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Recent variability and trends of Antarctic near-surface temperature

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Received 24 June 2007; revised 21 September 2007; accepted 16 November 2007; published 22 February 2008.

[1] A new monthly $1^\circ \times 1^\circ$ Antarctic near-surface temperature reconstruction for 1960–2005 is presented. The use of numerical model fields to establish spatial relationships between fifteen continuous observational temperature records and the voids to which they are interpolated inherently accounts for the effects of the atmospheric circulation and topography on temperature variability. Employing a fixed observation network ensures that the reconstruction uncertainty remains constant in time. Comparison with independent observations indicates that the reconstruction and two other gridded observational temperature records are useful for evaluating regional near-surface temperature variability and trends throughout Antarctica. The reconstruction has especially good skill at reproducing temperature trends during the warmest months when melt contributes to ice sheet mass loss. The spatial variability of monthly near-surface temperature trends is strongly dependent on the season and time period analyzed. Statistically insignificant ($p > 0.05$) positive trends occur over most regions and months during 1960–2005. By contrast, 1970–2005 trends are weakly negative overall, consistent with positive trends in the Southern Hemisphere Annular Mode (SAM) during summer and autumn. Subtle near-surface temperature increases during winter from 1970 to 2000 are consistent with tropospheric warming from radiosonde records and a lack of winter SAM trends. Widespread but statistically insignificant ($p > 0.05$) warming over Antarctica from 1992 to 2005 coincides with a leveling off of upward SAM trends during summer and autumn since the mid-1990s. Weakly significant annual trends ($p < 0.10$) of about +1 K decade^{-1} are found at three stations in interior and coastal East Antarctica since 1992. The subtle shift toward warming during the past 15 years raises the question of whether the recent trends are linked more closely to anthropogenic influences or multidecadal variability.

Citation: Monaghan, A. J., D. H. Bromwich, W. Chapman, and J. C. Comiso (2008), Recent variability and trends of Antarctic near-surface temperature, *J. Geophys. Res.*, *113*, D04105, doi:10.1029/2007JD009094.

1. Introduction

[2] Inhomogeneous climate changes have been observed in the Antarctic since continuous monitoring began with the International Geophysical Year (IGY) in 1957. *Turner et al.* [2005] examine station temperature records for the past 50 years and report statistically insignificant temperature fluctuations over continental Antarctica excluding the Antarctic Peninsula, with the exception of Amundsen-Scott South Pole Station, which cooled by −0.17 K decade^{-1} for 1958–2000 ($p < 0.10$). *Turner et al.* [2005] find major warming over most of the Antarctic Peninsula, including a trend of +0.5 K decade^{-1} at Faraday/Vernadsky station for 1951–2000 ($p < 0.05$), compared to a global trend of +0.2 K decade^{-1} for 1975–2004 (during which global temperatures increased more rapidly than any other period in the 20th century; [*Hansen et al.*, 2006]). However, *Turner et al.* [2005] report that the more recent data (1971–2000) have smaller warming (greater cooling) trends than the longer record (1961–2000) at all but 2 coastal stations. The finding of increasingly negative trends in the most recent decades is corroborated by *Chapman and Walsh* [2007]; they perform a gridded objective analysis of Antarctic near-surface temperatures and note that prior to 1965 the continent-wide annual trends (through 2002) are slightly positive, but after 1965 they are mainly negative (despite warming over the Antarctic Peninsula). Likewise, *Kwok and Comiso* [2002a] find a statistically insignificant cooling trend over continental Antarctica from 1982 to 1998, inferred from skin temperatures from Advanced Very High Resolution Radiometer (AVHRR) instruments on polar orbiting satellites. *Schneider et al.* [2006] reconstruct Antarctic temperatures from ice core stable isotope records and find that despite large annual and decadal variability, a

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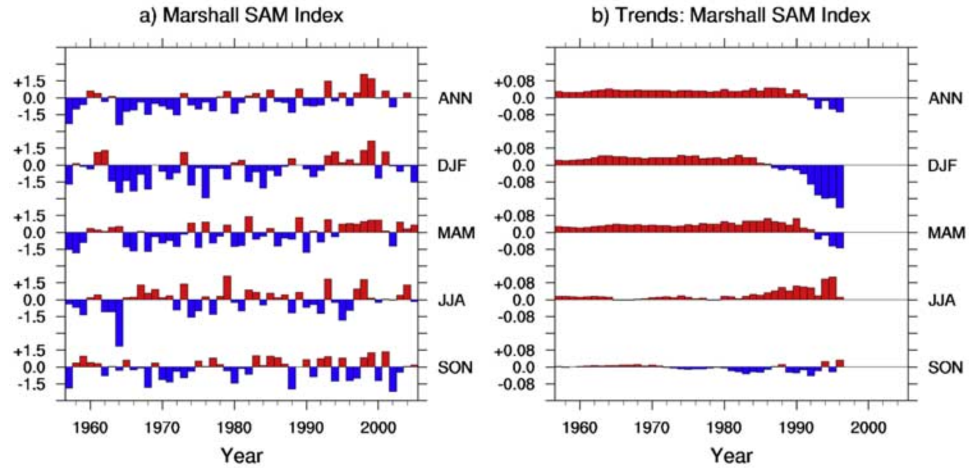

Figure 1. (a) Annual and seasonal time series of the *Marshall* [2003] station surface pressure-based SAM index. The values are standardized with respect to the 1980–1999 period. (b) Annual and seasonal ''running'' trends of the standardized SAM indices presented in Figure 1a. The trends are calculated from the corresponding year on the *x* axis through 2005. For example, the value at 1970 represents the SAM trend from 1970 to 2005, while the value at 1980 represents the SAM trend from 1980 to 2005. Trends are not calculated after 1996 because the period is too short (<10 years).

slight warming of about 0.2 K century^{-1} has occurred since $\sim$1880 which appears to be weakly in phase with the rest of the Southern Hemisphere.

[3] The ''warm-Peninsula-cold-continent'' temperature trend pattern that emerges in most Antarctic temperature evaluations has been attributed mainly to a positive trend in the leading mode of Southern Hemisphere climate variability, the Southern Hemisphere Annular Mode (SAM) [*Rogers and van Loon*, 1982; *Thompson and Wallace*, 2000; *Marshall*, 2003, 2007; *Schneider et al.*, 2006; *Gillet et al.*, 2006]. The SAM causes this pattern by altering the strength and direction of geostrophic flow around the continent, bringing enhanced northwesterly winds and associated warming in the Peninsula region, and acting to weaken turbulent sensible heat exchanges near the surface over much of continental Antarctica, with associated cooling [*van den Broeke and van Lipzig*, 2003, 2004]. The SAM has steadily increased annually since the 1960s [*Marshall*, 2003], although it has leveled off since approximately the mid-1990s (Figure 1). The cause of the increase in the SAM is still not entirely clear, although recent modeling studies suggest it may be linked to anthropogenic changes due to greenhouse gas increases and decreasing stratospheric ozone over Antarctica [e.g., *Thompson and Solomon*, 2002; *Shindell and Schmidt*, 2004; *Arblaster and Meehl*, 2006; *Cai and Cowan*, 2007]. The seasons for which the positive SAM trends have been strongest are summer and autumn, and accordingly these are the seasons in which the temperature trends at many continental stations have been most strongly negative in recent decades. Over the Peninsula, the seasonal temperature changes are complicated. The strongest warming trends are in winter on the western side of the Peninsula, a season for which the SAM has not changed much over the past several decades, but there has been a regional reduction of sea ice extent [*Jacobs and Comiso*, 1997; *Kwok and Comiso*, 2002b; *Zwally et al.*, 2002] and length of sea ice season [*Parkinson*, 2002]. Along the northeastern tip, the warming trends have the greatest statistical significance in summer, which *Marshall et al.* [2006] attribute to changes in the SAM that increase the frequency of air masses that are advected over the Peninsula orography. The SAM has an important influence on observed Antarctic near-surface temperature variability, but other factors also play key roles, such as regional ocean circulation variability and air-sea-ice feedbacks [*Vaughan et al.*, 2003], and the El Niño-Southern Oscillation [*Kwok and Comiso*, 2002a; *Bromwich et al.*, 2004].

[4] In summary, despite a strong global warming trend [*Hansen et al.*, 2006], recent literature suggests there has been little overall change in Antarctic near-surface temperature during the past 5 decades, notwithstanding some important seasonally dependent regional changes [e.g., *Turner et al.*, 2005]. The absence of widespread Antarctic temperature increases is consistent with studies showing little overall change in other Antarctic climate indicators during the past 50 years such as sea ice area [*Fichefet et al.*, 2003] and snowfall [*Monaghan et al.*, 2006a]. However, because of the sparse network of continuous, long-term near-surface temperature records (about 15 stations on a continent 1 1/2 times as large as the United States), there is still considerable uncertainty as to (1) the spatial and temporal variability of Antarctic near-surface temperature trends and (2) whether the existing network of stations provides a temperature record that is representative of the entire continent. This work sets out to address these questions by employing a new Antarctic near-surface temperature data set, presented here for the first time. The data set is validated by comparison with independent observations from stations not included in its construction, and by comparison with existing Antarctic near-surface temperature data sets. The methodology employed to construct our data set is distinguished from other techniques by the use of numerical model fields to establish spatial relationships between observational temperature records and the voids to which temperatures will be extrapolated, thereby providing

Table 1. Description of the 15 Stations Used in the Temperature Reconstruction[a]

Station Number	Station	Latitude	Longitude	Elevation, m	Country
1	Faraday/Vernadsky	−65.3	−64.3	11	UK/UKR
2	Bellingshausen	−62.2	−58.9	15	RUS
3	Orcadas	−60.8	−44.7	6	ARG
4	Halley	−75.5	−26.7	30	UK
5	Novolarevskaja	−70.8	11.8	119	RUS
6	Syowa	−69.0	39.6	21	JAP
7	Mawson	−67.6	62.9	16	AUS
8	Davis	−68.6	78.0	13	AUS
9	Mirny	−66.6	93.0	40	RUS
10	Casey	−66.3	110.5	42	AUS
11	Dumont D'Urville	−66.7	140.0	43	FRA
12	Vostok	−78.5	106.9	3490	RUS
13	Scott Base	−77.9	166.8	24	NZ
14	Amundsen Scott	−90.0	0.0	2835	US
15	Byrd	−80.0	−119.5	1515	US

[a]The locations are indicated by the gold dots in Figure 2.

a more realistic proxy of atmospheric and topographic variability compared to traditional kriging procedures. Additionally, our methodology uses a fixed number of continuous observational records over the entire 1960–2005 period to avoid spurious near-surface temperature trends that may arise from discontinuities or from adding/removing records from the data stream.

[5] In section 2, data and methods are outlined. In section 3, the new Antarctic near-surface temperature record is evaluated and compared to other existing data sets. In section 4, the spatial variability of Antarctic near-surface temperature trends is evaluated for annual, seasonal, and monthly timescales for several periods. Conclusions are presented in section 5.

2. Data and Methods

2.1. Existing Records

[6] The new record is compared with several existing near-surface temperature data sets that are representative of the entire Antarctic continent, including (1) time series of annual and seasonal near-surface air temperature from gridded objective analysis (1° × 1°) of automatic and manned station records and ocean observations (1950–2002) [*Chapman and Walsh*, 2007]; (2) a time series of annual near-surface air temperature derived by linearly regressing stable isotope records from ice cores onto a representative Antarctic temperature record from station data (1800–1999) [*Schneider et al.*, 2006]; and (3) time series of annual and seasonal skin temperature from a gridded 12.5 × 12.5 km polar stereographic AVHRR data set (1982–2005) [*Kwok and Comiso*, 2002a].

[7] All three temperature data sets have been validated within their respective citations. Below they are compared to the new temperature reconstruction presented here. As the data sets result from different data and methods, comparing them provides a means of assessing their robustness and reaching consensus on how Antarctic near-surface temperatures have fluctuated in recent decades.

2.2. A New Near-Surface Temperature Reconstruction

[8] Monthly mean near-surface air temperature records from manned stations have been acquired from the Reference Antarctic Data for Environmental Research (READER) database (http://www.antarctica.ac.uk/met/READER/) [*Turner et al.*, 2004]. The fifteen records (Table 1) were selected on the basis of their length and continuity. The READER data have been quality controlled to remove spurious observations and to ensure that means are calculated only if 90% of data are available for a given month [*Turner et al.*, 2004]. Temporal discontinuities due to instrument or location changes are not explicitly accounted for because of the sparse amount of metadata available. However, it is likely that any discontinuities from changes in instrumentation that are not implicitly removed during quality control will have a negligible impact on the trends calculated from the data (S. Colwell, personal communication, 2007). This assertion is supported by comparing temperature trends calculated from our reconstruction with those from independent stations not used in our reconstruction (presented in section 3). The trends from the new temperature reconstruction show good agreement with observed trends from the independent stations.

