Air temperature trends and extreme warming events across regions of Antarctica for the period 2003-2021

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Abstract

We have characterized the magnitude and spatial extent of observed regional and inter-regional air temperature trends and warming extremes across Antarctica. Prior studies have used localized observational records to analyze air temperature trends across distinct geographical regions, leaving local and inter-regional variations to be undetected. Using the high-resolution temperature product AntAir ICE, air temperature trends and extreme warming events during austral summers were identified across Antarctica for the period 2003-2021. Unsupervised clustering was applied to austral summer and annual mean air temperature trends to divide Antarctica into 12 regions exhibiting similarity in temperature trends. Our results show a significant annual mean cooling trend of -0.12 °C/Yr for the terrestrial Antarctic Peninsula, and an austral summer (annual) warming trend of +0.08 °C/Yr (+0.07 °C/Yr) in the Ross Sea region’s Victoria Land and Transantarctic Mountains. The spatial extent of each of the 12 clusters’ extreme air temperature events was mapped revealing that West Antarctica has spatially confined events, while East Antarctica events are widespread. ERA5 data indicates that West Antarctica’s extreme air temperature events are associated with consistent meridional atmospheric flows. Local to regional extreme warming events in East Antarctica are associated with inland high-pressure systems, which enhance katabatic winds. Localized warming events around complex coastal geographies were detected and appear to be related to mesoscale wind systems such as foehn but require further investigation using mesoscale numerical weather models. This work highlights the necessity for ongoing and new monitoring in regions where critical ecological and physical thresholds are being surpassed.
Air temperature trends and extreme warming events across regions of Antarctica for the period 2003-2021

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Key Points:
- A significant warming air temperature trend was found in parts of the Ross Sea region for both annual and austral summer mean for 2003-2021
- West Antarctica's extreme air temperature events are linked to high-pressure systems causing meridional advection of warm, moist air
- Spatially extensive East Antarctica extreme events are associated with inland high-pressure systems and katabatic winds

Abstract
We have characterized the magnitude and spatial extent of observed regional and inter-regional air temperature trends and warming extremes across Antarctica. Prior studies have used localized observational records to analyze air temperature trends across distinct geographical regions, leaving local and inter-regional variations to be undetected. Using the high-resolution temperature product AntAir ICE, air temperature trends and extreme warming events during austral summers were identified across Antarctica for the period 2003-2021. Unsupervised clustering was applied to austral summer and annual mean air temperature trends to divide Antarctica into 12 regions exhibiting similarity in temperature trends. Our results show a significant annual mean cooling trend of -0.12 °C/yr for the terrestrial Antarctic Peninsula, and an austral summer (annual) warming trend of +0.08 °C/yr (+0.07 °C/yr) in the Ross Sea region’s Victoria Land and Transantarctic Mountains. The spatial extent of each of the 12 clusters’ extreme air temperature events was mapped revealing that West Antarctica has spatially confined events, while East Antarctica events are widespread. ERA5 data indicates that West Antarctica’s extreme air temperature events are associated with consistent meridional atmospheric flows. Local to regional extreme warming events in East Antarctica are associated with inland high-pressure systems, which enhance katabatic winds. Localized warming events around complex coastal geographies were detected and appear to be related to mesoscale wind systems such as foehn but require further investigation using mesoscale numerical weather models. This work highlights the necessity for ongoing and new monitoring in regions where critical ecological and physical thresholds are being surpassed.
Plain Language Summary

In this study, we document air temperature trends and extreme events across Antarctica for the period 2003 to 2021 using satellite derived air temperature product AntAir ICE. We divide Antarctica into 12 regions based on their air temperature trends during the austral summer season and annual mean. We have confirmed the significant cooling that other studies have reported for the Antarctic Peninsula. We have furthermore identified areas of the Ross Sea Region as warming significantly, especially near coastal Victoria Land and the Transantarctic Mountains. Extreme air temperature events were mapped for each region, and their relationship with regional weather patterns was explored. West Antarctica experiences localized extreme temperatures due to the transport of warm moist air from further north, while East Antarctica shows widespread warming driven by a large inland high-pressure system leading to northward air flow from the interior towards the coastline.

1 Introduction

In a warming global climate, melting of Antarctica’s ice sheets plays a key role in the contribution to global sea level rise, and recent studies have shown that there currently is an acceleration in Antarctic ice mass loss (Rignot et al., 2011; Shepherd & Wingham, 2007; Velicogna et al., 2014). A controlling factor for the rate of mass loss through surface melt is the near-surface air temperature (Scambos et al., 2004; Trusel et al., 2015). Mapping the spatial patterns of air temperature trends across Antarctica and localised austral summer air temperature extreme events is highly important to assess if critical thresholds are being crossed causing stress on the Antarctic cryosphere. Furthermore, understanding regional weather patterns causing extreme events is crucial for assessing how these events might occur in the future across Antarctica.

