Decadal-Length Composite Inland West Antarctic Temperature Records

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ABSTRACT

Decadal-length, daily average, temperature records have been generated for four inland West Antarctic sites by combining automatic weather station (AWS) and satellite passive microwave brightness temperature records. These records are composites due to the difficulty in maintaining continuously operating AWS in Antarctica for multiyear to multidecade periods. Calibration of 37-GHz, vertical polarization, brightness temperature data during periods of known air temperature by emissivity modeling allows the resulting calibrated brightness temperatures (TC) to be inserted into data gaps with constrained errors. By the same technique, but with reduced constraints, TC data were also developed through periods before AWS unit installation or after removal.

The resulting composite records indicate that temperature change is not consistent in sign or magnitude from location to location across the West Antarctic region. Linear regression analysis shows an approximate 0.9°C increase over 19 yr at AWS Byrd (0.045 yr^{-1} $\pm$0.135°C), a 0.9°C cooling over 12 yr at AWS Lettau ($-$0.078 yr^{-1} $\pm$0.178°C), a 3°C cooling over 10 yr at AWS Lynn ($-$0.305 yr^{-1} $\pm$0.314°C), and a 2°C warming over 19 yr at AWS Siple (0.111 yr^{-1} $\pm$0.079°C). Only the Siple trend is statistically significant at the 95% confidence level however. The temperature increases at Siple and possibly Byrd are suggestive of a broader regional warming documented at sites on the Antarctic Peninsula. The cooling suggested by the shorter records in the vicinity of the Ross Ice Shelf is consistent with results recently reported by Comiso and suggests that significant regional differences exist. Continued data acquisition should enable detection of the magnitude and direction of potential longer-term changes.

1. Introduction

Increasing temperatures possibly linked to global climate warming have been detected at sites on the Antarctic Peninsula (King 1994; Vaughan and Doake 1996) and at coastal stations (Jacka and Budd 1992). In addition, remote sensing studies (Comiso 2000) have suggested warming across the Antarctica Peninsula but relative cooling elsewhere in the past two decades. Unfortunately, ''ground truth'' in the form of surface temperature data has only just begun to achieve sufficiently long records to detect trends in temperature from interior portions of the Antarctic ice sheet. Because inland bases with year-round, human-operated, meteorological instruments are decreasing in number, data are necessarily being obtained from automated equipment (see discussion in Comiso 2000). This paper uses the longest available near-surface temperature records from four United States Antarctic Program (USAP) automatic weather station (AWS) sites to document recent climate variability around the West Antarctic Ice Sheet.

The rationale for this project is simple: decadal-length, automatic weather station temperature records from inland Antarctica now have sufficient length to provide a baseline for a meteorological variable of critical importance. Establishment and maintenance of these multiparameter AWS at remote locations since 1980 (Stearns et al. 1993) is a critical project due to the possible climatic sensitivity of the West Antarctic region, its possible contribution to sea level rise, and its role in global climate (Bindschadler 1998; Bindschadler et al. 1998; IPCC 1996a,b).

Unfortunately, due to damage from extreme conditions or simple equipment malfunction, AWS observations are occasionally incomplete for significant periods of time (see, e.g., Bromwich et al. (1993), Table 2). Although temperature is typically the most reliable parameter monitored, significant data gaps can occur making statistical evaluation of temperature trends problematic especially in the interior of Antarctica (see Com-

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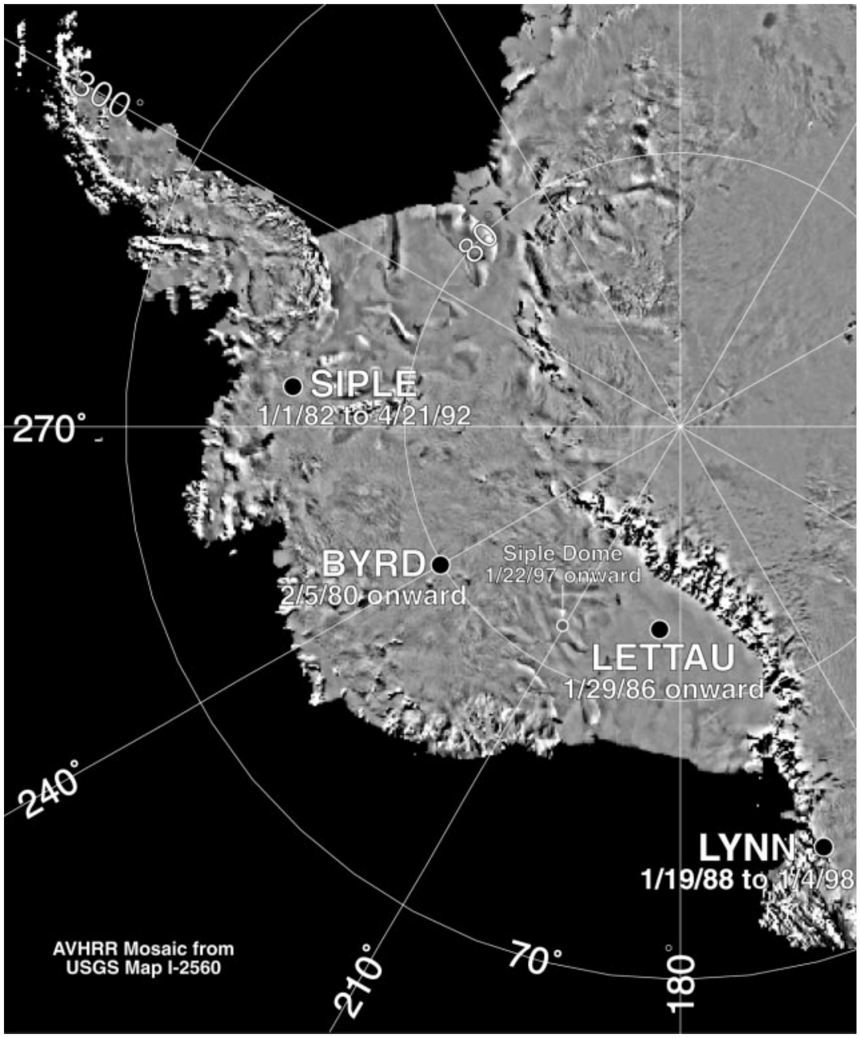


FIG. 1. Illustration of the locations and dates of operation of the four automatic weather stations whose temperature data form the basis of this analysis. To facilitate perspective on the spacing of these sites, the distances between each closest pair of sites is similar to the distance between Washington, D.C., and Atlanta, Georgia. The location of the Siple Dome record is also shown.

iso 2000). Fortunately, the impact of discontinuities in AWS site air temperature (TA) records can be minimized through the calibration of satellite passive microwave brightness temperatures (TB) to produce a calculated temperature value (TC) that can accurately complete the AWS record (Shuman et al. 1995, 1996). An additional benefit of this approach, given effectively continuous and consistent passive microwave observations of the polar regions since 1978 (Gloersen and Barath 1977; Jezek et al. 1993), is the development of multiyear data on approximate microwave emissivity from ice sheet locations.

