

Assessing the Likelihood of Unprecedented Antarctic Heat in the Current Climate

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ABSTRACT: East Antarctica experienced two recent heat waves with no historical precedent, in March 2022 in Wilkes Land (WL) and in July–August 2024 in Dronning Maud Land (DML). In this study, a large ensemble of seasonal hindcasts is used with the “unprecedented simulated extremes using ensembles” (UNSEEN) technique to contextualize these events by determining whether similar or even more extreme events are possible in the current climate. The observed WL March 2022 event was so extraordinary that the anomaly in UNSEEN’s most extreme event was at least 7.5 K smaller, and it is suggested that small-scale processes contributing to this heat wave are not represented accurately in the ensemble. However, record-breaking geopotential height anomalies are possible, exceeding 100 m above the observed, but only have a 0.1% chance of occurring every year. Furthermore, the UNSEEN ensemble suggests that the magnitude of the winter 2024 event could be exceeded in DML by up to 0.7 K, albeit with a very low likelihood. Similarly, across the Antarctic continent as a whole, UNSEEN analysis suggests that temperature anomaly records could be broken almost anywhere, by several kelvins in the most extreme cases. Additionally, the UNSEEN method is applied to January to ascertain the risk of unprecedented impacts during the peak melting season. If the temperature extremes from UNSEEN are realized, unprecedented melting frequency and intensity over ice shelves in the Antarctic Peninsula in particular could occur under current climatic conditions, impacting ice shelf stability and global sea levels.

KEYWORDS: Antarctica; Extreme events; Snowmelt/icemelt; Temperature; Hindcasts; Ensembles

1. Introduction

In recent years, severe heat waves have occurred over Antarctica which have broken long-standing observational temperature records. One such event occurred over the Pacific sector of East Antarctica in March 2022, which has since been shown to be the largest heat wave ever recorded on Earth in terms of the deviation from climatology (Blanchard-Wrigglesworth et al. 2023). This event was remarkable for its spatial extent, magnitude, and duration, with March temperature anomaly records broken in an area exceeding 3 million km². During this event, near-surface temperature anomalies were widely 30–40 K above the March climatology for several days (Blanchard-Wrigglesworth et al. 2023; Wille et al. 2024a). An even more recent example of unusually large positive temperature anomalies in Antarctica occurred further west in Dronning Maud Land in July–August 2024 (the middle of austral winter), where temperature anomalies were also record breaking in places (Zhai et al. 2025). Both of these heat waves were also notable for their longevity, with extreme anomalies present for several days in the case of March 2022 (Blanchard-Wrigglesworth et al. 2023; Wille et al. 2024a) or several weeks in winter 2024 (Zhai et al. 2025). Thus, despite occurring at much lower temperatures

than in other parts of the world, these Antarctic heat waves share the large-scale spatiotemporal characteristics of other terrestrial heat waves.

Temperature extremes such as these have contributions from dynamical processes on multiple scales. On the synoptic scale, warm extremes in Antarctica are predominantly driven by warm air advection. Flow with a strong northerly component leads to the advection of warmer air from lower latitudes into Antarctica and has been identified as a main driver of anomalous warmth here (Sinclair 1981; King et al. 2017; Carrasco 2018; Scott et al. 2019; Turner et al. 2021; Blanchard-Wrigglesworth et al. 2023; Orr et al. 2023; Xu et al. 2024). Most of the time, the circulation pattern in these scenarios is such that anomalously high pressure (or blocking) is situated to the east of the warmest air, with this resulting northerly flow promoting warm advection (Turner et al. 2021; Blanchard-Wrigglesworth et al. 2023; Xu et al. 2024). If the anticyclone is positioned even further to the east, a cyclone can also become more influential in providing the synoptic-scale pattern for warm advection, for example, in a high–low pressure couplet (Lu et al. 2023; Bozkurt et al. 2024). Additionally, cyclones can also be important for temperature extremes in Antarctica independently of an anticyclone (Turner et al. 2021), especially if they are associated with atmospheric rivers (ARs). ARs can contribute to the warming of the Antarctic surface, both dynamically through the transport of warm air from the tropics to the continent (Bozkurt et al. 2024; Wille et al. 2024a) and thermodynamically via enhanced emission of long-wave radiation from their deep, moisture-laden bands of cloud (Djoumna and Holland 2021).

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Certain local-scale phenomena can also lead to temperature extremes in Antarctica, albeit on a smaller spatial scale and duration. The foehn effect warms the air downwind of high ground and also contributes to warm extremes on the continent, for example, over the Peninsula (Elvidge et al. 2016; Gilbert et al. 2022) and Ross ice shelf (Zou et al. 2021). The foehn effect also warms the upwind side of high ground and can lead to additional warming of extremes through increased longwave radiation from the presence of clouds with liquid water, especially if accompanied by an AR (Wille et al. 2024b). Other types of wind, namely, katabatic winds (Parish and Bromwich 1989; Lenaerts et al. 2017) and barrier winds (Orr et al. 2004), can also result in locally increased temperatures in Antarctica.