A shift in air temperature trends has been observed across Antarctica over the past decades (Xin et al., 2023). Before 2000, a warming trend has been identified on the Antarctic Peninsula (Steig et al., 2009; Turner et al., 2005) and West Antarctica (Bromwich et al., 2013) in Automatic Weather Station (AWS) observations. After 2000, this warming trend has been reported absent in AWS data for both regions for the Austral summer period (Turner et al., 2016). Zhang et al. (2022) showed an annual cooling trend on the Antarctic Peninsula and West Antarctica along with a warming trend in the annual mean in East Antarctica in a satellite-derived temperature reconstruction from 2001 to 2018. This air temperature trend is consistent with the above-mentioned change in trends in AWS records (Xin et al., 2023).

When focusing on air temperature extremes across Antarctica from AWS records, Wei et al. (2019) found that between 1999 and 2013, extreme air temperature patterns varied across sub-regions and seasons, with no consistent trend observed continent-wide. A similar observation was made by Turner et al. (2021), who observed extreme cold and warm events in observational records from AWS and linked the occurrence to large-scale forcing. Turner et al. (2021) highlighted the importance of the foehn effect in generating extreme events when the air was passed over areas of high orography. In East Antarctica, they found that air descending from the interior with a high potential temperature led to the highest air temperatures measured in coastal AWSS. For the Amundsen-Scott South Pole, Clem et al. (2020) linked extreme warming in the observational record to a low-pressure anomaly in the Weddell Sea and warmer sea surface.
temperatures in the western tropical Pacific. Previous case studies across Antarctica of extreme warming or even heatwaves observed across multiple weather stations have linked the warming to key synoptical features (González-Herrero et al., 2022) (Wille et al., 2024). Both East and West Antarctica experienced extensive warming linked to atmospheric rivers causing enhanced water vapour fluxes (Wille et al., 2024; Wille et al., 2019).

The observational AWS network across Antarctica has therefore provided useful information for studying air temperature variabilities both for long-term trends (Bromwich et al., 2013; Clem et al., 2020; Turner et al., 2020) and for extreme air temperature events (Turner et al., 2021; Wei et al., 2019; Xin et al., 2023). Although the AWS are dispersed across the continent (Wang et al., 2022), the low density of their spatial coverage means that spatial variability of local atmospheric processes are not adequately resolved. Remote sensing observations, such as the MODIS thermal products, can give spatial-temporal information about air temperature variability across Antarctica (Retamales-Muñoz et al., 2019; Zhang et al., 2022) at a much higher spatial resolution than most reanalysis products. MODIS is well suited for use in Antarctica where gaps due to cloud cover are minimal compared to other regions in the world, due to Antarctica’s low air temperatures and low moisture availability because of strong sublimation and pronounced coastal barriers. (Bromwich et al., 2012). Satellite derived temperature products are therefore now routinely used for long-term climate analysis.

While prior studies (Retamales-Muñoz et al., 2019; Zhang et al., 2022) assessed annual and seasonal trends spatially across Antarctica, the trends were considered across broad regions such as East Antarctica, West Antarctica, and the Antarctica Peninsula. Smaller scale spatial variations in air temperature trends were therefore not investigated. Furthermore, ice shelves across Antarctica were not included, leaving areas of large significance for the Antarctic mass balance without consideration. For air temperature extremes, the spatial extent of the warming has only been observed in case studies and no Antarctic-wide investigation into the spatial extent of extremes events has been done. The newly developed AntAir ICE near-surface air temperature product is available across all of Antarctica and the surrounding ice shelves with a daily temporal resolution and a high grid resolution of 1 km (E. B. Nielsen et al., 2023). By utilising this comprehensive air temperature dataset, we can resolve air temperature patterns caused by regional weather patterns across Antarctica. The localised variability in air temperature patterns is resolved with the high spatial resolution.

This study therefore aims to deepen our understanding of the spatial and temporal variability of air temperature trends and extreme events across Antarctica for the period 2003 to 2021. The paper has two main objectives: 1) Identifying regional air temperature trends across Antarctica from AntAir ICE and 2) Identify air temperature extreme events and assess the regional weather patterns during these events. We achieved this by using a k-means clustering technique to divide Antarctica into 12 clusters based on the seasonal and annual mean warming trend from AntAir ICE. Extreme air temperature events within the clusters are identified based on the spatial extent of the area exceeding the 95th percentile of the observed temperatures, thereby using a similar threshold as Turner et al. (2021). By examining the large-scale atmospheric circulation features associated with these extreme air temperature events, we investigated the large-scale forcing driving such occurrences across Antarctica. This provides a new understanding of the
spatial impact of synoptic-scale atmospheric circulation causing extreme warming across Antarctica.

