A Synthesis of Antarctic Temperatures

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(Manuscript received 24 March 2005, in final form 2 November 2006)

ABSTRACT

Monthly surface air temperatures from land surface stations, automatic weather stations, and ship/buoy observations from the high-latitude Southern Hemisphere are synthesized into gridded analyses at a resolution appropriate for applications ranging from spatial trend analyses to climate change impact assessments. Correlation length scales are used to enhance information content while limiting the spatial extent of influence of the sparse data in the Antarctic region. The correlation length scales are generally largest in summer and over the Antarctic continent, while they are shortest over the winter sea ice. Gridded analyses of temperature anomalies, limited to regions within a correlation length scale of at least one observation, are constructed and validated against observed temperature anomalies in single-station-out experiments. Trends calculated for the 1958–2002 period suggest modest warming over much of the 60°–90°S domain. All seasons show warming, with winter trends being the largest at +0.172°C decade\(^{-1}\) while summer warming rates are only +0.045°C decade\(^{-1}\). The 45-yr temperature trend for the annual means is +0.082°C decade\(^{-1}\) corresponding to a +0.371°C temperature change over the 1958–2002 period of record. Trends computed using these analyses show considerable sensitivity to start and end dates, with trends calculated using start dates prior to 1965 showing overall warming, while those using start dates from 1966 to 1982 show net cooling over the region. Because of the large interannual variability of temperatures over the continental Antarctic, most of the continental trends are not statistically significant. However, the statistically significant warming over the Antarctic Peninsula is the strongest and most seasonally robust in the spatial patterns of temperature change.

Composite (11-model) global climate model (GCM) simulations for 1958–2002 with forcing from historic aerosol and greenhouse gas concentrations show warming patterns and magnitudes similar to the corresponding observed trends for the 45-yr period. GCM projections for the rest of the twenty-first century, however, discontinue the pattern of strongest warming over the Antarctic Peninsula, but instead show the strongest warming over the Antarctic continent.

1. Introduction

Various studies in recent years have presented evidence of warming over portions of Antarctica. These studies used station data, which are preferentially distributed over the Antarctic Peninsula and the coast of the continent. Among the studies to have utilized the station data are those by Schwerdtfeger (1976), Raper et al. (1984), Jacka (1990), Weatherly et al. (1991), King (1994), Jones (1990), Jacka and Budd (1998), King and Harangozo, (1998), Jones et al. (1999), van den Broeke (2000), and Vaughan et al. (2001). These studies are essentially unanimous in their finding that the Antarctic Peninsula has warmed since the 1950s, when many of the surface stations were established. The reason for the warming over the peninsula is unclear, however, and several possible mechanisms have been noted by Orr et al. (2004), Vaughan et al. (2001), and Turner et al. (2007). Variations of the atmospheric circulation, possibly influenced by changes in stratospheric ozone concentrations, appear to drive interannual and low-frequency temperature fluctuations in at least some of the coastal regions of Antarctica (Thompson and Solomon 2002). On interdecadal time scales, trends in Antarctic surface air temperatures are correlated with the intensity of the Southern Hemisphere “annular mode” of circulation, for which an association with stratospheric ozone trends has recently been reported (Thompson and Solomon 2002). There is some evidence that natural climate variability can also strongly influence the state of the Southern Hemisphere annular mode (Goodwin et al. 2004; Jones and Widmann 2004).
Turner et al. (2006) report significant midtropospheric warming for the past few decades using radiosonde observations, but the picture at the surface is not as clear. While surface observations show that the Antarctic Peninsula has warmed in recent decades, the corresponding trends over the remainder of the Antarctic continent are more problematic. Recent summaries of station data (Houghton et al. 2001, p. 117; Hansen et al. 2001, p. 23 595; Marshall 2002; Reynolds 1981; Scambos et al. 2000; Kejna 2003) show that, aside from the Antarctic Peninsula and the McMurdo area, one is hard-pressed to argue that warming has occurred, even at the Antarctic coastal stations away from the peninsula and McMurdo. Thompson and Solomon (2002, their Fig. 3) present maps of Antarctic surface air temperature trends for 1969–2000, indicating summer and autumn cooling over much of the continent, but only two data points can be considered “interior” locations on the Antarctic continent. Recent attempts to broaden the spatial coverage of temperature estimates have shown a similar lack of evidence of spatially widespread warming. Comiso’s (2000) satellite-derived estimates of temperature trends for January and July of the 1979–98 period show at least as much cooling as warming, while Doran et al.’s (2002) spatial interpolation based on an objective analysis showed a similar mix of areas of cooling and warming, with a preponderance of cooling in the summer season. However, the continent-wide temperature analyses in both studies are open to question. Comiso’s IR-derived temperatures from satellites are biased toward clear-sky conditions, and the trends in Comiso’s study were presented for January and July only. The validity of the spatial analysis procedure used by Doran et al. is dependent on the correlation length scales (CLSs) of the station temperatures, and specifically the length scales of the departures from normal temperatures at the various stations. The radius of influence used by Doran et al.’s analysis was approximately 2000 km. While the size of the influence region is of little concern when station reports are available from the vicinity of a pixel, the 2000-km radius of influence is highly questionable in data-sparse regions (Turner et al. 2002; Walsh et al. 2002). A key issue concerning the validity of the procedure used by Doran et al., and of the robustness of their conclusions about large-scale temperature variations, is the radius of influence used and whether it is justified by the length scales of temperature variations in the Antarctic.