Extreme warm events can be impactful for the numerous ice shelves around the coastline of Antarctica. During austral summer, surface liquid water pooling on the surface of ice shelves is common (Kingslake et al. 2017; Stokes et al. 2019; Dell et al. 2020) as a response to the melting of snow and ice. These meltwater ponds can seep into cracks in the ice shelf and then refreeze, expanding the cracks and increasing ice shelf instability, in a process known as hydrofracturing (Munneke et al. 2014). Ultimately, this process can contribute to the complete collapse of ice shelves (Lai et al. 2020) after gradual thinning and calving events, with Larsen A and B in the Antarctic Peninsula (AP) the most well-known examples of this (Banwell et al. 2013). Given suitable preconditioning arising from antecedent conditions, extreme Antarctic heat can result in hydrofracturing cascades, due to the formation of large melt ponds on the top of the ice shelf. This response to elevated surface temperatures can result in the complete collapse of ice shelves (Robel and Banwell 2019; Wille et al. 2022). For example, the March 2022 severe heat event coincided with the final collapse of the Conger Ice Shelf in East Antarctica (Wille et al. 2024b). Loss of such Antarctic coastal ice shelves can not only result in changes to the ecosystem around the collapse (Gutt et al. 2011; Ingels et al. 2021) but also lead to a more unstable continental ice sheet (Pritchard et al. 2012), leaving it more vulnerable to glacial flow into the ocean and thus a rise in global sea levels (Rignot et al. 2019; DeConto et al. 2021).

These potential impacts have motivated many previous studies into extreme Antarctic temperatures from the perspective of case study analyses (e.g., Blanchard-Wrigglesworth et al. 2023; Wille et al. 2024a,b; Zhai et al. 2025), continentwide studies (e.g., Orr et al. 2023), and future projections of Antarctic heat wave persistence and severity (e.g., Feron et al. 2021). The March 2022 and winter 2024 events were locally record breaking, but due to the sparsity of observational records in Antarctica in both space and time, it is difficult to ascertain precisely how unexpected they were or what the return period of such an event is (Wille et al. 2024a). A way in which these issues can be overcome is to use the unprecedented simulated extremes using ensembles (UNSEEN) approach (e.g., Thompson et al. 2017; Kelder et al. 2020, 2022). This approach exploits large ensembles to ascertain plausible, but unrealized, representations of meteorological conditions in the current climate, provided that the ensemble output is statistically indistinguishable from observations. The UNSEEN methodology has previously been used to examine the likelihood of various low-probability

hydrological events, such as extreme precipitation in the United Kingdom (Thompson et al. 2017; Kent et al. 2022), Norway (Kelder et al. 2022), and Australia (Irving et al. 2024), and high river flows (Kay et al. 2024). UNSEEN has also been used to quantify the risk of rare heat events, for example, heat waves in China (Thompson et al. 2019) and the United Kingdom (Kay et al. 2020, 2025) as well as drought in Australia (Squire et al. 2021) and Indian monsoon rainfall (Jain et al. 2020). However, it has yet to be used to analyze the probability of extreme positive temperature anomalies in Antarctica.

Before considering any UNSEEN analysis on unprecedented extremes in the Antarctic, a short summary of the aforementioned 2022 and 2024 heat waves in East Antarctica is provided for context. Figure 1 describes the evolution of the synoptic conditions during the March 2022 Wilkes Land (WL) and winter 2024 Dronning Maud Land (DML) heat waves. Further details on the March 2022 WL event can be found in Blanchard-Wrigglesworth et al. (2023) and Wille et al. (2024a,b), and the DML winter 2024 event is detailed in Zhai et al. (2025). In WL, the March 2022 event was remarkable in terms of its peak 2-m temperature (T2m; 25.1 K) and 500-hpa geopotential height (Z500; 310 m) anomalies (Fig. 1a), which both markedly exceeded the 99th percentiles. In WL as a whole, the daily mean T2m was over 10 K above the March average for six consecutive days and above the 99th percentile for 4 days (17–20 March). Over a large swathe of WL, record-high gridpoint T2m anomalies were set from 15 to 24 March (Fig. 1b). During this event, most of eastern East Antarctica was at least 6 K above average and under the influence of a strong blocking anticyclone centered slightly east of WL. This meant that WL was on the western flank of the block, resulting in strong warm, moist advection (partly caused by an AR) into the region from lower latitudes, explaining the exceptionally high temperature anomalies recorded here (Blanchard-Wrigglesworth et al. 2023; Wille et al. 2024a).

The winter 2024 DML warmth covers the period from 18 July to 12 August (Fig. 1c). There were three peaks in T2m anomaly, with the largest occurring on 30 July at 17.6 K. The Z500 anomaly in DML also peaked at similar times at around 300 m. Unlike the WL heat wave in March 2022, the whole Antarctic continent was under the influence of anomalously anticyclonic conditions during the DML heat wave, associated with record-negative values of the Southern Annular Mode (SAM) and a weakening of the stratospheric polar vortex which resulted in a longer period of above-average temperatures across East Antarctica (Zhai et al. 2025). The warm anomaly was thus almost ubiquitous over Antarctica (Fig. 1d) but concentrated in the DML sector where the largest (and record-setting) T2m anomalies were found. Like with the March 2022 event, these highest temperatures are slightly to the west of the center of the block, which again promotes warm, moist advection toward the region from the midlatitudes, along with additional heat and moisture in the form of an AR (Zhai et al. 2025).