2 Data and methods

2.1 Air temperature trend estimations

Near-surface air temperature data from the newly developed dataset, AntAir ICE (E. B. Nielsen et al., 2023) was used in this study, hereafter referred to as air temperature. Data are available from 2003 until 2021 for terrestrial Antarctica and the surrounding ice shelves in a spatial grid resolution of 1 km and a temporal resolution of daily mean. The product was developed by calibrating MODIS skin temperature against AWS records across Antarctica, which is described in more detail in E. B. Nielsen et al. (2023). Data are available from Pangaea (https://doi.org/10.1594/PANGAEA.954750) (E. S. B. Nielsen et al., 2023). A non-parametric monotonic Mann-Kendall test (Kendall, 1948; Mann, 1945) was applied by estimating a Sen slope (Sen, 1968) along the time distribution for trend estimation and a Kendall’s tau test to estimate the significance of the trend. The advantage of the Mann-Kendall test is that data do not need to follow a normal distribution. The annual mean is from year 2003 to 2021 and austral summer trends are calculated from the 2003-2004 season to the 2020-2021 season.

2.2 k-means clustering technique

In this study, we used the k-means unsupervised clustering method to divide Antarctica into clusters based on air temperature trends. Normalised seasonal and annual mean air temperature trends for each grid cell estimated using Sen slope, along with the spatial 2-dimensional information were used as input for the classification. The k-means clustering technique has been proven useful for clustering environmental data (Clifton & Lundquist, 2012; Jiang et al., 2016; Sathiaraj et al., 2019). For example, Carvalho et al. (2016) used k-means to divide Europe into climate regions with coherent changes in air temperature and precipitation. Clustering using k-mean has also been used previously in Antarctic atmospheric research by Coggins et al. (2014) for identifying synoptic clusters over the Ross Ice Shelf.

The k-means algorithm assigns each grid cell into a cluster based on the distance to the cluster’s centroid. Here we used the K-means clustering method, employing the algorithm introduced by Lloyd (1982). This algorithm aims to divide a given dataset X with n observations into K clusters, C_k. The objective is to minimize the sum of squares from each point x to its assigned cluster center μ_k. This is expressed mathematically as:

\[ \sum_{k=1}^{K} \sum_{x_n \in C_k} \| x_n - \mu_k \|^2 \]  

Lloyd’s algorithm is an iterative process that converges to a minimum following two operations. Initially, for a set of centroids, the clusters are updated to include points that are closest in distance to each other. Following:

\[ C_k = \{ x_n : \| x_n - \mu_k \| \leq \text{all } \| x_n - \mu_l \| \} \]
Secondly, for the given clusters, the centroids are relocated to the means of all points belonging to a particular cluster, following:

$$\mu_k = \frac{1}{C_k} \sum_{x_n \in C_k} x_n$$  (III)

To summarize, Lloyd’s algorithm iteratively updates clusters by incorporating nearby points and adjusting centroids to represent the means of the points within each cluster. This iterative process persists until they convergence, effectively minimizing the sum of squares in the clustering arrangement.

A weakness of using k-means clustering is that the algorithm requires a predefined number of clusters. To overcome this problem we performed a sensitivity analysis based on the within-cluster sum of square values (Nainggolan et al., 2019). The optimal K value was found to be 12 as hereafter the total within the sum of squares did not update much per added cluster (Fig. 1). An initial clustering revealed that there were still a few pixels that were widely affected by cloud artifacts and edge errors in the transition between MODIS land and ice surface temperature that AntAir ICE is built on. Prior to the final set of clustering these pixels was discarded.

![Sensitivity plot for the number of clusters chosen using k-means using total within cluster sum of squares. Red marked the chosen number of clusters, 12.](image)

The 12 clusters across Antarctica were divided and labelled as follows: two Ross Sea Region clusters (RS1, RS2), two West Antarctica clusters (WA1, WA2), an Antarctica Peninsula cluster (AP), a South Pole cluster (SP) and six East Antarctica clusters (EA1-EA6) starting from the Weddell Sea sector to Ross Sea in a clockwise orientation (Fig. 2). The spatial extent of each cluster varies with the RS1 and AP being the smallest and the East Antarctica clusters being the largest (Fig. 2b). A by-product of the clustering is that small areas within larger clusters are linked to other clusters, due to the local trends. EA2 has for instance a couple of coastal cells included
that are outside the main coastal region. However, analysis has shown that these minor areas do not contribute significantly to the larger analysis and will not be addressed further. For visualisation, a simplified aggregated version of the outline of the clusters has been constructed, but not used for any analysis.

**Figure 2:** a) The spatial extent of the 12 clusters found by k-means clustering. The clusters are labelled into regions following: Ross Sea Region clusters, (RS1, RS2), West Antarctica clusters (WA1, WA2), Antarctica Peninsula cluster (AP), South Pole cluster (SP), and six East Antarctica clusters (EA1-EA6) starting from Weddell sea sector to Ross Sea in a clockwise orientation. b) the spatial extent of each cluster in km².