One objective of this paper is a determination of the extent to which this type of objective analysis can yield meaningful results. CLSs can be evaluated using historical station data from Antarctica, and such evaluations are part of our analysis. However, the fact that the manned stations are almost all located in coastal regions, where open water (at least in summer) and coastal wind effects can be significant, calls into question their suitability for evaluations of CLSs over the interior of the continent. Additional data for this purpose are available from the Automated Weather Station (AWS) network (e.g., Shuman and Stearns 2001). The number of sites at which AWS units have been deployed since 1980 is now approximately 100 (http://amrc.ssec.wisc.edu/aws.html), and the number in operation simultaneously has been 20–40 in recent years. Temperature measurements are now available for record lengths ranging from several months to nearly 20 years at these sites, many of which are at inland locations. While engineering and logistical limitations result in temporal gaps in the records for some sites, the type of application described here does not require continuous records; rather, the key requirement is a sample of common years in the records of pairs of stations. The number of years must be sufficient for the evaluation of meaningful statistics (means, variances, and covariances), and we cite Comiso’s (2000) sensitivity analysis of Antarctic station temperatures showing that 10 years is a threshold for the evaluation of meaningful statistics.

In this study, a primary objective is the evaluation of trends over a 45-yr period using CLSs to enhance the information content of temperature measurements distributed irregularly in space and time. We pursue this objective by evaluating the spatially and seasonally varying CLSs of surface air temperatures reported at coastal and interior continental land stations, as well as ocean data points. Such an evaluation permits the construction of the following:

1) Gridded analyses of temperature and temperature anomalies on a monthly basis for the past several decades. Values are defined only for those areas in an analysis that can be justified by the use of a radius of influence no larger than the CLS.

2) Annual and seasonal maps of temperature trends over Antarctica and the nearby ocean areas, with areas of insufficient information for meaningful trend calculation identified on each grid. (The “anchor points” of these trend analyses will be points for which data are available in at least 70% of the number of months in the period of the analysis.)

The spatial and temporal limitations of the observation network deployed in the Antarctic set strict upper limits on the quality of our analysis. Indeed, the extent and quality of our monthly analyses vary with time as stations initiate observations and subsequently go offline during the 1958–2002 period. Nevertheless, these products provide enhanced depictions in the sense that
they 1) are valid for all cloud conditions and 2) augment the use of available information without unjustified interpolation or extrapolation.

2. Data

We have collected monthly surface temperature data for 460 locations in the Southern Hemisphere. The locations and color-coded data sources are indicated in Fig. 1. We utilize data from 19 manned surface observing stations from the World Monthly Surface Station Climatology (Spangler and Jenne 1990) network located on the Antarctic continent. With the exception of the South Pole and one Antarctic plateau location, data from the manned surface observing station network (Fig. 1; red) are confined to coastal locations and the Antarctic Peninsula.

Yellow locations in Fig. 1 indicate the positions of 73 AWSs deployed through support of the National Science Foundation Office of Polar Programs in remote areas of Antarctica in support of meteorological research and aviation operations (Keller et al. 2004). The AWS data are uplinked to the Argos Data Collection System onboard the National Oceanic and Atmospheric Administration series of polar-orbiting satellites. While the AWSs in Antarctica fill some of the voids of the manned surface station network, they are also preferentially deployed near coastal locations, specifically ice shelf locations, and the Antarctic Peninsula. However, several of the AWSs have been strategically placed on the Antarctic plateau and have proven crucial to constructing the temperature analyses presented here.

For ocean and coastal areas, we utilize gridded sea surface temperatures (SSTs) obtained from the International Comprehensive Ocean–Atmosphere Dataset (ICOADS; Worley et al. 2005). Global marine observations made between 1784 and 2002 (the currently available period of record), primarily from ships of opportunity, have been collected, edited, and aggregated by ICOADS statistically into 2° latitude × 2° longitude resolution grids for each month of each year of the period. We have averaged the original 2° × 2° monthly summaries into 4° latitude × 6° longitude grids to more closely match the spatial density of the land-based surface data sources and to increase the temporal likelihood of observations for each grid cell in the data-sparse Antarctic region (Fig. 1; blue). While the northern cutoff of our derived analyses is 50°S, inputs into our analyses may include any ICOADS gridded data south of 20°S provided their inclusion is justified by their CLSs.

Monthly anomalies from 1961–90 means are calculated for each of the 460 time series. The inventory of temperature anomalies (Fig. 2) shows the temporal characteristics of the temperature anomaly data for each data source. Monthly anomalies, color-coded when and where available, show a general increase in frequency over time with a few abrupt increases (decreases) coinciding with the start (end) of regional observing initiatives. Since our analyses are constructed using these temporally varying inputs, and assuming that the quality of analyses increases with increased availability of data, our derived analyses likely improve in quality and become more comprehensive throughout the first half of the 1958–2002 record. While the AWS data come online relatively late in the record and show varying levels of temporal density and record lengths, the remote locations of the AWSs make this data indispensable for this project. Some of the land station data records begin during the mid-1940s but a majority of the stations start reporting during International Geophysical Year 1958. Since the land-based station temperatures form the core of our analyses over Antarctica, our trend calculations will begin in 1958 and end in 2002. In addition to this inventory plot, we include an interactive map of the station locations and corresponding temperature anomaly time series for each land-based station used in this analysis at the project Web site (http://igloo.atmos.uiuc.edu/ANTARCTIC/).
The ICOADS inventory shows sporadic data prior to 1958, a significant improvement in coverage post-1958, and another discontinuous increase in 1979, the year of the First Global Atmospheric Research Programme (GARP) Global Experiment (FGGE). An annual cycle can be seen in the banded nature of the ICOADS observation density. More observations are available during the austral summer months [December–February (DJF)] than in winter [June–August (JJA)] when sea ice extent over much of the region curtails shipping operations. Given the relative continuity of the coverage for most months from 1958 onward, there is a good basis for starting our primary analyses in 1958.

