at least 25 yr of data in each of the two periods, with no more than three consecutive years missing. Positive differences indicate that values were larger in 1981–2010.

Acknowledgments. The authors gratefully acknowledge the helpful comments from the anonymous reviewers.

APPENDIX A

Quality Assurance of the Normals Parameters

Once all of the calculations had been completed, a suite of internal consistency and spatial consistency checks was applied to the calculated normals parameters. Their purpose was twofold: 1) to ensure that the statistics were free from computational or formatting errors and 2) to identify parameters that were suspect as the result of lingering data problems at individual stations.

The internal consistency checks were designed to identify inconsistencies among parameters for the same station. For monthly, seasonal, and annual precipitation-related statistics, these procedures checked that all of the following conditions were true:

1) For each station and month, the frequencies of precipitation, snowfall, and snow depth exceeding various thresholds decreased with increasing threshold. For example, the average number of days with PRCP ≥ 0.01 in. (0.254 mm) should be greater than or equal to the average number of days with PRCP ≥ 0.1 in. (2.54 mm).
2) For each station and month, the lower quartile of monthly precipitation and snowfall totals did not

exceed the corresponding median, and the median did not exceed the upper quartile.

3) Each seasonal or annual average monthly total or average frequency of occurrence was equal to the sum of the corresponding average monthly values.
4) When the average monthly precipitation or snowfall total was equal to 0, the average number of days with measurable precipitation or snowfall for the same station and month was also 0.
5) At stations where the average frequency of occurrence of measurable snowfall was equal to 0 in all 12 months, the average frequency of a measurable amount of snow on the ground was also 0 throughout the year.

The first three of these conditions were never violated, as one would expect if the original calculations were performed correctly. Violations of the fourth and fifth conditions often could be traced to underlying data problems (see below).

To check for spatial inconsistencies, several measures of agreement were calculated between a station's monthly normals parameters and the corresponding parameters at each of its neighbors within a horizontal distance of 100 km and within 200-m elevation of the target station. The results for each target–neighbor pair were averaged over all available neighbors. For each normals parameter, the measures of agreement included the following:

1) average correlation between the 12 monthly values (e.g., the average monthly PRCP totals for January–December) at the station and its neighbors,
2) average absolute difference between the station's monthly values and corresponding values at its neighbors,
3) average absolute difference between a station's maximum monthly value (e.g., the highest of all 12 average monthly PRCP totals) and corresponding maxima at its neighbors, and
4) average absolute difference between a station's minimum monthly value and corresponding minima at its neighbors.

For each normals parameter and each measure of spatial consistency, the stations were ranked in order of increasing agreement with their neighbors (i.e., increasing correlation or decreasing absolute difference), and the most egregious cases of disagreement were examined for possible underlying data issues.

The two most common data issues identified with the help of all of these checks were 1) the prevalence of untagged multiday precipitation accumulations at some stations, which is known to cause an inflation of precipitation intensity and a suppression of precipitation frequency (Viney and Bates 2004), and 2) the former NCDC practice of filling in a ''presumed zero'' whenever a precipitation, snowfall, or snow-depth value was left blank (rather than filled with either 0 or ''M'' for missing) by a precipitation observer, which has led to a systematic overreporting of snowfall and snow-depth zeros at some locations (e.g., Christy 2012).

All in all, data-reporting issues affecting PRCP normals parameters were identified at 258 stations. These stations, located across the United States and the Caribbean, were excluded entirely from the published 1981–2010 U.S. Climate Normals. At another 320 stations, data problems were found to affect one or more of the SNOW and SNWD parameters. For these stations, the PRCP normals were published but the SNOW and SNWD normals were not.

APPENDIX B

Method for Estimating Yearmonth Totals

For precipitation, an attempt was made to fill in monthly totals that were missing during the years of 1981–2010. The primary purpose of generating these estimates was to ensure that unusually wet or dry years were reflected in the station's average monthly totals and other related statistics even when observations from those years were missing from the station's data record, thereby producing an average monthly total that is more representative of the full 1981–2010 period. Although analogous estimates for snowfall would have been desirable for the same reason, monthly snowfall totals were not estimated because of the larger number of zeros and the greater spatial variability of nonzero monthly totals, which would lead to estimates that would likely be less reliable than those for precipitation.

Estimates were generated using least median absolute deviation regression (Mielke and Berry 2001), which is a technique that is less sensitive to the influence of a few large deviations than is the more widely used least squares regression. Regression relationships were developed separately for every station–calendar month for which at least one year's monthly PRCP total was missing. For September at Enka, North Carolina, for example, an estimate was needed during 10 of the 30 years between 1981 and 2010 because the data required for computing an observed monthly total either were not available at all or were insufficiently complete (Fig. B1).

