A Dozen Years of Temperature Observations at the Summit: Central Greenland Automatic Weather Stations 1987–99

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ABSTRACT

On 4 May 1987, the first automatic weather station (AWS) near the summit of the Greenland Ice Sheet began transmitting data. Air temperature records from this site, AWS Cathy, as well as nearby AWS at the Greenland Ice Sheet Project II (GISP2, now Summit) camp have been combined with Special Sensor Microwave Imager brightness temperature data to create a composite temperature history of the Greenland summit. This decadal-plus-length (4536 days) record covers the period from May 1987 to October 1999 and continues currently. The record is derived primarily from near-surface temperature data from AWS Cathy (May 1987–May 1989), AWS GISP2 (June 1989–November 1996), and AWS Summit (May 1996 and continuing). Despite the 35-km distance between them, the AWS Cathy data have been converted to the equivalent basis of temperatures from the AWS GISP2 and AWS Summit locations. The now completed ''Summit'' temperature time series represents a unique record that documents a multiyear temperature recovery after the eruption of Mt. Pinatubo in June 1991 and that initiates a baseline needed for climate change detection.

1. Introduction

Because of societal concerns and scientific curiosity, the complex nature of our dynamic climate system is the focus of extensive study. However, despite the devotion of growing computational and observational resources to the study of our climate, significant regions of the earth remain poorly monitored or understood. Consequently, these regions are not well represented in predictive climate models (Fawcett et al. 1997). This is generally a result of their relative inaccessibility, their harsh climate, or both conditions. Among these regions are the great polar ice sheets, which may be most affected by projected rising global temperatures associated with increases in greenhouse gas concentrations (Houghton et al. 1996).

In order to document the current climate state as well as to provide the raw data needed to improve predictive models, University of Wisconsin researchers installed a series of multisensor automatic weather stations (AWS) in the vicinity of the Greenland summit (Fig. 1) beginning in 1987. This effort was also in support of the deep ice cores being drilled at the Greenland Ice Sheet Project II (GISP2) and nearby Greenland Icecore Project (GRIP) sites. The first University of Wisconsin AWS began recording meteorological data on 4 May 1987, and the monitoring program lasted until 19 June 1998 (Table 1). Fortunately, as the GISP2 site evolved into a semipermanent research station (so-called Summit, despite its approximately 30-km offset from the true summit at the GRIP site), a new multisensor AWS was installed nearby (Table 2). AWS Summit was installed as part of the Program for Arctic Regional Climate Assessment's (PARCA) Greenland Climate Network (GC-

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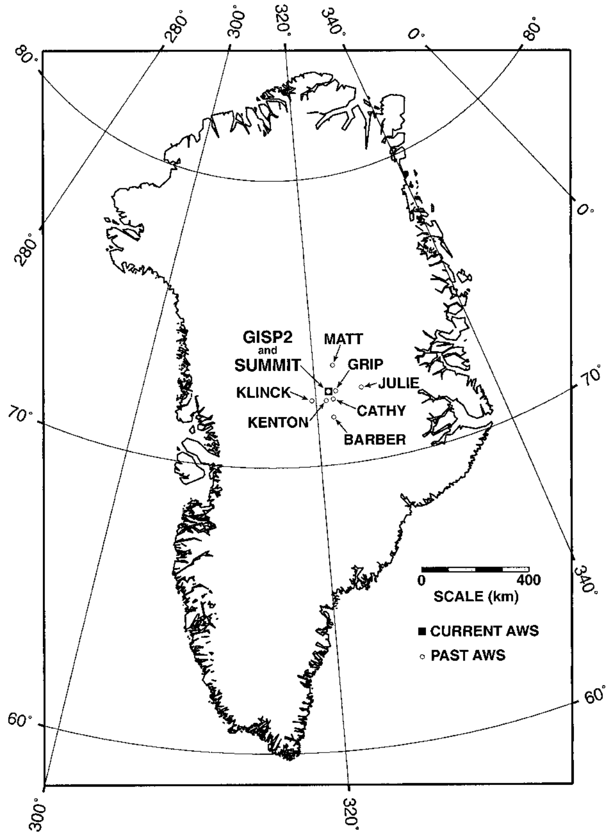

FIG. 1. Map of the AWS located in the vicinity of the Greenland summit. AWS Cathy, GISP2, and Summit provide the basis of this study, with some additional data coming from AWS Kenton.

Net) by researchers from the University of Colorado. In this paper, we discuss a unique composite 12+-year record of daily, monthly, and annual average temperatures derived from these AWS for the ''Summit'' area in central Greenland.

2. Methodology

As the data in Fig. 2 clearly illustrate, the temperature records from central Greenland are not continuous. The observed near-surface air temperature record is composed of multiyear segments from multiple AWS. In addition, individual records contain gaps that can last for a few days to many months. As a result, establishing a temperature history for this critical area is difficult, even without considering the differences between AWS locations and the temperature equipment installed at them. This paper will describe an effort to develop a consistent temperature history for this area employing Special Sensor Microwave Imager (SSM/I) brightness temperature data. This satellite-derived brightness temperature record represents part of the longest observational time series across the polar ice sheets (Abdalati et al. 1995; Shuman et al. 1997).

TABLE 1. Summary of the Greenland Summit Network AWS available for this study.

Name	Start-stop date[a]	Lat (°N)[b]	Long (°W)[b]	Elev (m)[b]	SSM/I *i*/*j*[c]
Barber	7/90–6/96	71.67	38.17	3170	164/314
Cathy	5/87–5/89	72.30	38.00	3210	164/311
GISP2	6/89–1/97	72.58	38.46	3205	163/310
GRIP[d]	3/90–6/90	72.57	37.62	3230	164/310
Julie	8/91–5/95	72.57	34.63	3100	168/309
Kenton	6/89–6/98	72.28	38.82	3185	163/311
Klinck	8/90–5/95	72.31	40.48	3105	161/312
Matt	8/91–5/95	73.48	37.62	3100	164/306
Summit[e]	5/96–	72.58	38.50	3205	163/310

[a] The month/year that accurate meteorological data began or stopped being received.

[b] Location data from the University of Wisconsin archive (ftp.ice.ssec.wisc.edu) on 22 Oct 1999.

[c] The SSM/I grid identifier of the 25 km × 25 km pixels covering the AWS sites from the National Snow and Ice Data Center program LOCATE (NSIDC 1992).

[d] The GRIP AWS had data-quality difficulties and was removed after limited service.