This study seeks to quantify the magnitude and likelihood of unprecedented Antarctic heat waves using the UNSEEN technique, with a large ensemble of seasonal hindcasts. Four research questions are posed; the first two attempt to contextualize the magnitude of the recent March 2022 and winter 2024 events in East Antarctica:

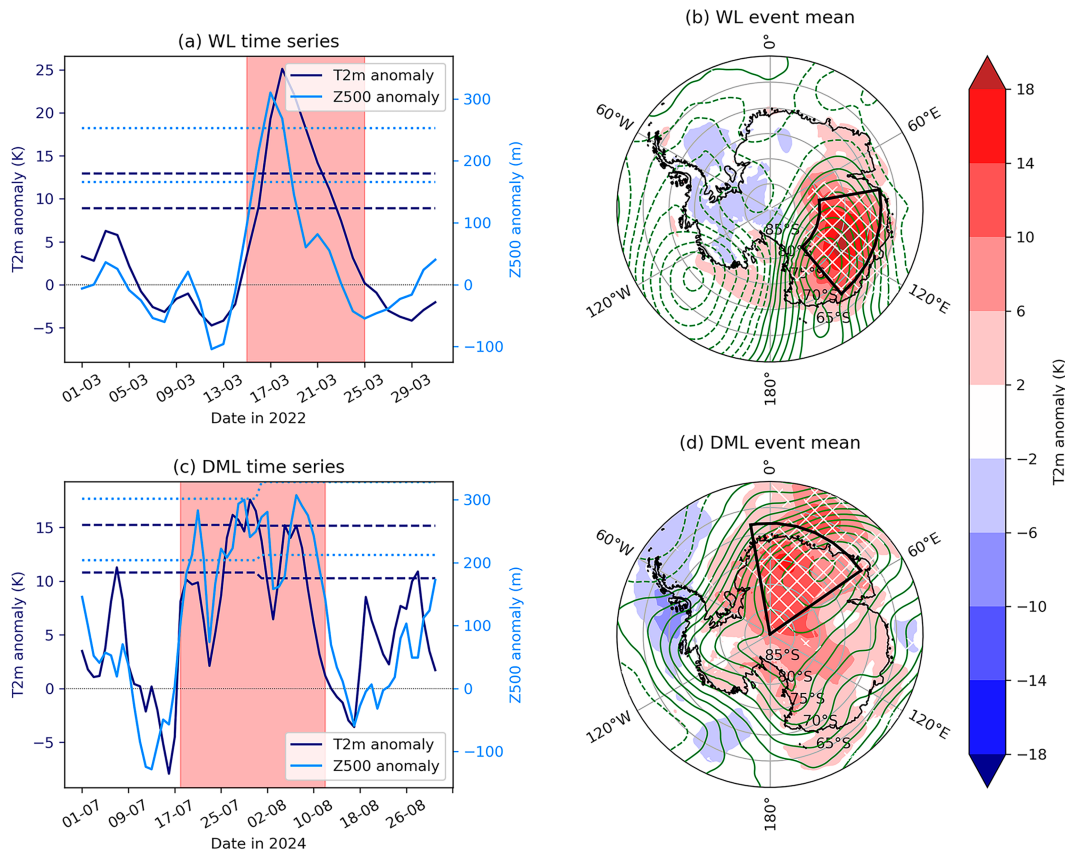


FIG. 1. Observed March 2022 and August 2024 heat waves. (a),(c) East Antarctic heat wave case study time series and (b),(d) mean synoptic patterns during the events of interest. Time series of T2m anomaly (navy; left axis) and Z500 anomaly (light blue; right axis) for (a) March 2022 in WL and (c) July–August 2024 in DML. T2m and Z500 anomalies are sourced from ERA5 (more details provided in [section 2a](#)). Dashed and dotted lines show the climatological 95th and 99th percentiles, respectively, of T2m/Z500 anomalies. Red shading shows the period over which fields in (b) and (d) are averaged. Mean T2m anomaly (shading) and Z500 anomaly (green contours, 25-m interval, negatives dashed) during the periods highlighted in (a) and (c) for the (b) WL event (black region) and (d) the DML event (black region). More details on the choices of the WL and DML domains are given in [section 2c](#). White hatching indicates grid points that have their record-highest monthly T2m anomaly during the (b) March 2022 or (d) winter 2024 events.

- (i) Were the March 2022 and winter 2024 events the strongest events in their respective locations that could have been expected under the current climate? Or, could as yet unrealized events in these regions be even more severe?
- (ii) Which weather patterns result in extreme events in these heat wave regions and are the unrealized extreme events driven by similar patterns to those already observed?

Then, an Antarctic-wide perspective is provided, and two further research questions are answered:

- (iii) Could unprecedented high temperature extremes occur elsewhere on the Antarctic continent, and how do their magnitudes compare to the 2022 and 2024 events?
- (iv) Could unprecedented surface ice melt occur?

The rest of this article is organized as follows. The datasets and methodology used for in this study are detailed in [section 2](#), and biases in the model data are examined in [section 3](#). The

observed events are compared to examples in the UNSEEN datasets in [section 4](#). Then, extreme temperatures in March, August, and January over the entire Antarctic continent in observations and in UNSEEN are discussed in [section 5](#), and [section 6](#) explores how UNSEEN extremes affect the melting characteristics of Antarctic ice shelves in these months. Finally, discussion and conclusions are provided in [section 7](#).

2. Data and methods

a. Observational dataset

In situ observations of Antarctic atmospheric variables from automatic weather stations (AWSs) are predominantly situated along coastal regions and are prone to discontinuities in their time series or observational bias (e.g., [Wang et al. 2023](#)). A particular concern regarding the usage of AWS data for this study is the fact that long-term inland observations in

the whole of East Antarctica are particularly sparse (Wang et al. 2023) and the fact that during calm clear-sky conditions in summer, AWS observations of temperature are prone to a positive bias (Genthon et al. 2011), which would lead to unrealistically extreme observed temperature events.