The estimation procedure consisted of three main steps. First, a pool of potentially useful neighboring stations was identified. Next, a regression relationship was developed between the target station's available

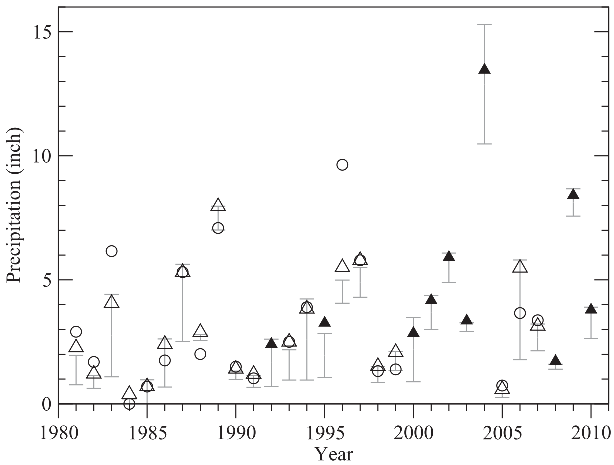

FIG. B1. Time series of September observed (circles) and estimated (triangles) precipitation totals (in.) between 1981 and 2010 at Enka (GHCN-Daily station USC00312837). Filled triangles denote estimated PRCP totals that fill in gaps in the observed record. Open triangles denote estimates for years during which observations are available and, when compared with the corresponding circles, provide a qualitative sense of the performance of the regression relationship used to generate the estimates. The vertical lines indicate the range of values at the three neighboring stations that were used to calculate the estimates: Asheville (USW00013872), Asheville Regional Airport (USW00003812), and Fletcher 3 W (USC00313106).

monthly PRCP totals and overlapping records at between one and five of the neighbors. Then this relationship was applied to the neighbors' data to estimate PRCP totals for the years that were missing from the target's record.

In step 1, candidates for use in the regression relationship were identified on the basis of the following criteria:

1) Any station with data in GHCN-Daily was a candidate, regardless of whether normals were calculated for it or whether it was operated by the NWS. This allowed for estimates to be generated with the help of stations operated by the Community Collaborative Rain, Hail, and Snow (CoCoRaHS) network, Canadian and Mexican stations located near the border with the United States, as well as Pacific Island and Caribbean stations operated by other countries. The inclusion of the stations increased the availability and accuracy of estimates in certain data-sparse, border, and island regions relative to what would be possible if only the normals stations were used.
2) Candidates were located within 500 km of the target station for which estimates were to be produced.
3) For the calendar month of interest, candidates further had at least 10 yearmonth totals during the normals period that overlapped with totals at the target station. They also had yearmonth totals during all years for which an estimate was needed at the target station.

In step 2, neighbors that satisfied the above criteria were sorted in order of descending index of agreement (Legates and McCabe 1999) between their monthly totals for the calendar month of interest and overlapping monthly totals at the target station. The regression model yielding the highest index of agreement between a target's estimated and observed totals was then determined through an iterative process in which successively more neighbors were added until the index of agreement decreased, no more qualifying neighbors were available, or the maximum allowable number of neighbors had been included. The maximum number of neighbors used in any particular model depended on the number of observations at the target but was not allowed to exceed five.

In step 3, the chosen model was used to estimate monthly totals for those years that were missing at the target location during the specific calendar month for which the model was developed. Since PRCP totals cannot be negative, yet the regression procedure can result in slightly negative estimates, such negative estimates were set to zero. At the stations for which normals were computed, this provision was invoked for about 1.8% of all estimated monthly totals.

Figure B1 illustrates the development and application of a regression model for September at Enka. In this case, the neighbor whose time series of September monthly PRCP totals showed the highest index of agreement with the overlapping Enka data was Asheville. Using this station to generate a one-neighbor model yielded an index of agreement of 0.791 between the resulting fit and the Enka observations. This model–observations agreement improved as the second- and third-best neighbors were added successively. Including a fourth neighbor, however, yielded slightly poorer agreement, and so the coefficients and intercept from the three-neighbor model were used to generate the estimated September PRCP totals for Enka in the years for which no corresponding observed monthly totals were available.

Of the 7484 stations with traditional PRCP normals, 185 had complete observed records during 1981–2010, 7249 were completed with at least one estimated yearmonth total, and 50 could not be completely filled in. Expressed another way, estimates were produced for 83% of the 89 808 station–calendar month time series for which a traditional PRCP normal was computed. Averaged over the stations–calendar months with at least one estimate, the difference between the means of the estimated and observed monthly totals during the respective periods of overlap was 0.03 in. (0.8 mm). The average absolute difference was 0.11 in. (2.7 mm), or 4.5% of the respective observation-based mean. Sensitivity tests suggest that increasing the minimum number of years of overlap or decreasing the neighbor search radius results in a slight improvement in these error statistics while reducing the number of stations for which estimates can be produced. As a consequence, the 10-yr minimum and 500-km radius appeared to be the most suitable compromise between minimizing estimation errors and maximizing spatial coverage.