[9] Each temperature record selected is representative of an area surrounding it (a "zone"), the size of which depends on factors such as the atmospheric circulation and the topography. Our kriging-like method employs multiyear meteorological model temperature reanalysis fields from the European Centre for Medium-Range Weather Forecasts 40-year Reanalysis (ERA-40) [*Uppala et al.*, 2005] as a background variable to determine zones of temperature coherence that correlate with the individual records at annual and monthly timescales. In section 3, ERA-40 temperature is compared to other Antarctic temperature records and shown to largely reproduce the interannual variability, justifying its use for this study. Given the network of available records, if the zones of temperature coherence cover most of the continent, the observational records can be synthesized into a continent-wide record of temperature in a self-consistent manner. The technique used here generates a result that has a greater physical basis than traditional objective analysis techniques, which typically rely on functions of distance as weighting schemes. Such methods can neglect the topographic variations, atmospheric teleconnections, or other atmospheric phenomena that are inherently accounted for in the meteorological reanalysis fields. The methodology for the new temperature reconstruction is similar to that used to reconstruct snowfall in the work by *Monaghan et al.* [2006a].

[10] The generalized objective analysis technique [*Cressie*, 1999] is specified as:

$$\hat{Z}(i,j) = \sum_{k=1}^{n} \lambda_{i,j,k} \times Z_k; \ \sum_{k=1}^{n} \lambda_{i,j,k} = 1 \tag{1}$$

where $\hat{Z}(i,j)$ is the predicted value of a quantity at a desired grid point with coordinates (i,j), n is the number of observations, Z_k is the known quantity at the kth observation site, and $\lambda_{i,j,k}$ is a predictor (weighting coefficient) that must sum to 1. The predictor, $\lambda_{i,j,k}$, is computed by exploiting the information about spatial variability provided by the 1980–2001 gridded 2-m temperature fields from ERA-40:

$$\lambda_{i,j,k} = \frac{r_{i,j,k}^2}{\sum_{k=1}^{n_r} r_{i,j,k}^2} \tag{2}$$

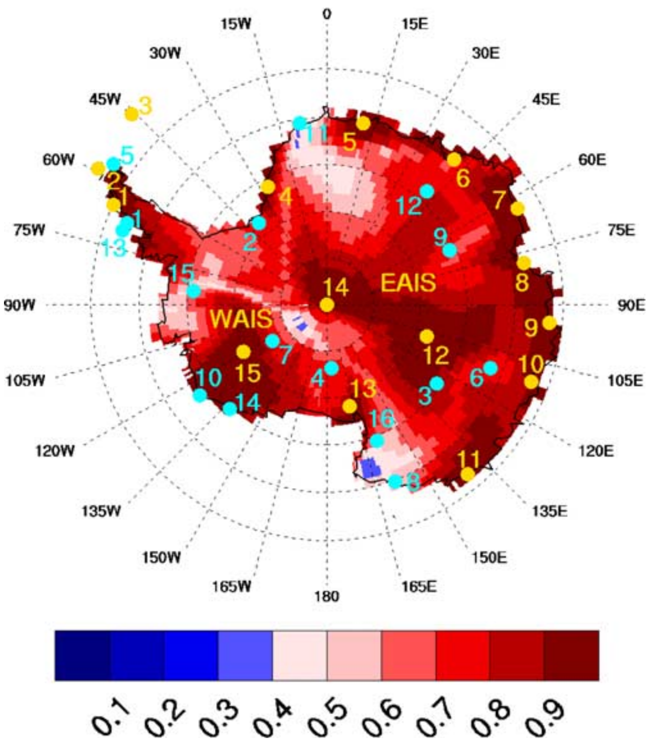

Figure 2. Composite map of the maximum absolute value of the Pearson's correlation coefficient (|r|) resulting from correlating the ERA-40 1980–2001 annual temperature change (with respect to the 1980–2001 mean) for the grid box containing each of the 15 observation sites with every other $1^\circ \times 1^\circ$ grid box over Antarctica (i.e., this map is a composite of 15 maps). Pink/red colors have correlations at approximately $p < 0.05$. The gold dots indicate the fifteen stations used in the reconstruction (described in Table 1). The cyan dots indicate the stations used in the independent validation (described in Table 2). Orcadas (gold dot 3) may be difficult to discern because of the color scale; it is located near the edge of the map at 45°W.

where $\lambda_{i,j,k}$ is the monthly or annual Pearson's correlation coefficient between 2-m temperature at any grid point and the grid point of the kth observation. Figure 2 shows a composite map of the maximum annual $r_{i,j,k}$ at each grid point (i.e., the highest correlation obtained by correlating temperature at each grid point with the n number of grid points corresponding to the observation locations). Statistically significant correlations ($r \geq 0.4$ $p < 0.05$) occur over 96% of the ice sheet surface area, and correlations of $r \geq 0.6$ occur over 90% of the area, indicating that the available observational records are representative of the continent-wide temperature variability. Equation (1) is next applied to interpolate the percentage monthly and annual temperature anomaly of the kth observation with respect to the 1980–2001 baseline period, $\Delta_{\bar{c}_k}$, to the entire grid:

$$\Delta_{t_{i,j}} = \sum_{k=1}^{n_r} \lambda_{i,j,k} \times \Delta_{\bar{c}_k} \times \eta_{i,j,k} \ ; \eta_{i,j,k} = \frac{r_{i,j,k}}{|r_{i,j,k}|} \tag{3}$$

where $\Delta_{t_{i,j}}$ is the percentage monthly temperature anomaly at each grid point with respect to the 1980–2001 period. Using percentage temperature anomalies, rather than absolute temperature anomalies (in units of K), is a means to account for differences in variance between the observation site and the interpolation point. The operator $\eta_{i,j,k}$ accounts for the sign of anticorrelations (it is assumed that if an observational site is anticorrelated with a grid point that the relationship is just as likely to be valid as a positive correlation since it too is likely to arise because of the atmospheric circulation). Equation (3) is applied to the monthly and annual averages for each year from 1960–2005. The resulting percentage anomaly is converted to a temperature anomaly (K) using the 1980–2001 mean temperature in ERA-40 at each grid point. To compensate for dampened variance due to the methodology, the reconstructed temperature is multiplied by $\sigma_{\mathrm{ERA-40}}/\sigma_{\mathrm{reconstruction}}$ at each grid point, where σ is the standard deviation from the 1980–2001 mean; the resulting standard deviation agrees well with observations (section 3.2). Seasonal temperature anomalies are computed from the monthly anomalies and averaged (area-weighted) over the continent, including ice shelves. Anomalies are recalculated with respect to the 1980–1999 mean for comparison with other data sets.

[11] The records obtained from the READER website are quality controlled and monthly means are calculated only if >90% of data are available. The READER data are supplemented by observations provided by Gareth Marshall (http://www.nerc-bas.ac.uk/icd/gjma/) in cases where his data are more complete. In order to have complete records for the entire 46-year period, missing months are filled in using single or multiple linear regression based on records at nearby stations. In most cases, these data outages are a few months, with the exception of Byrd Station. Byrd does not have year-round manned records after 1969, although there are scattered summer observations through January 1975. Efforts were made to fill in the missing data because Byrd is an isolated record in West Antarctica, where continuous data are otherwise unavailable. Automatic weather station (AWS) observations are available from 1980 to 2002, but the outages are frequent and data are available for only ~50% of the months during that period [*Shuman and Stearns*, 2001] (http://amrc.ssec.wisc.edu/aws.html). A reconstruction of Byrd temperature from 1978 to 1997 based on passive microwave data [*Shuman and Stearns*, 2001, 2002] was obtained from the National Snow and Ice Data Center (http://www.nsidc.org). The passive microwave record matches the AWS record closely for the months in which both are available ($r^2 = 0.999$, $n = 150$, $p < 0.0001$), and thus the passive microwave data are considered reliable. The station and passive microwave records were combined into one record, and then the remaining missing data were filled in by optimizing the multiple linear regression relationship between the Byrd Station temperature record and records from other Antarctic stations for each month, and for the annual means. The various time series of annual near-surface temperature at Byrd are shown in Figure 3. The regressed temperature record matches the observed Byrd records adequately ($r^2 = 0.65$, $n = 29$). To test the sensitivity to this record, the Antarctic temperature was reconstructed with and without the Byrd record (shown in section 3) and there is virtually no difference in the result. Thus, at the continental scale, the Antarctic temperature reconstruction is not sensitive to the Byrd Station record.

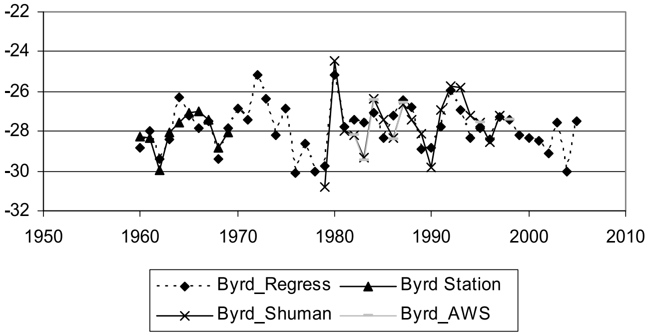

Figure 3. Various time series of Byrd Station annual near-surface temperature records (°C), as described in the text. The record used in the new Antarctic temperature reconstruction is a combination of "Byrd_Station" and "Byrd_Shuman," with any missing years filled in using the regression relationship, "Byrd_Regress." Time series for monthly data were constructed in a similar manner. Correlation statistics are provided in the text.

Including the passive microwave data at Byrd, 95.6% of station months for 1960 to 2005 are available for the 15 stations shown in Figure 2. If Byrd Station is omitted, 97.7% of station months are available.

3. Evaluation of Observationally Based Antarctic Near-Surface Temperature Records

3.1. Pros and Cons of Various Antarctic Temperature Data Sets

[12] In order to understand Antarctic climate variability and to diagnose global climate models (GCMs), having records that are representative of near-surface temperature over the entire Antarctic continent is desirable. One method of doing this is to simply take the linear average of all station records available [e.g., *Jones and Reid*, 2001]. Such analyses are useful for assessing year-to-year variability, but are not reliable for evaluating the spatial distribution of trends because of the relatively sparse network of observing stations. Temporal trends calculated by linear averaging indicate spurious warming for recent decades because a disproportionate number of stations are located on the Antarctic Peninsula, a region whose ice comprises only ~5% of the total surface area of the ice sheet [*Vaughan et al.*, 1999], where strong warming has occurred over the past 50 years [e.g., *Vaughan et al.*, 2003]. Individual station records suggest that there has not been statistically significant warming elsewhere on the continent [e.g., *Turner et al.*, 2005]. Because of the problems cited, linearly averaged Antarctic temperature records are not employed in this study.

[13] Objective analysis methods [*Doran et al.*, 2002; *Chapman and Walsh*, 2007] have reduced problems compared to linear averaging, as these methods interpolate/extrapolate to voids using station data (either trends calculated from the station data, or raw station data) that is weighted as a function of inverse distance or a natural neighbor scheme [*Cressie*, 1999]. These analyses do not show strong warming trends and indicate that Antarctic temperatures collectively have not changed significantly since the 1960s. Statistically insignificant cooling over most of the continent has occurred on an annual basis from about 1970 to 2002 [*Chapman and Walsh*, 2007]. The annual and seasonal time series from *Chapman and Walsh* [2007] are used in this study, as they provide the most recent and complete analysis of Antarctic temperatures.

[14] Numerical atmospheric model fields provide useful assessments of temperature over Antarctica, and they account for topography, storm activity, teleconnections, and other natural phenomena that impact climate. However, one problem that has plagued model reanalysis fields in Antarctica is the dearth of observational data assimilated into the models prior to the modern satellite era (~1979). This leads to relatively poor simulations before ~1979, and improved simulations thereafter [e.g., *Bromwich and Fogt*, 2004; *Bromwich et al.*, 2007]. Thus the evaluation and use of ERA-40 temperatures is limited to the period 1980–2001 in this study. The 1980–2001 ERA-40 annual and monthly temperature fields are used to create the background field for the statistical reconstruction, allowing temperature to be interpolated/extrapolated to data voids from station observations in a physically based manner.