[e] Summit data derived from the University of Colorado's Cooperative Institute for Research in Environmental Sciences Web site (http://cires.colorado.edu/steffen/gc-net.html).

a. Record components

The data presented in Fig. 2 document the available, daily average air temperature data from the longest-operating AWS sensors in central Greenland. It consists of three major components, AWS Cathy and AWS GISP2 (University of Wisconsin), with a minor gap separating them (in late May 1989, AWS Cathy was moved and became AWS Kenton; Fig. 1, Table 2), followed by AWS Summit (University of Colorado). Also note that the AWS GISP2 and AWS Summit portions of the record contain significant gaps. The following statistics will illustrate the impact of these gaps on a long-term temperature record. The AWS Cathy provided quality temperature data for 754 out of 757 days (or 99.6% complete) whereas AWS GISP2 operated for only 2624 out of 3555 days (or 73.8% complete) and AWS Summit's primary temperature sensor operated for 1141 days out of 1238 (92.2% complete to date). In total, the record of temperature from these stations is approximately 82% complete. The data from AWS Cathy and GISP2 are taken from a custom platinum resistance thermometer (Stearns et al. 1993) whereas the AWS Summit data come from a type-E thermocouple (sensor TC1) (Steffen

TABLE 2. Approximate elevation differences (m) and distances (km) between the Summit network AWS used in this study. Distances were calculated from the location data from Table 1 and the online Great Circle calculator (http://www.best.com/~williams/gccalc.htm.).

Name	Cathy	Kenton	GISP2	Summit
Cathy		25 m	5 m	5 m
Kenton	27.9 km		20 m	20 m
GISP2	34.9 km	35.6 km		0 m
Summit	35.5 km	35.2 km	1.3 km	

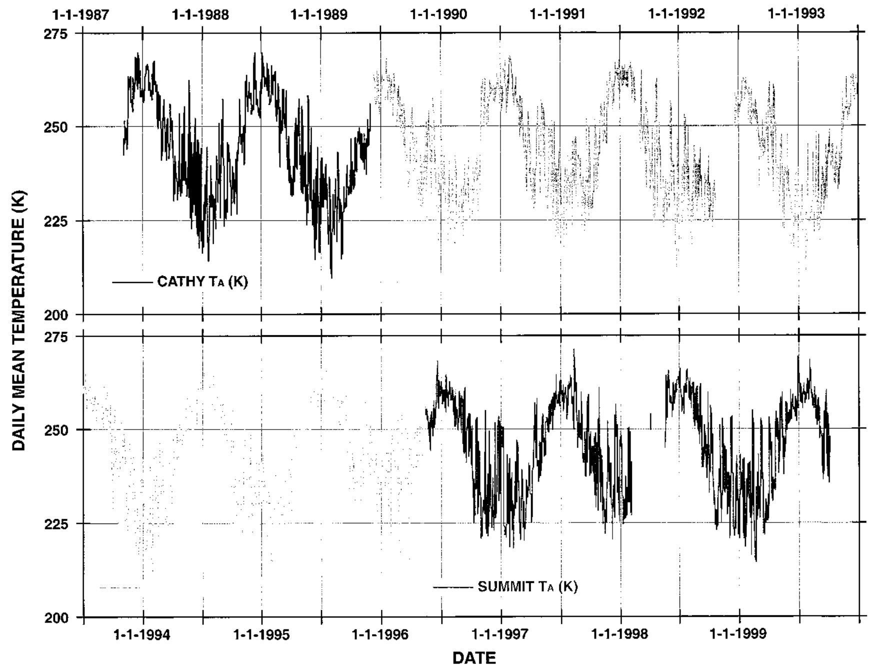

FIG. 2. Illustration of the main temperature records and data gaps for the Greenland summit for the period from May 1987 to Oct 1999. The portions of the record that required processing are described further in the text and are summarized in Table 3.

et al. 1996). These sensors have naturally aspirated (passive) solar shielding and relative accuracies of 0.125 and better than 0.3°C, respectively. The sensors are calibrated at the laboratory and in the field each time the AWS is maintained, typically annually, although this depends on accumulation rate and logistics constraints.

In order to complete a temperature record from the Greenland Summit (May 1987 to October 1999), it will be necessary to adjust the AWS Cathy temperature record to account for the difference in its location as well as to complete the AWS GISP2 and AWS Summit records across multiple periods of missing data (Table 3). The methods detailed in Shuman et al. (1996) or in Shuman et al. (1995), which rely on appropriately located and contemporaneous SSM/I brightness temperature data (Table 1), will be used to achieve a complete and consistent temperature record. Inconveniently, SSM/I data are not available from 4 May 1987 to 10 July 1987 and are missing from 3 December 1987 to 13 January 1988 (Table 3). Smaller gaps in the SSM/I or AWS record of less than 5 days will be dealt with by interpolation.

The 3-h average AWS data for the Cathy, Kenton, and GISP2 sites were obtained from the University of Wisconsin—Madison Internet site (ftp://ice.ssec.wisc.edu/). These data are quality controlled and averaged 10-min

TABLE 3. Summary of the adjustments needed to produce the composite daily temperature record. Note that a limited amount of original AWS temperature data may have been discarded during the analysis because of deviations from adjacent records, suggesting sensor or transmission error. Also, where gaps existed in the T_B/T_B ratio data, linear interpolations were made to allow continuous conversion of the AWS Cathy or AWS Kenton data to the equivalent basis of AWS GISP2 or AWS Summit.

Record segment	Segment dates (month/day/year)	Technique used
AWS Cathy T_A	5/4/87 to 5/29/89	Multiple
	7/26/87, 6/15/88, and 11/16/88	Linear interpolation
	5/4/87–7/9/87 and 12/3/87–1/13/88	Equivalent basis (with model T_B ratio)
	7/10/87–12/2/87 and 1/14/88–5/29/89	Equivalent basis
AWS Cathy to Kenton	5/30/89–6/7/89	Emissivity model
AWS GISP2 T_A	6/8/89 to 5/13/96	Multiple
	5/16/90, 7/29/91, 11/14/92, 1/16/93, 1/30/95–1/31/95, and 1/18/96–1/19/96	Linear interpolation
	8/13/91–8/29/91	Emissivity model
	2/1/92–6/17/92 and 11/1/92–11/4/92	Equivalent basis
AWS Summit TC1 T_A	5/14/96 and continuing	Multiple
	12/11/97	Linear interpolation
	2/5/98 to 5/14/98	Equivalent basis

AWS observations. The AWS Summit 1-min temperature observations are extensively quality controlled and compiled into hourly averaged data that are available from the GC-Net Web site (http://cires.colorado.edu/steffen/gcnet.html). Daily average temperature values are then calculated from these ''raw'' data for comparison to the daily average passive microwave, brightness temperature (T_B) required by the equivalent basis technique. Information on the AWS units, including data transmission and quality control, is presented in Stearns and Weidner (1991), Stearns et al. (1993), and Steffen et al. (1996).