The 199 series at 50 stations that could not be completed account for 0.2% of all stations–calendar months whose observed records were incomplete. Six of the stations are in remote locations of Alaska or the Pacific where no neighbors were available within 500 km. In other cases, either the available neighbors did not meet the data requirements of the procedure or the observed monthly totals at the target station did not include any nonzero values, making the development of a regression relationship impossible. There were data configurations, mostly in dry areas, that resulted in degenerate or nonunique regression solutions. In all of these cases, averages, medians, and quartiles of monthly totals were calculated from the incomplete observed record rather than from a combination of observed and estimated yearmonth totals (see sections 2 and 3), and the resulting statistics were identified accordingly in the output files.

APPENDIX C

Estimation of Average Monthly Precipitation Totals for Quasi-Normals Stations

The following describes our implementation of Sun and Peterson's (2005, 2006) approach for estimating climatological averages, or quasi normals, at stations with extremely short PRCP records (see section 2). The quasi normal for a particular station and calendar month (e.g., July at Zuni; Fig. 3) was estimated using three steps. Step 1 consisted of estimation of anomalies. As an example, for each July with an observed monthly total at Zuni the corresponding anomaly relative to the presumed 30-yr average was estimated as the weighted average of the anomalies at the 10 nearest neighbors within 500 km for which both an observed July total in the same year and a traditional normal were available. The weight of a neighbor's anomaly was equal to the inverse squared difference between the PRCP totals at the target and neighbor stations; if the target and neighbor values were equal, however, the weight was set to 0.01 in. (0.254 mm). Step 2 consisted of creation of multiple estimates of the normal. Subtracting the estimated anomaly from Zuni's observed July total, for example, yielded one estimate of the normal. The anomaly calculation and subtraction were repeated for each year for which sufficient data were available, resulting in a set of estimated normals. In step 3 the final estimate was created by averaging the estimates computed in step 2 to obtain the final quasi normal. In the rare case in which this final estimate was negative (one occurrence across all stations and months), it was reset to zero.

REFERENCES

Arguez, A., I. Durre, S. Applequist, R. S. Vose, M. F. Squires, X. Yin, R. Heim Jr., and T. W. Owen, 2012: NOAA's 1981–2010 U.S. Climate Normals: An overview. *Bull. Amer. Meteor. Soc.,* **93,** 1687–1697.

Brown, R. D., and D. A. Robinson, 2011: Northern Hemisphere spring snow cover variability and change over 1922–2010 including an assessment of uncertainty. *Cryosphere,* **5,** 219–229.

Cayan, D. R., M. D. Dettinger, H. F. Diaz, and N. E. Graham, 1998: Decadal variability of precipitation over western North America. *J. Climate,* **11,** 3148–3166.

Changnon, S. A., 2006: Problems with heavy snow data at first-order stations in the United States. *J. Atmos. Oceanic Technol.,* **23,** 1621–1624.

Christy, J. R., 2012: Searching for information in 133 years of California snowfall observations. *J. Hydrometeor.,* **13,** 895–913.

Daly, C., W. P. Gibson, G. H. Taylor, M. K. Doggett, and J. I. Smith, 2007: Observer bias in daily precipitation measurements at United States Cooperative Network stations. *Bull. Amer. Meteor. Soc.,* **88,** 899–912.

Diamond, H. J., and Coauthors, 2013: U.S. Climate Reference Network after one decade of operations: Status and assessment. *Bull. Amer. Meteor. Soc.,* **94,** 485–498.

Doesken, N. J., and A. Judson, 1997: The Snow Booklet: A guide to the science, climatology, and measurement of snow in the United States. Colorado State University Rep., 87 pp.

——, and D. A. Robinson, 2009: The challenge of snow measurements. *Historical Climate Variability and Impacts in North America,* L.-A. Dupigny-Giroux and C. J. Mock, Eds., Springer Science+Business Media, 251–273.

Durre, I., M. J. Menne, B. E. Gleason, T. G. Houston, and R. S. Vose, 2010: Comprehensive automated quality assurance of daily surface observations. *J. Appl. Meteor. Climatol.,* **49,** 1615–1633.

Dyer, J., and T. L. Mote, 2006: Spatial variability and trends in observed snow depth over North America. *Geophys. Res. Lett.,* **33,** L16503, doi:10.1029/2006GL027258.