This project used two types of temperature data that were spatially and temporally coregistered: 1) quality-controlled, 3-hourly average TA records from the University of Wisconsin's four longest running AWS closest to West Antarctica (see Fig. 1 and Table 1) and 2) daily average 37-GHz, vertical polarization (V) TB data from the Scanning Multichannel Microwave Radiometer (SMMR) and Special Sensor Microwave/Imager (SSM/I) from the National Snow and Ice Data Center (NSIDC). From these two sources of surface temperature information, continuous, daily average, composite temperature records have been produced for use by the broader community.

The annual-average temperature records derived here consist of almost 20-yr records (7008 days) from Siple and Byrd with 10- (or more) yr records at Lettau and Lynn (see Figs. 2a–d, respectively). Comiso (2000) conducted a sensitivity analysis of long-term surface temperature records in Antarctica (gaps were filled by polynomial interpolation) and suggests that 10 yr is the minimum period to develop a stable climate trend and 20-yr records are more stable. In addition to monitoring

Table 1. Site data for longest inland West Antarctic AWS temperature records.*

AWS name	Lat	Long	Elev (m)	Grid**	Start date	Stop date
Byrd	80.00°S	120.00°W	1530	121 196	5 Feb 1980	
Lettau	82.59°S	174.27°W	55	155 206	29 Jan 1986	
Lynn	74.21°S	160.39°E	1772	182 239	19 Jan 1988	4 Jan 1998
Siple	75.90°S	83.92°W	1054	97 168	1 Jan 1982	21 Apr 1992

* This analysis is based on available 3-h average data taken from the University of Wisconsin anonymous ftp server as of Mar 1999.
** The grid column contains the coordinates of the 25-km Scanning Multichannel Microwave Radiometer (SMMR) or special Sensor Microwave Imager (SSM/I) pixel covering the AWS location.

the behavior of the climate system across a broad region (see Fig. 1 and Tables 1 and 2), these records can be used to calibrate general circulation model results from ice sheet locations (Fawcett et al. 1997). In addition, they can be used to validate global climate reanalyses, such as those from the European Centre for Medium-Range Weather Forecasts or National Centers for Environmental Prediction, and to calibrate temperature proxy records from ice core stable isotope profiles from locations adjacent to AWS.

2. Statement of problem

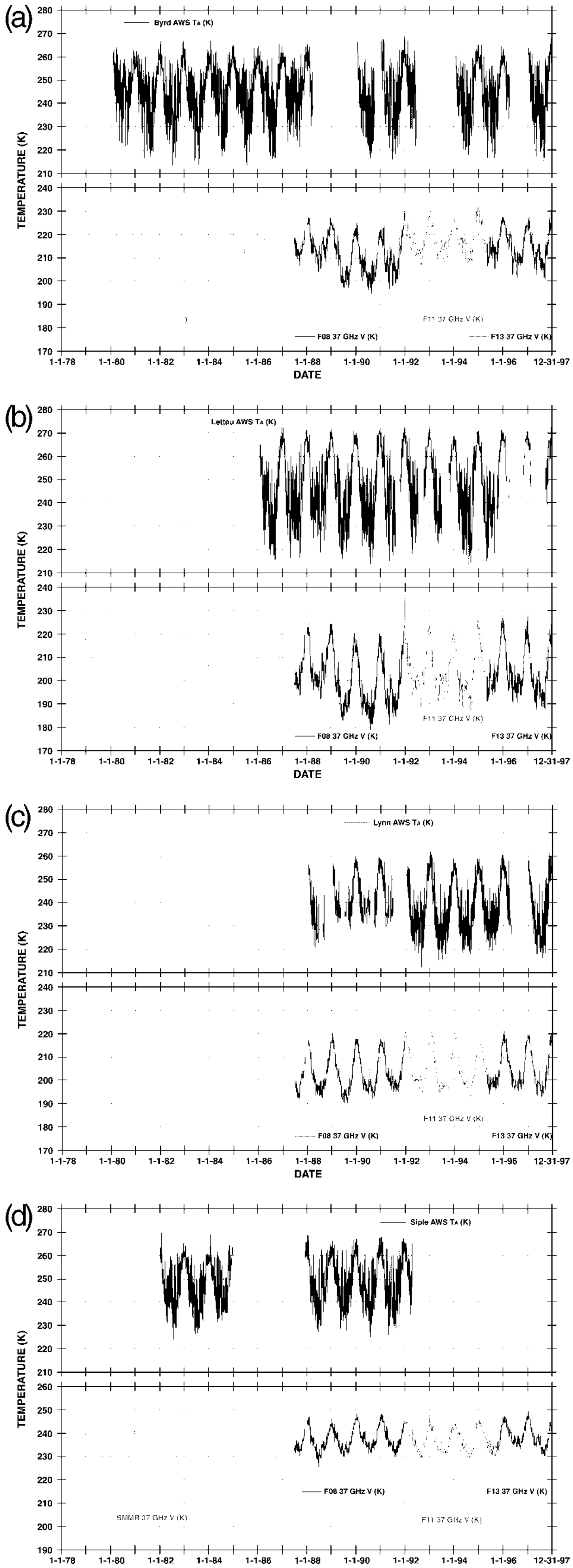
As the data in Fig. 2 illustrate, the original temperature records from Antarctic AWS are not continuous. The observed TA record is composed of multiyear segments that may be separated by temporal gaps of considerable length. It should be noted that in most cases, these installations were not meant to be permanent and even under optimal circumstances snow accumulation requires timely maintenance of these sites for consistent operation. The problem of accumulating snow changing the effective height of the AWS temperature sensor is a persistent problem at many ice sheet sites. The following statistics indicate the completeness of the USAP AWS TA records studied here (AWS Byrd—69.68% complete, AWS Lettau—80.33% complete, AWS Lynn—69.36% complete, and AWS Siple—38.13% complete). Significant data discontinuities complicate efforts to compile a continuous temperature record from inland Antarctica suitable for long-term climate monitoring. Unfortunately, it is in the polar regions that the effects of global climate variability could produce dramatic changes and thus be readily detected (IPCC 1996a,b). Developing a climate baseline for statistical change detection is the primary reason for completing these existing TA records around the potentially unstable West Antarctic Ice Sheet (Oppenheimer 1998).

