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Distribution and temporal trends of temperature extremes over Antarctica

Ting Wei¹, Qing Yan²,³,⁴,⁵, and Minghu Ding¹,²,⁶

¹ State Key Laboratory of Severe Weather, Chinese Academy of Meteorological Sciences, Beijing, People’s Republic of China
² Nansen-Zhu International Research Centre, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, People’s Republic of China
³ Key Laboratory of Meteorological Disaster/Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disasters, Nanjing University of Information Science and Technology, Nanjing, People’s Republic of China
⁴ CAS Center for Excellence in Tibetan Plateau Earth Sciences, Chinese Academy of Sciences (CAS), Beijing, People’s Republic of China
⁵ Authors to whom any correspondence should be addressed.
E-mail: yangqing@mail.iap.ac.cn and dingminghu@foxmail.com

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Abstract

The spatiotemporal characteristics of temperature extremes over Antarctica remain largely unknown. Here, we use quality-controlled daily datasets from Antarctic weather stations to show that the annual maximum and minimum temperatures exhibit a decreasing pattern over Antarctica from the coast to inland regions. This feature holds for the warmest daily maximum and coldest daily minimum temperatures, which define the intensity of extremes, but not for the number of warm (cold) days measuring the frequency of extremes, which show limited dependence on latitude or elevation. During 1970–2000, the temperature extremes in the South Orkney islands and on the margins of East Antarctica show opposite trends, especially with a significant increasing and decreasing trend in warm events, respectively. During 1999–2013, the intensity and frequency of extreme temperatures decrease significantly over West Antarctica, but the trends vary greatly across sub-regions of Antarctica. Despite the limited number of stations and the potential time dependence of trends, these results not only help to decipher the climate regimes of Antarctica and fill current gaps in the map of global climate extremes, but also may guide the future design of Antarctic observational networks and be used to assess the capability of reanalysis datasets and climate models.

1. Introduction

Present day Antarctica, the Earth’s southernmost continent, is permanently covered with a ~2000 m thick layer of ice (Fretwell et al 2013). The loss of mass from this huge ice sheet has contributed to a rise in global sea-levels of about 14.0 mm since 1979 and this loss is currently accelerating (Velicogna et al 2014, Paolo et al 2015, Shepherd et al 2018, Rignot et al 2019). An increase in the near-surface air temperature is considered to be one of the factors responsible for this recent rapid loss of mass (Scambos et al 2004, Kuipers Munneke et al 2014, Trusel et al 2015). However, harsh weather conditions and a lack of permanent inhabitants make observations challenging in Antarctica, limiting a comprehensive understanding of the Antarctic climate and the behavior of the ice sheet. Nevertheless, the establishment of an observational network in Antarctica and satellite remote sensing has significantly advanced our knowledge of the spatial variability of Antarctic temperatures. Observations have shown that the Antarctic Peninsula and West Antarctica have been among the most rapidly warming regions on Earth from the International Geophysical Year (1957–1958) to ~2000 (Steig et al 2009, Bromwich et al 2013), after which a cooling trend was observed over the Antarctic Peninsula (Turner et al 2016). By contrast, the annual mean temperature over East Antarctica shows no significant long-term trend, although there has been a slight...
seasonal cooling (Comiso 2000, Turner et al 2005 Monaghan et al 2008, Screen and Simmonds, 2012, Nicolas and Bromwich, 2014). These changes in the near-surface air temperature in Antarctica are closely linked with the variability in the Southern Annular Mode (SAM) and tropical forcing. The tropical forcing primarily affects Antarctic climate through the poleward propagation of Rossby waves associated with anomalous tropical deep convection, and the SAM impacts on Antarctic climate via modulating the midlatitude westerlies and hence the heat advection and katabatic wind events (e.g. Thompson and Solomon 2002, Turner 2004, Marshall 2007, Ding et al 2011, Ding and Steig 2013, Clem et al 2018).