The passive microwave data were retrieved from National Snow and Ice Data Center (NSIDC) CD-ROMs (NSIDC 1992). The T_B data from a 37-GHz V (0.81-cm wavelength, vertical polarization) channel are available from SSM/I sensors starting with the Defense Meteorological Satellite Program (DMSP) platform *F-8* from July 1987 to December 1991. Data from subsequent DMSP platforms, such as *F-11* starting in December 1991 and followed by *F-13* in May 1995, are available from the NSIDC. The SSM/I *F-8* record between 3 December 1987 and 13 January 1988 is missing because of sensor malfunction (Table 3) (Hollinger et al. 1990). Daily average, 37-GHz V T_B from the SSM/I (*F-8*, *F-11*, and *F-13*) for each AWS 25 km $\times$ 25 km grid cell (Table 1) are compiled as a time series. The DMSP satellite orbital time period is 102 min (Hollinger et al. 1990), and the SSM/I sensor can view the summit region up to 6 times per day. Typically, multiple daily T_B observations for each 25 km $\times$ 25 km polar stereographic grid cell are then averaged to represent one daily value in the SSM/I data set (NSIDC 1992). Unfortunately, there is no convenient way to retrieve the number or the time of day of the observations that make up the daily average for each cell from the NSIDC SSM/I Grid CD-ROMs. This may introduce some uncertainty to the technique. The measurement accuracies of the 37-GHz V channels on these instruments are ± 2 K (Hollinger et al. 1990). The relationship of the 37-GHz V T_B data that are a function of physical snow temperature to near-surface AWS air temperatures is described more thoroughly in Shuman et al. (1995).

b. *Equivalent-basis technique*

This technique allows the ''adjustment'' of one AWS air temperature (T_A) record to the equivalent basis of another AWS T_A record, despite differences in location and elevation (Table 2). Hence, data gaps can be filled with observed air temperature data, which, because of its relative proximity, have a close association with the temperature record of the malfunctioning AWS. The justification for this technique follows.

According to the Rayleigh–Jeans approximation, the relationship of T_B and the near-surface snow temperature can be described as follows:

$$T_B = \varepsilon T, \qquad (1)$$

where ε is the emissivity and T is the temperature of the near-surface snow and ice over the effective emission depth of the 37-GHz V microwave signal. The near-surface snow temperature depends strongly on the T_A, as shown in Shuman et al. (1995), so it is substituted for T. If we assume that the snow emissivities at both AWS sites are equal, then the contemporaneous ratios of T_B and T_A should be equivalent, as in the relationship

$$T_{B_1}/T_{B_2} = T_{A_1}/T_{A_2}, \qquad (2)$$

where the numeric subscripts are associated with the pair of AWS whose data is to be merged. This relationship can be tested over the summit region using T_A and T_B data from the GISP2 and Kenton AWS during 18 months from 1992 to 1993 (Fig. 3). Although there are differences, most significantly in the relative ranges of the two ratios because of larger daily variability in air temperature between the sites, the two ratios are quite similar in mean magnitude over the time period. Thus, the relationship of the ratios for these two sites justifies the assumption above and allows AWS record T_{A_2} to be converted to the equivalent basis (eb) of T_{A_1} by manipulating Eq. (2):

$$\text{eb}T_{\mathbf{A}_1} = \mathbf{T}_{\mathbf{A}_2}(\mathbf{T}_{\mathbf{B}_1}/\mathbf{T}_{\mathbf{B}_2}). \qquad (3)$$

With this approach, we converted the AWS Cathy temperature record to the equivalent basis of the AWS GISP2 record (Shuman et al. 1996). Although the $\mathbf{T_A}$ *and* $\mathbf{T_B}$ *ratio assumption cannot be tested for Cathy and GISP2 because of the lack of overlapping* $\mathbf{T_A}$ *records, we assumed that the same general relationship applies for this pair of sites as it does across the similar distance from AWS Kenton to AWS GISP2 (Table 2). This assumption will be discussed further in this paper.*

3. Composite record development

Two segments of the AWS Cathy data could not be directly converted to the equivalent basis of AWS GISP2. First, the AWS Cathy record began before SSM/I *F-8* data were available (4 May 1987 vs 10 July 1987). Second, the SSM/I sensor was not operating between 3 December 1987 and 13 January 1988. As a result, the 37-GHz V T_B ratio between the two sites had to be synthesized during these segments. We used the proprietary software package Igor (http://www.wavemetrics.com/) to generate an annual sinusoid model based on the phase and amplitude of the available T_B ratio data [see Shuman et al. (1995) for more detail on the modeling technique]. Despite a decrease in sensitivity in the modeled T_B ratios relative to actual ratios (Table 4), we were able to convert the Cathy T_A record from its start date.

The next gap of 10 days resulted from the move of the Cathy instruments to the site of AWS Kenton (30 May 1989 to 8 June 1989) (Fig. 2). The resulting data gap between Cathy (now Kenton) and the main AWS GISP2 record was filled using the emissivity modeling technique detailed in Shuman et al. (1995). The same

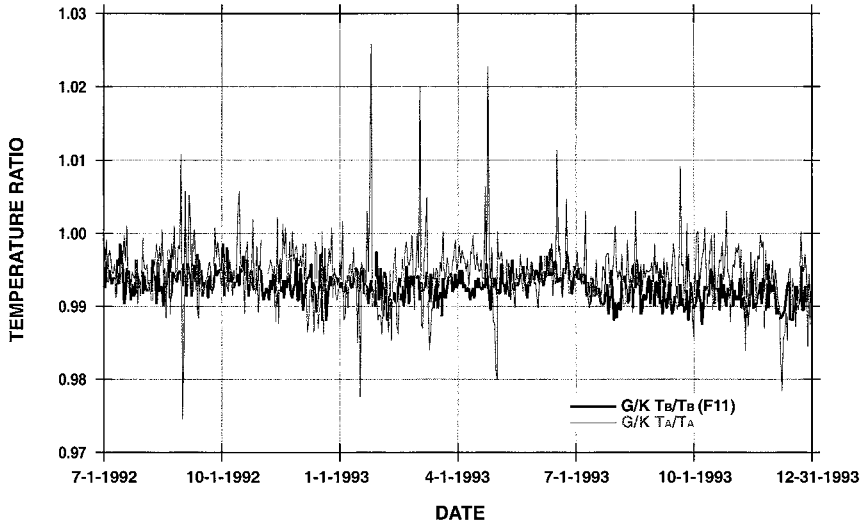

FIG. 3. Comparison of brightness temperature (T_B/T_B) and observed temperature (T_A/T_A) ratio trends for the AWS GISP2 and Kenton sites. The general similarity of their trends justifies a key assumption used in the equivalent-basis technique. Note the outliers (primarily in air temperature) that indicate significant differences between the two AWS sites. The overall similarity in these trends is also used to justify the adjustment of the AWS Cathy record to the equivalent basis of the AWS GISP2 record (Table 2).

procedure was also used to fill a second data gap in the AWS GISP2 record (13–29 August 1991). A 500-day T_A subset centered on the missing data was extracted from the combined AWS GISP2 and equivalent-basis AWS Cathy temperature time series along with the contemporaneous 37-GHz V T_B daily averages from the GISP2 site for modeling the emissivity cycle. The modeled emissivity cycle was then used with the T_B data to generate the missing temperatures. Although these assimilated temperature data are of lesser quality than the observed and equivalent-basis records (Table 4), they were included to make the composite record complete.