The ICOADS archive contains observed surface air temperatures and SSTs. While the two variables show similar temporal and spatial observation densities over the high-latitude Southern Hemisphere, we chose to include the SST data rather than the surface air temperature data in our analyses for two reasons. First, Rayner et al. (2003) report observation biases in the daytime ICOADS surface air temperatures. Second, our diagnostics indicate that SSTs are more highly correlated than the ICOADS air temperatures with nearby land surface station air temperatures, indicating that the SSTs are likely better integrators of recent climatic conditions than the infrequently sampled surface air temperatures of the Southern Ocean.

Finally, we submitted the data from each observation location through an objective search for potential changepoints or discontinuities in the time series. We followed the procedure of Lund and Reeves (2002) in our search for undocumented changepoints by iteratively separating the time series into two segments of varying duration and evaluating the means and trends.
for each segment separately. The means and trends of the two subsets are compared and statistically evaluated for a changepoint in the mean and/or trend of the dataset. Using this procedure we isolated seven potential changepoint dates in the land station and AWS time series and several more from the ICOADS time series. The grid points for the ICOADS data that triggered the changepoint detection flag are located near the seasonal sea ice zone and, as such, observations in these time series are temporally sporadic. We removed these grid points from our analyses. We subjectively evaluated the time series of each of the land-based station locations that indicated potential changepoints to determine if these changepoints were data artifacts (station moves, etc.) or part of the climate record. In one case, the changepoint occurred near a station move and the data were removed from our analyses. In the six other cases, the potential changepoint was not near a station move but was indicated at or near a time of an anomalous warm winter month that could be characterized as a data outlier. For three of the potential candidates in the later half of the record, Special Sensor Microwave Imager (SSM/I) ice concentrations for the corresponding month showed anomalous low concentrations and/or open water near the coastal station location that could explain the outlying 6°–10°C positive temperature anomaly. We have observed similar monthly temperature anomalies from Arctic stations that have warmed 10°–15°C in recent winter months when sea ice is not present nearby but historically has been. We concluded that it would be prudent to include these station time series in the analyses since the outlying temperature anomaly responsible for triggering the changepoint detection algorithm was physically plausible. For the three changepoints (positive anomaly outliers) that occurred prior to when the SSM/I ice concentration data were available, we also retained the time series in our analyses. We reason that, for a lack of evidence to the contrary, those anomalies are just as likely accurate given that they also occurred at coastal station locations. We document the time series flagged as potential changepoints and the series removed from our analyses at the project Web site (http://igloo.atmos.uiuc.edu/ANTARCTIC/).

3. Results of observational synthesis

a. Correlation length scales

We use station pair correlations, together with least squares best-fit curves, to evaluate and map the spatial fields of each month’s CLS, defined as the distance over which the correlation between a station’s temperature anomaly and surrounding anomalies exceeds 1/e, or approximately 0.37. The spatial distribution of temperature data in the high-latitude Southern Hemisphere presents unique challenges in determining CLSs. Station density as a function of distance for most Antarctic points is far from uniform. For the South Pole location, for example, large distances (1000–2000 km) separate AWS, coastal land stations, and ICOADS data locations from the South Pole. A preponderance of data at relatively large distances from the Pole and the paucity of data at shorter and mid-distances results in a curve fit to the raw station pair correlations that is influenced too strongly by the large number of data points at large distances (and a lack of stations nearby). The resulting curve is biased toward the generally lower correlations at greater distances and the derived CLS is also biased artificially low. We address this type of bias by averaging the correlation-distance pairs into 100-km bins and computing a mean distance and correlation for each bin. In this way, equal weighting is given to correlations at all distances in the fitted curve. The binned values for the South Pole example (our worst-case scenario) are shown as red squares in Fig. 3. An exponential curve is fit to the binned data (red line) and the CLS is determined (dashed black lines) from the fitted curve.

Fig. 3. Schematic demonstrating the construction of the CLS of monthly surface air temperatures at the South Pole. Station pair correlations are plotted as a function of separation distance (small black dots) and averaged into 100-km bins (red squares). An exponential curve is fit to the binned data (red line) and the CLS is determined (dashed black lines) from the fitted curve.
Fig. 4. Monthly CLSs for the high-latitude Southern Hemisphere ranging from 500 to 700 km (blues), to more than 1300 km (reds and violets).
weighted by the inverse cubed of the distance from their corresponding locations. Figure 4 shows the resulting spatial maps of monthly CLS and the data locations used in their calculations. CLS values for the summer months (DJF) are generally larger (900–1300 km) than those in winter (JJA) months (600–1300 km). The lowest CLS values, indicated by shades of blue in Fig. 4, occur during the winter months over regions generally sea ice covered. The seasonal void and sporadic coverage of temperature observations due to the winter expansion of sea ice surrounding the Antarctic continent likely lower the temperature cross correlations in the marginal ice zone. Unfortunately, these are precisely the regions and seasons where large CLS values would be the most useful, expanding the influence of the sporadic temperature observations to proximal regions in the analyses. CLS values at the Pole, however, are some of the largest in the domain, providing justification for extending the influence of the anomaly data large distances in the analyses.

b. Gridded analyses

Using the CLS, we have assembled $1^\circ \times 1^\circ$ gridded monthly analyses of surface air temperature anomalies for the period 1958–2002 for the high-latitude Southern Hemisphere domain (50°–90°S). The temperature anomalies are relative to the 1961–90 mean. A natural neighbor analysis was performed using the anomaly data available for each month. Details of the natural neighbor interpolations are found in Sibson (1981), but we summarize its application here.