Therefore, in this study, output from the fifth generation European Centre for Medium-Range Weather Forecasts (ECMWF) atmospheric reanalysis (ERA5) (Hersbach et al. 2020) is used as the best estimate of present-day “observed” events, as this provides complete spatiotemporal coverage of this region. ERA5 is considered to be the most reliable reanalysis for near-surface temperatures over Antarctica (Gossart et al. 2019), with mean correlation coefficients with weather station observations during July and August being 0.95 (Zhai et al. 2025) and annual mean biases being a maximum of 3 K in magnitude (Wang et al. 2025). Six-hourly (0000, 0600, 1200, 1800 UTC) T2m and Z500 are used to calculate daily means at each grid point in the Southern Hemisphere (SH) high latitudes ($\geq 60^\circ\text{S}$), at a resolution of 0.25° . Data for March and August are used for analysis of extreme temperatures and circulation patterns to compare with the observed (ERA5) March 2022 and winter 2024 East Antarctic heat waves. Data from January are also obtained to provide additional analysis of heat waves in summer, when the Antarctic continent is at its warmest (Gossart et al. 2019), and ice sheet melt is most frequent and widespread.

Although the ERA5 archive contains data of past weather conditions from 1940 onward, only data from 1979 to 2024 are used for the analysis in this work due to the unreliability of ERA5 in the presatellite era (before 1979) over the Antarctic (Bromwich et al. 2024) and the SH as a whole (Soci et al. 2024). This results in 46 years of observational data, with each month having $31 \text{ days} \times 46 \text{ years}$ of observed daily mean T2m and Z500 (1426 total days for each month). Anomalies in T2m and Z500 are additionally calculated to be deviations from the 1979–2024 monthly climatology at each grid point.

b. UNSEEN datasets

Two global seasonal hindcast ensembles are used for the UNSEEN analysis of unprecedented extremes. The first is Global Seasonal Forecast System, version 6 (GloSea6), from the Met Office (Met Office 2025), which is an updated version of GloSea5 documented in MacLachlan et al. (2015). Its hindcast of seven members is initialized on 1, 9, 17, and 25 of every month from February 1993 to December 2016 and run for 7 months. The second set of hindcasts come from fifth-generation seasonal prediction system (SEAS5) from the ECMWF (Johnson et al. 2019), which are 7-month, 25-member forecasts initialized on 1 of every month from January 1981 to December 2016. Both GloSea6 and SEAS5 hindcasts are output on a 1.0° grid.

In this study, the hindcast data are analyzed with lead times of 3–6 weeks after initialization, to allow the members within each initialization to be independent from each other while also not being long enough to let the ensemble drift toward its climatology (Kelder et al. 2022). Three initializations from GloSea6 from each year provide output for simulated days in

TABLE 1. Details of the UNSEEN data used in this study.

	GloSea6	SEAS5
Hindcast period	1993–2016	1981–2016
Jan initializations	25 Nov, 1 Dec, 9 Dec	1 Dec
Mar initializations	25 Jan, 1 Feb, 9 Feb	1 Feb
Aug initializations	25 Jun, 1 Jul, 9 Jul	1 Jul
Members per initialization	7	25
Simulated days	15 624	27 900

January, March, and August, while only one initialization per month is used from SEAS5. Full details of the hindcast data used are given in Table 1. The data from the two models are then pooled together into one dataset (hereafter referred to as the “UNSEEN ensemble”) of 43 544 simulated days, over 30 times more than in ERA5.

Before using the UNSEEN ensemble to examine extreme temperature and circulation patterns, it must be evaluated to ensure that its unprecedented extremes are realistic representations of the current climate. In other words, the distribution of T2m and Z500 from the ensemble should appear consistent with the same distributions of T2m and Z500 from ERA5 after accounting for sampling uncertainty. For example, if the ensemble simulates more warm extremes than ERA5, it could only be considered to be reliable if there was no climatological warm bias to the ensemble compared to the ERA5 record. The UNSEEN ensemble is evaluated in a process known as “fidelity testing,” detailed in section 3a.

c. Areas of focus

The focus in section 4 will be on the extreme T2m and Z500 over similar regions to the recent observed heat waves. As shown by the white hatching in Fig. 1, vast areas of Wilkes Land and Dronning Maud Land experienced record-breaking daily temperature anomalies from the monthly means during March 2022 and winter 2024, respectively. Therefore, further analysis is performed on two domains that contain these record-breaking grid points during the events, namely, WL (80° – 140°E , 68° – 80°S) and DML (-10° to 55°E , 68° – 90°S). Analysis was also performed on domains with slightly different boundaries, which drew the same qualitative results (not shown). The ice shelf masks were obtained from the National Snow and Ice Data Center (<https://nsidc.org/data/nsidc-0709/versions/2>; Mougnot et al. 2017).

d. Melt potential index

A recently devised metric called the melt potential index (MPI; Orr et al. 2023) exploits the close relationship between near-surface air temperature and melting of ice (Deb et al. 2025) and is used in this study to determine the frequency and intensity at which Antarctic ice shelves are at risk of melting, both in ERA5 and in the UNSEEN time series. Here, the MPI definitions are adapted slightly from those in Orr et al. (2023) to better quantify the risk of unprecedented melting frequencies and intensities. Daily mean T2m from January, March, and August is used to determine both a frequency

(MPI-freq) and intensity (MPI-int) component of melt potential for every year in the January/March/August time series (and every member for the UNSEEN data). In this study, MPI-freq quantifies the number of days in that particular month for each year, out of the maximum 31, where the daily mean T2m at a grid point exceeds the melting point of 273.15 K. However, it should be noted that depending on the characteristics of the ice, some melting can occur at temperatures slightly lower than this (Nicolas et al. 2017). Second, MPI-int is defined to be the difference at each grid point between the 100th percentile (i.e., the maximum daily mean value every month, not the 95th percentile used in Orr et al. 2023) of daily mean T2m and the melting point, where the 100th percentile is already above the melting point. Higher MPI-int therefore implies higher extreme temperatures and more intense melting with higher surface run off and more potential for ice-shelf instability. Additionally, instead of calculating the MPI on data from the high-resolution models in Orr et al. (2023), in this study, models with a coarser resolution are used to determine melting potential. It is therefore likely that smaller-scale processes that locally increase temperature (e.g., foehn winds) that could lead to surface melting are not resolved as well (or at all) in this study's models.