For the ''Summit'' site, the only major gap in the AWS GISP2 record (1 February 1992 to 17 June 1992) (Fig. 2) was completed using the air temperature record from AWS Kenton located approximately 36 km to the south (Fig. 1, Table 2). The AWS Kenton data were adjusted by the T_B ratio technique. A minor gap in the AWS GISP2 record (1–4 November 1992) was approximated using the same technique. Also, we used AWS Summit data (TC1: type-E thermocouple) beginning on 14 May 1996, despite AWS GISP2's continued operation through November 1996. The only significant gap in AWS Summit's record, extending from 5 February

TABLE 4. Estimates of temperature errors for the major segments of the composite record.

Major segment(s)	Segment dates (month/day/year)	Estimated error (±)
AWS Cathy ebT_A*[a]	5/4/87–7/9/87 and 12/3/87–1/13/88	1.296 K
AWS Cathy ebT_A[b]	7/10/87–12/2/87 and 1/14/88–5/29/89	1.162 K
Modeled T_B/T_A[c]	5/30/89–6/7/89	3.474 K
AWS GISP2 obsT_A[d]	6/8/89–8/12/91, 8/30/91–1/31/92, 6/17/92–10/31/92, and 11/15/92–5/13/96	0 K
AWS Summit TC1 obsT_A[e]	5/14/96–2/4/98 and 5/15/98–10/3/99	0 K
Modeled T_B/T_A[f]	8/13/91–8/29/91	2.866 K
AWS Kenton ebT_A[b]	2/1/92–6/17/92, 11/1/92–11/14/92 and 2/5/98–5/14/98	1.162 K

[a] Estimated as equal to the std dev of the GISP2–Kenton comparison (Fig. 3) exaggerated by the ratio of the std devs of the observed and modeled T_B/T_B ratios during the AWS Cathy segment.

[b] Estimated as equal to the std dev of the GISP2–Kenton comparison (Fig. 3).

[c] Conservatively estimated as equal to the std dev of the differences between the daily T_C temperatures produced by the emissivity modeling technique (see Shuman et al. 1995) and the adjusted and then observed GISP2 T_A data during May and Jun 1989. Here, T_C is the temperature calculated from Eq. (1) when both T_B and modeled ε are known.

[d] Values are the daily mean of all quality-controlled observed temperatures from the University of Wisconsin AWS GISP2 that are each reportedly accurate to ±0.125 K. For average error calculations over the whole record, a temperature offset of 0.81 K has been assumed for all daily values between May 20 and Aug 20 (see discussion relating to Figs. 6 and 7).

[e] Values are the daily mean of all quality-controlled observed temperatures from the University of Colorado AWS Summit's main sensor (TC1) that are each reportedly accurate to better than ±0.3 K.

[f] Conservatively estimated as equal to the std dev of the differences between the daily T_C temperatures from the approximate emissivity modeling technique (see Shuman et al. 1995) and the observed GISP2 T_A temperatures during Jul and Aug 1991.

1998 to 14 May 1998 (Fig. 2), was completed by insertion of AWS Kenton data that were adjusted by the T_B ratio technique. Although temperature data were available during this data gap from a secondary AWS Summit sensor (CS2: Vaisala, Inc., CS500 platinum resistance thermometer), the daily average values substantially differ from TC1 (frequently >5 K) between mid-October and mid-April. The Vaisala CS500 sensor apparently has difficulties reading at low temperatures (−40°C and lower). Further analysis of the data showed that AWS Kenton ebT_A data were more reliable. Comparisons of these temporally overlapping records will be discussed below.

a. Error analysis

To illustrate the accuracy of the equivalent-basis technique, the observed AWS Kenton T_A were first differenced from temporally equivalent GISP2 T_A data over the 18-month period shown in Fig. 3. The AWS Kenton data were then converted to the equivalent basis of AWS GISP2 and then differenced again from the observed GISP2 data. Statistical analysis of these difference distributions (Fig. 4) yields a histogram of daily difference errors with a mean of −1.35 K and a standard deviation of 1.08 K between the unconverted AWS Kenton data and the AWS GISP2 data. This confirms that Kenton is generally warmer than the higher and more northerly GISP2 site (Tables 1 and 2). After adjusting the AWS Kenton data by the equivalent-basis technique, the mean difference changes to 0.47 K, and the standard deviation increases slightly to 1.16 K. This suggests that converting the AWS Kenton T_A data produces an improvement in the mean value but slightly reduces the overall accuracy of the distribution.

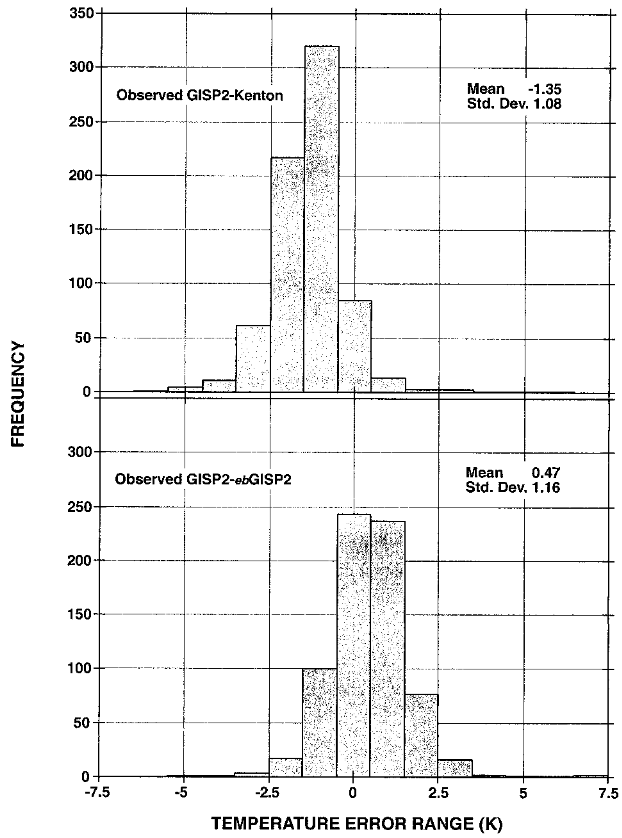

FIG. 4. Histograms of the mean daily difference errors between the observed AWS GISP2 T_A data and the observed AWS Kenton T_A data without and with equivalent-basis adjustment for the time period in Fig. 3. This shows that the technique improves the distribution mean (−1.35–0.47 K) but does not improve the standard deviation (1.08–1.16 K).

As noted above, the lack of contemporaneous T_A records for AWS Cathy and AWS GISP2 prevents direct assessment of temperature errors resulting from the technique. However, it seems reasonable to assume that the errors are similar to those observed between AWS GISP2 and AWS Kenton, despite differences between the locations of Cathy and Kenton (Fig. 1, Table 2). The distribution of daily difference errors between GISP2 and equivalent-basis Kenton T_A suggests that converting the AWS Cathy air temperature data by the equivalent-basis technique produces an improved assimilated GISP2 temperature record than would use of the unadjusted Cathy data. However, as will be discussed later, the approximately 0.5-K mean difference (Fig. 4) suggests that the resulting equivalent-basis data from Kenton (and by extension, Cathy) might be slightly too low.