Groisman, P. Ya., and D. R. Legates, 1994: The accuracy of United States precipitation data. *Bull. Amer. Meteor. Soc.,* **75,** 215–227.

Heim, R. R., Jr., 1996: An overview of the 1961–90 climate normals products available from NOAA's National Climatic Data Center. Preprints, *22nd Conf. on Agricultural and Forest Meteorology,* Atlanta, GA, Amer. Meteor. Soc., 193–196.

Higgins, R. W., and V. E. Kousky, 2013: Changes in observed daily precipitation over the United States between 1950–79 and 1980–2009. *J. Hydrometeor.,* **14,** 105–121.

Jutla, A. S., D. Small, and S. Islam, 2006: A precipitation dipole in eastern North America. *Geophys. Res. Lett.,* **33,** L21703, doi:10.1029/2006GL027500.

Kunkel, K. E., and A. Court, 1990: Climatic means and normals—A statement of the American Association of State Climatologists (AASC). *Bull. Amer. Meteor. Soc.,* **71,** 201–204.

——, M. A. Palecki, K. G. Hubbard, D. A. Robinson, K. T. Redmond, and D. R. Easterling, 2007: Trend identification in twentieth-century U.S. snowfall: The challenges. *J. Atmos. Oceanic Technol.,* **24,** 64–73.

Legates, D. R., and G. J. McCabe Jr., 1999: Evaluating the use of ''goodness-of-fit'' measures in hydrologic and hydroclimatic model evaluation. *Water Resour. Res.,* **35,** 233–241.

Mekis, É., and L. A. Vincent, 2011: An overview of the second generation adjusted daily precipitation dataset for trend analysis in Canada. *Atmos.–Ocean,* **49,** 163–177.

Menne, M., I. Durre, R. S. Vose, B. E. Gleason, and T. G. Houston, 2012: An overview of the Global Historical Climatology Network-Daily database. *J. Atmos. Oceanic Technol.,* **29,** 897–910.

Mielke, P. W., and K. J. Berry, 2001: *Permutation Methods: A Distance Function Approach.* Springer-Verlag, 352 pp.

Owen, T. W., and T. Whitehurst, 2002: United States climate normals for the 1971–2000 period: Product descriptions and applications. Preprints, *Third Symp. on Environmental Applications: Facilitating the Use of Environmental Information,* Orlando, FL, Amer. Meteor. Soc., J4.3. [Available online at https://ams.confex.com/ams/annual2002/webprogram/Paper26747.html.]

Robinson, D. A., 1989: Evaluation of collection, archiving, and publication of daily snow data in the United States. *Phys. Geogr.,* **10,** 120–130.

Small, D., and S. Islam, 2008: Low frequency variability in fall precipitation across the United States. *Water Resour. Res.,* **44,** W04426, doi:10.1029/2006WR005623.

Sun, B., and T. C. Peterson, 2005: Estimating temperature normals for U.S. CRN stations. *Int. J. Climatol.,* **25,** 1809–1817.

——, and ——, 2006: Estimating precipitation normals for U.S. CRN stations. *J. Geophys. Res.,* **111,** D09101, doi:10.1029/2005JD006245.

Tokay, A., P. G. Bashor, and V. L. McDowell, 2010: Comparison of rain gauge measurements in the mid-Atlantic region. *J. Hydrometeor.,* **11,** 553–565.

Viney, N. R., and B. C. Bates, 2004: Why it never rains on Sunday: The prevalence and implications of untagged multi-day rainfall accumulations in the Australian high quality dataset. *Int. J. Climatol.,* **24,** 1171–1192.

Wijngaard, J. B., A. M. G. Klein Tank, and G. P. Konnen, 2003: Homogeneity of 20th century European daily temperature and precipitation series. *Int. J. Climatol.,* **23,** 679–692.

Wilks, D. S., 2006: *Statistical Methods in the Atmospheric Sciences.* Elsevier, 627 pp.

Woolhiser, D. A., and J. Roldán, 1986: Seasonal and regional variability of parameters for stochastic daily precipitation models: South Dakota, U.S.A. *Water Resour. Res.,* **22,** 965–978.

WMO, 1989: Calculation of monthly and annual 30-year standard normals. World Meteorological Organization Tech. Doc. WMO-TD 341, 12 pp.

——, 2007: The role of climatological normals in a changing climate. World Meteorological Organization Publ. WCDMP 61, 46 pp.

Zhong, Y., Z. Liu, and M. Notaro, 2011: A GEFA assessment of observed global ocean influence on U.S. precipitation variability: Attribution to regional SST variability modes. *J. Climate,* **24,** 693–707.