3. UNSEEN model evaluation

a. Fidelity testing

Fidelity testing is performed in this study by performing a “moments” test on the UNSEEN ensemble (e.g., Thompson et al. 2017; Kelder et al. 2020, 2022). The process is as follows and is performed for each calendar month and region for both T2m and Z500:

- 1) If evaluating over a specific area (WL/DML), an areal mean is taken for each time step of the hindcast for each member and initialization time. Otherwise, the raw ensemble data are kept at a gridpoint resolution.
- 2) Bootstrap the large hindcast ensemble (after pooling all days, members, models, and initializations into one large dataset) to construct a proxy time series of the same length as the common time period between GloSea6, SEAS5, and ERA5 (i.e., 1993–2016).
- 3) Take the first two moments [mean and standard deviation (std dev)] of the resulting distribution.
- 4) Repeat steps (2)–(3) 10 000 times, with replacement, to create a distribution of the possible means and standard deviations of the UNSEEN ensemble.
- 5) Take the areal mean of the ERA5 data (regridded to the ensemble grid), and then find the mean and standard deviation of the resulting distribution.
- 6) If the ERA5 moments fall within the central 95% of the bootstrapped UNSEEN ensemble distributions for each moment, then the ensemble can be considered to be statistically indistinguishable from each ERA5, thus meaning that it has passed the fidelity test. Otherwise, the ensemble has failed the test.

An example of a T2m fidelity test for the mean and standard deviation (for DML in August) using raw UNSEEN

ensemble data is shown in Figs. 2a and 2b (red bars). It can be seen that the raw data fail in both cases in this example. The ERA5 moments (black lines) do not fall within the 95% confidence interval of the hindcast moments for mean and standard deviation (red dashed lines): The UNSEEN ensemble mean is too small, while the standard deviation is too large.

Moments fidelity tests for mean and standard deviation were carried out for other combinations of variable, month, and location, for raw UNSEEN ensemble data. The results of these tests are shown in Table A1 in the appendix. Almost all situations fail this first test, and in most of these cases, the hindcasts have a significant positive temperature and Z500 bias (compared to ERA5), along with deviations from the mean that are too large. Therefore, before the ensemble can be used to examine the likelihood of extreme temperatures or circulation patterns in WL or DML, these differences must be corrected to improve their fidelity.

b. Bias correction

It was decided to only account for the differences between the UNSEEN and ERA5 means and standard deviations. This was to ensure that any modeled unprecedented T2m or Z500 anomalies from the mean were comparable with those in the ERA5 record and also to provide comparable variability to ERA5. The corrected UNSEEN ensemble data are obtained by multiplying the raw data by the ratio of standard deviations of ERA5 and hindcasts and then subtracting the resulting mean bias of this result when compared to ERA5. The adjustment to the variable X is thus as follows:

$$X_{\text{adj}} = X_{\text{ERA5}} \frac{\sigma_{X,\text{ERA5}}}{\sigma_{X,\text{hc}}} - \left(X_{\text{hc}} \frac{\sigma_{X,\text{ERA5}}}{\sigma_{X,\text{hc}}} - \overline{X_{\text{ERA5}}} \right), \quad (1)$$

where X_{adj} is the adjusted variable X in the hindcast; X_{hc} is the raw, uncorrected variable for a particular member; $\sigma_{X,\text{ERA5}}$ and $\sigma_{X,\text{hc}}$ are the standard deviations of X in ERA5 (containing all years) and member, respectively; $\overline{X_{\text{ERA5}}}$ is the ERA5 variable; and an overbar indicates a time mean (a mean among all times and members within each hindcast model for the hindcasts).

This adjustment is made both to the domain-mean data in the WL and DML boxes and on a gridpoint level. After correction, the moments fidelity test is performed again, and the fidelity of the higher-order moments of skewness and kurtosis is also considered. When applied to the WL and DML boxes, the UNSEEN ensemble now always passes the moments tests for the first two moments by design (blue bars in Fig. 2). It is hard to correct for differences in skewness and kurtosis, so no attempt is made to alter their values in the UNSEEN ensemble via bias correction. Additionally, it should be noted that the ERA5 skewness and kurtosis are rather uncertain. For example, their values for WL in March for T2m change from 0.14 to 0.55 and from −0.37 to 1.83, respectively (cf. Table A1), with negligible change to mean and standard deviation, when the whole 1979–2024 period is instead used. This uncertainty in the higher-order ERA5 moments (and relative lack of uncertainty in the first and second moments) justifies the decision to not