The previous assumption requires a limited spatial variability in emissivity, as demonstrated in this area by Chang et al. (1976). Shuman et al. (1995, 1996) showed that distances on the order of 70 km between central and supporting AWS may affect this technique because of variability in snow characteristics. Outliers in the difference histograms (Fig. 4) are probably the result of local meteorological variability (clouds in one area vs sun at the other) as well as the SSM/I ''drop-in-the-bucket'' gridding technique.

Final completion of the composite record was hindered by data gaps in the SSM/I record needed for equivalent-basis calculations or by days where the AWS records had no quality data (note that the AWS may have transmitted temperature data but subsequent quality control studies determined them to be unreliable). This led to a small number of data gaps (typically one day and occasionally up to four days) in the composite record (<1% in total). These gaps were filled by linear interpolation using the mean of the days on either side of the gap. In order to assess the significance of this interpolation on the T_A record, the following analysis was done. A portion of the completed record was differenced from a modified version of the same record that contained approximately 100 gaps of 1, 2, 3, and 4 days that were filled by linear interpolation (Fig. 5). The resulting difference statistics are an estimate of the error in the daily average temperature likely to result on a given day or days because of the interpolation process. In all the gap sizes studied, the typical error

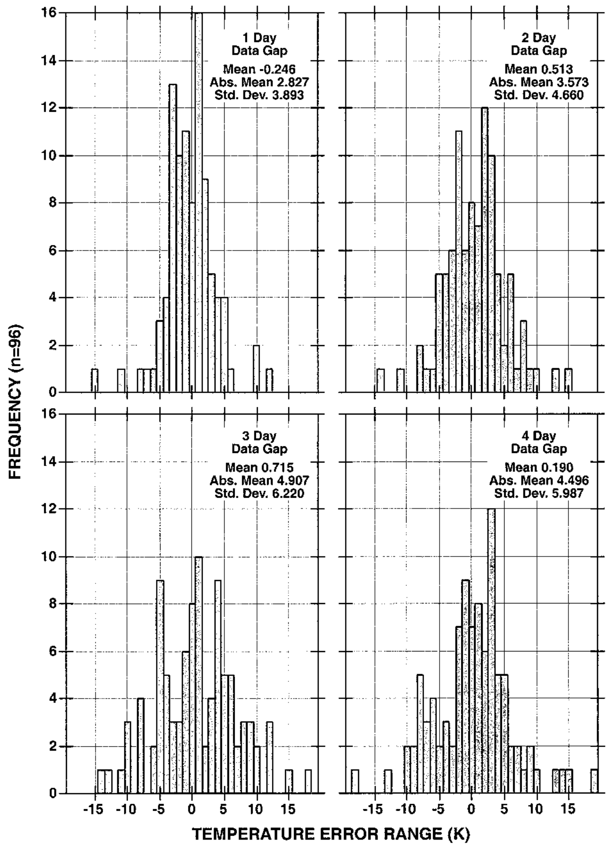

FIG. 5. Interpolation statistics for the typically observed T_A data gaps. The daily average temperature record was progressively degraded, with data gaps of 1–4 days that were then linearly interpolated and differenced from the observed record. The generally symmetric nature of the error distributions indicates that there is no systematic bias, either warmer or cooler, due to the interpolation technique.

(assuming one standard deviation) was less than 7 K, and for 1-day gaps, the interpolation error was less than 5 K per day. Similarly, the average absolute value of the observed differences was always less than 5 K. In addition, the distributions in Fig. 5 indicate that there was no systematic bias toward either warmer or cooler temperatures. This suggests that the limited interpolation of T_A or T_B data over small gaps should have minimal impact on the longer-term averages needed for monitoring climate behavior.

b. Intercomparison of Summit AWS records

Additional analyses were conducted by comparing the daily mean T_A records observed at AWS GISP2 and Summit (14 May 1996 to 14 November 1996) and AWS Kenton and Summit (July 1996 to January 1998). The periods that these stations were operating simultaneously allow relative sensor accuracy and possible data quality factors to be assessed. Other pairs of AWS could be examined (Table 1), but this analysis was focused on the one continuing AWS at Summit as a test of its reliability.

In the first test, the daily average temperatures from AWS GISP2 and Summit were directly compared during their main period of overlap (Fig. 6). The day-by-day variations compare well until the very end of the period (14 November 1996) following which the University of Wisconsin quality-control procedures discarded transmitted data. The daily difference plot shows a large departure (nearly 10 K) on this date that illustrates the effective termination of AWS GISP2 based on quality-control criteria. Other departures of 2–5 K are also observed, suggesting that particular meteorological events (such as riming) may be affecting the AWS differentially. For the period of overlap overall, the temperature differences between the two AWS (separated by about 1 km) (Table 2) average less than 0.5°, with GISP2 recording warmer temperatures than Summit. However, there appears to be some structure to the differences, with relatively warmer GISP2 observations primarily during the summer months that diminish as insolation decreases in late August. This suggests that solar heating affects the GISP2 sensor slightly more than the Summit sensor. In fact, the data show that GISP2 is warmer than Summit by an average of 0.81 K from 20 May 1996 to 20 August 1996 and that otherwise the overall difference between them during the period of overlap is negligible (averaging −0.02 K).

In order to determine if the design of the AWS sensor was responsible for the differences illustrated in Fig. 6, a similar analysis was conducted for the AWS Kenton and Summit T_A records during their period of overlap (9 July 1996 to 4 February 1998, with Kenton operating intermittently to 19 June 1998) (Fig. 7). This figure confirms that both sensor configurations agree fairly well in tracking temperature variations. However, we found a similar temperature difference structure during the summer months between the two stations. The distance between this pair of stations is much greater, and AWS Kenton is about 20 m lower than AWS Summit. Ordinarily, we would expect a difference of approximately 0.2 K (wet-adiabatic gradient) at most, yet Kenton averages almost 1° warmer than Summit. As with the GISP2–Summit comparison, the 20 May 1997 to 20 August 1997 difference is enhanced, with Kenton being almost 1.85 K warmer than Summit during the period of high solar insolation. With the May–August periods excluded, the Kenton data appear to be warmer than Summit by only 0.61 K. Examination of AWS GISP2 and AWS Kenton daily differences shows no seasonal variation during their period of common record, suggesting that both of those T_A sensors are affected similarly by slight insolation problems that may be enhanced during periods of low wind speed. The alternative, that the AWS Summit is somehow preferentially cooled during the summer months, does not seem likely. In any case, these analyses suggest the magnitude and possible cause of some small problems with AWS T_A

