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Antarctic atmospheric temperature trend patterns from satellite observations

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[1] Tropospheric temperatures in the Antarctic are retrieved by linearly combining satellite-borne Microwave Sounding Unit (MSU) channels 2 and 4 observations. We show good agreement between satellite-inferred temperature trends and radiosonde observations. It is illustrated that the Antarctic troposphere has cooled in the summer and fall seasons since 1979, in agreement with Thompson and Solomon (2002). It is shown that significant tropospheric warming prevails during Antarctic winters and springs, but we also find significant winter cooling over half of East Antarctica. We find the largest winter tropospheric warming of about 0.6 K/decade for 1979–2005 between 120°W and 180°W. Homogeneous winter tropospheric warming over Antarctica from the ERA-40 reanalysis is not supported by the MSU observations. While MSU stratospheric temperatures exhibit the expected large cooling during the spring and summer seasons, we also find large stratospheric warming over half the southern hemisphere high latitudes in the winter and spring seasons. **Citation:** Johanson, C. M., and Q. Fu (2007), Antarctic atmospheric temperature trend patterns from satellite observations, *Geophys. Res. Lett.*, *34*, L12703, doi:10.1029/2006GL029108.

1. Introduction

[2] Recent temperature trends in the southern hemisphere high latitudes are spatially complex and highly seasonally dependent [e.g., *Comiso*, 2000; *Doran et al.*, 2002; *Thompson and Solomon*, 2002; *Vaughan et al.*, 2003; *Jacka et al.*, 2004; *Turner et al.*, 2006]. This is because these trends are linked to atmospheric circulation changes related to stratospheric ozone depletion [e.g., *Thompson and Solomon*, 2002; *Gillett and Thompson*, 2003], increased greenhouse gases [*Kushner et al.*, 2001; *Shindell and Schmidt*, 2004], and natural variabilities of the climate system [e.g., *Jones and Widmann*, 2004; *Bertler et al.*, 2004]. Long-term temperature data with spatially complete coverage over the southern hemisphere high latitudes are therefore critically important to understand the recent climate changes in the Antarctic.

[3] Much research has gone into investigating surface temperature changes across the Antarctic. In-situ surface observations show warming of several K on the Antarctic Peninsula over the past several decades [e.g., *Vaughan et al.*, 2003; *Jacka et al.*, 2004] while the interior of the Antarctic continent has cooled during summer and autumn [e.g., *Thompson and Solomon*, 2002]. *Turner et al.* [2002] pointed out that the surface temperature trends from in-situ climate measurements at various stations present a spatially complex picture of change across the continent during recent decades. Satellite-based observations of skin temperatures confirm recent widespread and non-uniform changes of the Antarctic surface temperatures [*Comiso*, 2000].

[4] By contrast, there are fewer studies concerned with the tropospheric temperature changes [*Turner et al.*, 2006]. Using radiosonde data along with tropospheric geopotential height from the National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis, *Thompson and Solomon* [2002] documented tropospheric cooling over the Antarctic during the summer and fall seasons and suggested that such cooling can be traced to the positive trend in the Southern Hemisphere Annular Mode (SAM). In a more recent study *Turner et al.* [2006] reported a major uniform warming of about 0.5 to 0.7°C per decade since the 1970s in the Antarctic winter troposphere by analyzing radiosonde and the European Center for Medium-Range Weather Forecasts (ECMWF) reanalysis (ERA-40). Since the radiosonde stations over the Antarctic continent are confined mainly to coastal margins and huge areas are devoid of long-term, in-situ tropospheric temperature observations, the sparse network of radiosonde observations provides only a partial picture of tropospheric temperature changes. Although reanalyses have incorporated the satellite observations which offer spatially complete observations since 1979, several important calibrations concerned with temporal homogeneity of satellite observations have not been considered in these datasets [e.g., *Christy et al.*, 2003; *Mears et al.*, 2003].