### 2.3 Extreme temperature events detection

Extreme air temperatures are in this study defined as values exceeding the 95th percentile of the air temperature distribution within a grid cell for the austral summer months December to February, (DJF). This is a similar threshold as used by Turner et al. (2021). The accumulative sum of pixels for each day exceeding this threshold within each cluster was estimated to identify the spatial extent of the extreme air temperature. Based on the spatial extent of the extreme air temperatures within a cluster, the days that fall within the 99th percentile of the distribution of spatial extent, equalling 10 events, are hereafter classified as an extreme event. An extreme air temperature pixel needed to be present for more than one day within the cluster to obtain the event with the largest impact, however only the day with the extreme event is included for analysis. The air temperature anomaly for each event was calculated as the difference between the austral summer mean of the cluster and the mean air temperature across the cluster for the event with the largest impact, however only the day with the extreme event is included for analysis. The air temperature anomaly for each event was calculated as the difference between the austral summer mean of the cluster and the mean air temperature across the cluster for the
day of the event. A focus on the extreme events occurring in austral summer was chosen since these events have more impact on ice mass loss during these events.

To assess the synoptic to large scale atmospheric conditions as part of objective 2 we used 3-hourly meteorological data, including mean sea level pressure (MSLP), 500 hPa geopotential height (GPH), and 10m wind vectors U and V, from The European Center for Medium Range Weather Forecasts (ECMWF), ERA5 reanalysis at a horizontal resolution of 30 km (Hersbach, 2023). Data from 2003 to 2021 were obtained from ECMWF (https://apps.ecmwf.int/datasets/). Daily statistics of vertical integral of northwards water vapour flux were calculated from ERA5 using daily statistics tool developed by ECMWF.

4 Results

3.1 Air temperature trends across Antarctica

We find warming trends during austral summer across most of Antarctica (Fig. 3a), except for the Marie Byrd Land coastline, East Antarctic Coastline at 45°E, Amery Ice Shelf, and inland East Antarctica at around 90°E – 135°E (see Fig. 2a for location names). For austral summer clusters RS1, WA2, SP, EA1, and EA3 show an increasing air temperature trend (Tab. 1, Fig. 4a). EA2 show a decreasing but insignificant trend. For the remaining clusters, no trends can be assumed (Tab. 1). The Ross Sea region is experiencing significant warming near the Transantarctic Mountains and the Victoria Land coastline (Fig. 5b). Cluster RS1 is the only cluster with a significant trend in austral summer mean, with a warming trend of 0.081 °C/yr (Tab. 1). In West Antarctic, cluster WA2 is observing the second highest summer positive air temperature trend of

Figure 3: a) Trend of AntAir ICE austral summer December to February, (DJF), for 2003-2021. b) Trend of AntAir ICE annual mean for the period 2003-2021.
Similar to SP cluster, there is an insignificant warming rate at 0.022 °C/yr. A pattern of the summer season 2007-2008 being colder for most clusters is generally observed (Fig. 4a).

Table 1: Austral summer, December to February (DJF) and annual mean trends for each cluster and p-value. Kendall’s tau test was used to estimate the significance of the trend and a Sen slope was used to estimate the trend. Numbers in bold indicate a significant trend with p-value < 0.05.

<table>
<thead>
<tr>
<th>Cluster</th>
<th>DJF</th>
<th>Annual Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Slope</td>
<td>p-value</td>
</tr>
<tr>
<td>RS1</td>
<td>0.081</td>
<td>0.004</td>
</tr>
<tr>
<td>RS2</td>
<td>0.013</td>
<td>0.773</td>
</tr>
<tr>
<td>WA1</td>
<td>-0.010</td>
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<tr>
<td>WA2</td>
<td>0.071</td>
<td>0.174</td>
</tr>
<tr>
<td>AP</td>
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<td>0.902</td>
</tr>
<tr>
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<td>0.022</td>
<td>0.650</td>
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<td>0.387</td>
</tr>
<tr>
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<td>-0.040</td>
<td>0.484</td>
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<td>EA3</td>
<td>0.028</td>
<td>0.592</td>
</tr>
<tr>
<td>EA4</td>
<td>-0.007</td>
<td>1.000</td>
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<tr>
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<td>0.484</td>
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<tr>
<td>EA6</td>
<td>-0.018</td>
<td>0.837</td>
</tr>
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</table>

When zooming in on the clusters with significant trends, spatial variation in the trend is observed especially for the AP and EA2 regions (Fig. 5). The significant cooling trend is observed on the western side of the Antarctica Peninsula, whereas the Larsen and other ice shelves on the eastern side are warming but insignificantly (Fig. 5a). For the Ross Sea Region, the Victoria Land coastline is warming significantly, along with the area around the Transantarctic Mountains (Fig. 5b). The northern and western parts of the Ross Ice Shelf is also warming drastically with some areas being significant. In East Antarctica significant cooling is present in a band following topography (Fig. 5c). The King Baudoin, Fimbul and Jelbart ice shelves and further inland are experiencing the opposite insignificant warming.
Figure 4: a) Austral summer, December to February (DJF) mean air temperatures for each cluster with corresponding Sen slope trend line. b) Annual mean air temperature trend for each cluster with corresponding Sen slope trend line.
3.4 Extreme air temperature events during austral summer