Natural neighbor interpolation is a weighted interpolation based on a Thiessen polygon network of data locations (Fig. 5)—one Thiessen polygon for each data location. Each polygon is formed by perpendicular bisects of lines representing the shortest distance between each data location pair. Intuitively, each Thiessen polygon surrounds an area that is closer to the enclosed data location than any other data location. Additionally, two points are considered natural neighbors if they share an interface that is equally close to each point and all other points are no closer. The weights used in the natural neighbor interpolation are based on the subset of local coordinates which define the “neighborliness” or amount of influence any data location will have on the computed value at the interpolation point. The neighborliness is a function of the area of influence of the Thiessen polygons of the surrounding data locations. A location whose value we would like to interpolate is placed into the network of Thiessen polygons and the network is recast. Only those data locations whose polygons have been altered by the addition of the interpolation point are used in interpolating the new value. The weights are defined as the area shared by the Thiessen polygon defined by the interpolation point, and the Thiessen polygon defined by each point before the interpolation point is added. The greater the common area, the larger the weight or influence the original data location has on the interpolated value. When complete, the interpolated surface mimics a taut rubber sheet stretched to meet the data. Because the resulting function is continuous everywhere, has a continuous slope everywhere (except at the data themselves, where the analysis results should be identical to the input data) and the natural neighbor algorithm’s adaptability to varying spatial densities of input data, we consider the natural neighbor approach to be superior to the Cressman analysis technique for this application. We have modified the standard natural neighbor approach by using the spatially and seasonally varying CLS to limit the analyses to locations within the corresponding CLS radius of a valid observation, and we flag all regions outside the radius of influence of all data locations as “undetermined.”

Analyses produced by interpolation procedures often suffer from excessive smoothing of the original data. We chose the natural neighbor algorithm over a Cressman analysis technique because it produces no smoothing of the analysis at the known observation (anchor) points. Some limited smoothing related to the spatial resolution of the grid cells in the analysis remains, however. In Fig. 6 we plot the observed temperature anomalies (input data) as a function of the derived-analysis anomaly (output data) for the closest corre-
sponding grid point. These relationships are plotted for four points representing distinct geographic/data source regimes in our analyses: an AWS location, the South Pole, the Antarctic Peninsula, and an ocean point (Figs. 6a–d, respectively). Correlation coefficients between the observed temperature anomaly and corresponding analysis temperature anomaly are noted in the lower right of each panel. The interior continent points (Figs. 6a,b) benefit both from smaller analysis grid cells (i.e., the $1^\circ \times 1^\circ$ latitude–longitude grid converges at the pole), and they are located at significant distances from other data source points whose weighting could contaminate their analysis result. These analysis points near the South Pole and the AWS grid point correlate with their corresponding observed data at 0.954 and 0.984, respectively. The Antarctic Peninsula and ocean location analysis grid cells are larger and therefore may not collocate as well with their respective observation locations. In addition, the proximity of many more stations within the respective CLS radius can influence the analysis at these points by effectively smoothing the result. The latter is especially true for ocean points (Fig. 6d) where the spatial density of our observed data is highest. Nevertheless, the correlations at the coastal/ocean points exceed 0.8.

A parallel comparison of the same data points from analyses constructed using a Cressman analysis procedure shows a similar relationship between the analysis and observed data but the correlation coefficients average 0.2 lower than the natural neighbor algorithm (not shown). Continental points correlate at about 0.85 and the peninsula and ocean points correlate at 0.75 and 0.53, respectively. Even with highly nonlinear weighting, the Cressman technique degrades the analy-
ses via influences from distant data. Increasing the CLS threshold above $1/e$ in an attempt to decrease the CLS and limit contamination from distant points is a viable option, but the sparseness of the observing network in the high-latitude Southern Hemisphere would introduce many more “undefined” gaps in the resulting analyses.