[15] Skin temperature from AVHRR instruments onboard the National Oceanic and Atmospheric Administration's suite of polar orbiting satellites is the final Antarctic temperature data set used. AVHRR records provide the most spatially comprehensive observations of Antarctic temperatures. AVHRR temperature records must be used with caution as they are only valid for clear-sky conditions, an issue that can be problematic in the coastal Antarctic regions where conditions are more often cloudy than not [e.g., *Guo et al.*, 2003]. However, statistical sampling is relatively good, especially in the Antarctic region where overlapping orbits enable as many as 12 measurements of the same surface per day. It should be noted that the skin temperatures inferred from thermal-infrared sensor data may be significantly different from the 2 meter air temperature observed by meteorological stations, especially in spring and summer. Also, a fixed emissivity close to unity is assumed for the surface for all seasons in the retrieval algorithm. This may cause a slight error in melt areas (near the coast) in the spring and summer. A thorough description of the AVHRR record and its quality over Antarctica is given by *Comiso* [2000]. The most recent realization of the AVHRR temperature data set is used in this study. The most recent published version of the data set for Antarctica is *Kwok and Comiso* [2002a].

3.2. Validation

[16] Monthly temperature records from sixteen stations were selected from the READER database to validate our Antarctic temperature reconstruction (Table 2 and Figure 2). None of the sixteen records were used in our reconstruction, and therefore they provide an independent means of assessment. Eight of the sixteen records were used in the reconstruction of *Chapman and Walsh* [2007], and therefore only the eight independent stations (indicated in Table 2) are used to calculate statistics in cases where the data sets are compared. The sixteen stations were chosen on the basis of completeness of record, and to provide a representative sampling of the climatic variability across Antarctica. Eight stations are located on the coast, and eight are in the interior

Table 2. Description of the Independent READER Temperature Observations Used to Validate the Reconstruction[a]

Station Number	Station	Latitude	Longitude	Elevation, m	Type	Country	Duration	n (60-02)	n (82-02)	$\sigma_{RECON}/\sigma_{READER}$	$\sigma_{CHAPMAN}/\sigma_{READER}$	$\sigma_{COMISO}/\sigma_{READER}$
1	Adelaide[b]	−67.8	−67.9	26	manned	UK	1962–1974	152	-	0.74[c]	0.76[c]	-
2	Belgrano_I[b]	−78.0	−38.8	50	manned	ARG	1960–1979	237	-	0.71[c]	0.50[c]	-
3	Dome C_II	−75.1	123.4	3280	AWS	US	1996–2005	69	69	1.01	0.79	1.01
4	Elaine	−83.1	174.2	60	AWS	US	1986–2001	131	131	0.88	0.67	0.53
5	Esperanza	-63.4	-57.0	13	manned	ARG	1960–2005	497	246	0.68	0.43	0.70
6	GC41[b]	−71.6	111.3	2763	AWS	AUS	1984–1997	96	96	0.94	0.63	0.78
7	Harry[b,d]	−83.0	−121.4	954	AWS	US	1987–2001	113	113	0.63	0.54	0.43
8	Leningradskaja[b]	−69.5	159.4	304	manned	RUS	1971–1991	240	110	1.17	0.71	0.91
9	LGB35[b]	−76.0	65.0	2345	AWS	AUS	1994–2005	103	103	1.01	0.89	0.95
10	Mount Siple	−73.2	−127.1	30	AWS	US	1992–2005	111	111	1.13	0.84	0.88
11	Neumayer	−70.7	−8.4	50	manned	GER	1981–2005	260	251	0.91	0.71	0.69
12	Relay Station	−74.0	43.1	3353	AWS	US	1995–2005	77	77	0.90	0.85	1.03
13	Rothera	−67.5	−68.1	16	manned	UK	1976–2005	308	250	0.95	0.66	0.82
14	Russkaya[b]	−74.8	−136.9	124	manned	RUS	1980–1990	119	98	1.06	0.79	0.59
15	Siple	−75.9	−84.0	1054	AWS	US	1982–1992	85	85	1.17	0.78	0.68
16	Tourmaline Plateau[b]	−74.1	163.4	1702	AWS	ITL	1990–2001	114	114	1.13	0.87	1.04

[a]The locations are indicated by cyan dots in Figure 2. The number of monthly means available for each station is denoted by "n." Monthly means were computed if >90% of possible observations were available for a given month. The ratios of the reconstructed-to-observed standard deviations (of the monthly temperature anomalies) are shown in the last column.

[b]Stations were not used in RECON or CHAPMAN reconstructions (i.e., they are independent).

[c]Ratio based on data prior to 1982. All others ratios are based on data from 1982–2002.

[d]Harry Station data are suspicious after 1998; data used in analysis are through 1998.

of Antarctica, six of which are >1000 m ASL. Five of the stations have records that begin prior to 1980, the beginning of the calibration period for the reconstruction. For ease of comparison, the following nomenclature will be used henceforth: "READER" are the observed temperature records; "RECON" is our new near-surface temperature reconstruction; "CHAPMAN" is the reconstruction of *Chapman and Walsh* [2007]; and "COMISO" is the AVHRR temperature data set [*Comiso*, 2000; *Kwok and Comiso*, 2002a].

[17] Figure 4 shows the monthly and annual correlation (Figure 4a), root mean square error (RMSE; Figure 4b) and ratio of RMSE to standard deviation (RMSE/σ) between the READER (observed) near-surface temperature anomalies and those from RECON, CHAPMAN, and COMISO for the independent station data available for the common period 1982–2002. Of the eight stations that are independent of both the RECON and CHAPMAN data sets, six have data during this period (stations 6, 7, 8, 9, 14, and 16). The statistics for January, for example, are calculated for all available January observations from the six stations. The total number of observations for all months from each station are shown in Table 2 (column "n (82–02)"). The comparison for each data set and each station is exact (months in each data set for which there are no observations are excluded). The results presented in Figure 4 provide an estimate of the average reconstruction skill at a single grid point. In RECON, correlations are $r > 0.7$ during seven months; in CHAPMAN $r > 0.7$ during 10 months; and in COMISO, $r > 0.7$ during 4 months. In most of the remaining months, $r > 0.6$ in all three data sets. In general, correlations are lowest in the summer and highest during the cold months, in part related to minimum sea ice cover in summer which enhances localized temperature effects at coastal stations. Annual correlations in all three data sets are lower than expected (0.25–0.35), an issue caused by having few total station years ($n = 33$) for which to calculate the statistics, and also because one of 33 observations is questionable. If the questionable record is removed, the annual correlations are 0.50, 0.58, and 0.47 for RECON, CHAPMAN, and COMISO, respectively.

[18] The RMS errors in all three data sets have strong seasonality (Figure 4b), being largest in winter and smallest in summer. However, when standardizing the errors to account for dampened temperature variability during summer (due to the enhanced maritime effect), it is seen in Figure 4c that the largest "relative" RMS errors occur during the late summer and early autumn months (January–April), when the greatest fraction of open water is present around Antarctica [*Gordon*, 1981; *Parkinson*, 1992]. The RECON data typically have higher RMS errors than the CHAPMAN data (Figure 4b), but they have lower relative RMS errors (Figure 4c), a condition that arises because the RECON data are adjusted to match the observed temperature variance (otherwise the kriging method dampens the variability), and thus have larger variability than CHAPMAN. Examination of the ratios of the standard deviations of the reconstructed data sets versus observations (the last three columns in Table 2) indicates that the RECON variability is close to that observed (0.94 on average). The CHAPMAN and COMISO data slightly underestimate the observed variability (on average, 0.72

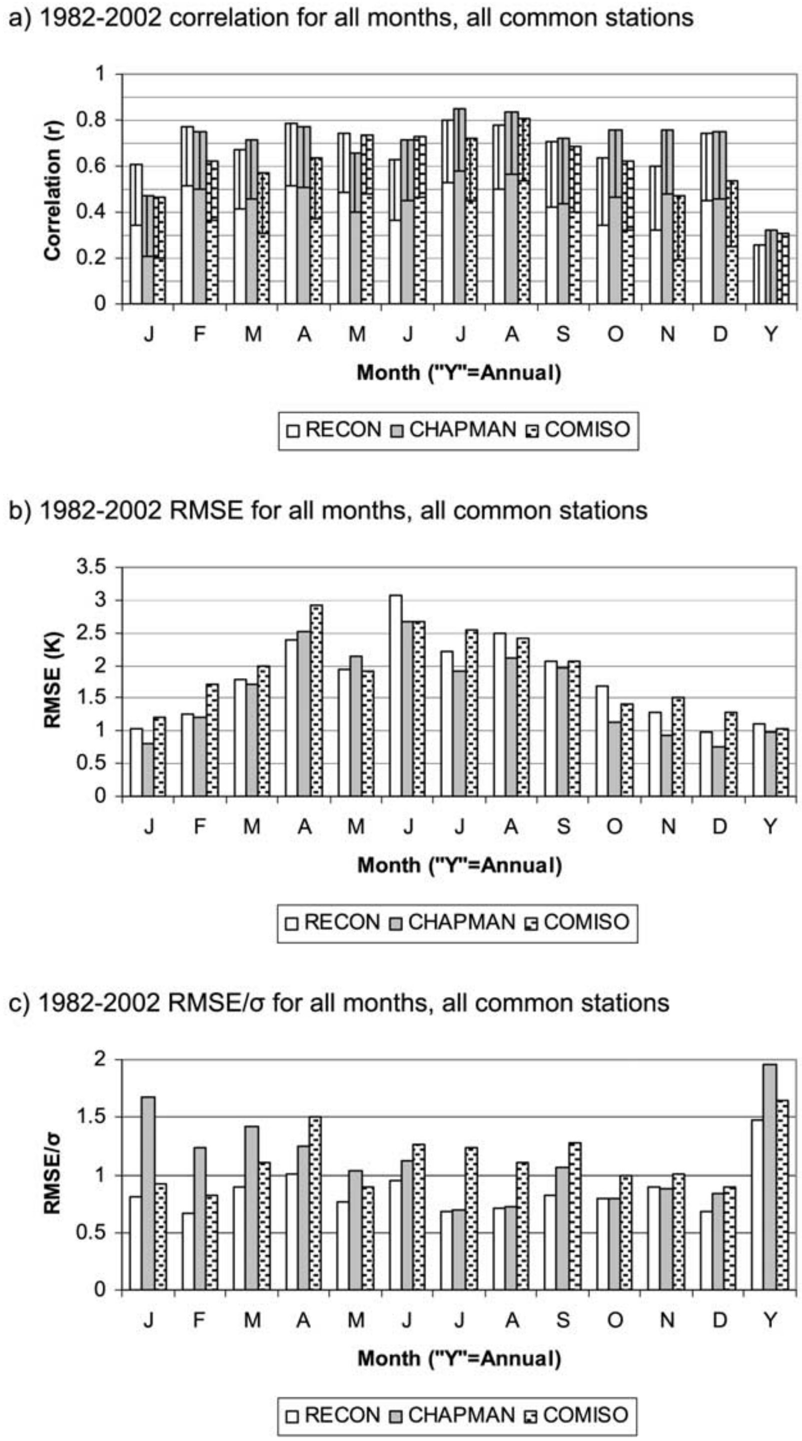

Figure 4. For the three observational data sets, RECON, CHAPMAN, and COMISO, the (a) correlation, (b) RMSE (K), and (c) RMSE/σ between the observed and reconstructed temperature anomalies for all available observations for the six common independent stations placed into monthly and annual ("Y") bins. The stations are shown in Figure 2 and described in Table 2 (stations 6, 7, 8, 9, 14, and 16). Confidence intervals ($p < 0.05$) for the correlations are indicated by the error bars (only the lower bound of the uncertainty is shown).

and 0.79, respectively). Accounting for the seasonal cycle of variability in the RECON data set eliminates the seasonal cycle in the relative RMS errors (Figure 4c). In the CHAPMAN data, after accounting for the seasonal cycle of variability, the largest relative RMS errors occur in the late summer and early autumn months (JFMA). Correspondingly the average correlation coefficients in CHAPMAN during these months (Figure 4a) are lower compared to the other eight months ($r = 0.68$ versus $r = 0.76$). The average correlation coefficients in RECON are nearly identical between the two periods ($r = 0.71$ versus $r = 0.70$). The COMISO data have lower correlation coefficients during the warm months (on average, $r = 0.57$ for JFMA versus $r = 0.66$ for the remaining months), which may be due in part to surface melt conditions (for the coastal stations) which cause a decrease in surface emissivity and hence a slight error in the retrieval. Also, during melt the near-surface air temperature may be significantly different from the skin temperature (which is fixed at 0°C). Furthermore, the relatively coarse grid of 12.5 km for the AVHRR data would cause measurements in coastal stations to be partly that of ocean regions which are ice free and relatively warm in the summer.