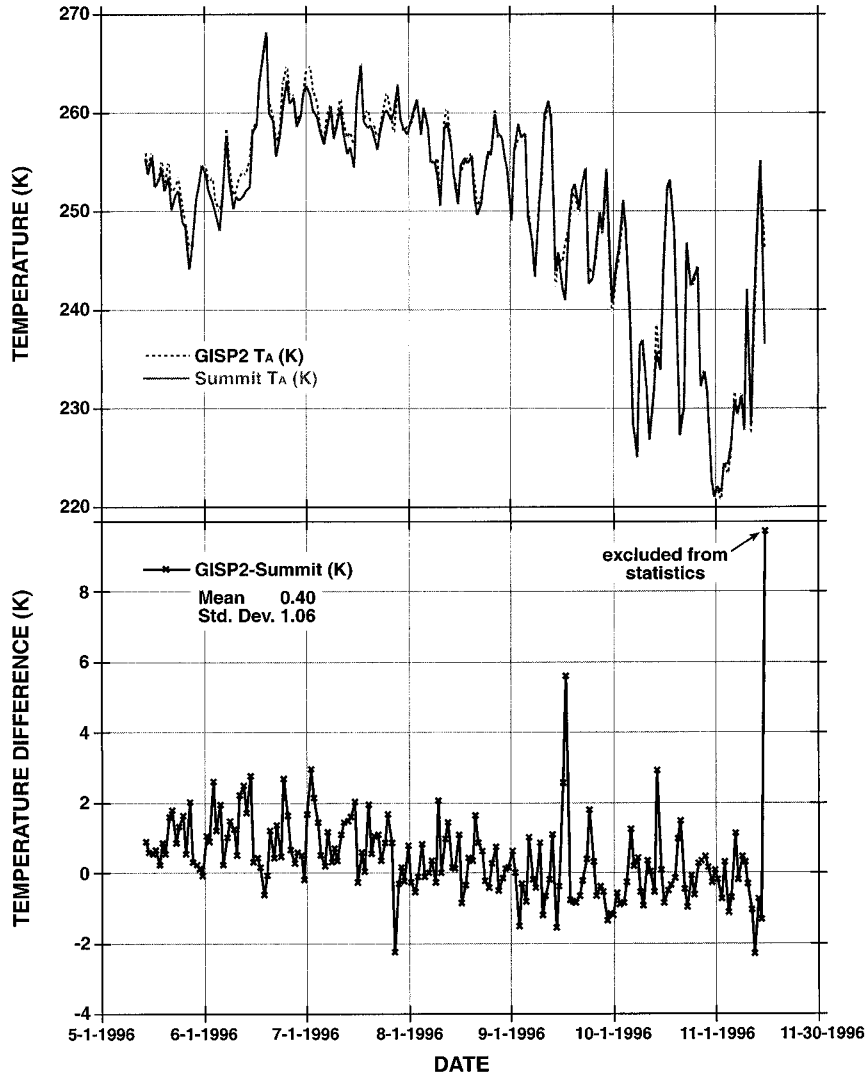

FIG. 6. Comparison of the mean daily temperature records from AWS GISP2 and AWS Summit for the period of common observation prior to the effective end of the GISP2 record in Nov of 1996. These two AWS were separated by only 1 km near the Greenland Ice Sheet summit (Table 2), so their mean difference is quite small. The difference data also indicate that, during the summer months, AWS GISP2 appears to be warmer than AWS Summit. Note the large difference on the last day of the GISP2 record prior to a quality-control determination that the AWS had become unreliable, although it continued to transmit for some time into 1997.

data. However, their impact on the climate trends discussed below is not well known.

4. Discussion

The final product of this effort is the composite daily average temperature record presented in Fig. 8. The components of the record are detailed in Table 3, along with estimates of their errors in Table 4. This air temperature record can now be used as an initial climate baseline for the Summit region of the Greenland Ice Sheet. Subsequent years of temperature records can be compared with the variability seen in this initial composite record. For simplicity, the composite record will be referred to as ''Summit,'' after the name of the current research camp and the GC-Net AWS located there.

a. Climate variability

A singe, long-term, continuously operating, accurate, and precise temperature sensor at a constant height above the ice sheet, ventilated and totally protected from insolation and other meteorological factors, would be the ideal source of data for determining a climate baseline for this site. Although this record cannot meet those standards, under the present circumstances, it is the best one available. It must be treated as an imperfect representation of reality (Table 4 and Figs. 4, 5, 6, and 7).

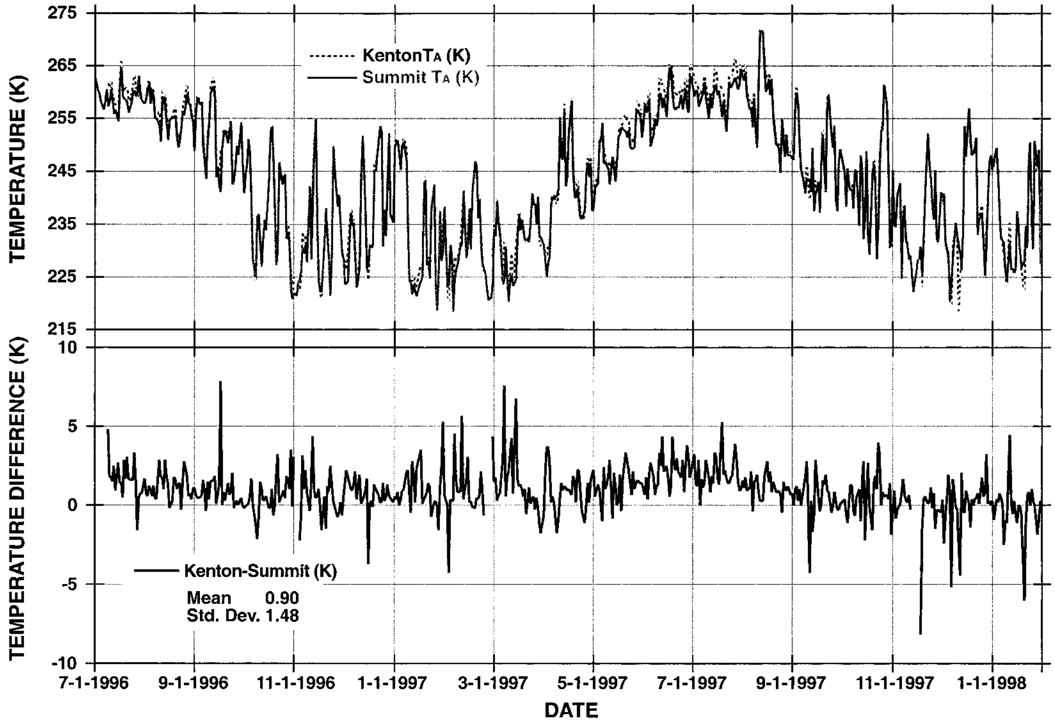

FIG. 7. Comparison of the mean daily temperature records from AWS Kenton and AWS Summit for a period of common observation prior to the end of the Kenton record in Jun of 1998. Approximately 36 km in distance and 20 m in elevation (Fig. 1 and Table 2) separated these two AWS so their mean difference is larger than for Fig. 6. These data also suggest that, during the summer months, the data from Kenton appear to be warmer than AWS Summit. Note the short period of data loss during Nov 1997 from AWS Kenton.