The method to determine CLSs used here assumes that the derived correlation function is isotropic. That is, a single correlation can be determined for any distance from a given location. Figure 3 shows that this is definitely not the case, at least for the South Pole. For example, the station pair correlations have a very wide spread for most distances beyond 1000 km. While it is likely that the South Pole point is one of the most egregious violators of this assumption, it is nevertheless most likely true for every point in the analysis. Thus, we have implemented an independent validation procedure in which we repeat the analysis once for every land station, AWS, and every second ICOADS grid cell location. At each of these iterations we leave out one of the station/grid cell time series from the analysis procedure and produce a corresponding reanalyzed time series to compare against the original data time series. In many cases, due to a lack of neighboring data sources, omitting a data source/location from the analysis results in a new undefined region. Nevertheless, we proceeded with the analysis for these grid points to compare with their original time series. Figure 7 shows the correlations between the observed temperature anomalies and those created in the validation analysis (omitting the original data). We composite the results into averages for 1) locations near the coast, 2) interior Antarctic stations, and 3) grid cells originally containing ICOADS data. The results are also segregated by locations that have a valid reanalysis grid cell created (within a CLS of another point; Fig. 7a), and those recharacterized as undefined (outside a CLS radius of influence in the reanalysis; Fig. 7b). The length of the bars in Fig. 7 shows the range of correlations produced by the validation reanalysis versus corresponding original values while horizontal lines within the bars indicate the means. Mean correlations are highest for the ocean grid points (~0.8) and lowest for the Antarctic interior grid cells (~0.6). Validation analysis time series for coastal locations correlate with corresponding observed time series at roughly 0.7 but range from 0.45 to near 0.95. In all geographic regimes, the correlations drop by 0.2–0.3 and the ranges broaden considerably for the interior and ocean regimes when comparisons include locations redefined as undetermined. Spatial maps made by performing a Cressman analysis on the validation correlations (Fig. 8, left) indicate the highest correlations near the South Pole, Ross Sea, Antarctic Peninsula, and over much of the coastal locations of the Antarctic continent. Correlation minima occur near the Amundsen Sea between the Ross Sea and the Antarctic Peninsula, and to a lesser degree, over the eastern continental interior and the seasonal sea ice zones. The pattern indicates that validation reanalyses correlate higher with the original analyses when they are close to a known data anchor point. The corresponding pattern of root-mean-square error (RMSE) of the validation experiment (Fig. 8, right) closely mirrors the spatial pattern of correlations. The largest errors are found in the data-sparse region between the Ross Sea and the Antarctic Peninsula and the seasonal sea ice zones. Relatively small errors occur over the Antarctic Peninsula, the South Pole, and coastal regions of the Antarctic. Mean biases (not shown) are small (less than ±0.3°C) and appear to be randomly distributed across the domain. The absolute magnitudes and standard deviations of the biases, however, follow the same general pattern of the correlations and RMSE. Together, these spatial patterns guide potential users to the geographic regions of the temperature analyses that can be most trusted, and alternatively, to those locations that should be used with caution. In addition, these validation
analyses may be interpreted as guidance broadly highlighting locations that would benefit most from additional in situ data streams.

We compare the gridded analyses with corresponding surface air temperature fields from the well-documented National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalyses. Twelve-month running mean time series of (top) area-weighted correlations, (middle) RMSE, and (bottom) biases for 50°–90°S are shown in Fig. 9. Biases are defined as differences of NCEP–NCAR reanalysis temperatures from our analyses (analyses − NCEP). The time series show that mean correlations improve from about 0.3 to more than 0.6 from the early part of the record to the mid-to-late 1980s. Similarly, RMSE values decline from 1.7°C in the late 1950s to 1.3°C in the mid-1980s. Surface station data from many of the same locations used in our analyses are assimilated into the NCEP–NCAR reanalyses. In data-void regions, both sets of analyses are not constrained by anchor points. Given the general increase in observation frequency from relatively few in the 1950s to a maximum in the late 1980s and early 1990s, the general pattern of historical correspondence of correlation and RMSE illustrated in Fig. 9 is consistent. The area-weighted biases (Fig. 9, bottom) of our analyses relative to the corresponding NCEP–NCAR reanalysis fields are generally positive in the first half of the
record and negative in the second half. This temporal history of biases implies that area-weighted linear trends based on NCEP–NCAR reanalyses for the same domain are more positive than those computed from our temperature analyses.

To further document the biases of our temperature analyses relative to the NCEP–NCAR reanalyses, Fig. 10 illustrates the spatial pattern of the biases of annual mean temperature anomalies for the 1958–2002 period (Fig. 10a), and the first (Fig. 10b) and last (Fig. 10c)
halves of the record. In general, the biases are fairly small. For the 1958–2002 record, bias magnitudes do not exceed 0.3°C anywhere in the domain, but biases can exceed 0.5°C in the shorter half-record subsets, especially the early period of 1958–80. Regions of the domain with the strongest and largest bias features (both positive and negative) appear to be confined to the data void regions of 1) the seasonal sea ice zone and 2) the interior eastern continental Antarctic. Seasonal plots of the temperature biases (not shown) indicate that the pattern shown in the annual fields is predominantly a summer (DJF) feature. Unrealistic extrapolations in our analyses of coastal temperature anomalies over the adjacent ocean waters that are constrained to near-freezing temperature by thawing and/or recently thawed sea ice likely cause the relatively large summer biases. We do not, however, rule out bias contributions from unrealistic surface air temperature estimations by the NCEP–NCAR reanalysis over these notoriously problematic regions. For example, Turner et al. (2006) report that warming of coastal radiosonde temperatures above the surface exceeds the warming near/at the surface. Since surface air temperatures in the NCEP–NCAR reanalysis are extrapolations of temperatures calculated and assimilated at higher vertical levels, the discrepancy between the surface trends (and therefore analyses) described here and those from the NCEP–NCAR reanalysis is consistent.