[19] Figure 5 shows the correlations between the READER (observed) near-surface temperature anomalies and those from RECON and CHAPMAN for the independent station data available for the common period 1960–2002. The objective of Figure 5 is to evaluate the performance of the data sets over a longer period than in Figure 4. Figure 5a is similar to Figure 4a, showing the monthly and annual correlations for all available observations from the 8 common independent stations (see figure caption for stations). Figure 5b shows the monthly and annual correlations from all available observations from the 8 independent stations after they have been averaged together first. Figure 5b estimates the ability of RECON and CHAPMAN to reproduce regional temperature variability, whereas Figure 5a estimates their average ability at a single grid point. Figure 5c shows the correlations at each station for all of the monthly observations available (counts are shown in the "n (60–02)" column in Table 2), and thus provides an estimate of the ability of RECON and CHAPMAN to reproduce the temperature variability across all months at a given station. The objective of presenting Figure 5a is to show that the correlations are similar to those in Figure 4a, and are thus not sensitive to the period chosen; RECON and CHAPMAN have consistent skill throughout 1960–2002. It is noteworthy that the annual correlations are higher than for the 1982–2002 period because more annual averages are available for the analysis ($n = 75$ for 1960–2002, versus $n = 33$ for 1982–2002). The RECON and CHAPMAN data sets are able to reproduce regional variability (Figure 5b) with strong statistical significance. RECON (CHAPMAN) has correlations exceeding 0.6 in 12 months (11 months), and correlations exceeding 0.8 in 4 months (5 months). The correlations are highest during the winter months. Evaluation of correlations at individual stations (Figure 5c) demonstrates that RECON and CHAPMAN are consistently able to reproduce observed variability with strong statistical significance ($r > 0.6$ in all instances, $r > 0.7$ in most instances). The correlations at the 4 independent low-elevation coastal stations (stations 1, 2, 8, and 14) are similar to those at the 4 independent high-elevation interior stations (stations 6, 7, 9, and 16). The RECON correlations are $r_{\_low} = 0.75$ versus $r_{\_high} = 0.76$, and the CHAPMAN correlations are $r_{\_low} = 0.80$ versus $r_{\_high} = 0.80$. In the RECON data set, for which all 16 stations are independent, the correlations between West Antarctica (stations 1, 2, 5, 7, 10, 13, 14, and 15) and East Antarctica (stations 3, 4, 6, 8, 9, 11, 12, and 16) are compared and found to be similar ($r_{\_west} = 0.73$ versus $r_{\_east} = 0.76$).

[20] Figure 6 shows the temporal trends of the temperature anomalies for the READER (observed), RECON, and CHAPMAN data sets for several cases. Figure 6a shows the monthly and annual trends for 1982–2002 for all available observations for the six common independent stations (the COMISO data are also included in Figure 6a since they cover the 1982–2002 period). The trends are calculated from the same data for which statistics are presented in Figure 4, and they demonstrate the ability of the data sets to reproduce observed trends at a single grid point. It is noteworthy that these statistics do not accurately depict the actual Antarctic temperature trends, as they represent an assemblage of discontinuous observational data sets. Figure 6b is similar to Figure 6a, but for the 1960–2002 period (based on the same data used to calculate the statistics in Figure 5a). Observation of Figures 6a and 6b for both periods (all months and annually) indicates that none of the data sets have trends that are statistically different from zero ($p < 0.05$), nor are the trends among data sets statistically different from each other. The RECON, CHAPMAN and COMISO data are of the same sign as the READER trends in all but a few instances, demonstrating that they are able to capture the weak observed trends at a grid point even though the trends are not statistically significant. Such a result infers that any statistically significant trends that occur will be easily reproduced by RECON, CHAPMAN, and COMISO. Figure 6c shows the 1962–2002 trends for the 8 common stations averaged together first (based on the same data used to calculate the statistics in Figure 5b), and thus provides an estimate of the ability of the data sets to reproduce regional trends. As with Figures 6a and 6b, despite statistical insignificance, RECON and CHAPMAN produce trends of the same sign and similar magnitude as observed in all but one instance (CHAPMAN has a small positive trend versus a small observed negative trend in August). The results presented in Figure 6 indicate that all of the data sets can reproduce observed Antarctic temperature trends at individual grid points, and regionally, in all seasons.

[21] In summary, the RECON, CHAPMAN, and COMISO data sets have similar overall performance according to our validation. In nearly all cases the correlations of RECON, CHAPMAN, and COMISO with individual station data are highly statistically significant. The performance during the coldest months is similar among the data sets. During late summer and early autumn, when Antarctic sea ice cover is lowest, the RECON data set on average has the highest correlations and lowest relative RMS errors compared to observations. The strong performance of RECON during summer may be due to our methodology, which through the use of model fields to establish spatial relationships likely minimizes the impacts of localized influences on temperatures compared to conventional objective analysis techniques. All of the data sets reliably reproduce near-surface temperature trends at independent stations even though they are statistically insignificant, suggesting that they will easily reproduce stronger, statistically significant trends as well. The results of this validation provide quantitative evidence that the continent-averaged Antarctic temperature data presented next are accurate.

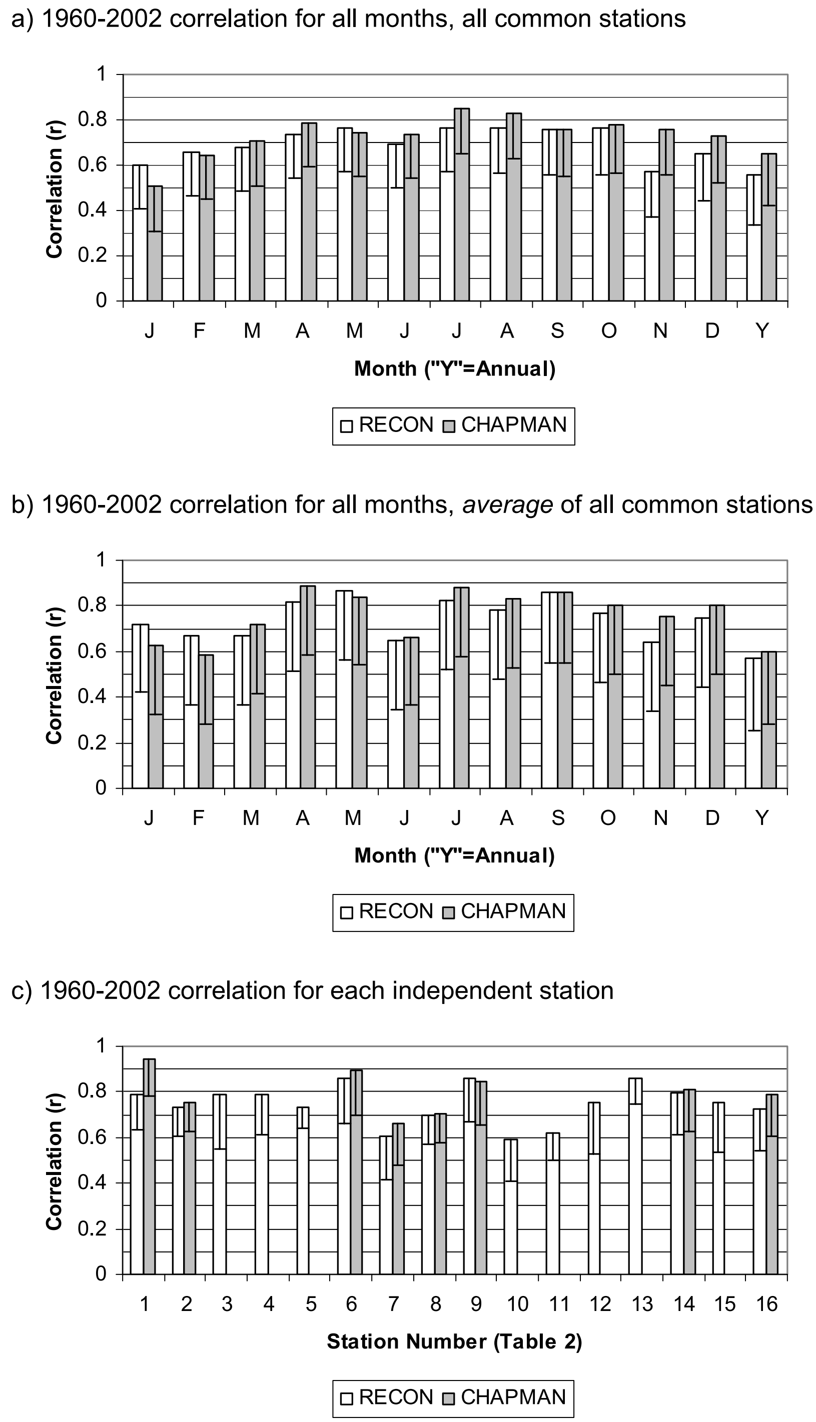

Figure 5. Correlation coefficients between the observations and the RECON and CHAPMAN near-surface temperature anomalies for the common period 1960–2002 for (a) all available observations from the eight common independent stations placed into monthly and annual ("Y") bins; (b) all available observations from the eight common independent stations averaged together first, then placed into monthly and annual bins; and (c) all monthly observations at each individual, independent station (the eight common stations, 1, 2, 6, 7, 8, 9, 14, and 16, plus an additional eight stations that are independent in the RECON evaluation only). Confidence intervals and station information are as described in Figure 4.

3.3. Comparison of Antarctic Temperature Data Sets

[22] Figure 7 shows the annual Antarctic near-surface temperature anomalies for various data sets for the 1950–2005 period (Figure 7a), and the more recent period from 1980 to 2005, which contains several additional data sets (Figure 7b). There is close agreement between RECON and CHAPMAN for the 1960–2005 period ($r = 0.96$; Figure 7a). Considering the small-scale noise and isotope diffusion that

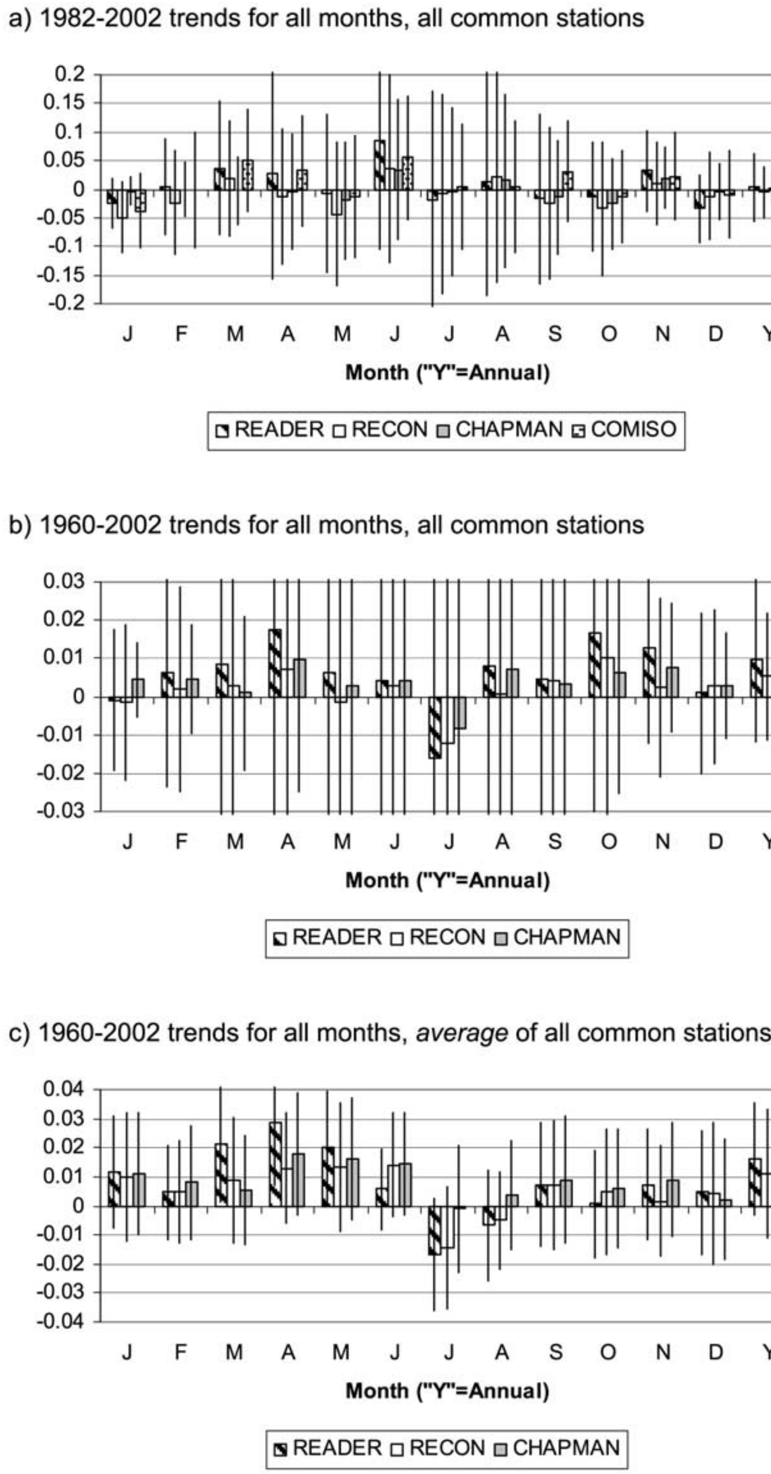

Figure 6

inherently occur in ice cores [e.g., *van der Veen and Bolzan*, 1999], the stable isotope reconstruction of *Schneider et al.* [2006] matches the RECON and CHAPMAN data sets quite well (r ≈ 0.65 compared to either data set for 1960–1999), especially after 1975 (r ≈ 0.78 for 1975–1999). For the 1980–2005 period (Figure 7b), the time series have similar interannual variability, including the reconstructions, the ERA-40 temperature data, and a "synthetic" reconstruction, using the same technique as RECON, that employs ERA-40 records from the 15 observation sites ("RECON_SYN"). If our reconstruction methodology were perfect, RECON_SYN would exactly match the ERA-40 record. The close match indicates that the synthetic reconstruction reproduces the ERA-40 record very well (r = 0.95). The inclusion of the "RECON_NO_BYRD" record in Figure 7b demonstrates that our result is insensitive to the omission of the Byrd