Although scientists are currently unlocking the characteristics of the Antarctic climate and identifying the underlying processes, little is known about the distribution or trend of weather/climate extremes, which could affect the Antarctic cryosphere and ecosystems by either crossing a critical threshold or occurring simultaneously with other events (e.g. Barnes and Peck 2008, Kaur et al 2013, Sancho et al 2017). This is in sharp contrast with our well-established knowledge of climate extremes over the northern hemisphere and the other continents of the southern hemisphere, where persistent changes to temperature extremes have already occurred, though the behind mechanisms still remain elusive (Bindoff et al 2013, Hartmann et al 2013, Wei et al 2016, Simmonds, 2018). Quantifying the spatiotemporal characteristics of climate extremes over Antarctica will help to increase our understanding of Antarctica’s distinct climatic regimes, fill gaps in the database of climate extremes across the globe, and guide the future design of observational networks in Antarctica. Here, we provide the first map of the temperature-related extremes over Antarctica and examine their temporal trends during the time periods 1970–2000 and 1999–2013 using daily data from all the available staffed and automatic weather stations (AWSs) in Antarctica.

2. Methodology

2.1. Temperature data

We collect daily maximum and minimum temperatures from 102 staffed stations and 127 AWSs in Antarctica (figure 1(a)). The daily datasets at staffed stations are obtained from the Global Historical Climatology Network-Daily (Menne et al 2012), with the exception of the Great Wall and Zhongshan stations, which are provided by the Chinese Academy of Meteorological Sciences. The operation time of the staffed stations varies from <1 to >60 years (1954–present day). The Antarctic Meteorological Research Center provides daily maximum and minimum temperatures from 127 AWSs based on 10 min interval data received by satellite and accumulated by the Argos system (e.g. Lazzara et al 2012). The time interval covered by the AWSs ranges from <1 to 30 years (1984–2013).

2.2. Data quality control

We perform a three-step data quality control procedure for the daily temperature data from all stations to take into account the spatial distribution of temperature extremes. First, we replace all the unreasonable values with ‘not available’, including (1) the daily maximum temperatures less than the daily minimum temperature and (2) outliers in the daily maximum and minimum temperatures, defined as daily values three times larger or smaller than the standard deviation for the day. Next, we ask that no block of daily maximum (minimum) temperature is unavailable for >5 d (not necessarily continuous) in each month of a year; if not, we set the datasets in the year to ‘not available’. Finally, the length of the records passing the two-step quality control at a station should be ≥5 years, but not necessarily continuous. Data from 58 of the 229 stations meet these criteria (figure S1 is available online at stacks.iop.org/ERL/14/084040/mmmedia) and are used to calculate the temperature extremes over Antarctica. Among the 58 stations, 41 stations have quality-controlled records longer than 10 years (figure 1(b)), including 12 staffed stations and 29 AWSs covering the time periods 1954–2004 and 1984–2013, respectively. Although the original daily datasets from the staffed stations cover the time period 1954–2018, the maximum and minimum temperatures during the time period 2005–2018 do not pass the three-step quality control process (figure S2).

For the temporal trend, we further require that the number of years with quality-controlled datasets at a station must be ≥90% of the length of the period considered (referred to as C1). However, the number of stations meeting this criterion decreases with increasing time span and the time interval covered by the staffed stations and the AWSs does not overlap well (figure 1(b)). To maximize the number of daily data points and select a relatively longer interval, we examine the trends of temperature extremes during the time periods 1970–2000 and 1999–2013, respectively. Four staffed stations meet the C1 criterion during the time period 1970–2000 and these stations are located in the South Orkney islands (Orcadas) and on the margins of East Antarctica over the Indian Ocean sector (Mawson, Davis, and Casey) (figure 1(c)). Eight stations are selected for the time period 1999–2013 and these stations are distributed over King George Island, the northern tip of the Antarctic Peninsula (Great Wall), West Antarctica (Harry and Siple Dome), the vicinity of the Ross Ice Shelf/Ross Island (Marble Point, Gill, and Marilyn), and marginal and inland East Antarctica (Zhongshan and Dome C II) (figure 1(c)).
2.3. Extreme indices
In addition to maximum (minimum) temperature and diurnal temperature range, we use another four indices introduced by the Expert Team on Climate Change Detection, Monitoring and Indices to estimate the intensity and frequency of temperature extremes (table S1). Specifically, we use the warmest daily maximum temperature ($TX_x$) and the coldest daily minimum temperature ($TN_n$) to measure the intensity of extreme daily temperatures. The number of days with a daily maximum temperature above the 90th percentile ($TX_{90}$; warm days) and number of days with a daily minimum temperature below the 10th percentile ($TN_{10}$; cold days) are adopted as indicators for the frequency of extremes.