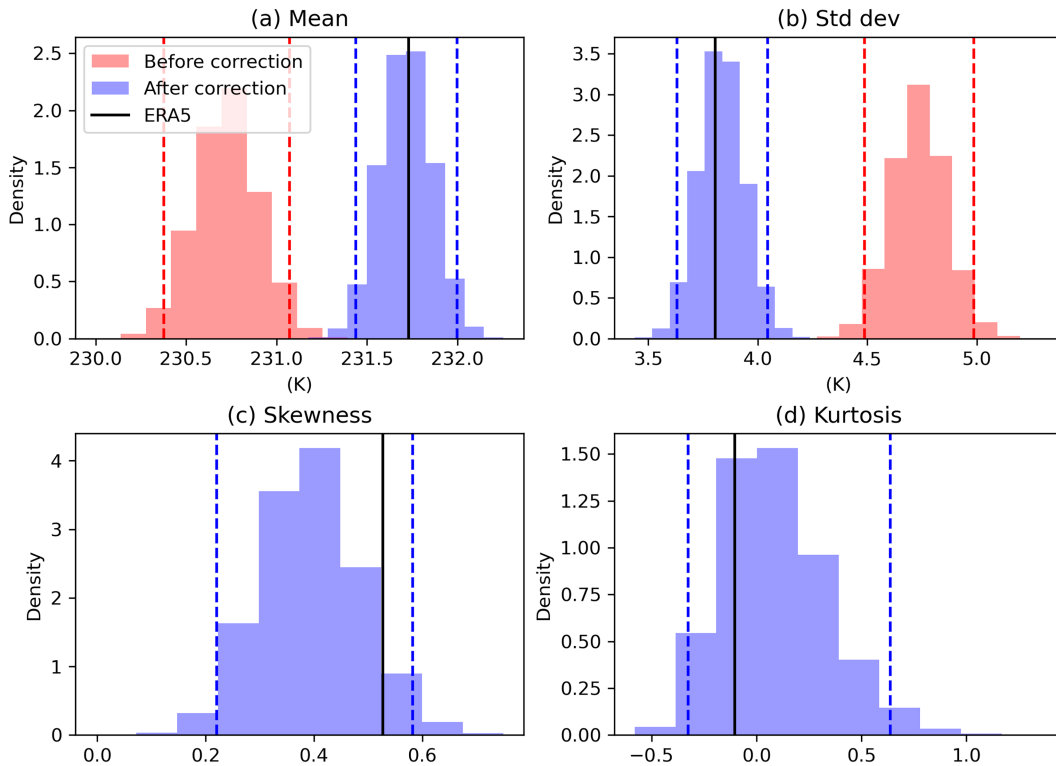


FIG. 2. Moments fidelity test example for August T2m in DML. The red bars show the results of the first moments fidelity test for the (a) mean and (b) std dev test. Blue bars show the results for the UNSEEN ensemble post-bias correction (as detailed in section 3b by correcting the mean and std dev only), for (a) mean, (b) std dev, (c) skewness, and (d) kurtosis. The 95% intervals are shown by the red and blue dashed lines. The ERA5 moments are shown by the black lines.

attempt to correct the UNSEEN ensemble for skewness and kurtosis. As such, in approximately half of the cases considered in Table A1, the ensemble fails the second fidelity test. However, it is possible that these statistical differences between skewnesses and kurtoses of the ERA5 and UNSEEN datasets are the result of severe outliers in ERA5. For example, the observed WL event in March 2022 (and to a lesser extent, the August 2024 event in DML) consisted of temperatures that were unexpectedly high given the corresponding Z500 anomaly that they occurred under (Figs. A1a,c), which would affect the skewness and kurtosis of the observed dataset that UNSEEN is being compared to. Since the corrected UNSEEN ensemble does not contain similar outliers (Figs. A1b,d), it is perhaps unsurprising that its higher-order moments are statistically different to those in ERA5 (Table A1) and that the moments test has failed even for the corrected data.

Therefore, an additional type of fidelity test is carried out to test whether the ERA5 and UNSEEN distributions of T2m and Z500 anomalies are not statistically different. In order for the ensemble to be considered reliable, they need to be statistically indistinguishable from the observed dataset (Thompson et al. 2017). To test this, a two-tailed Kolmogorov–Smirnov test is performed for each combination of region, hindcast, month, and variable (as done in Table A1). In each case, the

null hypothesis that the ERA5 and hindcast data are drawn from the same distribution cannot be rejected ($p > 0.05$), and therefore, there is no statistical difference between the observed and UNSEEN anomalies. Thus, the UNSEEN ensemble is deemed suitable for further analysis in this study.

c. Synoptic conditions during extreme temperatures

Now, the synoptic conditions during the most extreme T2m events are studied, in both the ERA5 and UNSEEN ensemble datasets, to ascertain the large-scale dynamics during such periods. If the synoptic patterns are similar in the two datasets, then confidence in the accuracy of the UNSEEN ensemble can be gained, despite it failing some of the moments fidelity tests above. Figure 3 shows the composite mean Z500 and T2m anomalies on the top 5% of days with the highest temperatures in WL in March and DML in August. Results are shown for ERA5 (left) and the UNSEEN ensemble (right). In each case, the composites show the mean fields from days in which the T2m is above the 95th percentile. As a result, over 30 times more days are averaged in the UNSEEN composites than the ERA5 ones.