Satellite passive microwave brightness temperatures are an effective surrogate temperature indicator over polar snow and can be used to define near-surface temperature trends (see Fig. 2, Shuman et al. 1995). However, the passive microwave data do not provide a pure temperature signal; it is a function of the characteristics of the snow and ice over the depth of emission. In dry snow zones, satellite brightness temperature is effectively the physical temperature of the near-surface snow multiplied by its emissivity and is described by the Rayleigh-Jeans approximation (Hall and Martinec 1985). Atmospheric effects on brightness temperature can be considered negligible due to the low temperatures and limited water vapor content found in this area (Maslanik et al. 1989). Radiative scattering from the ice grains over a skin depth of a meter or so controls emissivity for the 37-GHz channels used by the technique (Shuman et al. 1995). However, it is dominated by the top few tens of centimeters (Rott et al. 1993) or about the depth of effect of the diurnal temperature cycle (Alley et al. 1990). The emissivity of the snow and ice is controlled primarily by grain size (Chang et al. 1976; Armstrong et al. 1993), which varies over an annual period (Benson 1962). This means that TB data cannot be used directly to substitute for missing TA data but must first be calibrated to account for approximately annual variations in snow emission characteristics.

As discussed in Shuman et al. (1995), radiative transfer modeling will account for all the factors that influence the conversion of TB data into temperature estimates. However, current efforts require field observations to account for variations in snow characteristics, are necessarily data intensive, and thus are not widely applicable. In the interim, passive microwave data can be calibrated to fill AWS TA data gaps despite accuracy limitations (Shuman et al. 1995), which will be discussed further below. An additional complication is introduced by brief melt events in the vicinity of some of these West Antarctica AWS (Zwally and Fiegles 1994). Large TB increases associated with the presence of liquid water and their impact on this analysis will also be discussed later (see Fig. 3 and corresponding dates in the AWS Lettau TB record, Fig. 2b) (Abdalati and Steffen 1997).

3. Methodology

The AWS data were obtained from the 3-hourly files at the anonymous ftp site operated by the University of Wisconsin—Madison (see Table 1). These data are quality-controlled averages of 10-min AWS observations that are also available from this site. Daily average temperature values are then derived from the 3-h data for comparison to the daily average passive microwave TB (see Figs. 2a–d). Detailed information on the AWS units that are used here, including data transmission and qual-



ity control techniques, is presented in Stearns et al. (1993) and Stearns and Weidner (1993). These papers specify the resolution of the AWS temperature sensors utilized in this study as 0.125°C. For validation, Hogan et al. (1993) confirms a close correlation of AWS temperature data with traditional manned station observations at South Pole Station. Unfortunately, the long South Pole record cannot be completed by this technique as it is not covered by SMMR or SSM/I passive microwave data (see Fig. 3).

The passive microwave data used here were extracted from National Snow and Ice Data Center CD-ROMs (NSIDC 1992). Daily averaged, 37-GHz, vertical polarization (V) brightness temperatures (TB) from SMMR and SSM/I-F08, SSM/I-F11, and SSM/I-F13 for the 25 km $\times$ 25 km grid cell covering each AWS site were compiled to document the multiyear ''temperature'' trends for each site (see Figs. 2a–d). The SMMR data has been corrected for a small drift in the 37-GHz V channel (Gloersen et al. 1992). Brightness temperature data from the 37-GHz V (0.81 cm wavelength) channel begin in 1978 and continue through the present day. The TB measurement accuracy of the 37-GHz V channels on these instruments are ± 5 K for the SMMR (Gloersen 1987) and ± 2 K for the SSM/I (Hollinger et al. 1990).

The 37-GHz V TB data can be related to near-surface AWS air temperatures by a technique first described in Shuman et al. (1995). Intermittent TA and temporally equivalent TB data are used to generate an approximate emissivity time series. Because of small differences between the series of passive microwave sensors providing coverage of the polar ice (SMMR 1978–87, SSM/I-F08 1987–91, SSM/I-F11 1991–95, and SSM/I-F13 1995–currently) the approximate emissivity records are segregated by sensor time period. For each portion of this record, an annual-period sinusoid is then fit to the approximate emissivity data using the modeling program Igor®. Because the modeling approach can bridge significant data gaps, this allows definition of a modeled emissivity cycle for the entire period. The modeled emissivity cycle can then be used to convert the longer records of TB data into a calibrated near-surface air temperature (TC) with reasonable accuracy during periods with and without confirmatory AWS TA data. The use of SMMR data will introduce some uncertainty as power problems with the satellite caused observations

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FIG. 2. Illustration of the daily average AWS and multisensor satellite temperature time series information used in this study: (a) AWS Byrd, (b) AWS Lettau, (c) AWS Lynn, (d) AWS Siple. All records are presented with the same unit ranges for the *x* and *y* axes to aid comparison. Note the number of data gaps in all records, the greater temperature variation, and the TB ''spikes'' associated with melt in the austral summers of 1982–83 and 1991–92 for Lettau, as well as the generally higher TB and smaller range for Siple. The time periods covered by the four passive microwave sensors (SMMR, SSM/I F08, F11, and F13) are indicated by changes in grayscale.

TABLE 2. Distance* and elevation** offsets for inland West Antarctic AWS temperature records.

AWS pair	Byrd (km)	Byrd (m)	Lettau (km)	Lettau (m)	Lynn (km)	Lynn (m)
Lettau	935.08	1475				
Lynn	1954.69	242	1072.30	1717		
Siple	933.58	476	1877.89	999	3448.83	718

* This analysis is from the Table 1 latitude and longitude coordinates and the program Great Circle.
** This is based on data taken from the University of Wisconsin anonymous ftp server in March 1999.

to be made on alternate days for most of the record (Gloersen et al. 1992). This problem was not encountered in Shuman et al. (1995) and techniques necessary for dealing with it will be discussed later.

4. Results

The composite daily average temperature records for the four AWS are presented in Fig. 4. The missing portions of the air temperature records were generated using the temporally closest approximate emissivity data to derive modeled annual-period sinusoids. These sinusoids were then used to convert the daily values of SMMR or SSM/I TB to temporally equivalent TC values for insertion into the TA record. These TC values were generated and then compared to all periods of available TA data for exact analysis of temperature accuracy (see error analysis discussion below). In addition, for AWS Byrd, AWS Lettau, and AWS Siple, TC values were generated for significant periods prior to the presence