3. Results
3.1. Distribution of temperature extremes
The annual maximum and minimum temperatures over Antarctica broadly show a decreasing pattern from the coast to inland areas (figures 2(a), (b)).
over the Antarctic Peninsula is $-4.9\,^\circ C$ ($-15.0\,^\circ C$). This decreases to $-18.6\,^\circ C$ ($-27.5\,^\circ C$) over West Antarctica and to $-44.8\,^\circ C$ ($-51.9\,^\circ C$) around the South Pole. There is a linear decrease in the annual maximum temperature of $-1.24\,^\circ C/\text{degree latitude}$ and by $-11.2\,^\circ C/\text{km}$ for elevations $>100\,\text{m}$ (figure S3), and a linear decrease in the annual minimum temperature of $-1.29\,^\circ C/\text{degree latitude}$ and $-12.1\,^\circ C/\text{km}$ for elevations $>100\,\text{m}$. The general pattern of the maximum (minimum) temperature largely holds for different seasons (figure S4). To understand the relative role of latitude and elevation on temperature, the partial correlation between temperature extremes and latitude/elevation is calculated. We find that both latitude and elevation have considerable influence on the distribution of annual maximum and minimum temperature (table S2). However, the uneven distribution of stations over Antarctica (e.g. significant under-representation of stations above 2000 m and co-location of some stations) introduces uncertainties into the estimated relative contributions of latitude and elevation (e.g. the multiple regression functions in table S2). In contrast, the distribution of the annual diurnal temperature range shows a limited dependence on latitude or elevation (figure 2(c), figure S3). The South Pole experiences a similar diurnal temperature range ($-6\,^\circ C$–$8\,^\circ C$) to marginal Antarctica. This is attributed to the fact that favorable weather conditions (e.g. the clear sky, weak winds, and very dry atmosphere) promote the loss of heat via the emission of longwave radiation and lead to extreme low temperature at nighttime (Turner et al 2009, Scambos et al 2018) and hence large diurnal temperature range, though the diurnal variation of solar altitude is small. A larger diurnal temperature range ($>10\,^\circ C$) is mainly found over the interior of East Antarctica, Palmer Land, and in the vicinity of Ross Island. The large diurnal temperature range over the Palmer Land and Ross Island partially benefits from the favorable surface conditions (bare rock).

The decreasing pattern from the coast to inland is also observed in TXx and TNn (figures 2(d), (f)). The annual TXx generally decreases by $-0.63\,^\circ C/\text{degree latitude}$ and by $-6.6\,^\circ C/\text{km}$ for elevations $>100\,\text{m}$ (figure S5). It is above freezing across Antarctica except for the interior of East Antarctica, in contrast with the annual maximum temperature, which broadly lies below $0\,^\circ C$ (figures 2(a), (d)). The annual TNn also shows a high dependence on latitude ($-1.55\,^\circ C/\text{degree latitude}$) and elevation ($-12.8\,^\circ C/\text{km}$ for elevations $>100\,\text{m}$) (figure S5), but with a relatively large regional variability.

Figure 2. Distribution of annual temperature extremes over Antarctica for (a) maximum temperature, (b) minimum temperature, (c) the diurnal temperature range, (d) the warmest daily maximum temperature, (e) the number of warm days, (f) the coldest daily minimum temperature, and (g) the number of cold days.
3.2. Trends of temperature extremes

3.2.1. From 1970 to 2000

The temperature extremes show an opposite trend during the time period 1970–2000 between staffed stations in the South Orkney islands and the margins of western East Antarctica. The annual maximum and minimum temperatures increase significantly over the South Orkney islands from 1970 to 2000, whereas they show an insignificant decrease over the margins of western East Antarctica (figures 3(a), (b)). The most intense seasonal increase in maximum and minimum temperatures over the South Orkney islands occurs in the austral autumn, when they cool significantly over the margins of East Antarctica. The annual diurnal temperature range does not show a significant trend over the two regions, but shows clear seasonal differences. The diurnal temperature range increases significantly over the margins of East Antarctica in the austral autumn and winter (figure 3(c)), largely as a result of stronger warming in the maximum temperature and cooling in the minimum temperature, respectively.