[5] Here, we present nearly spatially complete distributions of tropospheric and stratospheric temperature trends in the southern hemisphere high latitudes using the climate quality records of satellite Microwave Sounding Unit (MSU) observations [*Mears et al.*, 2003; *Christy et al.*, 2003]. A comparison with individual radiosonde tropospheric trends indicates that the trend pattern is dataset-independent. The emerging pattern of tropospheric temperature changes shows that large cooling in the summer and fall seasons largely compensates the warming during the winter and spring seasons so that the annual mean trend is small. We find that during the winter, a considerable portion of the East Antarctic troposphere has cooled, while on the west side of Antarctica (near 150°W) a large warming of about 0.6 K/decade has occurred in a region devoid of radiosonde observations. The MSU stratospheric trends show the expected ozone related cooling during the spring and summer seasons but also an unexplained warming in the winter and spring seasons over half of southern hemisphere high latitudes.

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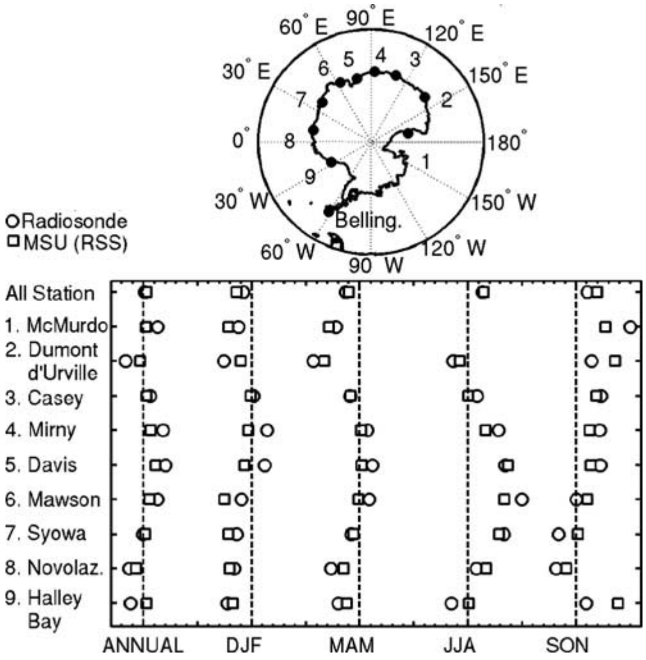

Figure 1. Tropospheric temperature trends for 1979–2005 from radiosondes (circles) at locations indicated by the station map above and collocated MSU (squares). Each tick corresponds to 0.1 K/decade and the dashed lines show the lines of zero trends for each season.

[6] This paper is organized as follows. Section 2 describes the data and methods used. Section 3 shows the comparison of tropospheric temperature trends between radiosonde and MSUs. The satellite-derived spatial tropospheric and stratospheric trend patterns are presented in Section 4, where the reanalysis results are also discussed. Conclusions are given in Section 5.

2. Data and Methods

2.1. Radiosonde Data

[7] Radiosonde temperatures from the Reference Antarctic Data for Environmental Research (READER) dataset [*Turner et al.*, 2004] are used in the comparison with the MSU-derived tropospheric temperature trends. These trends were computed at nine stations with upper air observations between Jan 1979 and Dec 2005. These stations are located along the coastal margins of Antarctica, as shown in Figure 1, and were required to have observations for more than 75% of the months in this time period. Although a long temperature record is available at the South Pole, this station was not included in the analysis since there are no observations poleward of 82.5 degrees from the polar orbiting satellites. The Antarctic Peninsula radiosonde station, Bellingshausen, was also excluded from the trend analyzes because of its data problem (see auxiliary materials).[1]

[8] For a direct comparison with the MSU retrievals of tropospheric temperature anomalies, tropospheric monthly anomalies at each station, T_{Trop}, were derived from a vertical average of anomalies at all levels between the surface and 250 hPa, weighted by the MSU channel 2 weighting function [see *Johanson and Fu*, 2006, equation (2)]. T_{Trop} is thus a deep-layer mean temperature between the surface and the tropopause. Herein T_{Trop} was not computed if 2 or more troposphere levels had missing data in a given month.