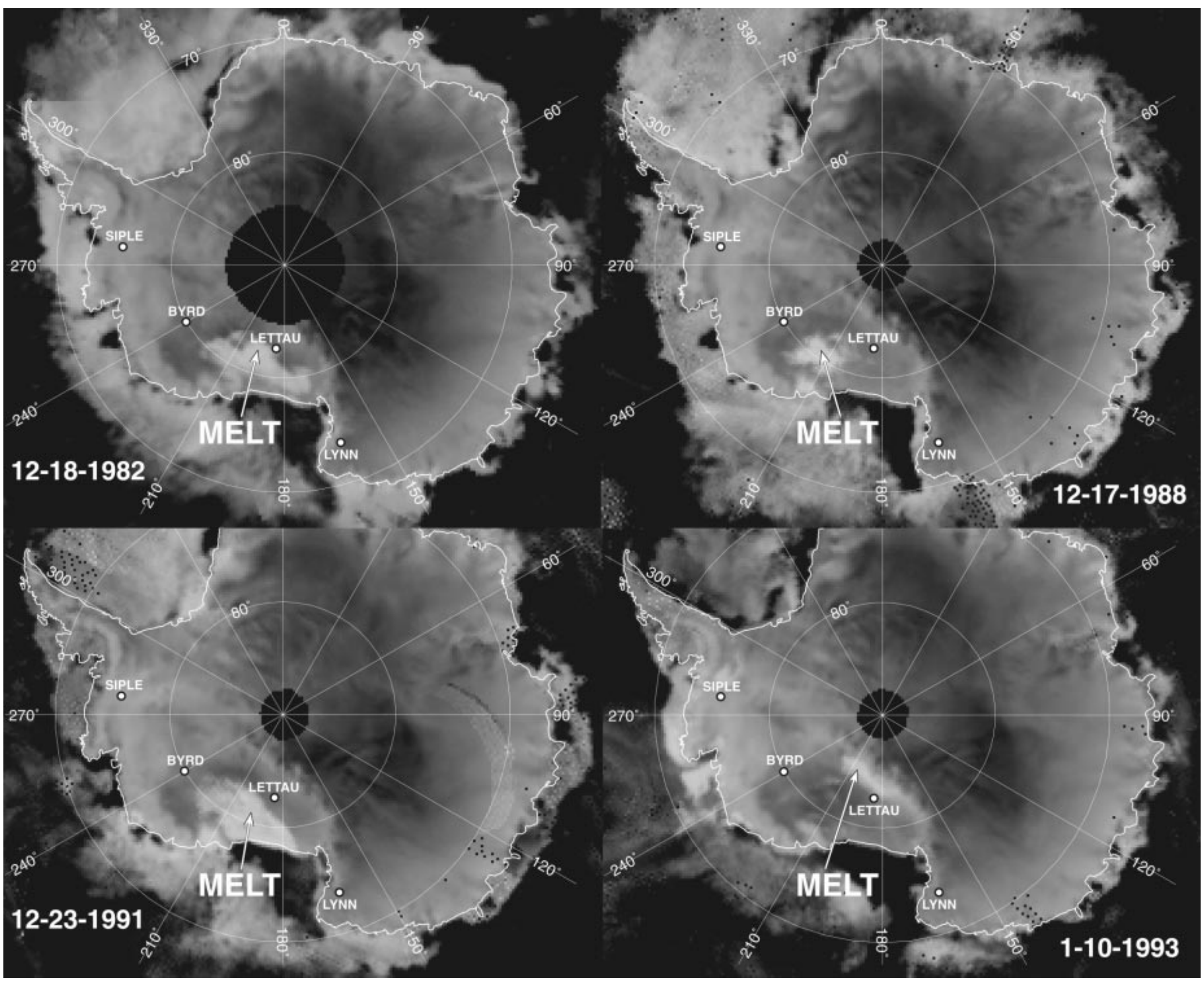

FIG. 3. Selective illustration of the spatial extent of all known significant melt events (lighter gray patches) across West Antarctica prior to the 1997–98 austral summer using single-day 37-GHz averages from the multisensor brightness temperature records used in this study. The TB ''spikes'' associated with melt in the austral summers of 1982–83, 1988–89, 1991–92, and 1993–94 are indicated by brighter gray-scale tones.

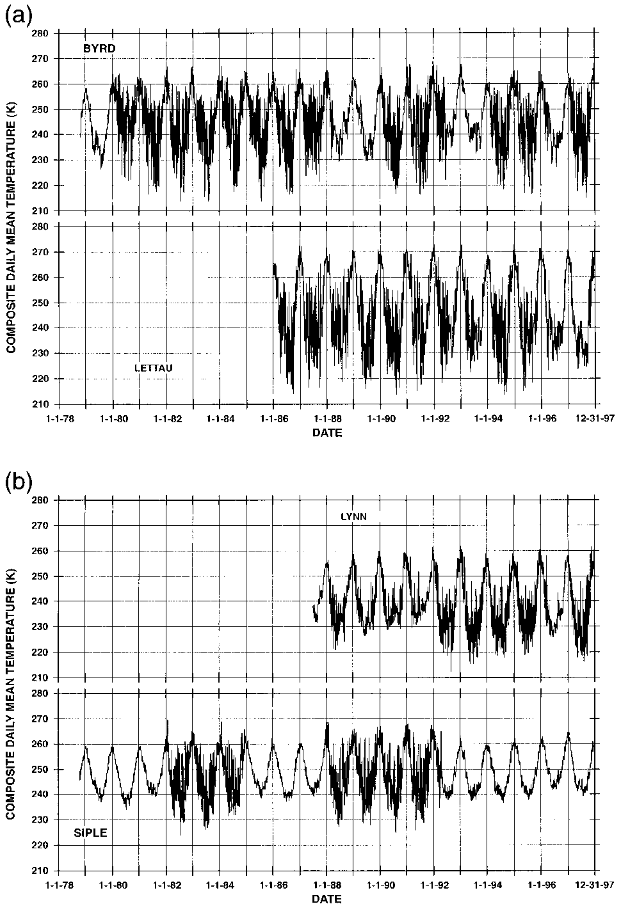

FIG. 4. The resulting composite daily average temperature trends for each site: (a) AWS Byrd and Lettau, (b) AWS Lynn and Siple. Note the reduced sensitivity in the daily TC temperatures (compare the composite records to their equivalent in Fig. 2).

of an AWS in the field through extrapolation of emissivity cycles from periods of synchronous TA and TB data. This was done for only a few months at AWS Lynn to the beginning of the SSM/I data period, as there was no overlap of TA data with SMMR TB data at this site. The evident stability in TB (see Fig. 2d) and thereby approximate emissivity at Siple allows for extrapolation and generation of TC values following final removal of that AWS in 1992.

The temperature records presented in Fig. 4 (4a for the Byrd and Lettau AWS sites and 4b for the Lynn and Siple AWS sites) show the complete composite air temperature histories of these AWS. The reduced temporal variability of the TC data that were inserted into the record is visible by inspection or comparison to Fig. 2. The most notable feature of these records collectively is the significantly increased temperature variability of the austral winters compared to the summers. The presence of inflection points or significant secondary increases or decreases in temperature in the daily record is more clearly illustrated by the mean monthly records presented in Fig. 5. These ''steps'' in the temperature history of these sites can be correlated with appropriately detailed stable isotope ''proxy'' temperatures from snow pits and firn cores (see Shuman et al. 1998). Each mean annual trend is also plotted here for relative comparison to the monthly average data.

The mean annual trend data are considered useful for climate change detection and are the most immediate and significant result from this project (see Fig. 6; Shuman et al. 1996). Details of the reliability of these data will be discussed below. From inspection of Fig. 6, it is clear that the four AWS have different magnitudes and signs of temperature trend. Specifically, the data show an approximate 0.86°C increase over 19 yr at Byrd, a 0.94°C cooling over 12 yr at Lettau, a 3.05°C cooling over 10 yr at Lynn, and a 2.11°C warming over 19 annual years at Siple. The year-by-year change in temperature is indicated by the slope values given from the regression line equations. Although the meteorologic boundaries are not defined, it is likely that each site represents a larger region that is strongly influenced by elevation (Comiso 2000).