All extreme events occurred during December and January, leaving February without any major events detected for all clusters (Tab. 2). RS1 has the warmest mean air temperature within the cluster of -3.9 °C during the extreme event on 20 December 2021. Cluster EA4 had the coldest mean air temperature across the cluster of -22.8 °C on the 15 December 2003. The air temperature anomaly between the extreme event to the austral summer mean is largest for the EA6 cluster of a mean air temperature across the whole cluster that is 8.2 °C warmer on the 2 January 2014. For the extreme event on the 19 December 2021, in cluster E2 the temperature
Table 2: Dates for extreme austral summer air temperature events for each cluster along with warming extent in km$^2$ and mean air temperature across the cluster. An extreme event for a cluster is defined as an event that falls within the 99th percentile of the spatial extent within the cluster that is experiencing an extreme air temperature.

<table>
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<tr>
<th>Cluster</th>
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<th>Extreme events</th>
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<td>5.4</td>
</tr>
<tr>
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<td>Area [km$^2$]</td>
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<td></td>
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<td>478226 553479 552803 459000 397902 515181 599847 670796 720791</td>
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<tr>
<td></td>
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</tr>
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<td>11/12/05</td>
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anomaly across the cluster is not above the seasonal mean indicating that there must have been
a large temperature differences within the cluster during that event. Certain events occur across
more than one cluster, with the most extensive being the 20 - 21 of December 2018 event that
occurs across 6 clusters.

When mapping the spatial extent of extreme air temperature events (Fig. 6) it is clear that
for clusters WA1, WA2, AP and EA5 the warming is very localized within each cluster. The
opposite is true for the RS1, RS2 and remaining East Antarctic clusters have wide inland warming
extending to multiple other regions. The East Antarctica and Ross Sea clusters have a defined
spatial extent within the clusters that most of the events have in common (Fig. 6). The Ross Sea
clusters have a very similar spatial extent, with warming in the areas around and further inland
of the Transantarctic Mountains and the Ross Ice shelf. The SP cluster is experiencing widespread
warming during all events in the region between the South Pole and the Ronne Ice Shelf (see Fig.
2 for location names).

3.6 Atmospheric circulation patterns during extreme events

The GPH and MSLP composite for the extreme events show a very similar pattern for the
Ross Sea region clusters, with a low-pressure anomaly on the coast of Marie Byrd Land and an
inland high-pressure system, causing a strong pressure gradient across the Ross Ice Shelf (Fig. 7
and 8). In cluster RS1 the center of the high-pressure system is located further towards the east
of the South Pole (Fig. 8). The mean wind direction is from the south with flow from the interior
over the Ross Ice Shelf. The inland EA4 has a similar pattern with a large inland high and a low-
pressure located near the Amundsen Sea Embayment causing a strong pressure gradient across
the Ross Ice shelf.

WA1 and WA2 have a very strong, elongated, high-pressure anomaly stretching offshore
and inland in the GPH composite (Fig. 8). The high-pressure center is located off Amundsen Sea
Embayment on cluster WA1, with a corresponding low-pressure system on either side. For WA2
this high-pressure center is further north near the Bellingshausen Sea, with a corresponding low-
pressure system near the Marie Byrd Land coastline. For the AP cluster there is a high to the
north of the Antarctic Peninsula and a low-pressure system in the Bellingshausen Sea (Fig. 8). The
wind vectors indicate winds flowing towards the Marie Byrd Land coastline for both clusters (Fig.
7). From the GPH composite the SP cluster has a strong high-pressure system inland (Fig. 8) and
two low-pressure systems in the Weddell Sea and Bellingshausen Sea, respectively (Fig. 7).

For East Antarctica the inland high-pressure system stretching across the continent is
present in all clusters (Fig. 8) along with smaller and weaker low-pressure systems in the
Circumpolar pressure Trough (Fig. 7). The mean wind composites (Fig. 7) the wind is mostly
occurring downslope the terrain and towards the coastline. Cluster EA3 does however have a
strong low-pressure system near Wilkes land. EA4 and EA6 the high-pressure system is located
across the coastline at Wilkes land.
Figure 6: Accumulated spatial extent of the identified extreme events listed in Table 2 for each cluster. Red marks the cluster outline. An extreme event for a cluster is defined as an event that falls within the 99th percentile of the spatial extent within the cluster that is experiencing an extreme air temperature.
Figure 7: ERA5 Mean Sea Level Pressure (MSLP) composite during extreme events from Table 2 for each cluster and average wind vectors. Red marks the cluster outline.
Figure 8: ERA5 500 hPa geopotential height (GPH) composite during extreme events from Table 2 for each cluster. Red marks the cluster outline.
3.7 Vertical integral of northwards water vapour flux for extreme events