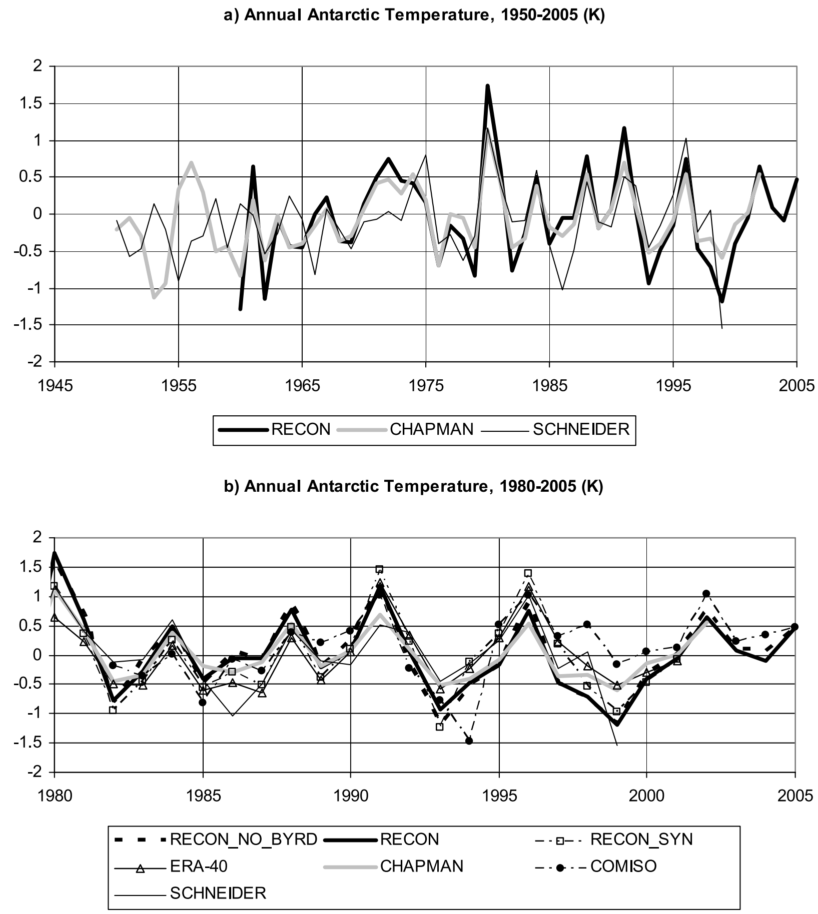

Figure 7. Annual Antarctic near-surface temperature (K) anomalies (with respect to the 1980–1999 mean) for various data sets for (a) 1950–2005 and (b) 1980–2005. Abbreviations are as follows: "RECON_NO_BYRD" is the reconstruction with Byrd Station record omitted, and "RECON_SYN" is the reconstruction using "synthetic" temperature records extracted from the 15 ERA-40 grid points that correspond to the observation sites. The COMISO data begins in 1982, thus the anomalies are with respect to the 1982–1999 mean.

Station record, as the RECON and RECON_NO_BYRD records are nearly identical (r = 0.99). Because it is based on AVHRR skin temperatures, the COMISO record provides an independent constraint on the other records. The correlation of COMISO with RECON and CHAPMAN, and ERA-40 is r = 0.61 and r = 0.64, and r = 0.70 respectively.

[23] The annual and seasonal Antarctic near-surface temperature trends are calculated for 1960–2002 and 1982–2001 (Table 3). The difference in end years (2002 versus 2001) between the two periods is due to the ERA-40 records ending in 2001 (actually, in mid-2002). The 1960–2002 annual and seasonal trends are statistically insignificant in all of the available data sets, and the 95% confidence intervals are at least twice as large as the trends in nearly every instance. The trends are of similar magnitude for the two reconstructions, CHAPMAN and RECON, indicating that at the continental scale the results are insensitive to which technique is employed.

[24] The annual and seasonal trends are stronger over the 1982–2001 period, but they are statistically insignificant in

Figure 6. Temporal trends of the temperature anomalies (K a^{-1}) for the observed READER (observed), RECON, CHAPMAN, and COMISO data sets for (a) all available observations for the six common independent stations for 1982–2002 placed into monthly and annual ("Y") bins; (b) all available observations from the eight common independent stations for 1960–2002 placed into monthly and annual ("Y") bins; and (c) all available observations from the eight common independent stations for 1960–2002 averaged together first, then placed into monthly and annual bins. Note that y axis scales vary. COMISO data are only shown in Figure 6a because they start in 1982. The error bars indicate 95% confidence intervals for the trends, estimated as $t_{05}*SE_{b1}$, where t_{05} is the t value for p = 0.05 and SE_{b1} is the standard error of the regression slope (i.e., of the trend). In subsequent figures and in Table 3, uncertainty is estimated as $t_{05}*SE_{tot}$, where $SE_{tot} = \sqrt{SE_{b1}^2 + SE_m^2}$, and SE_m accounts for additional uncertainty due to imperfect methodology/algorithms for RECON, CHAPMAN, and COMISO, estimated as the average standard error between the three data sets.

Table 3. Temporal Trends and 95% Confidence Intervals of Average Annual and Seasonal Antarctic Near-Surface Air Temperature (K decade^{-1}) From Various Data Sets for Two Time Periods[a]

	Annual	DJF	MAM	JJA	SON
			1960–2002		
RECON	0.02 ± 0.18	0.01 ± 0.29	0.02 ± 0.37	0.12 ± 0.37	0.14 ± 0.27
CHAPMAN	0.04 ± 0.14	0.05 ± 0.17	0.01 ± 0.28	0.08 ± 0.30	0.05 ± 0.23
SCHNEIDER	0.01 ± 0.13				
			1982–2001		
RECON	−0.21 ± 0.57	−0.66 ± 0.92	*−1.09* ±1.07	0.63 ± 1.08	0.21 ± 0.81
ERA-40	0.21 ± 0.44	−0.41 ± 0.84	−0.26 ± 0.77	*1.07* ± 0.81	0.49 ± 0.75
CHAPMAN	−0.05 ± 0.42	−0.07 ± 0.55	*−0.78* ± 0.78	0.40 ± 0.88	0.23 ± 0.67
COMISO	0.24 ± 0.57	−0.16 ± 1.02	−0.19 ± 0.81	0.77 ± 0.81	0.50 ± 0.75
RECON_SYN	0.12 ± 0.58	−0.48 ± 0.83	−0.46 ± 0.91	*1.01* ± 0.90	0.38 ± 0.65
SCHNEIDER	−0.06 ± 0.50				

[a]Trends different from zero ($p < 0.05$) are italicized. *Schneider et al.* [2006] data are annual only, and end in 1999. The short-term trends are calculated from 1982 because that is when the "COMISO" data begin. The "RECON_SYN" trends are those created using the reconstruction method presented in this paper, but using time series of temperature extracted from ERA-40 at the fifteen stations, rather than the true observations.

all but four cases. The 95% confidence intervals are larger than the 1982–2001 annual temperature trends by a factor of two or more in all six data sets, indicating the annual trends are highly insignificant. For each of the four seasons, the trends for all of the data sets have the same sign (+ or −), suggesting robust results. The RECON and CHAPMAN near-surface air temperature trends are significantly ($p < 0.05$) negative in MAM (−1.1 and −0.78 K decade^{-1}, respectively), but it is noteworthy that the negative RECON trend is much smaller (−0.33 K decade^{-1}) and statistically insignificant if calculated through 2005. The negative trends in DJF and MAM are consistent with the strong upward trend in the SAM during summer and autumn [*Marshall*, 2003, 2007]. In JJA, the positive trends are consistent with middle and upper tropospheric warming (1970–2003) over Antarctica in winter based on weather balloon observations [*Turner et al.*, 2006]. The SAM has not been strengthening during the winter months (until perhaps more recently; Figure 1), raising the question of whether the JJA warming is an analog of how Antarctic temperatures may change in other seasons if the positive SAM trends subsided. *Marshall* [2007] notes that over East Antarctica the surface temperature response to SAM forcing displays little seasonality; that is, if SAM forcing in other seasons were similar to winter, the temperature response in those seasons might also be similar. One GCM study [*Shindell and Schmidt*, 2004] suggests the trends in the SAM might level off by mid-century if the Antarctic ozone hole mends itself. Other studies of GCM projections suggest the SAM will continue to strengthen throughout this century [e.g., *Lynch et al.*, 2006; *Fyfe and Saenko*, 2006]. Figure 1 suggests the DJF, MAM, and annual SAM trends may already be leveling off since about the mid-1990s, an issue that is discussed in more detail below when the spatial plots are presented. The positive temperature trends in ERA-40 and RECON_SYN are statistically significant in JJA. *Johanson and Fu* [2007] suggest that ERA-40 wintertime tropospheric temperature trends are too large in winter by a factor of about two; thus the veracity of these model-based trends is questionable. However, the good agreement between the ERA-40 and RECON_SYN trends indicates that our reconstruction methodology reliably reproduces the continental-scale trends.

[25] In summary, the two station-based near-surface temperature reconstructions (RECON and CHAPMAN) correlate strongly for annual and seasonal timescales for 1960–2005, and they agree reasonably with the *Schneider et al.* [2006] stable isotope reconstruction for annual timescales. RECON is representative of the entire continent, as indicated by the similar trends and the strong correlation between the ERA-40 and "synthetic" ERA-40 (RECON_SYN) data sets. All records correlate significantly with all other records during all seasons from 1982 to 2001 (not shown). Near-surface temperature trends are statistically insignificant ($p > 0.05$) on annual timescales within every data set analyzed, for both the longer (1960–2002) and shorter (1982–2001) periods. Continental-scale seasonal trends are of the same sign in all data sets. Collectively, these results suggest that RECON is a robust record. In the next section, the regional variability of Antarctic near-surface trends is evaluated.