[9] Among the nine stations considered in this study, McMurdo had the largest number of missing troposphere observations (24%), followed by Novolazarevskaja with 12% and Halley Bay with 3%. Since almost all of the missing observations at McMurdo occurred during the winter season [*Trenberth and Olson*, 1989], a winter trend could not be computed there.

2.2. MSU Data and Tropospheric Temperature Retrievals

[10] The MSU provides global coverage of temperature since 1979 for several atmospheric layers from NOAA polar-orbiting satellites. We used MSU channels 2 (T_2) and 4 (T_4) gridded (2.5° by 2.5°) monthly anomaly brightness temperature data compiled by the Remote Sensing System (RSS) team [*Mears et al.*, 2003] for 1979–2005. Although the RSS MSU data are used in this study, consistent results are obtained using the MSU data from the University of Alabama at Huntsville (UAH) team [*Christy et al.*, 2003]. Some comparisons between these two datasets are discussed in Section 4. We did not use the T_{2lt} data product [*Mears and Wentz*, 2005; *Christy et al.*, 2003] because of the effects of the sea ice and mountainous terrain [*Swanson*, 2003; *Fu et al.*, 2004]. Although the T_{2lt} trends in the Antarctic show broad agreement with our findings, they are conspicuously noisier (not shown).

[11] Tropospheric temperature anomalies were retrieved with a linear combination of T_2 and T_4 [*Fu et al.*, 2004] such that $T_{trop} = (1 - a_4)T_2 + a_4T_4$ where a_4 is −0.22 for the southern hemisphere extratropics which assumes an average tropopause of 250 hPa [*Johanson and Fu*, 2006]. The retrieval errors in trends are within about 0.03 K/decade over the extratropical regions [*Johanson and Fu*, 2006]. MSU stratosphere trends are directly from T_4 which has signal mainly from the lower stratosphere.

[12] MSU tropospheric and stratospheric trends were calculated at each of the 2.5 degree latitude/longitude grid boxes from 45°S to 82.5°S in order to examine the spatial pattern of changes in the southern hemisphere high latitudes. These trends reflect the entire period from Jan. 1979 to Dec. 2005 with no missing observations.

[13] The MSU tropospheric trend includes contributions from the entire troposphere and from the surface (see *Johanson and Fu* [2006, Figure 1] for the weighting functions). Over the higher parts of the Antarctic Plateau such as Vostok station where surface pressures are ~625 hPa, surface emissions account for about 40% of the signal but along the coast they account for ~5%. Thus, over the high Plateau, the MSU derived tropsopheric trends should be interpreted as the combination of tropospheric and surface temperature trends. A recent study (A. J. Monaghan, personal communication, 2007) indicates that over the Antarctic Plateau, the surface and tropospheric temperature trend patterns are similar.

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[1] Auxiliary materials are available in the HTML. doi:10.1029/2006GL029108.