The overall accuracy of daily average temperature record is estimated by determining the average of the positive and negative errors presented in Table 4 for the entire record. This calculation assumes that there is no systematic offset from true temperature for all the high-frequency values that were combined to make the daily averages for AWS GISP2 or AWS Summit and that such daily averages reflect reality. To compensate for the probable insolation bias in summer (20 May to 20 August) temperatures observed at AWS GISP2, the error calculation reflects a 0.81-K offset from 1989 to 1995 unless a larger error had been determined for those days. The number that results from this calculation is quite small (0.4-K average daily error) but is sufficient to complicate the detection of projected climate warming (Barron 1995; Houghton et al. 1996).

The daily average data shown in Fig. 8 tend to emphasize the overall regularity of the annual cycle of temperature. In other words, the variability on the day-to-day scale tends to obscure the year-to-year differences. Despite this, it can be seen that there is increased temperature variability in the autumn and winter, with sizable temperature variations on the temporal scale of a few days to weeks that can almost equal the summer-to-winter temperature range. In addition, the arrival of warmer temperatures in the spring can be quite rapid (see 1990) but may also occur in a series of one or more significant "steps." The summers of 1992 and 1993 and the winters of 1992/93 and 1993/94 appear to be colder than usual, while the winter of 1995/96 is much warmer. To further illuminate the climate variations at Summit, examination of monthly and annual averages will be helpful.

The monthly and annual average data presented in Fig. 9 show several interesting temperature variations. The period from autumn 1991 to summer 1994 appears cooler than normal by about 2 K. This period is thought to show the influence of the eruption of Mt. Pinatubo on 14–15 June 1991 in the Philippines (McClelland et al. 1991) followed by a gradual warming as stratospheric dust settled out (Robock and Mao 1995; Hansen et al. 1996; Abdalati and Steffen 1997). The period of July–June for averaging was selected to try to maximize this cooling, as seen by annual average values. The surprisingly warm winter of 1995/96 (monthly values 5 to 10 K higher than average) may be associated with reduced sea ice near Greenland, but cause and effect are difficult to separate (Parkinson et al. 1999). Further examination of the mean annual data presented in Fig. 9 indicates that post-Pinatubo warming at Summit, although apparently diminishing, has a magnitude of just over 0.25° yr^{-1} (Fig. 10a) (Hansen et al. 1996; Abdalati and Steffen 1997). Plotting the data in this fashion magnifies the impact of the eruption and indicates that this area has yet to reach the higher temperatures seen before 1991. It is worth noting that the pre-Pinatubo temper-

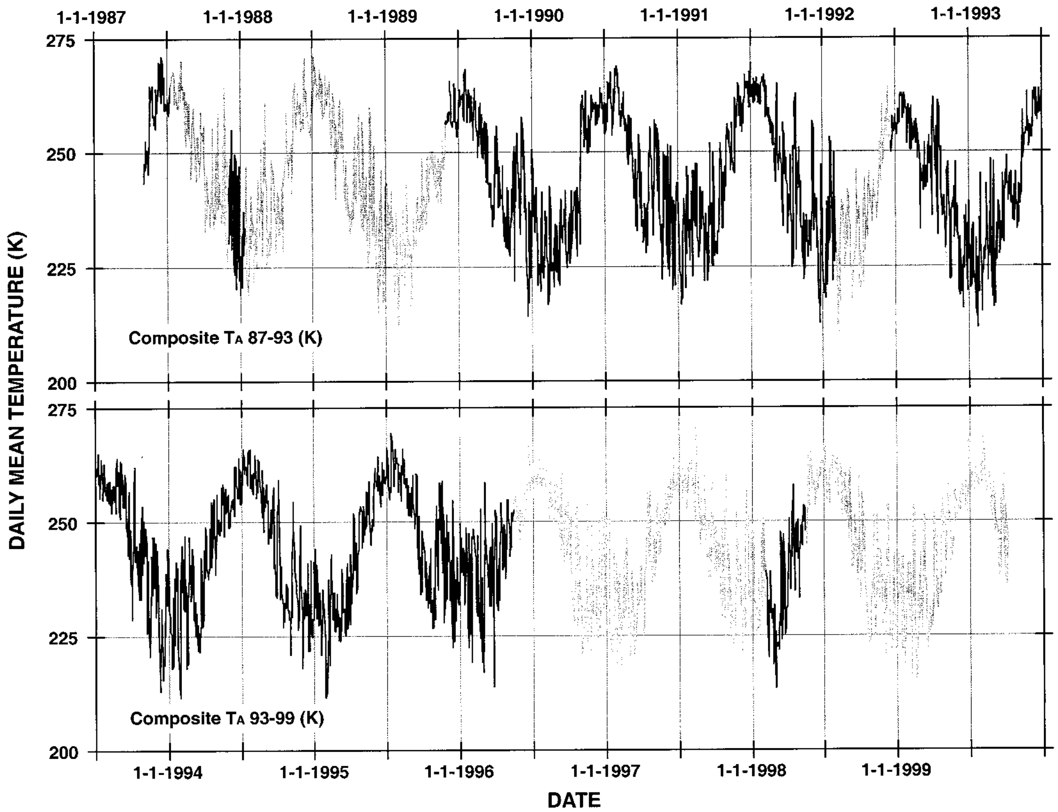

FIG. 8. The composite mean daily Summit temperature record. Shades of gray are used to indicate the different data sources for all major components of the composite record (Fig. 2 and Table 3 for details). Note the strong variations in autumn and winter temperatures that produce secondary maxima in temperature proxy data from snow and ice stable isotope profiles in this area (Shuman et al. 1998).

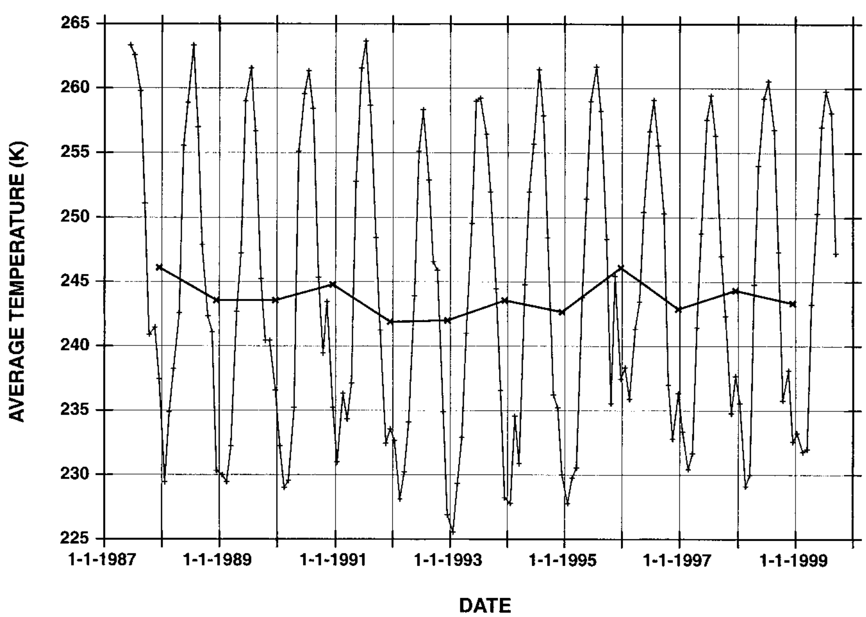

FIG. 9. Mean monthly and mean annual temperature variations for AWS Summit. Note the lower mean annual temperature for the 2 yr following the Mt. Pinatubo eruption in Jun 1991 and the subsequent rise in the years afterward. Note the impact of the warm winter period in 1995–96.