4. An Evaluation of the Spatial Variability of Antarctic Near-Surface Temperature Trends

[26] Figure 8 presents the spatial plots of the temporal trends of annual near-surface temperature (1982–2001) for eight data sets, five of which are from models. Statistically significant trends ($p < 0.05$) are indicated by regions encompassed by black contours. The three "observed" data sets (Figures 8a–8c) all show warming over the Peninsula and cooling over the East Antarctic plateau. The results are in disagreement over West Antarctica, with COMISO indicating strong warming, CHAPMAN showing weaker warming, and RECON showing slight cooling. None of the trends are statistically different from zero, however. COMISO has positive trends around the coastal margin and over West Antarctica, which are regions that have climatologically higher cloud fraction [e.g., *Guo et al.*, 2003] that may diminish the quality of the AVHRR skin temperature measurements. The PMM5_ERA-40 data set (Figure 8d) is similar to ERA-40 (Figure 8e), the data set that provided its initial conditions. The PMM5_ERA-40 data set is from a series of limited area model simulations whose initial and boundary conditions were provided by ERA-40 [*Monaghan et al.*, 2006b]. The RECON_SYN data set (Figure 8f) is also similar to ERA-40, indicating that the 15 chosen stations can

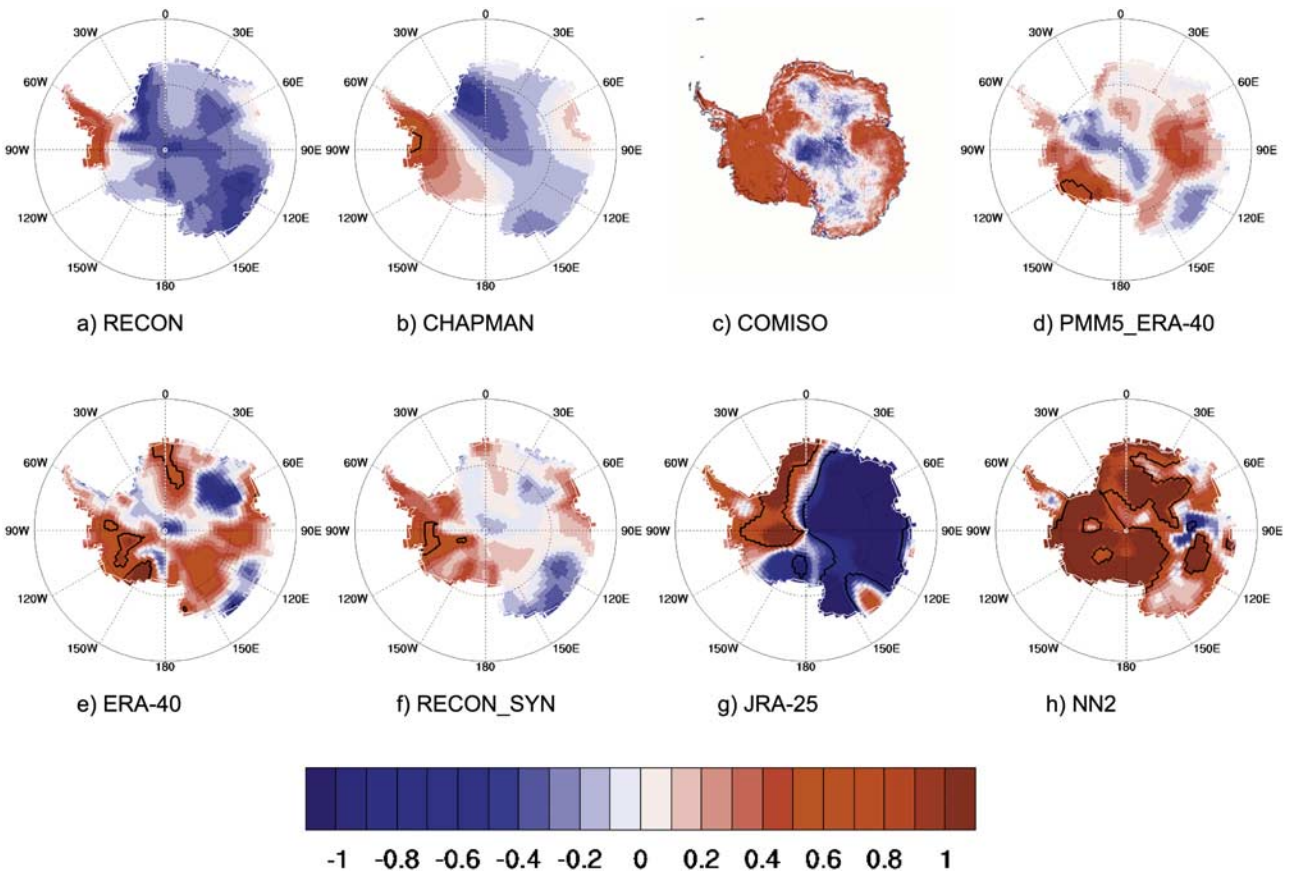

Figure 8. Spatial plots of the temporal trends (K decade^{-1}) of annual (near) surface temperature for the period 1982–2001 for eight data sets. Abbreviations are as follows: PMM5_ERA-40, Polar MM5 runs driven by ERA-40; JRA-25, the Japanese 25-year Reanalysis Project; NN2, the NCEP/DOE Reanalysis II. Statistically significant trends ($p < 0.05$) are encompassed by black contours.

realistically reproduce the spatial variability of temperature trends across the continent. JRA-25 (Figure 8g) [*Onogi et al.*, 2007] is the reanalysis that is most similar to the observed data sets, having a large region of cooling over East Antarctica and warming over the Peninsula. However, the warming over the Ronne-Filchner ice shelf and Halley Station (75.5°S, 26.7°W) in JRA-25 is not consistent with the station record from Halley in the READER database for the 1982–2001 period, which indicates slight cooling. The NN2 data set (Figure 8h) [*Kanamitsu et al.*, 2002] indicates strong, statistically significant warming over much of the ice sheet, and is inconsistent with observations from the READER database. The NN2 data set was also found to have unrealistically strong precipitation trends for a similar period (1985–2001) by *Monaghan et al.* [2006b]. The disagreement between the reanalysis data sets emphasizes the challenges faced by reanalyses over Antarctica. Overall, the annual near-surface temperature trends in the "observed" data sets demonstrate broad agreement over the Antarctic Peninsula and the East Antarctic Plateau; in West Antarctica the trends in RECON and CHAPMAN are of different signs, but are relatively small and not statistically different from zero.

[27] Figure 9 shows the spatial plots of the temporal trends of annual near-surface temperature for three different periods in RECON and CHAPMAN. The objective of the plot is to demonstrate the agreement between the two data sets, and to show that recent Antarctic temperature trends are strongly dependent on the period analyzed. The RECON and CHAPMAN data sets are broadly consistent with each other and show gradually more negative (positive) trends over continental Antarctica (the Antarctic Peninsula) as time progresses. The shift in the temporal trends coincides with the gradual positive trend in the SAM that began in the mid-1960s (Figure 1). The annual trends over the Antarctic Peninsula are statistically significant for the 1960–2002 period in both data sets. An independent borehole temperature measurement taken in 1958 [*Kodama*, 1964] at 10-m depth in the firn at 77.6°S, 95.9°W was measured again 46 years later in 2004 and found to be nearly identical to the 1958 measurement (D. Vaughan, personal communication, 2007). Promisingly, both of the data sets presented in Figure 9 indicate a small and statistically insignificant change in near-surface temperature at that site for a similar period (1960–2002). Because of the similarity between our reconstruction and that of *Chapman and Walsh* [2007], and because our data set extends through 2005 (CHAPMAN extends through 2002), only RECON will be used to examine monthly near-surface temperature trends in the remainder of the text.

[28] Figures 10 and 11 show the spatial plots of the temporal trends of monthly near-surface temperature from RECON for 1960–2005 and 1970–2005, respectively. The

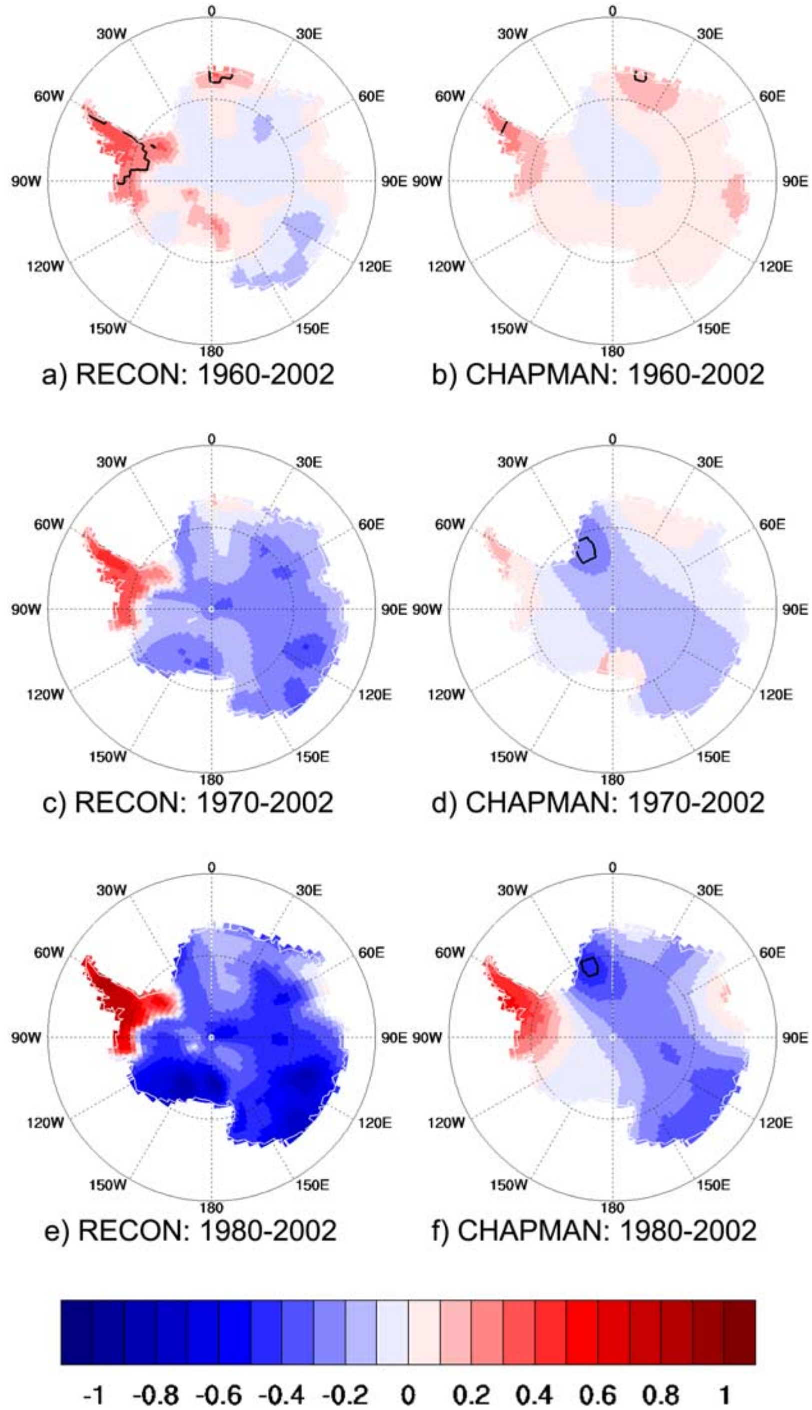

Figure 9. Spatial plots of the temporal trends (K decade^{-1}) of annual near-surface temperature for three different periods: (a and b) 1960–2002, (c and d) 1970–2002, and (e and f) 1980–2002. Figures 9a, 9c, and 9e are from RECON, and Figures 9b, 9d, and 9f are from CHAPMAN.