Additionally, surface air temperatures over the Southern Ocean depend strongly on the presence or absence of sea ice. For the early record, sea ice inputs into the NCEP–NCAR system rely on a sparse observational database and/or climatological ice conditions since the majority of the period is presatellite era. A climatological sea ice extent derived during the satellite era may differ substantially from actual surface ice conditions for 1958–80, potentially impacting the NCEP–NCAR reanalysis surface temperatures over the seasonal sea ice zones. Nevertheless, these biases point to a need to further refine CLS definitions and/or analysis procedures (perhaps as a function of surface type) in future analyses for domains including multiple surface types.

c. Observed time series and trends

Using the gridded fields obtained by the natural neighbor approach described in section 3b we plot time series of the area-weighted annual and winter (JJA), spring [September–November (SON)], summer (DJF), and autumn [March–May (MAM)] seasons for the 60°–90°S domain in Fig. 11. The interannual variability in temperatures is largest in the winter and smallest in summer, but some of the largest seasonal departures from normal occur in the spring and autumn seasons. Linear trends of annual and seasonal mean Antarctic temperatures (also shown in Fig. 11) are all positive but vary in magnitude. The 45-yr linear temperature change is largest in winter (+0.776°C) and spring (+0.405°C), and smallest in summer (+0.193°C) and autumn (+0.179°C). These temperature changes correspond to linear trends of +0.172°C decade⁻¹ (winter), +0.090°C decade⁻¹ (spring), +0.045°C decade⁻¹ (summer), and +0.040°C decade⁻¹ (autumn). The 45-yr (1958–2002) linear temperature change of annual mean Antarctic temperatures is +0.371°C with a corresponding trend of +0.082°C decade⁻¹.

Spatial patterns of gridded linear trends (°C decade⁻¹) of annual mean surface air temperature for the period 1958–2002 are presented in Fig. 12. Linear trends that exceed the 95% statistical significance threshold are indicated with single hatching, and trends exceeding the 99% statistical significance threshold are denoted with crosshatching. Trend significance is estimated using a Student’s $t$-test evaluation that assumes statistically independent or temporally unrelated data points. Our seasonal and annual time series are not independent, however, and show some weak autocorrelation (generally <0.3) over much of the domain. We use the method of Santer et al. (2000) to determine an “effective sample size” for each time series and modify the $t$-test parameter accordingly. In this method, as the autocorrelation of a detrended temperature series increases, the effective sample size decreases and the confidence interval broadens (uncertainty increases). The increase in uncertainty for an autocorrelated series results in fewer statistically significant trends than if the autocorrelation in the series is ignored.

Annual trends for 1958–2002 indicate that more than 70% of the domain has experienced slight warming. The greatest warming is centered on the Antarctic Peninsula with values exceeding 0.3°C decade⁻¹. While these warming rates indicate a warming of more than 1.3°C over the 1958–2002 period, they are relatively small when compared to some Northern Hemisphere land areas (Chapman and Walsh 1993, updated at http://arctic.atmos.uiuc.edu), which have rates of warming more than twice this magnitude. Regions of slight cooling include the central Antarctic continent (not statistically significant) and the span of the Southern Ocean between the South African coast and Antarctica (significant). Statistically significant warming is confined to the Antarctic Peninsula and a small region along the eastern coast of the continent. Temperature
Fig. 11. Annual and seasonal mean time series and linear trends of area-averaged surface air temperature anomalies for 1958–2002. Means shown are for the Antarctic domain of 60°–90°S.
trends over the remainder of the Antarctic continent do not exceed significance thresholds. A larger fraction of the Southern Ocean has seen significant warming over the past 45 years than have the land/ice masses.

We show the seasonal breakdown of the 1958–2002 trends in Fig. 13. Monthly trend maps can be seen online (at http://igloo.atmos.uiuc.edu/ANTARCTIC/TRENDS/). Areas of warming and cooling are found during all months and seasons. The Antarctic Peninsula exhibits warming throughout the entire year, with the strongest warming occurring during winter (JJA) months. The Southern Ocean south of Africa has warmed considerably in summer and autumn, but has cooled even more during the winter and spring. Regions exhibiting statistically significant temperature trends on the Antarctic continent are confined to the warming over the peninsula for winter, summer, and autumn; a small area of significant coastal cooling east of the peninsula in autumn; and a significant springtime warming near the Adelie Coast. As with the annual trends, significance thresholds are more often exceeded over the Southern Ocean than continental Antarctica.

Figure 14 summarizes the area-averaged mean temperature change (1958–2002) for each calendar month compositied into ocean-only areas (blue), land-only areas (gray), and total area (black), for the 50°–90°S region. Antarctic land temperature trends are positive in all months with the exception of October, and the month-to-month variability of the land-only trends is much greater than the ocean-only trends. Seasonal values of ocean-only, land-only, and the total area trends peak in the winter months and are near their minimum in autumn (April), but other minima in April and October complicate the message of seasonal change in the Antarctic.

In section 1, we highlighted recent trend work from a variety of sources that document cooling over the interior Antarctic continent. The apparent inconsistency with trends presented here is explained by different beginning and end dates (and corresponding record lengths) used in the trend analyses. To illustrate this point, we calculate trends using our gridded analyses for 1969–2000 using only the months December–May (Fig. 15b) to compare directly to the published Antarctic station trends of Thompson and Solomon (2002, their Fig. 3, bottom; Fig. 15a). Trends made using the years chosen by Thompson and Solomon are comparable with strong cooling (>1°C in many areas) over the majority of Antarctica and modest warming over the Antarctic Peninsula for both data sources. Apparently, extending the period of the trend computations 11 yr back and 2 yr forward can dramatically impact the conclusions regarding recent climate change in Antarctica.