As cluster WA1, WA2, SP, EA1 and EA5 have a southward flow onto the continent (Fig. 7), the contribution from warm maritime air is assessed by studying the vertical integral of northwards water vapour flux (Fig. 9). West Antarctica clusters indicate a large southwards flux extending from the Pacific Ocean region. For the WA1 cluster, the largest southwards water vapour flux occurs near the Marie Byrd Land coastline, whereas WA2 is closer to the Amundsen Sea Embayment. The SP and EA clusters show a less distinct but still present southwards flux, especially on the eastern side of the Weddell Sea for the SP. The EA5 cluster is experience a meridional flux to the west of the cluster at 120°E-180°E.

**Figure 9:** Vertical integral of northwards water vapour flux composite from ERA5 for extreme events for West Antarctica cluster 1 and 2 (WA1 and WA2), South Pole cluster (SP) and East Antarctic cluster (EA1 and EA5). Red marks the cluster outline.
4. Discussion

4.1 Air temperature trends across Antarctica

By utilizing the high grid resolution of the near-surface air temperature product AntAir ICE and deploying an unsupervised clustering technique we mapped regional air temperature trends across Antarctica for the annual and austral summer season for the period 2003-2021. Our results show a significant cooling trend (p-value <0.05) on the Antarctic Peninsula cluster with an annual mean trend of -0.12 °C/yr. This significant negative trend post 2000 agrees with multiple studies of AWS records on the Antarctic Peninsula (Oliva et al., 2017; Turner et al., 2016; Xin et al., 2023). The spatial trend (Fig. 5a) shows a clear significant cooling along the terrestrial part for both sides of the Peninsula, with the western side having the largest cooling trend. In contrast the ice shelves, including the Larsen Ice Shelf, are warming but not significantly. Turner et al. (2016) linked the cooling to a strengthening of the mid-latitude jet causing an increase in cyclonic conditions in the northern Weddell Sea and thereby creating a higher frequency of east-to-south-easterly cold winds. It has been suggested that these large scale circulation changes are driven by the Antarctic ozone recovery (Xin et al., 2023). For the Amundsen-Scott South Pole weather station, previous literature reported a warming trend (Clem et al., 2020) in both austral summer and annual mean air temperatures, with the latter being significant (Turner et al., 2020). Clem et al. (2020) link this warming to a low-pressure anomaly in the Weddell Sea as well as the Western Pacific having increasing sea surface temperatures. Our results for the SP cluster showed a similar but insignificant warming trend both in the annual and austral summer means.

This study has identified cluster RS1 covering coastal Victoria land and the area around the Transantarctic Mountain as having a strong and significant warming trend in both annual and austral summer mean air temperature. The warming trend is largest during the austral summer (0.081 °C/yr), an annual mean air temperature increase is equal to 0.069 °C/yr. For the annual mean the warming is occurring in the complex topography along the Victoria Land coastline, the Transantarctic Mountain area and along the Ross Ice Shelf. The significant warming trend near the eastern Ross Ice shelf coincides with the positive air temperature anomaly induced by the Ross Air Stream found by Coggins et al. (2014). The Ross Air Stream temperature anomaly is present in periods of strong wind propagating along the Transantarctic Mountains extending to Ross Island causing vertical mixing, along with drainage from West Antarctica forced by the synoptic pressure gradient over West Antarctica. A strengthening in the Ross Air Stream might be causing this air temperature trend on the Ross Ice Shelf.

We found a significant annual mean cooling trend in the East Antarctic cluster EA2. The spatial extent of the significant annual mean cooling trend shows a band between 10°W and 60°E following the 2000m elevation line. In contrast the King Baudoin, Fimbul, and Jelbart ice shelves and further inland warming (p-value >0.05). The annual cooling trend in the EA2 cluster cooling was found to be a magnitude of -0.044 °C/yr (Tab. 1). An annual cooling trend has previously been reported at Novolazarevskya and Syowa stations for the period 1979–2018 (Turner et al., 2020). However, this is the first time it has been reported as significant and the spatial extent of this significant trend has been mapped.
4.2 Extreme air temperature events within clusters

By using our clusters, extreme temperature events in each cluster were identified along with the spatial extent, the mean air temperature and the air temperature anomaly within the cluster during the event (Tab. 2). Here we provided the first map of the spatial extent of air temperature extremes across Antarctica from high resolution temperature products along with the corresponding regional weather patterns. The SP cluster has a large high-pressure anomaly with a center east of the South Pole and a low-pressure system of the Weddell Sea (Fig. 8). This agrees with extreme air temperatures events at the Amundsen-Scott AWS at the South Pole (Clem et al., 2020). A previous study has shown that warm air advection occurs during periods of low pressure over the Weddell Sea (Clem et al., 2020). The widespread warming across the interior during such events (Fig. 6) is likely caused by the inland high creating clear sky conditions allowing for enhanced incoming shortwave radiation. The most persistent warming extent is on the slopes between the South Pole and the Ronne Ice Shelf aligning with the northwards katabatic flow. Topographic channeling and low-level adiabatic warming associated with downslope airflow are the likely drivers of the heating signature.