Understanding the cause or causes of such regional differences is of interest. Breaking the annual data into seasonal components (see Fig. 7) may enable identification of causal links to changes such as an observed increase in sea ice extent over the recent past (Cavalieri et al. 1997). Subsetting the data this way indicates that the warming at Byrd has been occurring in the spring, summer, and winter with relative cooling in the fall. The Lettau seasonal components indicate slight warming in spring and summer temperatures with slightly greater cooling in fall and winter. The Lynn data suggest no change in the summer temperatures but cooling in the other seasons with a maximum cooling trend in the winter, which appears compatible with a longer sea ice season in this area reported in Cavalieri et al. (1997). The data from Siple document warming in all seasons and this result is compatible with station observations from the Antarctic Peninsula and Comiso's (2000) results. These data suggest that West Antarctica's recent climate history is not uniform and that there is detectable variability across this large region. However, statistics are necessary to assess if these changes can be confidently distinguished from no change.

Analysis of the annual average data and each linear regression line fit to the data enables this evaluation (see Fig. 6 and Table 3). The statistics suggest that the observed changes are not different from no change (zero regression slope) at three of the four sites. This finding is similar to the regression statistics reported in Comiso (2000) for the past two decades. Although the largest temperature change is at AWS Lynn, only the increase in temperature at AWS Siple is significant at the 95% confidence level. That is, only the temperature change at Siple is very likely to be different than no change. This statistical result suggests that the temperature in-

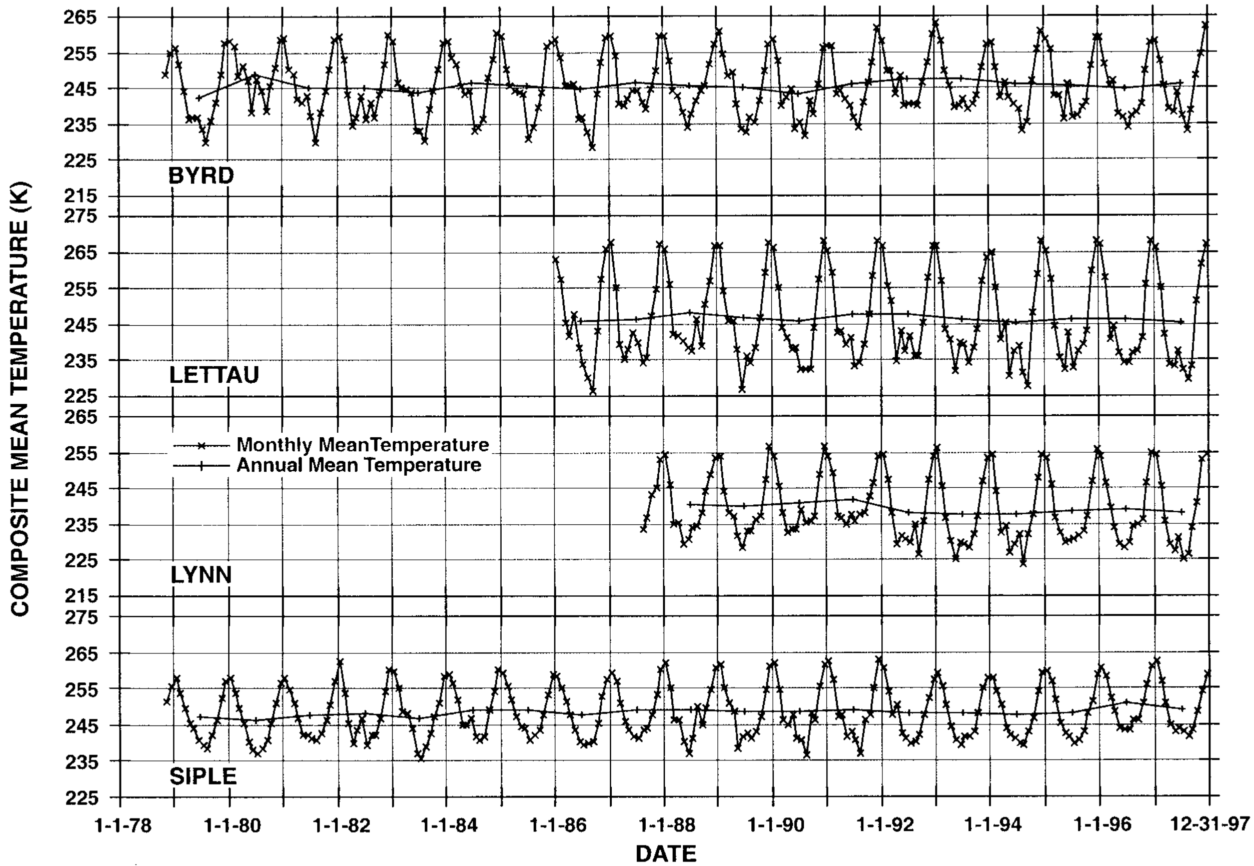

FIG. 5. The resulting monthly and annual-average temperature trends for the four AWS sites. A sense of the trend for the periods covered is suggested by examination of the annual data. All records are presented with the same unit ranges for the *x* and *y* axes to aid comparison.

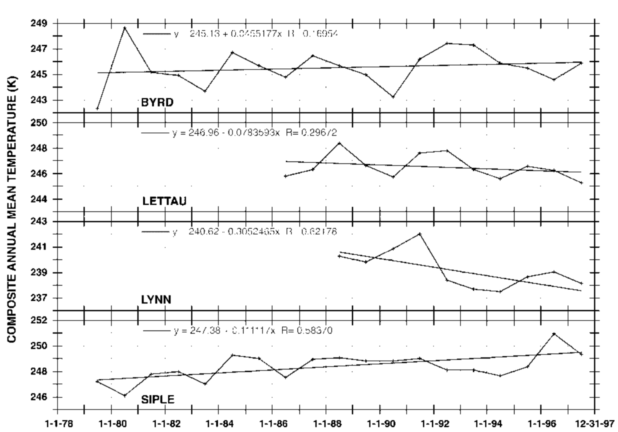

FIG. 6. A detailed presentation of the annual-average trend data including linear regression lines is presented here. The magnitude of the temperature change over the time period as well as the interannual variability is suggested by inspection of these plots. Note some similarity in peaks and troughs in these composite annual average records. All records are presented with the same unit ranges for the *x* and *y* axes to aid comparison.

creases detected along the Antarctic Peninsula may be reaching further inland.