To further document the sensitivity of trends to the record length, Fig. 16 shows the area-averaged linear annual surface air temperature change for land-only (gray), ocean-only (blue), and total area (black) for the 50°–90°S domain using a range of starting years and record lengths. Note that the ending dates of the trend calculations are fixed at 2002; therefore the temperature changes noted in Fig. 16 are based on varying record lengths. A corresponding plot showing trends (instead of change) in °C decade⁻¹ is provided online (at http://igloo.atmos.uiuc.edu/ANTARCTIC/TRENDS). Linear temperature changes calculated using starting dates prior to 1965 are positive for land-only, ocean-only, and total area. Starting dates of 1966–82 have negative trends for the Antarctic land-only trend points with mixed results for ocean-only and total area. Interestingly, most of the recent literature has determined trends using starting dates from the 1966–82 period and therefore show negative trends of varying degrees over much of Antarctica. Thompson and Solomon (2002) started their trends in 1969, near the minimum of the trends versus the starting-years plot of Fig. 16. Our trend analyses begin in 1958 based on the
abrupt increase in land station observation frequency during 1958. Figure 16 shows the choice of 1958 as a starting year produces the near-maximum possible positive trends over the Antarctic continent of the possible starting years. We note that the large fraction of negative temperature anomalies prior to 1958 seen in the time series for stations with available data suggests that trends from analyses including data prior to 1958 would likely reveal positive trends at least as large as those starting in 1958.

4. Trends simulated by global climate models

To place the observed trends into the broader context of the climate change debate, we compare trends based on our observation analyses with those simulated
by global climate models (GCMs). Similarities of trends from GCM output simulated using historic solar, greenhouse gas, and aerosol forcing to observed trends for the same period may add credence to our ability to

Fig. 16. Area-averaged linear changes in annual mean temperature plotted as a function of starting year for 50°–90°S (black), land-only (gray), and ocean-only (blue) areas. Ending date of the trend calculations are fixed at 2002. Starting dates, and therefore record lengths, vary from 1958 (45-yr record) to 1993 (10-yr record).

Fig. 17. Eleven-model composite annual trends of surface air temperature for 1958–2002 as simulated by the GCMs used in the IPCC AR4 forced by historic greenhouse gas concentrations. Significant trends are indicated by hatching (95% = single hatching; 99% = crosshatching).
simulate the present, and hence, future climate. Eleven-model composite annual trends of surface air temperature simulated by the state-of-the-art models used in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) with historic forcing for the 1958–2002 period are shown in Fig. 17. Trends and significance parameters are computed and displayed identically to the corresponding observed trends from section 3. The model outputs used here are listed in Table 1 along with a list of the modeling centers that incorporate historic stratospheric ozone forcing into their twentieth-century simulations. (Details of all forcing for the models available online at http://www-pcmdi.llnl.gov/ipcc/about_ipcc.php.)

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<td>Institut Pierre-Simon Laplace (IPSL)/Laboratoire des Sciences du Climat et l’Environnement (LSCE), France</td>
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simulate the present, and hence, future climate. Eleven-model composite annual trends of surface air temperature simulated by the state-of-the-art models used in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) with historic forcing for the 1958–2002 period are shown in Fig. 17. Trends and significance parameters are computed and displayed identically to the corresponding observed trends from section 3. The model outputs used here are listed in Table 1 along with a list of the modeling centers that incorporate historic stratospheric ozone forcing into their twentieth-century simulations. We caution that there are many forcing differences between the model simulations in addition to the stratospheric ozone, but we highlight this issue given the unique interaction of stratospheric ozone on the Antarctic climate. Forcing details for the individual models can be found online (at http://www-pcmdi.llnl.gov/ipcc/about_ipcc.php). There are striking similarities between the trends produced by the GCMs and the observed annual trends (Fig. 12). Similarities include the small region of relatively strong warming over the Antarctic Peninsula and Ross Ice Shelf, the neutral or slightly negative trends over the sea ice-covered regions of the Southern Ocean, and the warming indicated near coastal Antarctica. As with the observed trends, significant continental warming is simulated over the Antarctic Peninsula. The models, however, simulate additional significant warming over the Ross Sea, the central Antarctic continent, and scattered regions along the east and west coasts. The models simulate a significant warming over most of the Southern Ocean, with the exception of the seasonally ice-covered region. Differences include an observed cooling in the central Antarctic continent and the Southern Ocean south of Africa (simulated as warming by the GCMs) and a neutral GCM-simulated trend over the eastern Antarctic plateau (Wilkes Land), which has warmed according to our observed analyses. In general, the areal coverage of simulated trends highlighted as statistically significant is greater than for the observed analyses because the simulated data represent composites of gridpoint output from 11 GCMs and therefore have less interannual variability than observed. In fact, the areal
fraction of trends flagged as significant in the individual models is similar to the observed for output from each individual GCM (not shown).

The similarities, noted in the annual trend maps, extend to the seasonal trend maps as well (Fig. 18 versus Fig. 13). The significant warming over the Antarctic Peninsula noted in the annual trends is strongest in the GCM-simulated winter months, as in the observed winter trends. Large regions of the Southern Ocean cool in the GCM-simulated and observed summer months. The seasonal patterns of change simulated by the GCMs show more geographic homogeneity, attributable, at least in part, to the fact that Figs. 17 and 18 are means (composites) of results from 11 models.