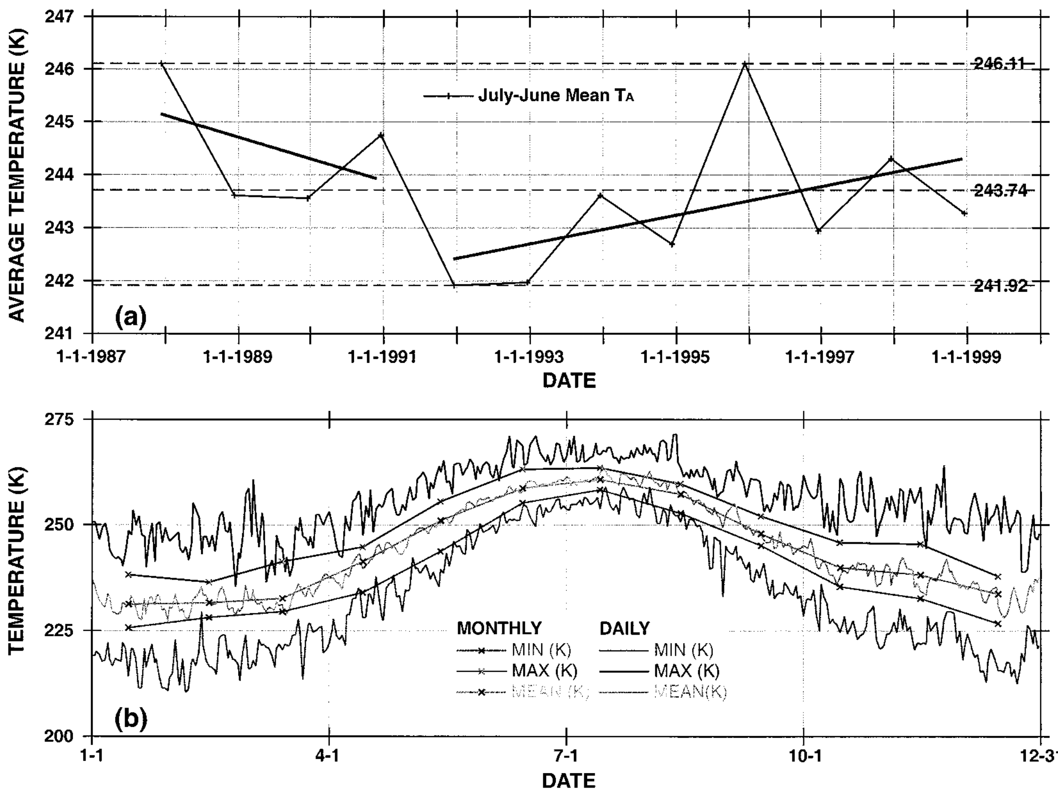

FIG. 10. Illustration of "climate baseline" data for the Summit site. (a) Mean annual temperature data, including minimum, maximum, and mean annual values. Regression lines are shown to accentuate the difference between pre- and post-Pinatubo temperatures. (b) Statistically sorted, minimum, maximum, and mean daily and monthly average temperature data over the whole 12-yr record. These limits provide a reference frame to gauge potential climate change in the future.

atures plotted here are from AWS Cathy and that the analysis of the equivalent-basis technique (Fig. 4) suggests those daily average values may be about 0.5° too cool. Of course, this conclusion is dependent on equivalent emissivity conditions between the Cathy and Kenton sites to the GISP2 site that we cannot confirm.

The relationship of the Summit temperature record to factors such as the El Niño–Southern Oscillation index (SOI) and North Atlantic oscillation (NAO) is not pursued here. The impact of these factors on regional Greenland conditions, such as melt extent and sea ice cover, are not clearly defined (Abdalati and Steffen 1997; Parkinson et al. 1999), although some association is likely. Additional years of observations may assist studies of this sort, and because continued operation of Summit as a semipermanent research station is expected, this will further document the behavior of the climate system at this site.

b. Climate baseline

In an attempt to provide a simple means of detecting potential temperature changes at this site, the daily, monthly, and annual average temperatures have been processed to yield the minimum, maximum, and mean observations for each day and month of a statistically defined year. In addition, the annual data have been examined to determine their minimum, maximum, and mean values over the period of record. Basically, the 12+-year daily record and its resulting averages have been sorted to determine the area's temperature variability. The minimum, maximum, and mean annual temperatures over the whole composite record are indicated in Fig. 10a as dashed lines. The impact of the Mt. Pinatubo eruption is emphasized in Fig. 10a by pre- and post-eruption regression lines. These lines indicate that this area is experiencing a multiyear recovery toward pre-Pinatubo temperatures. The minimum, maximum, and mean of all the daily and monthly values are plotted as a statistically sorted year in Fig. 10b. This approach should allow subsequent years of temperature record to be plotted against these data to detect whether they fall inside or outside the previously observed daily or monthly temperature ranges for the site. For simplicity, February 29 has been eliminated for all leap years. The spread in the minimum and maximum temperatures lines in Fig. 10b also indicates the tendency toward greater variability in autumn and early winter, which produces a slight asymmetry to the daily and monthly minimum, maximum, and mean temperatures.

5. Summary

This analysis details the combination of near-surface and satellite temperature information needed to develop a multiyear temperature record for the Greenland Ice Sheet summit region. The composite record comprises more than 12 years of daily average temperature history, characterizes distinctive aspects of the Summit temperature cycle at various temporal resolutions, and provides a basis for comparison with other model or isotope temperature records from this region. The record is derived from multiple segments with differing accuracy but has an average accuracy of 0.4 K day^{-1}. The equivalent-basis technique used here allows accurate integration of multiple AWS temperature records across the Greenland summit. Daily differences in temperature between adjacent (up to 36 km apart) stations are not large but may be influenced by different meteorological conditions or responses that depend on sensor configurations. Future ice sheet research sites should be supported by multiple AWS to ensure acquisition of a complete temperature record. A post-Pinatubo warming trend appears to be diminishing and has a magnitude of approximately 0.25 K yr^{-1} since 1992. This effort's resulting daily, monthly, and annual mean temperature records define a climate baseline that will help to identify potential climate change.

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