The broad-scale Z500 anomaly pattern in and around WL during March events is very similar between the observations and the UNSEEN composite (Figs. 3a,b). WL is situated on

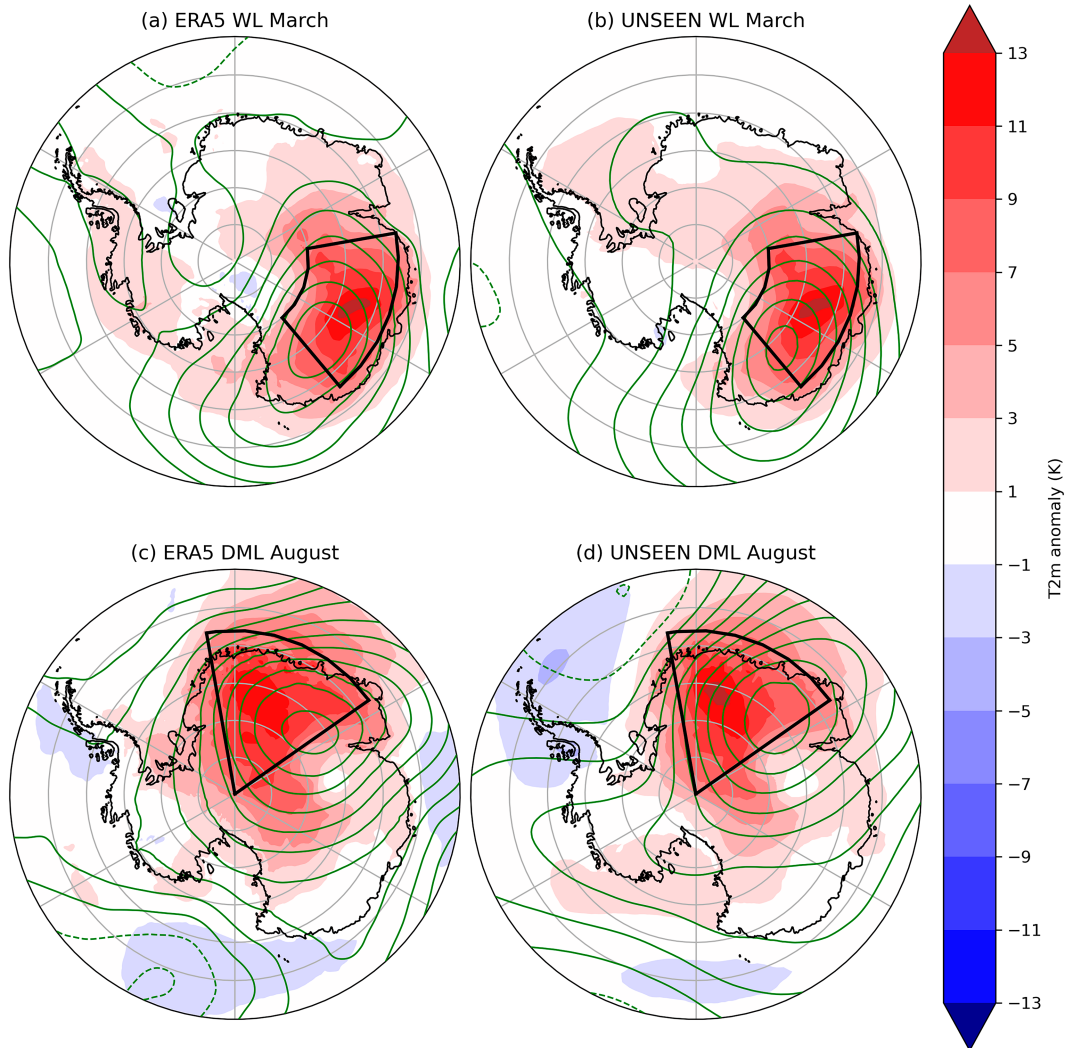


FIG. 3. Composite circulation patterns during March WL and August DML heat events. Composite T2m anomalies (shading) and Z500 anomalies (green contours, every 25 m with negatives dashed) during days where the daily mean T2m anomaly is above the 95th percentile of model monthly climatology (within the black outline). Results are shown for (a),(b) March in WL and (c),(d) August for DML in (a),(c) ERA5 and (b),(d) the UNSEEN ensemble.

the western flank of a positive Z500 anomaly, which results in an anomalously northerly wind pattern at this level. As in the case studies outlined in [section 1](#), this would lead to strong warm advection from the midlatitudes and increased temperatures ([Xu et al. 2024](#)), which are concentrated in WL. The role of warm air advection in raising temperatures during these weather patterns is clear because although the entire continent is anomalously anticyclonic during WL extreme events, the highest T2m anomalies are found only on the western edge of the strongest anticyclone. Modest anomalous warmth is also found over DML in the UNSEEN ensemble and the Peninsula in ERA5 during WL warm extremes.

The difference in the broad-scale synoptic patterns in the August DML warm extreme composites between ERA5 and the UNSEEN ensemble is also almost indistinguishable ([Figs. 3c,d](#)). Similar to March WL events and the winter 2024 case study,

DML is situated in an area of strong anomalous northerly flow on the western half of a large anticyclone, which again promotes warm advection into the region. The composite anticyclone during August DML events is larger and stronger than during the March WL events, though it should be noted that Antarctic circulation patterns tend to have larger anomalies in winter than in autumn ([Xu et al. 2024](#)). In the ERA5 and UNSEEN composites, anomalous warmth extends around the southern flank of the anticyclone into inland Wilkes Land. Finally, modest anomalously cold conditions are found over the Weddell Sea, Peninsula, and Ross Sea during warm events in DML.