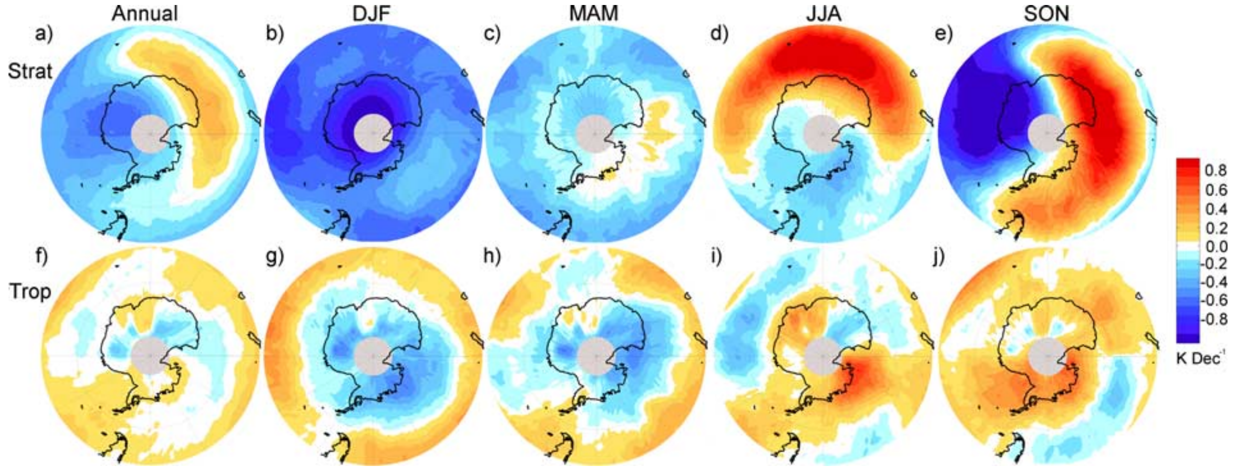

Figure 2. MSU (a–e) stratospheric and (f–j) tropospheric temperature trends for 1979–2005.

[14] For the comparison between radiosonde and MSU trends, time series of MSU brightness temperature anomalies were obtained at each of the 2.5 degree grid boxes collocated with the radiosonde stations. To avoid any temporal bias, missing observations at each of the radiosonde stations were removed from each of the MSU collocated time series.

2.3. Reanalysis Datasets

[15] The reanalysis datasets including ERA-40 and NCEP/NCAR for 1979–2002 are examined in terms of trends in T_{Trop} (see 2.1) using radiosonde and MSU observations. We found that both reanalysis datasets overestimate the winter tropospheric temperature trends since 1979 by about 0.4 K/decade at the Antarctic radiosonde stations. The reanalysis results are discussed in Section 4.

3. MSU Versus Radiosonde Observations: Trend Comparison

[16] A comparison between the MSU and radiosonde tropospheric trends at individual stations for different seasons and the entire year illustrates good agreement, as shown in Figure 1. The differences in all-station average trends are 0.001, 0.075, −0.074, 0.004, and 0.002 K/decade, respectively, for JJA (winter), SON (spring), DJF (summer), MAM (fall), and the entire year. The seasonal and spatial patterns of warming and cooling are independent of dataset. Both radiosonde and MSU trends indicate that at these stations the summers and autumns are largely cooling while the winters and springs are warming. In both datasets, the troposphere cooling from December to May partly cancels the warming from June through November such that the annual mean trend is small. Figure 1 also indicates that the pattern of cooling and warming over the Antarctic is not uniform. In the summer, both MSU and radiosonde show cooling at six of the stations but the sign is uncertain at Casey, Mirny, and Davis. In the fall, the trends from Mirny to Syowa are weak but both datasets indicate tropospheric cooling at the other five stations.

[17] In the winter and spring seasons, both MSU and radiosonde show substantial tropospheric warming. In the winter, the warming is largest between Mirny and Syowa but cooling is also apparent at Dumont d'Urville. During the springtime, both datasets indicate warming at all stations except Novolazarevskaja and Syowa. Nonetheless, winter and springtime warming is a robust feature of both datasets and the trend appears particularly large in the western Antarctic troposphere during spring and the eastern troposphere during winter.

[18] The accuracy of radiosonde trends is diminished by biases introduced into the observational record that may result from instrument upgrades or changes in observing times [*Hurrell and Trenberth*, 1998; *Lanzante et al.*, 2003; *Karl et al.*, 2006]. Sudden jumps in the temperature record are difficult to find and remove and can have a significant impact on decadal temperature trends. It is likely that such biases exist in the READER dataset at other stations besides Bellingshausen. Biases may also exist in the MSU-derived tropospheric trends related to satellite MSU calibration [e.g., *Fu and Johanson*, 2005; *Karl et al.*, 2006] and retrieval scheme [*Johanson and Fu*, 2006]. However, the general agreement between the radiosonde and MSU trends indicates that any biases that may be present in the READER network and MSU are small relative to the large seasonal trends over the past three decades.