The intensity of warm events measured by the annual TXx increases significantly over the South Orkney islands during the time period 1970–2000, in tandem with a significant increase in the number of annual warm days (figures 3(d), (e)). This feature is also observed in all seasons, although with a different amplitude. By contrast, the annual TXx shows a weakening trend over the margins of East Antarctica, accompanied by a significant decrease in the number of annual warm days, although the trends vary with the season. The intensity and frequency of cold events, measured by the annual TNn and TN10, respectively, show no significant change over Antarctica (figures 3(f), (g)). Seasonally, TNn warms significantly over the South Orkney islands in the austral summer, with a significant decrease in TN10. Conversely, there is a significant cooling trend in TNn over the margins of East Antarctica in the austral autumn, in tandem with a significant increase in TN10.

3.2.2. From 1999 to 2013

The evolution of temperature extremes varies greatly across the sub-regions of Antarctica and seasons during the time period 1999–2013. The observations from eight stations show a decreasing trend in the annual maximum temperature over Antarctica, except...
for the Ross Ice Shelf (figure 4(a)), but this decreasing trend is only statistically significant over West Antarctica, especially in the austral spring. By contrast, the linear trend calculated for the annual minimum temperature shows warming over Antarctica, except for King George Island (figure 4(b)), although this is only statistically significant over the Ross Ice Shelf and West Antarctica in the austral summer. The annual diurnal temperature range decreases over Antarctica, except for King George Island (figure 4(c)). However, the decreasing trend is only statistically significant over West Antarctica and is seen in all seasons as a result of the opposite trend between the maximum and minimum temperatures. A significant decreasing trend is also observed over marginal and inland East Antarctica in the austral winter and summer, respectively.

The annual TXx shows a cooling trend over Antarctica from 1999 to 2013, indicating a reduced intensity of warm events, although the trend is statistically insignificant over the Ross Ice Shelf and the interior of East Antarctica (figure 4(d)). The most intense decrease in the annual TXx occurs over West Antarctica and the cooling trend is observed in all seasons, especially in the austral winter. By contrast, the annual TNN shows an overall warming trend over Antarctica (i.e. a weakened intensity of cold events), but with clear regional differences (figure 4(f)). The annual TNN warms significantly over West Antarctica and inland East Antarctica, whereas it cools significantly over marginal East Antarctica. The number of annual warm days shows a significant increasing trend over the Ross Ice Shelf and inland East Antarctica, but a modest significant decreasing trend ($P < 0.1$) over West Antarctica. There is a decreasing trend in the number of annual cold days over Antarctica, except for King George Island (figure 4(g)), but this only passes the 90% statistical test over West Antarctica and the Ross Ice Shelf. Given the large discrepancy in trends across the sub-regions of Antarctica, there is generally no significant trend in the intensity and frequency of temperature extremes averaged over Antarctica.

4. Discussions and conclusions

Based on the daily datasets from all the available staffed stations and the AWSs, we provide the first map of the distribution of temperature extremes over Antarctica and show the temporal trends during the time periods 1970–2000 and 1999–2013, when most of the quality-controlled records overlap. Our results show that the annual maximum and minimum temperatures broadly decrease from coastal to inland Antarctica in terms of spatial distribution, with a high dependence on latitude and elevation. The decreasing pattern from the coast to inland Antarctica is also observed in the annual TXx and TNN, but not for the annual diurnal temperature range and the annual number of warm/cold days, which show little dependence on latitude or elevation. The distribution of these temperature extremes largely holds in different seasons.

The temperature extremes show opposite trends between the observation stations in the South Orkney islands and the margins of East Antarctica (over the Indian Ocean sector) during the time period 1970–2000, with a significant increasing trend in the
intensity and frequency of annual warm events over the South Orkney islands, but a significant decreasing trend over the margins of East Antarctica. The linear trends show no significant change in the intensity and frequency of annual cold events, but a significant decreasing (increasing) trend is observed over the South Orkney islands (margins of East Antarctica) in the austral summer (autumn). During the time period 1999–2013, the trends in the temperature extremes vary greatly, both across the sub-regions of Antarctica and between seasons. Although there is generally no robust signal in the temperature extremes averaged across the entire continent of Antarctica, West Antarctica experiences the clearest changes, with a significant decreasing trend in the intensity and frequency of warm and cold events.