1960–2005 monthly near-surface temperature trends in Figure 10 indicate a slight, statistically insignificant warming overall, with little seasonal variability. The exception is strong warming on the Antarctic Peninsula during the winter months that has been linked to regional decrease in sea ice extent and in the length of the sea ice season [*Jacobs and Comiso*, 1997; *Parkinson*, 2002; *Zwally et al.*, 2002; *Vaughan et al.*, 2003]. The 1970–2005 trends (Figure 11) are in general more negative than the 1960–2005 trends during the summer (DJF) and autumn (MAM) months, consistent with the recent strengthening of the SAM, mainly in these two seasons. However, the trends are not as strong and spatially homogeneous as might be expected considering the robust relationship between the SAM and Antarctic temperature variability [*Schneider et al.*, 2004; *van den Broeke and van Lipzig*, 2004]; that is, one might expect

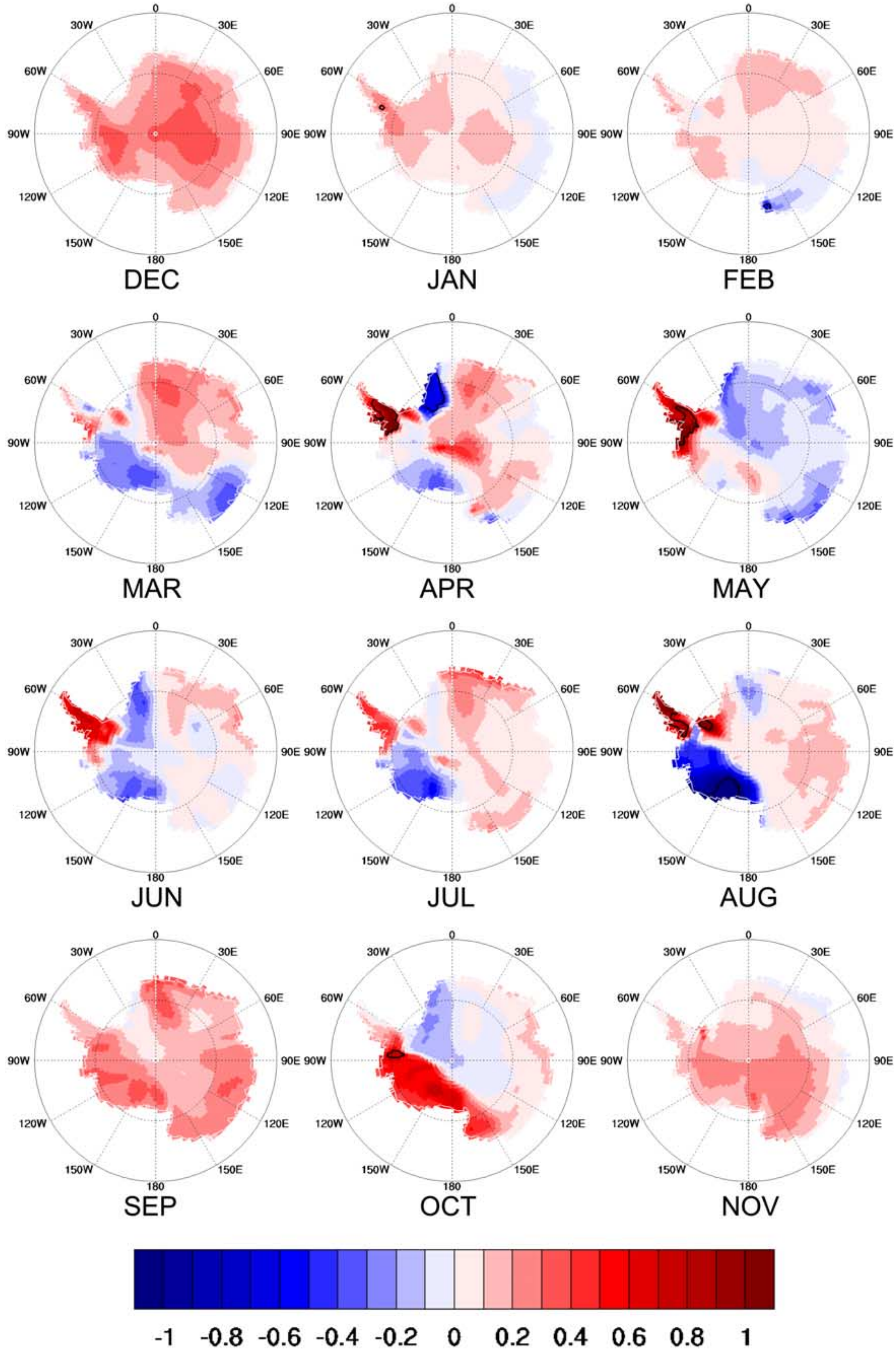

Figure 10. Spatial plots of the temporal trends (K decade^{-1}) of monthly near-surface temperature for the period 1960–2005 from RECON.

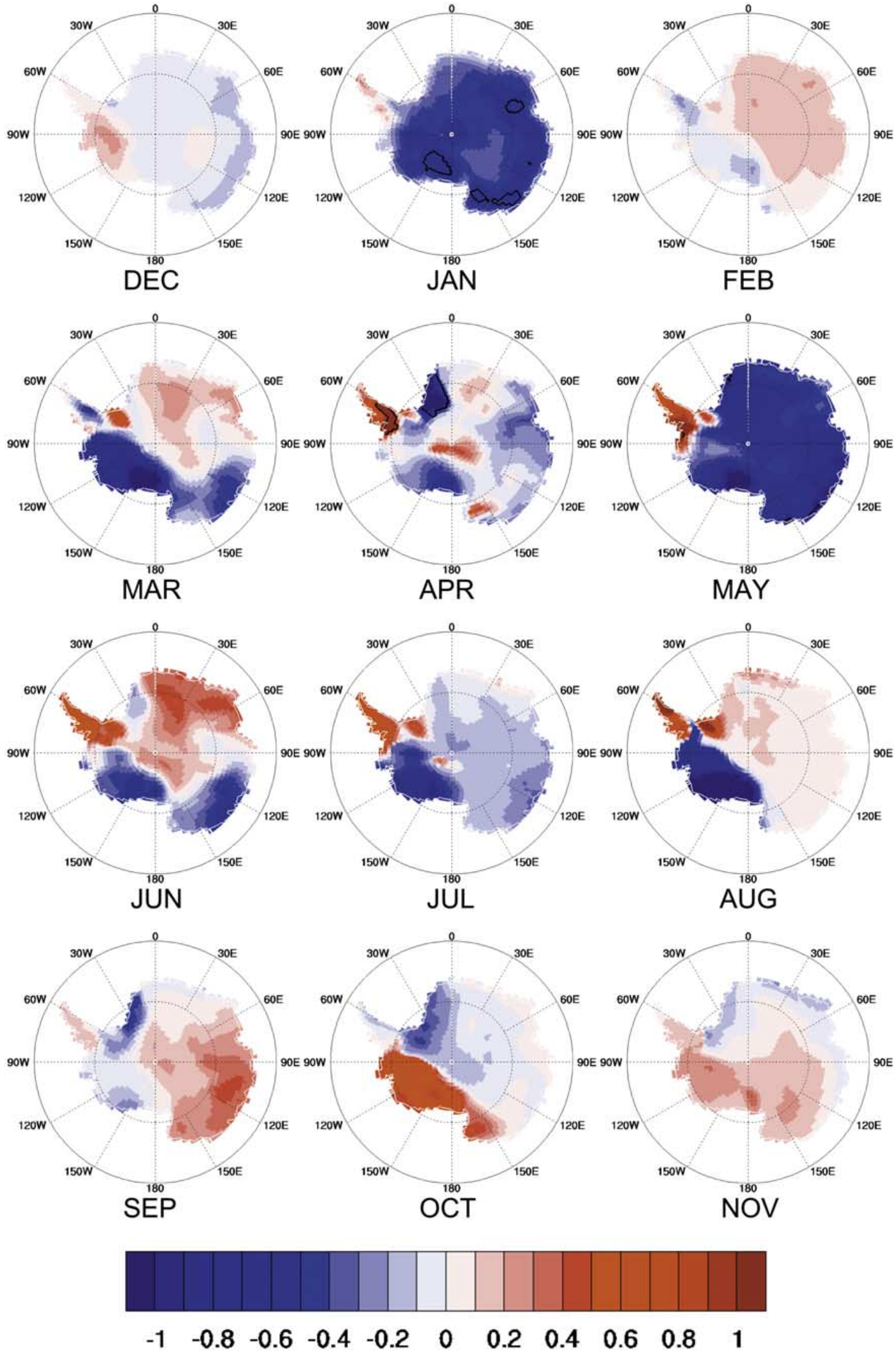

Figure 11. As described in Figure 10 but for the period 1970–2005.

the DJF and MAM trends to be more widely negative in the presence of an upward trend in the SAM. Examination of Figure 1 suggests that the SAM trends that began in ~1965 have leveled off in DJF and MAM, and have perhaps even been slightly downward in DJF, since the mid-1990s.

[29] To examine whether the recent leveling off of the SAM has impacted temperature trends, plots of the 1970–2000 monthly near-surface temperature trends were examined (i.e., the data presented in Figure 11 were shorted by 5 years; not shown). Compared to the 1970–2005 period shown in Figure 11, the signature of the SAM during 1970–2000 is more strongly manifested in the results. The summer and autumn months have stronger negative near-surface temperature trends (or weaker positive trends), consistent with the strongest positive SAM trends during these two seasons through the mid-1990s (Figure 1). Conversely, the winter months have stronger positive (or weaker negative) near-surface temperature trends for the 1970–2000 period compared to 1970–2005, a result that is also consistent with the observed SAM variability (Figure 1); the winter SAM trends are modest until the late-1980s, and continually strengthen through the 1990s.

[30] The results above suggest that the recent leveling off of the SAM (mainly in summer and autumn) since the mid-1990s is now having an influence on the long-term near-surface temperature trends. To examine whether this is true, spatial plots of the temporal trends of monthly near-surface temperature anomalies for 1992–2005 are presented in Figure 12. The 1992–2005 period was chosen because 1992 is the first year the annual "running" SAM trends become negative (Figure 1b). Compared to the 1970–2005 near-surface temperature trends (Figure 11), the 1992–2005 trends are quite different. For example, the 1992–2005 trends are mainly positive in the summer and autumn months (December–May), but they are mainly negative from 1970–2005. This strongly suggests that the overall leveling off of the SAM since the mid-1990s has influenced Antarctic temperatures in a manner that has caused net warming over the continent since 1992. To examine the net impact, the spatial plot of the temporal trends of the annual near-surface temperature for 1992–2005 is shown in Figure 13. Positive, statistically insignificant temperature trends are present over most of the continent (Figure 13a). In West Antarctica, strong and statistically significant cooling trends are evident, supported by the observed downward trend at Byrd Station AWS since 1992 (Figure 3). Because portions of the Byrd record have been reconstructed, the negative temperature trends may be viewed with skepticism. The 1992–2005 annual trends are thus plotted for the RECON_NOBYRD record to test the sensitivity of the West Antarctic temperature trends to the Byrd record (Figure 13b). The region of cooling still exists after removing the Byrd record, but it is smaller and statistically insignificant. Additionally, Figure 13c indicates similar regions of cooling in West Antarctica and near Cape Adare (on the western side of the Ross Sea near 160°E), from the COMISO AVHRR data set.

[31] Other records were investigated to determine whether the temperature trends suggested for 1992–2005 in Figures 12 and 13 are realistic. The coastal cooling during January in West Antarctica along the Amundsen and Bellingshausen Sea coasts and on the Antarctic Peninsula is supported by satellite microwave observations of decreased melt extent [*Liu et al.*, 2006] and melt duration [*Picard et al.*, 2007] in that region during the same period. Conversely, *Liu et al.* [2006] and *Picard et al.* [2007] also show that summer melt has remained unchanged or slightly increased along most of coastal East Antarctica since the mid 1990s, consistent with the near-surface temperature increases in East Antarctica indicated in Figure 12 for DJF. Examination of temperature observations from the Cape King AWS (73.6°S, 166.6°E, not shown) confirms that statistically insignificant cooling is occurring (−0.39 K decade^{-1}, $r^2 = 0.13$) from 1989 to 2005, similar to the negative trends indicated in Figures 13a–13c near Cape Adare (160°E).

[32] Figure 14 shows the observed near-surface temperature trends from the 15 stations with continuous records from 1960 to 2005 that were used to create our RECON record. The trends are shown for three periods: 1960–2005, 1992–2005, and 1992–2006. The 2006 data became available after our reconstruction was performed using data through 2005. The 1992–2006 results are presented here to show that when calculated through 2006, the trends are nearly identical to those calculated through 2005; no strong cooling occurred after 2005. The trends from three additional stations with nearly complete records that were not used in RECON are also shown. Compared to the small, mainly positive trends over the longer 1960–2005 period, stronger positive trends occurred from 1992–2005 overall. Exceptions include slight negative trends near 0°E (Neuymayer and Novalarevskaja) and on the Ross Ice Shelf (Scott Base), and a strong negative trend at Byrd that is statistically significant ($p < 0.05$). Positive trends of about 1 K decade^{-1} have occurred at Davis ($p < 0.1$) and Mirny ($p < 0.1$) in coastal East Antarctica, and at Vostok ($p < 0.1$) and South Pole (not significant) in interior Antarctica from 1992–2005. The trends at stations along the rapidly warming Antarctic Peninsula (Faraday, Bellingshausen, and at nearby Orcadas) have also strengthened compared to the 1960–2005 period, although because of the large interannual variability the trends are only statistically significant for the 1960–2005 period. The pattern of positive trends over nearly the entire continent from 1992–2005 is in contrast to the typical "warm-Peninsula-cold-continent" pattern typical of strong SAM forcing [*Schneider et al.*, 2006]. The widespread temperature increases suggest that, in addition to the SAM, other factors have important impacts on Antarctic climate for the period after the SAM leveled off in the mid-1990s.

5. Conclusions

[33] A new near-surface temperature reconstruction for 1960–2005 that encompasses all of Antarctica is presented. It is concluded that the new reconstruction is useful for evaluating regional near-surface temperature variability and trends in Antarctica because of the following:

[34] 1. The new reconstruction is able to reproduce the monthly and annual near-surface temperature variability and trends compared to sixteen independent temperature records representing various climatic regions in Antarctica.