The Ross Sea region clusters, have a low-pressure system off the coast of Marie Byrd Land and an inland high-pressure system, causing a strong pressure gradient across the Ross Ice Shelf (Fig. 8). Such a pressure pattern was previously reported by Zou et al. (2019) and Coggins et al. (2014) during warming events. Both clusters have a very similar spatial extent, with the area around and further inland of the Transantarctic Mountains and the Ross Ice shelf (Fig. 6). This corresponds to areas of significant air temperature trends discussed above (Fig. 5b). 6 of the 10 extreme events occur in both clusters (Tab. 2) leading to the RS1 and RS2 clusters having a very similar spatial extent in extreme temperatures (Fig. 6). Over the Ross Ice Shelf the extent of the extreme air temperature events correlates with where the Ross Ice Shelf airstream is particularly strong (Nigro & Cassano, 2014). Coggins et al. (2014) found that warmer events on the Ross Ice Shelf related to West Antarctic drainage especially when there is a strong Ross Ice Shelf airstream event. These events were linked to periods of fast moving air where warming was caused due to increased vertical mixing and adiabatic heating of descending air. Maximum windspeeds in this region was caused by barrier wind corner jet by Nigro et al. (2012). With this region being the fastest warming of all clusters and with a mean air temperature across the cluster of -3.9°C during the extreme event on the 20 December 2021 this region could be vulnerable to extreme events causing widespread above freezing temperatures in the future if this trend persists.

From the results it is clear that West Antarctica warming events are linked to the meridional flow of northerly moist air masses onto the continent (Fig. 9), caused by a blocking high (Fig. 8), sharing some characteristics to an atmospheric river signature. Atmospheric rivers in the Amundsen Sea Embayment have been previously linked to blocking highs over the southeast Pacific and a deep low-pressure system near Marie Byrd land or further over the Ross Sea (Djoumna & Holland, 2021; Maclennan et al., 2023; Scott et al., 2019). From our identified extreme events the January 2016 extensive summer melt event in West Antarctica studied by Nicolas et al. (2017) was also detected both in the WA1 and WA2 cluster from the 11 to 14 of January 2016 (Tab. 2). This event was linked to a strong El Niño event and caused by sustained
and strong advection of moist northerly air towards the continent (Nicolas et al., 2017). The atmospheric rivers transport warm moist air and are possibly a trigger for mesoscale foehn wind events in this area leading to extensive warming and surface melt during the summer (Djoumna & Holland, 2021; Scott et al., 2019; Wille et al., 2019). A low pressure system over 150°W – 180°W and a high-pressure ridge has been described by Zou et al. (2019) as leading to foehn conditions near Simple Coast, and the closer the high-pressure system is to the coastline the stronger the foehn at Simple Coast. While this study did not investigate mesoscale wind systems (such as Foehn winds), the high spatial resolution of the air temperature dataset (AntAIR ICE, 1km grid resolution) could detect these events and the warming events for cluster WA2 over Ellsworth Land and the Ross Ice Shelf (Fig. 6) could be linked to foehn-induced warming as air being advected onto the continent, pushed over the topography, and adiabatically warming while descending towards Ellsworth Land.

East Antarctica clusters were mainly dominated by a strong northwards flow from the interior toward the coastline (Fig. 7) reinforced by a strong inland high-pressure system and a weaker low in the circumpolar pressure trough (Fig. 8). The warming extent of these weather patterns is, except for cluster EA5, widespread across multiple clusters on the inland plateau whereas the coastline only experiences warming within the extent of the cluster (Fig. 6). Cluster EA5 is the only East Antarctic cluster with a defined low-pressure system located in the circumpolar trough in the MSLP composite (Fig. 7), diverting maritime air onto the coastline as seen in the water vapour flux (Fig. 9). This pattern resembles the synoptic conditions during the record warming event in December 1989 reported by Turner et al. (2022), where an atmospheric river caused warm advection towards the pole followed by a downslope katabatic flow from the interior, which lead to further warming. The warming is localised slightly further inland on the plateau (Fig. 6), likely caused by the adiabatic compression with elevation change. For the remaining East Antarctica clusters, extreme events are linked to high incoming shortwave radiation from a high-pressure system causing widespread clear-sky conditions, leading to a widespread extent in the extreme temperatures. Gayathri and Laluraj (2024) studied the anomalous summer melt in the 2016-2017 austral summer season over East Antarctica, which they linked to the 20 – 21 of December 2016 melt event that resulted in wind-induced melting by strong katabatic winds causing high turbulent heat fluxes at the surface and resulting in diabatically driven warming. This event is observed as an extreme event in our results in cluster EA3 and EA5 (Tab. 2). This supports the wind composites (Fig. 7) from the extreme events, indicating that strong downslope katabatic winds (Fig. 7) are causing vertical mixing and a high turbulent heat fluxes that warm the surface in this area. For EA3 a topographic channeling towards the coastline appears to be present in the spatial extent of the extreme air temperatures (Fig. 6).