4. Temperature Trend Patterns

4.1. Troposphere

[19] The MSU-derived tropospheric temperature trends using RSS T_2 and T_4 are shown in Figures 2f–2j for the southern hemisphere high latitudes. Relatively small trends (poleward of 60°S) in the annual mean (Figure 2f) are due to the summer to fall tropospheric cooling compensating winter to spring warming.

[20] The December through May cooling of the Antarctic troposphere poleward of 60°S exhibits a high degree of zonal symmetry during summer (Figure 2g). This large summer cooling is consistent with the 500-hPa height trends based on observations and model results reported by *Thompson and Solomon* [2002] and *Gillett and Thompson* [2003]. Nearly all of the cooling can be traced to the positive trend in the Southern Hemisphere Annular Mode (SAM) index [*Thompson and Solomon*, 2002]. In its positive phase, the SAM is associated with cold temperatures

Table 1. Wintertime Tropospheric Trends (K/decade) From Radiosonde, MSU and Two Reanalysis Datasets Between January 1979 and August 2002[a]

	Radiosonde	MSU	NCEP	ERA-40
Halley Bay	0.039	0.259	0.895	0.697
Novolazarevskaja	0.434	0.588	1.031	0.815
Syowa	0.591	0.536	0.855	0.955
Mawson	0.775	0.562	0.998	0.936
Davis	0.572	0.523	0.793	0.901
Mirny	0.404	0.333	0.669	0.708
Casey	0.267	0.166	0.815	0.629
Dumont d'Urville	0.023	0.059	0.498	0.408
All	0.376	0.357	0.795	0.760

[a] August 2002 is the last available month of ERA-40 data.

and low geopotential heights over the polar cap and a strong circumpolar vortex. The stratospheric ozone depletion is responsible for most of the trend towards a higher index state [*Thompson and Solomon*, 2002; *Gillett and Thompson*, 2003], although the increases of greenhouse gases may also play a role in strengthening the SAM [e.g., *Shindell and Schmidt*, 2004]. While the large-scale summertime cooling occurs in response to downward propagation of stratosphere anomalies starting in late spring [*Thompson and Solomon*, 2002], recent local summer cooling in the western Ross Sea may also be influenced by ENSO related changes in atmospheric circulations [*Bertler et al.*, 2004].

[21] Figure 2i shows the MSU-derived tropospheric temperature trends in the winter, indicating a large warming over most of the continent. We also find that nearly half of the East Antarctic troposphere shows cooling during these months. Figure 2i also shows that the maximum winter tropsopheric warming occurs over the west side of the continent between 120°W and 180°W (and surrounding Ross Sea), which is about 0.6 K/decade since 1979. The other area of exceptional tropospheric warming, located near 60°E, shows trends of about 0.3 K/decade. From September through November, warming prevails nearly everywhere poleward of 60°S. Note that while the radiosonde stations have captured the overall warming from June through November, there are few stations on the west side of the continent where the warming is strongest and no stations in the vicinity of the maximum warming near 150°W. It is also worth mentioning that a large portion of the surrounding ocean equator-ward of about 60°S has been cooling in the winter and spring seasons. Trend patterns in Figures 2f–2j thus suggest a decreased meridional temperature gradient in the winter and spring but an increased gradient in the summer and fall.

4.2. Stratosphere

[22] Figures 2a–2e show the stratospheric trend patterns in southern hemisphere high latitudes for the entire year and four seasons. The annual mean stratospheric trend pattern in Figure 2a reflects the strong cooling in the spring (see Figure 2e between about 50°W and 90°E) and summer (Figure 2b over the entire southern hemisphere high latitudes) as well as the semi-annular patterns of warming which have occurred in the winter and spring (Figures 2d and 2e). Ozone depletion is responsible for the large spring and summer cooling in the stratosphere which has a maximum during November and lasts until February [*Thompson and Solomon*, 2002]. The MSU observations show that cooling continues between March and May but it is much weaker (Figure 2c). The largest stratospheric cooling is about -1.5K/decade (beyond the color scale in Figure 2) and occurs during spring.