[35] 2. The new reconstruction compares well with other gridded temperature data sets [*Chapman and Walsh*, 2007; *Comiso*, 2000], providing additional confidence that all of the data sets are robust. The data sets agree that Antarctic-

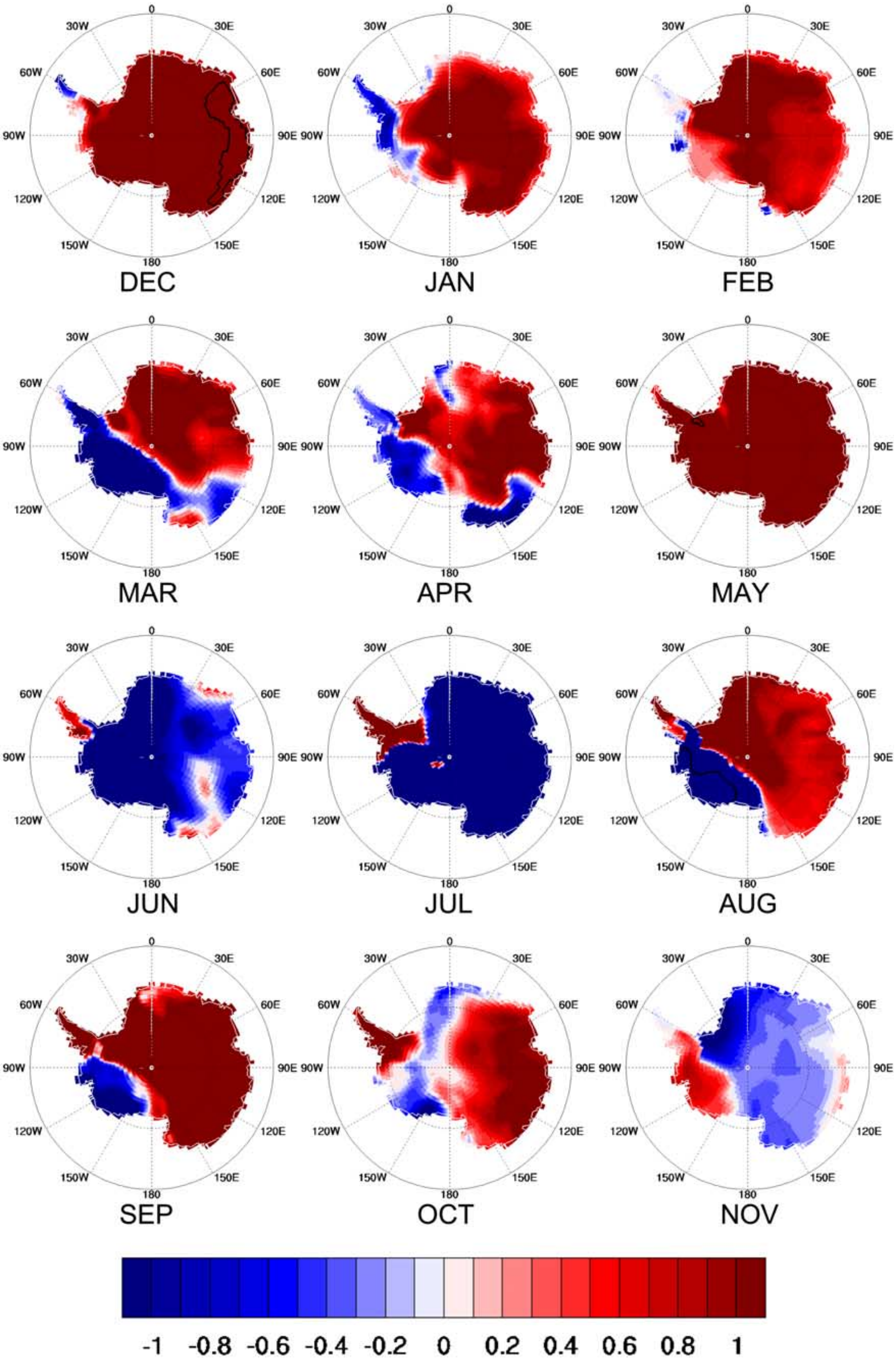

Figure 12. As described in Figure 10 but for the period 1992–2005.

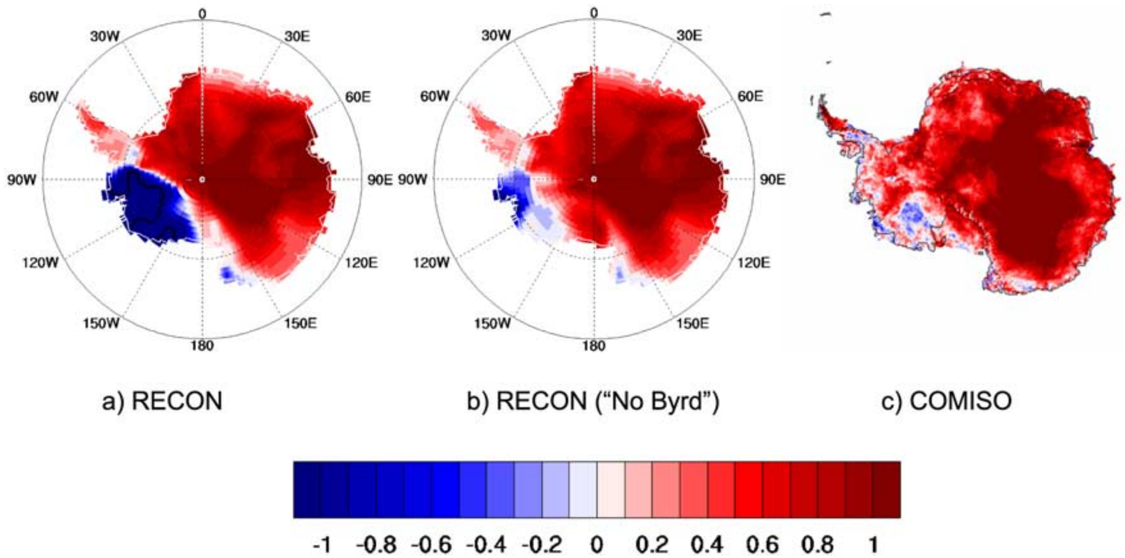

Figure 13. Annual near-surface temperature trends (K decade^{-1}) for 1992–2005 for (a) RECON, (b) the same as Figure 13a but the Byrd Station record was excluded when performing the reconstruction, and (c) the COMISO record based on AVHRR skin temperatures, which is completely independent of RECON.

averaged annual near-surface temperature trends are statistically insignificant for 1960–2002 and 1982–2001.

[36] 3. There is close agreement between the annual Antarctic near-surface temperatures from ERA-40 (which is used to create the background fields for the reconstruction), and the temperatures from a "synthetic" ERA-40 data set constructed from the technique used for the new reconstruction, indicating that the 15 near-surface temperature records used for the reconstruction are representative of temperatures across all of Antarctica.

[37] Compared to other data sets, the new reconstruction reproduces temperature especially well during the warm months, which is an important characteristic because during this season melt contributes to ice sheet mass loss [*Liu et al.*, 2006]. The enhanced skill of the new reconstruction during warm months, when localized phenomena affect temperatures in coastal regions, is likely due to the use of atmospheric model data to establish the background fields used in our methodology, as the model data account for atmospheric and topographic variability.

[38] A comparison of the spatial variability of the annual near-surface temperature trends is performed for eight data sets for their common period of overlap, 1982–2001. In the three "observed" data sets (our reconstruction, that of *Chapman and Walsh* [2007], and that of *Comiso* [2000]) the near-surface temperature trends are in broad agreement

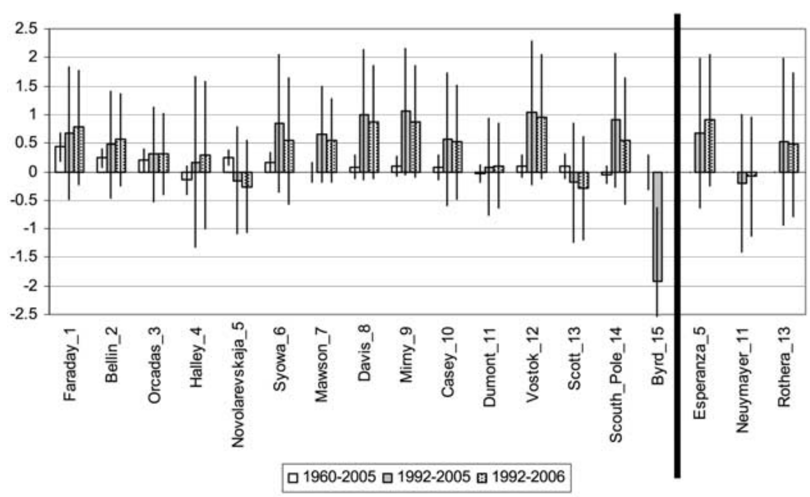

Figure 14. Observed temporal trends (K decade^{-1}) of near-surface temperature at the 15 stations used in the reconstruction (plus three additional independent stations) for three periods: 1960–2005, 1992–2005, and 1992–2006. The stations are shown in Figure 2 and described in Tables 1 and 2. Confidence intervals ($p < 0.05$) for the trends are indicated by the error bars

over the Antarctic Peninsula and the East Antarctic Plateau, but generally disagree over West Antarctica, a region that is nearly devoid of dependable observational records. The disagreement among data sets in West Antarctica emphasizes the pressing need to establish reliable long-term climate records there, especially considering increasing scientific interest in West Antarctic mass balance. The spatial variability of the 1982–2001 near-surface temperature in five model data sets shows inconsistent results, emphasizing the challenges faced by reanalyses over Antarctica. Although many of the near-surface temperature trends presented are not statistically significant, the overall reasonable agreement between data sets, as well as the large-homogenous regions that have trends of the same sign, suggest that the regional upward and downward trends occur by more than just random chance, and therefore have physical meaning.

[39] The spatial variability of monthly near-surface temperature trends in our reconstruction is strongly dependent on the season and duration for which trends are calculated. For example, trends for 1960–2005 indicate statistically insignificant warming over most regions in most months. During 1970–2005, the trends are more negative overall compared to 1960–2005, especially in summer and autumn. The dependency is consistent with trends in the SAM, which are positive annually, in summer, and autumn starting in about 1965, and have a net cooling effect on Antarctic near-surface temperatures. However, the SAM trends have leveled off since the mid-1990s, and temperature trends calculated for 1992–2005 indicate statistically insignificant warming over nearly all of Antarctica. These results suggest that a leveling off of the trends in the SAM since the mid-1990s has weakened the long-term Antarctic cooling trend that has existed since about 1970. Of particular note is warming at stations in interior and coastal East Antarctica of about +1 K decade^{-1} that is weakly statistically significant ($p < 0.1$) at three stations. The SAM undergoes considerable decadal variability [*Jones and Widmann*, 2004] and has also been linked to anthropogenic forcing [e.g., *Thompson and Solomon*, 2002; *Shindell and Schmidt*, 2004]. Therefore it is too early to speculate whether the recent leveling off of the SAM is a short-term fluctuation that will again continue upward in the future as projected by global climate models [*Fyfe and Saenko*, 2006], or whether the SAM trends will remain ‘‘neutral’’ for a longer period. Regardless, the intriguing question is now raised as to whether this large-scale warming is most closely linked to anthropogenic changes that will continue into the future, or whether a multidecadal fluctuation is impacting Antarctic climate.

[40] **Acknowledgments.** This research is funded by the National Science Foundation Office of Polar Programs Glaciology Program (grant NSF-OPP-0337948). The Japanese 25-year reanalysis was provided by the Japan Meteorological Agency and the Central Research Institute of Electric Power Industry (http://www.jreap.org). The ERA-40 data were obtained from the University Corporation for Atmospheric Research Data Support Section (http://www.dss.ucar.edu). The NCEP-DOE-II data were acquired from the National Oceanic and Atmospheric Administration's Climate Diagnostics Center (http://www.cdc.noaa.gov). Meteorological observations were downloaded from the READER database (http://www.antarctica.ac.uk/met/READER/), maintained by Steve Colwell of the British Antarctic Survey (BAS). Additional observations were obtained from Gareth Marshall of BAS (http://www.antarctica.ac.uk/met/gjma/) and from the National Snow and Ice Data Center (http://www.nsidc.org). David Schneider graciously provided his >100 year Antarctic temperature reconstruction for evaluation. Special gratitude is owed to the individuals who recorded the observations and the nations that support them, especially those individuals who are part of the AWS program at the Antarctic Meteorological Research Center at the University of Wisconsin-Madison. This paper is contribution 1363 of Byrd Polar Research Center.

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