The changes in temperature extremes are linked with the variations of the El Niño Southern Oscillation and the SAM. During 1970–2000, there is a strengthening trend of annual mean SAM (figure S8), especially in austral summer and autumn (Simmonds 2015), and hence an increase in the circumpolar westerlies. The enhanced westerlies reduce the occurrence of blocked flow conditions and enhances warm-air advection over the Antarctic Peninsula, leading to higher temperature over that region, especially during autumn and summer (Thompson and Solomon 2002, Marshall et al 2006, Marshall 2007, Orr et al 2008, van Lipzig et al 2008). The surface warming provides a favorable background for the increase (decrease) in extreme warm (cold) events over the Antarctic Peninsula. In contrast, the stronger westerlies reduce the poleward advection of heat toward the East Antarctica and the occurrence of katabatic wind events, which leads to cooling on the margins of East Antarctica (Van Den Broeke and Van Lipzig 2013, Marshall 2007, Marshall et al 2013, Clem et al 2018) and hence dampens (favors) the extreme warm (cold) events. Although a general increase in El Niño condition is observed during 1970–2000 (figure S8), this generally produces cooling over the Antarctic Peninsula and warming over the western East Antarctica (Turner 2004, Ding et al 2011, Ding and Steig 2013, Irving and Simmonds 2016, Marshall and Thompson 2016). Thus, the El Niño-like conditions may not be the dominant forcing for the variations of temperature extremes over this time.

During 1999–2013, the ocean temperature is generally higher over the maritime continent and lower over the eastern Pacific Ocean (Kosaka and Xie 2013, Turner et al 2016). The La Niña-like condition leads to a poleward migration of Rossby wave into Antarctica (i.e. a negative phase of Pacific-South American pattern) and stronger planetary wave activity (Raphael 2004, Irving and Simmonds 2015, 2016, Turner et al 2016), with a trough in the Drake Passage (figure S8). This leads to a cold, east-to-southeasterly flow, which negates the warming effect associated with La Niña-like condition and gives cooling over the Antarctic Peninsula (Turner et al 2016), whereas favors an increase in the advection of warm air to West Antarctica and higher air temperature (Bromwich et al 2013). These conditions are favorable for the observed decrease and increase in minimum temperature over the West Antarctica and Antarctic Peninsula, respectively. On the other hand, the La Niña-like condition produces anticyclonic circulation over the South Atlantic via forcing a Rossby wave into Antarctica, which enhances cold air advection over the western East Antarctica (Clem et al 2018). This results in cooling over the margins of East Antarctica and is hence conducive to the lower maximum temperature. Additionally, the westerlies slightly increase arising from the positive trend of SAM (figure S8), which may also contribute to the variations of temperature extremes over the coastal regions of East Antarctica via modulating extratropical cyclones (Murphy and Simmonds 1993, Grieger et al 2018).

There are, however, caveats to be considered. The estimated trends of temperature extremes vary across individual stations in terms of the magnitude (figures S9–S15), but the change in sign is generally the same. Meantime, the trends may depend on the choice of station and time period, owning to the sparse distribution of measuring stations over Antarctica and their relatively short operation time. Interestingly, the time period 1999–2013 is just the interval during which the global ‘warming hiatus’ occurred (e.g. Kosaka and Xie 2013). Thus, our results provide insights on how temperature extremes over Antarctica vary during this hotly discussed interval. Besides, the relationship between temperature extremes and large-scale circulation/tropical forcing is more complex than the mean temperature, and the dominating driving factor may vary with different extreme indices. Therefore, the evolution of temperature extremes and the underlying mechanisms require further investigation with additional daily data from a greater number of stations.

Nevertheless, we present here unprecedented information on the spatial distribution of temperature extremes in Antarctica and their trends. This will help to decipher the Antarctic’s distinct climatic regimes and fill gaps in the map of climate extremes across the globe. The features of these temperature extremes may contribute to the design of future Antarctic observational networks, the assessment of the effect of climate change on the Antarctic cryosphere and ecosystems, and the evaluation of the capability of reanalysis datasets and climate models. Additionally, we find that the variations of majority of temperature extremes share large similarity between Davis and Zhongshan during the overlapping interval (1990–2013; figure S16), highlighting the possibility to construct a relatively long time series of records by merging datasets from nearby stations.
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Data availability statement

Data sharing is not applicable to this article as no new data were created or analysed in this study.

ORCID iDs

Qing Yan ORCID iD: https://orcid.org/0000-0001-5299-7824

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