However, caution must be exercised in extending this result inland to AWS Byrd. This site's positive slope is dependent on the first annual value (cooler, see Fig. 6), which is derived solely from extrapolated TC values. Without that point, the Byrd trend would be slightly negative making it more compatible with the trends at Lettau and Lynn and in opposition to Siple. This is in close agreement with the results reported by Comiso (2000), who reports an overall tendency toward cooling across Antarctica over 1979–98 period but with warming along the Antarctic Peninsula (see Comiso 2000, Fig. 2). It must be noted here that the Siple record is the most heavily dependent on extrapolated TC data. In any event, replacement of the AWS units at both Siple and Lynn would allow continuation of the composite record into the future giving longer records that could better detect small but significant trends. This would also improve definition of climate baselines for these specific sites around West Antarctica.

5. Error analysis and discussion

As a test and illustration of this technique's relative accuracy for estimating daily average temperatures, it

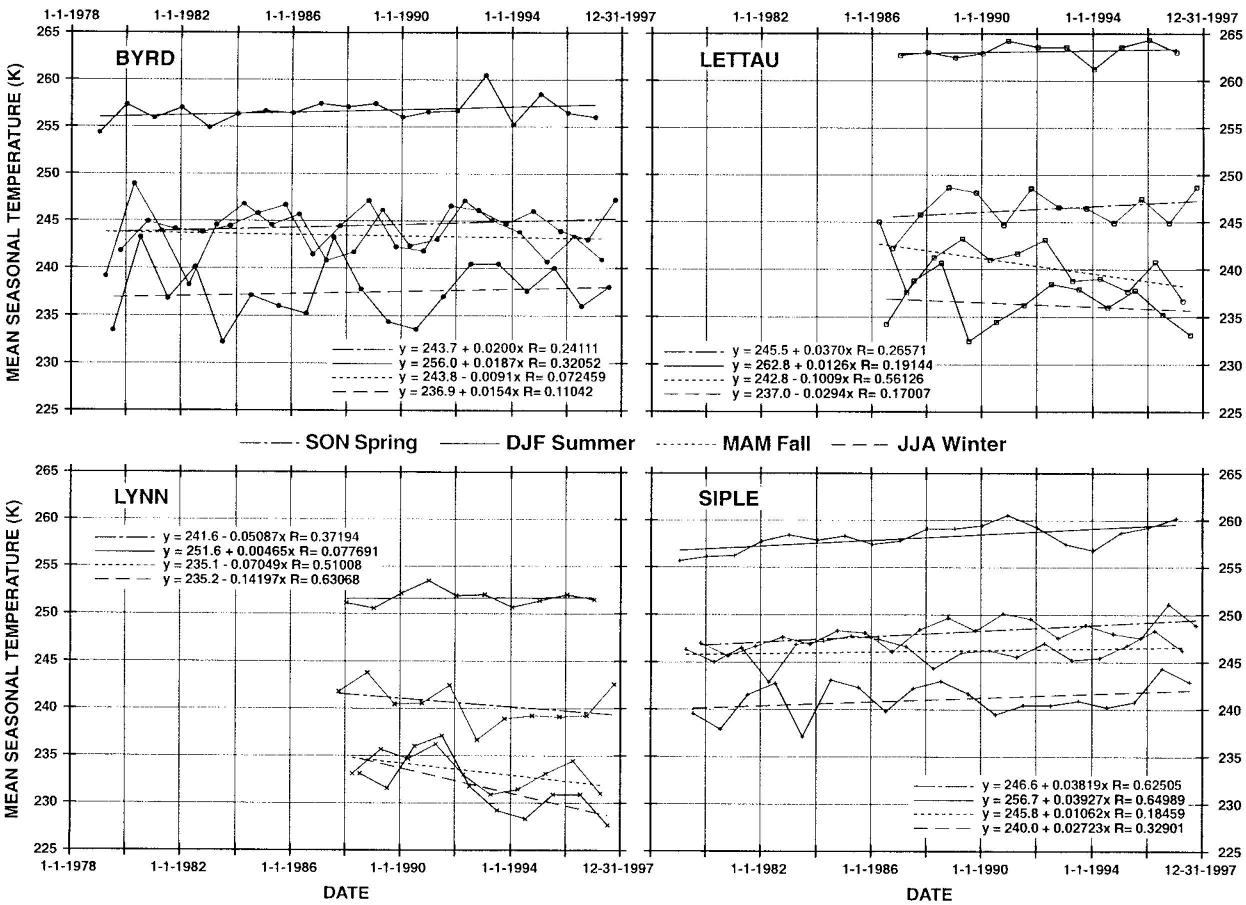

FIG. 7. The annual temperature trends from Fig. 6 are presented as seasonal average trends to determine what parts of the year are controlling the annual trends. The seasonal variability and trend of temperature over each record is suggested by inspection of these plots. Note the increased variability of temperature during the nonsummer periods. All records are presented with the same unit ranges for the *x* and *y* axes to aid comparison.

was applied to a new AWS installation at Siple Dome (see Fig. 1). Using just over 1 yr of TA data and the approximate emissivity technique, a multiyear TC temperature record was ''hindcast'' for this site in support of the ice core drilling operation being conducted at the site. Because of the relatively short period of TA record available for use, the approximate emissivity cycle data from AWS Lettau and Byrd were also used to mathematically guide the emissivity cycle used to calibrate the 37-GHz V TB data covering Siple Dome. Comparison of the resulting TC data to AWS TA data as well as to shorter periods of TA data when Siple Dome was just a small field camp reveals that the TC data is at least as accurate as reported in Shuman et al. (1995). In all cases, the daily average TC values had a mean difference of less than 1.5 K (see Fig. 8). It should be noted that the camp temperatures were not used to calibrate the TB data and thus provide an excellent inde-

TABLE 3. Regression statistics for annual mean temperatures.*

Statistic	Byrd	Lettau	Lynn	Siple
N	19	12	10	19
Mean	245.54	246.53	239.24	248.34
Std dev	1.5108	0.9522	1.4863	1.0712
R	0.16954	0.29672	0.62178	0.58371
Slope ($^\circ$ yr^{-1})	0.045518	−0.078359	−0.305246	0.111117
Std error slope	0.064172	0.079750	0.135937	0.037488
t slope	0.70930	−0.98255	−2.24550	2.96403
Slope 95% confidence interval	±0.135	±0.178	±0.314	±0.079

* Statistics courtesy of R. B. Alley, The Pennsylvania State University.

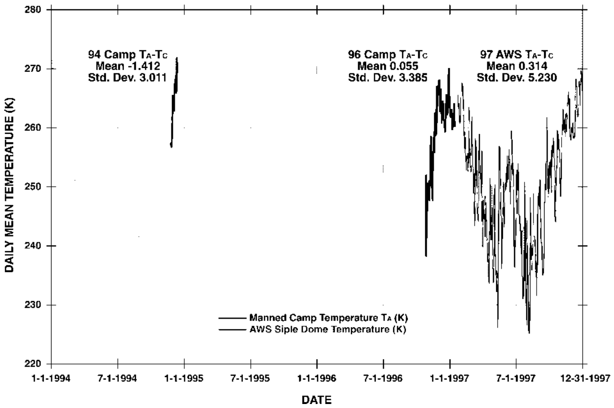

FIG. 8. The TC temperature cycle at Siple Dome (see Fig. 1 for location) created by emissivity modeling. From AWS TA (22 Jan 1997–31 Mar 1998) and SSM/I 37-GHz V TB data, guided by the emissivity cycle data generated at Lettau and Byrd, were used to create this record. Two separate periods of observed Siple Dome field camp daily average TA were available to validate the TC record and they provide an independent check on the technique's accuracy. The statistics included in the figure suggest the error range for the extrapolated daily average TC values.

pendent assessment of temperature record accuracy. This data also illustrates the difficulties of assessing temperature histories from intermittent observations that may or may not be as well calibrated as an AWS.