[23] Stratospheric temperature trend patterns in the winter and spring seasons are also characterized by semi-annular warming regions. In the winter, the warming is centered near 90°E and extends from about 0°E to 180°E (Figure 2d). The semi-annular warming pattern also occurs during spring, but it is shifted nearly 90 degrees eastward (Figure 2e). The maximum warming is more than 0.8 K/decade. These trend patterns are unaffected by the 2002 stratospheric sudden warming [*Newman and Nash*, 2005]; the warming is slightly weaker when that year is removed (not shown) but the spatial trend structure is unchanged.

[24] *Lanzante et al.* [2003] and *Compagnucci et al.* [2001] noticed the near-zero T_4 annual mean trend near New Zealand, consistent with results shown in Figure 2a. However the warming trend patterns shown in Figures 2d and 2e have not been documented before and further research is required to understand the mechanisms responsible for such patterns.

4.3. Trend Patterns Using MSU Data From UAH

[25] We have also derived the atmospheric trends using the UAH T_2 and T_4. The UAH trends in both stratosphere and troposphere are always more negative than the RSS trends. The differences in all-station average tropospheric trends between UAH and radiosonde are -0.1, 0.05, -0.1, -0.04, and -0.05 K/decade, respectively, for winter, spring, summer, fall, and the entire year. These differences are larger than those between RSS and radiosonde. Despite these larger differences, atmospheric trends from UAH and RSS datasets generally show consistent spatial patterns and seasonal dependences. (See auxiliary materials for a comparison between UAH and radiosonde trends and for UAH spatial trend patterns.)

4.4. Trends From Reanalyses

[26] The spatial distribution of Antarctic winter trends at 500 hPa based on ERA-40 dataset shown by *Turner et al.* [2006] revealed more homogeneous warming taking place at a much faster rate than the winter tropospheric warming shown in Figure 2i. A comparison of the winter tropospheric trends from ERA-40 and NCEP/NCAR with radiosonde and collocated MSU observations is shown in Table 1.

[27] Tropospheric trends from both reanalyses show tropospheric warming during the winter of about 0.4 K/decade larger than the warming observed by the radiosonde and MSU (Table 1). No cooling is apparent in the spatial distributions of ERA-40 troposphere trends during winter from 1979 to 2002 (not shown). The homogeneous winter tropospheric warming over the Antarctic from ERA-40 reanalysis since 1979 is therefore not supported by satellite microwave observations.

5. Conclusions

[28] We have derived the tropospheric temperatures in southern hemisphere high latitudes by linearly combining MSU T_2 and T_4 observations. The collocated MSU and radiosonde tropospheric trends for 1979–2005 show good agreement, especially during the winter. Both ERA-40 and

NCEP/NCAR reanalyses overestimate the winter tropospheric warming since 1979 by about 0.4 K/decade at the Antarctic radiosonde stations.

[29] We have produced trend maps that document the tropospheric and stratospheric temperature changes in the southern hemisphere high latitudes. The troposphere over the Antarctic continent is cooling in summer and fall seasons since 1979, in agreement with *Thompson and Solomon* [2002]. Although significant tropospheric warming prevails in the winter and spring seasons over most of the continent, half of the East Antarctic has experienced winter tropospheric cooling. We find that the strongest winter tropsopheric warming is about 0.6 K/decade over the west side of the continent between about 120°W and 180°W (and surrounding Ross Sea) where there are no radiosonde observations. The MSU stratospheric temperature trends exhibit the expected cooling during the spring and summer seasons but also show an undocumented warming in the winter and spring seasons over half of southern hemisphere high latitudes.

[30] Further investigation is required to understand the underlying causes of the spatial trend patterns during each season. While much of the tropospheric cooling in the summer and fall seasons can be accounted for by the strengthening of the SAM, it is still unclear how much of the winter and spring warming is related to increases in greenhouse gases and/or changes in local circulations. Additionally, the large stratosphere warming occurring between June and November warrants future observational and modeling study.

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