4.3 Limitations and future research

A limitation of AntAir ICE is the missing data during cloudy conditions from the MODIS product. The study by Gayathri and Laluraj (2024) also reported further melt events during the 2016-2017 austral summer season for East Antarctica, however, these events were linked to cloud-induced melt and therefore not detected by AntAir ICE. When working on a daily mean
timescale there will be a higher chance of a cloud free scene, but when using thermal satellite products, missing data are inevitable. Atmospheric rivers are associated with increased cloud cover and therefore reduce the availability of cloud free data. From our WA1, WA2, and EA5 clusters, extreme events related to meridional transport of moist air are detected indicating that extensive events are resolved with the AntAir ICE dataset. Our results are confirming previously identified trends such as the Antarctic Peninsula cooling trend which is the area with the most persistent cloud cover across the continent (Bromwich et al., 2012). Our results are thereby showing that the AntAir ICE temperature product is suitable for identifying temperature trends and extreme events. This analysis provides the first spatial distribution of the regionality of extreme warming events along with the physical drivers associated with atmospheric circulation patterns. Especially the warming trend of the RS1 cluster and the high mean air temperature across the cluster during the extreme events indicates that this region could be prone to extremes in a warming climate. Furthermore, the AnitAir ICE temperature dataset at 1km grid resolution means that the impact of localized weather patterns and mesoscale wind systems on air temperature can be detected (such as foehn wind induced warmings), however further case studies employing limited area numerical weather modelling and AntAIR ICE can be used to investigate drivers of very localized extremes within the regions identified in this study.

5 Conclusion

In this study, a k-means clustering was used to divide Antarctica into 12 clusters based on austral summer and annual mean air temperature trends from AntAir ICE for the period 2003-2021. The clusters were used to identify regional air temperature trends across Antarctica, as well as to assess the controls of regional weather patterns on extreme air temperature events.

This study confirmed previously observed trends such as a significant annual mean cooling trend on the Antarctic Peninsula and over East Antarctic between 100°W and 60°E and up to 2000m elevation, with the latter not being reported as significant previously. Our study has for the first time identified regions around the Victoria Land coastline and the Transantarctic Mountains as having strong and significant warming trends of \(0.08 \, ^{\circ}C/\text{Yr}\) and \(0.07 \, ^{\circ}C/\text{Yr}\) in austral summer and annual air temperature, respectively.

By examining extreme air temperature events during austral summer, we identified distinct regional weather patterns associated with these events. The West Antarctic clusters were mostly affected by the interaction of blocking high-pressure systems with low-pressure systems embedded in the circumpolar westerlies, causing advection of warm, maritime air from more northerly sectors. This flow pattern has previously been attributed to atmospheric river signatures. The spatial extent of the extreme air temperature in the West Antarctica clusters was mostly constrained within the cluster. For East Antarctica, the extent of these extreme air temperature events was widespread and present simultaneously across multiple clusters. Extreme events are associated with intense high-pressure systems, resulting in widespread clear-
sky conditions and high incoming shortwave radiation, which favour the development of katabatic winds that enhance vertical mixing, the turbulent heat flux and adiabatic heating.

Our study highlights the importance of spatial air temperature data when considering local topography and regional climate interactions for assessing air temperature trends and temperature extremes across Antarctica. The spatial distribution and persistence of warming events were shown to be influenced by complex interactions between regional weather patterns and topography. By identifying regions prone to extreme air temperature events, our research provides the initial steps to guide strategic decisions to enhance monitoring in Antarctica. In conclusion, our analysis of air temperature trends and extreme events provides a stepping stone for further research on air temperature patterns across Antarctica and emphasizes the need for continued monitoring of climate change impacts in this critical region.

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Open Research
The AntAir ICE temperature product are available to download free from Pangaea https://doi.org/10.1594/PANGAEA.954750. ERA5 data from 2003 to 2021 were obtained from The European Center for Medium Range Weather Forecasts, ECMWF https://apps.ecmwf.int/datasets/. Results of vertical integral of northwards water vapour flux from ERA5 daily statistics tool developed by ECMWF is available at https://cds.climate.copernicus.eu/apps/user-apps/app-c3s-daily-era5-statistics.

References