To further assess the TC technique used to complete the composite records, all days for the four sites that have both TA and TC values were simply compared. This approach was also applied to those annual periods where both types of temperature data were available for more than 340 days. In any case, only the same exact periods were compared. This accuracy analysis is critical as the paper's major conclusions are drawn from the daily and annual-average data. Despite the variability indicated by these comparisons, it must be kept in mind that these composite records are approximately 70% or greater actual observed air temperatures, except for Siple, and the synthesized values are used only when there is no ground truth available.

The first comparison, between daily TA and TC values, is presented in Fig. 9 and Table 4. This series of plots shows that the vast majority of TC values are within the ± 10 K range from the corresponding daily TA value. Differences between the SMMR and SSM/I sensor's accuracy (± 5 K and ± 2 K, respectively) may be responsible for larger TA $-$ TC differences derived from the former sensor's coverage periods. The slightly larger standard deviations ($\sim$9%) in the TA $-$ TC difference for the SMMR record may also be attributed to the interpolation of the every-other-day SMMR record (Gloersen et al. 1992), which would tend to increase error values slightly. Overall, the standard deviations of the differences between daily TA and TC values are substantially less than 10 K; this is especially true for the record from AWS Lynn that had no SMMR overlap.

The curvatures of the scatter fields in these plots, especially for Byrd and Lettau, indicate a tendency for the TC values to be too low in the spring and fall and to be too high in the summer and winter (see Fig. 9). This is due to the technique's known tendency to slightly underestimate the approximate emissivity in winter and summer and slightly overestimate it in spring and fall (see Shuman et al. 1995, Fig. 8). Although higher-order components could be added to the sinusoid model, we have not done so here to avoid decreasing the general applicability of the technique. Interestingly, this problem does not appear to be such an issue at AWS Lynn as evidenced by little curvature to the scatter field suggesting the sinusoid model of annual emissivity variation is a close fit to reality. This problem also does not appear to influence summer temperatures at Siple significantly (see Fig. 9). Further improvements in radiative transfer modeling may explain the differences between these sites.

The impact of melt events on the AWS Lettau record (see Fig. 3 for a major melt event in late 1991) can be identified by the number of TC values above 273 K and their clear departure from the midline (zero difference) at the upper right side of the plot. This is due to the significant increase in TB due to the presence of small amounts of liquid water in the snowpack even on days where the mean air temperature can be below freezing (Zwally and Fiegles 1994). In general however, the TC values that are actually inserted into the AWS Lettau composite record appear to closely correspond to observed temperatures, as this site has no significant summer data gaps. See Shuman et al. (1995) for further discussions of the accuracy and limitations of this technique.

The utility of the technique is further supported by the comparison of annual average temperatures illustrated in Fig. 10 and in Table 5. Only years where more than 340 days of TA data were available to compare directly to the equivalent TC data were used to generate this plot. The general placement of the data points on the plot also indicates the relative temperature differences from location to location (see Fig. 1 and Table 3). The Lynn TA and TC data are very similar and are the coldest values; this may be due to the elevation of this site (see Table 1). The fact that all the annual average differences for the four AWS fall within approximately $\pm 2°$ of the plot midline indicates that the TC values that are directly calibrated with the available TA data do accurately reflect ground truth temperatures.

The standard deviations of these differences (see Figs. 9 and 10 and Tables 4 and 5) also suggest the error range appropriate to assign to daily and annual periods without confirmatory TA data. For periods when only extrapolated approximate emissivity curves are available to convert TB to TC, it should be assumed that daily and annual differences between TA and TC would be somewhat larger than the listed standard deviations. Where TA data gaps are relatively short and fall entirely within a single passive microwave sensor's period of