Despite some differences, the similarities between the simulated and observed trends for the past 45 years are notable enough to consider the future climate projected by the 11 GCMs in the Antarctic, if for no other reason than to identify whether the pattern of warming and cooling simulated for the last half of the twentieth century is projected to continue throughout the next century. Figure 19 shows the 11-model composite annual trends of surface air temperature projected by the models used in the IPCC AR4 for the twenty-first cen-

Fig. 18. Same as in Fig. 17, but for the (a) summer (DJF), (b) autumn (MAM), (c) winter (JJA), and (d) spring (SON) seasons.
tury (2001–2100) forced by the IPCC Special Report on Emissions Scenarios (SRES) A1B greenhouse gas concentration scenario. The warming over the entire domain is statistically significant, and the hatching is left off these panels of projected trends for clarity. The SRES A1B scenario is considered the “middle-of-the-road” scenario of the projected greenhouse gas concentration scenarios evaluated in the IPCC Fourth Assessment Report. The composite annual trends for the domain 50°–90°S show warming over the entire domain. The maximum warming occurs over the Antarctic continent and the Weddell Sea. Interestingly, there is no local maximum to the warming over the Antarctic Peninsula as in the observed and composite GCM output for the 1958–2002 period. Seasonally (Fig. 20), the projected temperature increases over the Antarctic continent are nearly the same in all seasons. The warming over the Weddell Sea is significantly larger in winter (JJA) and autumn (MAM) than in summer (DJF) and spring (SON), most likely due to significant decreases in regional sea ice coverage projected by most of the models. In contrast, ocean areas north of the seasonal sea ice edge have projected rates of warming that are the weakest in the domain.

The composite GCM projections do not provide a measure of the intermodel variability for the projections of change in simulated surface air temperature. Annual, seasonal, and monthly plots of Antarctic mean surface air temperatures and projected changes for each of the 11 GCMs used in the composites above are archived (see online at http://igloo.atmos.uiuc.edu/IPCC/index.antarctic.html). The projected time series of area-averaged annual surface air temperature departures from 1981–2000 means for the 11 GCMs for 60°–90°S over the period 1901–2100 are summarized in Fig. 21. All models project warming over the domain and the range of warming predicted varies from 2.0°–3.5°C by the end of the twenty-first century. The +11-GCM composite warming is projected to be 2.6°C over the present century. The projected changes in annual surface air temperature by the year 2100 exceed the interannual variability of the annual means for all models. The annual mean temperatures produced by our gridded analyses are plotted in context with the corresponding GCM-derived temperature anomalies for 1958–2002 in Fig. 21. Linear trends of 11-GCM composite temperature anomalies exceed the linear trend from our observed gridded analyses by only a small amount for the 1958–2002 period.

5. Conclusions

We have presented a comprehensive analysis of surface air temperature anomalies for Antarctica and the Southern Ocean at a grid resolution sufficient to capture regional variations of trends and to permit comparisons with climate model projections. A primary incentive in constructing our gridded air temperature anomalies was to increase the useful information content of the available data without overextending the influence of the sparsely distributed data in the high-latitude Southern Hemisphere. Land surface station, automatic weather station, and gridded summarized sea surface temperature data were used to construct monthly correlation length scales used to limit the radius of influence of the underlying temperature data on the resulting analyses. The correlation length scales are shown to be generally largest in summer and over the Antarctic continent, while they are shortest over the winter sea ice.

Trends based on our gridded analyses using a 45-yr record length differ substantially in several respects from those presented in other published works. Trends calculated for the 1958–2002 period show slight warming over most of the 50°–90°S domain, with significant warming over the Antarctic Peninsula in most seasons. The salient finding in the context of climate change is that the 45-yr trends are generally within a range of
$\pm 0.1 ^\circ C$ decade$^{-1}$ and not significant with the exception of the relatively strong warming localized over the Antarctic Peninsula. The statistically significant warming over the Antarctic Peninsula is strongest during the winter, but all other seasons show modest warming rates. The seasonality of the trends over the Antarctic continent roughly mirror those over Northern Hemisphere landmasses with a maximum in warming rates during the winter and a minimum from late spring through summer. Trends computed using these analyses show considerable sensitivity to start and end dates with starting dates before 1965 producing overall warming and starting dates from 1966 to 1982 producing net cooling rates over the region.

Composite (11-model) GCM simulations for 1958–2002 with forcing from historic greenhouse gas, aerosol, and stratospheric ozone concentrations show spatial warming patterns and magnitudes quite similar to the corresponding observed trends with localized maximum warming near the Antarctic Peninsula. GCM projections for 2001–2100 using the IPCC SRES A1B greenhouse gas forcing scenarios do not continue the pattern of strongest warming over the Antarctic Peninsula, but instead show the greatest warming over the

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**Fig. 20.** Same as in Fig. 19, but for the (a) summer (DJF), (b) autumn (MAM), (c) winter (JJA), and (d) spring (SON) seasons.
Antarctic continent. We provide maps of projections for each of the GCMs included in these composites in an online archive (http://igloo.atmos.uiuc.edu/IPCC/index.antarctic.html), which also provides access to the monthly analyses for applications ranging from trend evaluation to impact assessments.

Acknowledgments. This work was supported by the National Science Foundation, Office of Polar Programs, through Grant OPP-0229430.

REFERENCES


Fig. 21. Annual mean surface air temperatures for the 60°–90°S domain, expressed as departures from 1981 to 2000 means, as projected by the 11 global climate models (and 11-model composite mean) of the IPCC AR4 (SRES A1B forcing scenario). Corresponding anomalies of annual mean surface air temperature and associated linear trend from the gridded analyses are also shown for 1958–2002.

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