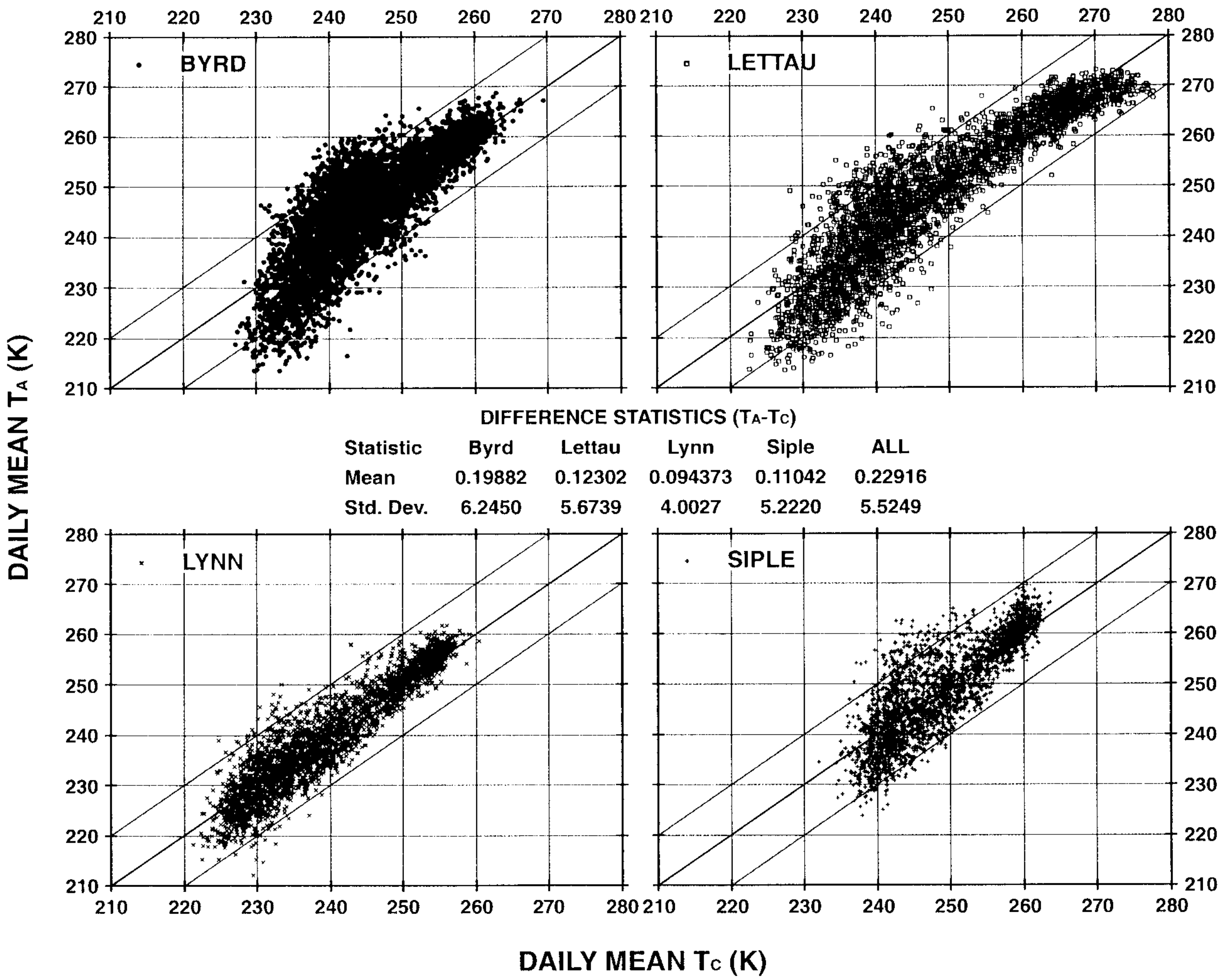

FIG. 9. Graphical presentation of the relationship between TA and TC values for all days with both an observed and calculated daily mean temperature for all four stations. The parallel lines adjacent to the central diagonal line indicate an error range of ±10 K. Note the "tail" at the upper end of the Lettau plot where increases in TC are the result of melt influencing the TB data. Also note the curvature in the data, especially for Byrd, which indicates that an emissivity sinusoid imperfectly calibrates the TB data (see Shuman et al. 1995).

coverage, the typical daily temperature error is expected to be similar to the overall TA − TC difference documented in Fig. 9 and Table 4. Slightly larger errors are expected on a daily basis for periods where the emissivity sinusoid is extrapolated forward or backward more than 1 yr (see Shuman et al. 1995, 1998). The data presented in Fig. 8 for Siple Dome suggest that errors due to emissivity cycle extrapolation are not necessarily severe. Hopefully, this is the case at AWS Siple where just over 7 yr of TA data have enabled calibration of more than 19 yr of TB data. Although caution is appropriate, the apparently stable 37-GHz V TB record observed at Siple enables confident use of the annual average TC values from this site. The relatively high accumulation rate in this area (Cullather et al. 1998) and the absence of melt events in the area (see Fig. 3) help account for this area's relatively consistent microwave emission (see Fig. 2d).

TABLE 4. Difference statistics (TA − TC)* for daily mean temperatures.

Statistic	Byrd	Lettau	Lynn	Siple	ALL
Mean	0.19882	0.12302	0.094373	0.11042	0.14198
Std dev	6.2450	5.6739	4.0027	5.2220	5.5249

* This analysis is based on all days where there was both a (TA) and a (TC).

There are also limited periods of missing daily data from the various passive microwave sensors. For example, the SSM/I F08 sensor experienced sensor degradation due to overheating, which necessitated a short hiatus in data acquisition during December 1987 into January 1988 (NSIDC 1992). Short periods of missing passive microwave data that were needed in order to complete the composite temperature records were interpolated or modeled from temporally adjacent SMMR

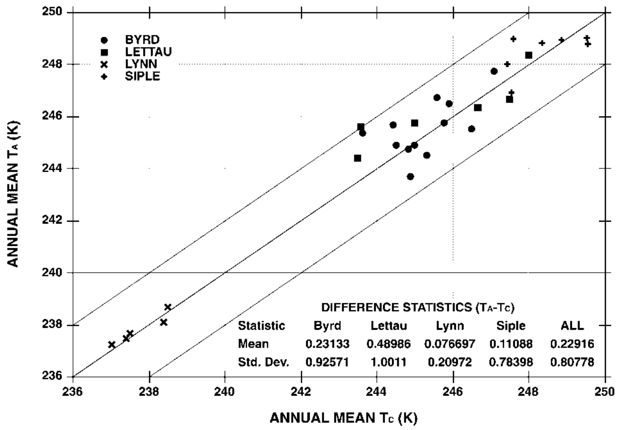

Fig. 10. Graphical presentation of the relationship between observed and calculated annual mean temperature for all four stations for all years with more than 340 days with both an observed and calculated daily average temperature (>93% of the year). The parallel lines adjacent to the central diagonal line indicate an error range of ±2 K. Note the low temperatures and relatively close association of TA and TC for AWS Lynn, the relatively higher annual temperatures for AWS Siple, and the broader range of values for AWS Lettau.

or SSM/I TB data. This was necessary during most of the SMMR alternate day record (as noted above), which reduces the day-by-day accuracy of these portions of the composite records. This should not impact the longer-term averages as no systematic bias is introduced. Overlapping data from the sequence of passive microwave sensors was also not an issue; the newer sensor was adopted as the source of the TB data in each case.

6. Conclusions

The temperature data being derived from AWS sites in Antarctica constitute measurements of critical climate variables from an area of significant global concern. Unfortunately, these records do not assess by themselves why the climate may be changing. The timing and magnitude of the temperature variability indicated here may assist identification of the causes of climate change and it is hoped that these composite records will be beneficial to further studies. The annual variability in these records and statistical strength of trends derived from them (0.9°C increase over 19 yr at AWS Byrd, a 0.9°C cooling over 12 yr at AWS Lettau, a 3°C cooling over 10 yr at AWS Lynn, and a 2°C warming over 19 yr at AWS Siple with only the Siple trend being statistically significant at the 95% confidence level) demonstrates the need for additional temperature data to ensure confident interpretation of temperature trends.

These temperature data provide a climate baseline that may be of value to climate modeling studies, assist calibration of proxy temperatures from ice cores, and confirm remote sensing estimates of temperature. However, significant data gaps through malfunction or damage reduce our ability to use individual AWS sites. This complicates long-term, statistical analysis of AWS data

Table 5. Difference statistics (TA − TC)* for annual mean temperatures.

Statistic	Byrd	Lettau	Lynn	Siple	ALL
Mean	0.23133	0.48986	0.076697	0.11088	0.22916
Std dev	0.92571	1.0011	0.20972	0.78398	0.80778

* This analysis is based on records where there was both a TA and a TC for more than 340 days of each calendar year.

at a time when discerning sign and magnitude of climate change is an increasing concern. Recognition of regional differences is especially critical if we are to distinguish cause from effect and identify the forcing functions of global change in the past, present, and future.

While the methods utilized in this study provide one means of completing temperature records, the approach has limitations that cause statistically documented errors. Further work is needed to ensure the most accurate methods and data are utilized. Despite this need for caution, if further studies also suggest that the multidecadal warming trend documented at AWS Siple is extending inland from the Antarctic Peninsula across the potentially unstable western portion of the Antarctic ice sheet, then we must discover the reasons and understand the consequences.

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