These composites, as well as manual inspection of the circulation on the heat wave days in the observations and hindcasts (not shown), demonstrate that the same circulation patterns are responsible for extremes in ERA5 and the UNSEEN ensemble. This provides additional confidence to the reliability

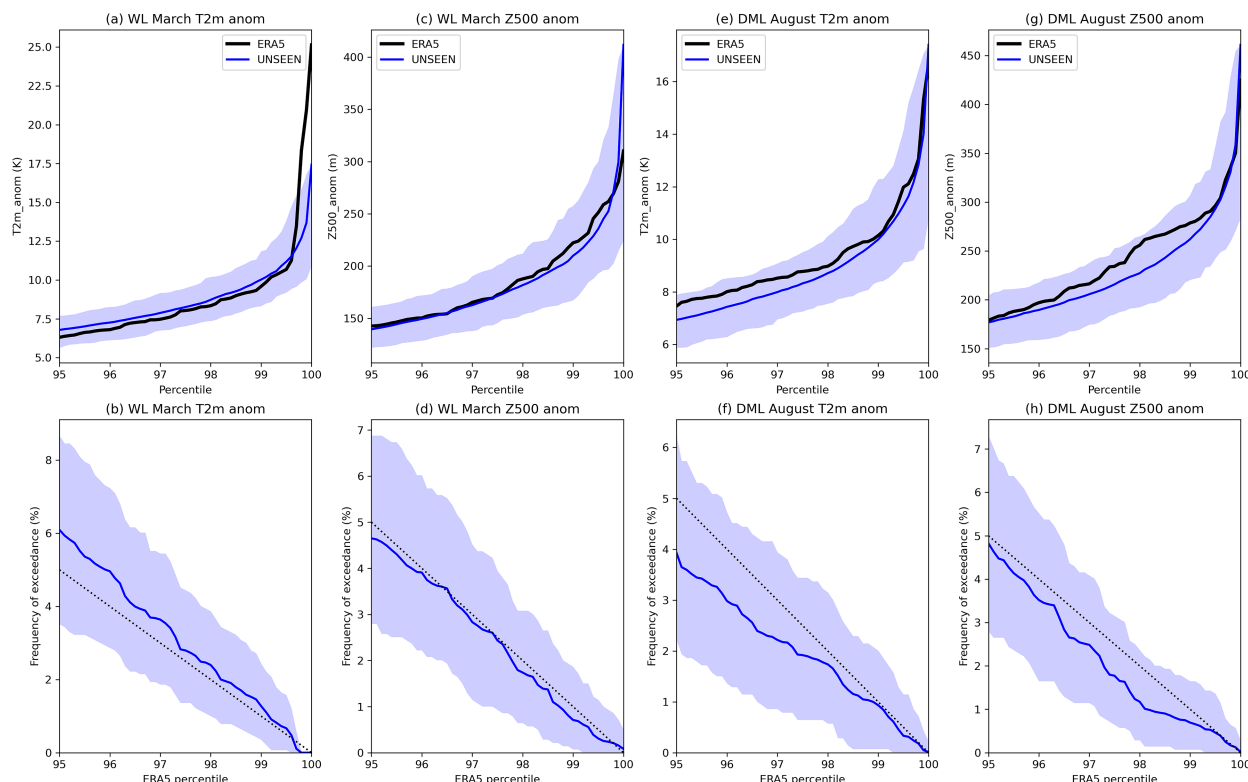


FIG. 4. Magnitude and likelihood of extreme WL and DML conditions. Top row: Comparison of the 95th–100th percentiles of the (a),(e) T2m anomalies and (c),(g) Z500 anomalies in (a),(c) WL in March and (e),(g) DML in August. ERA5 values are shown in the black line and UNSEEN ensemble in blue line, with the 95% confidence interval around the UNSEEN curve shown in blue shading. Bottom row: Frequency of exceedance of the UNSEEN ensemble of a given ERA5 percentile (solid) of (b) March WL T2m anomaly, (d) March WL Z500 anomaly, (f) August DML T2m anomaly, and (h) August DML Z500 anomaly, with 95% confidence interval (shading). The dashed line represents how often the percentiles are exceeded in ERA5. The confidence intervals are calculated in a similar way to in the fidelity tests, bootstrapping samples from the UNSEEN ensemble of the same length as ERA5 10 000 times.

of the UNSEEN ensemble, despite it failing some aspects of the fidelity tests.

4. Frequency and magnitude of unprecedented WL and DML extremes

This section examines the T2m and Z500 anomaly magnitudes during the most extreme 5% of days (quantified using T2m anomaly) over WL in March and DML in August, for ERA5 and the UNSEEN ensemble, and assesses the potential frequency of exceeding a particular ERA5 threshold in the UNSEEN ensemble. The top row of Fig. 4 shows the magnitudes of the 95th–100th percentiles in T2m and Z500 anomalies from ERA5 and the UNSEEN ensemble, while the bottom row quantifies how often these ERA5 percentiles are exceeded in the ensemble.

The 100th percentile (i.e., the highest on record) ERA5 WL March T2m anomaly is 25.1 K (black line in Fig. 4a), which occurred during the 2022 event (cf. Fig. 1b). The UNSEEN ensemble does not contain an event of similar magnitude, with the most extreme T2m anomaly here being 7.5 K smaller than during the March 2022 heat wave. As a result, there is a 0% chance that the 100th percentile in ERA5 T2m anomaly is exceeded in

the current climate, according to the hindcast models analyzed in this study (Fig. 4b). However, the UNSEEN ensemble suggests that ERA5 is inadequate in constraining the magnitude and frequency of the most extreme temperatures in WL outside of the March 2022 event. The 95th–99.5th percentiles of temperature are larger (Fig. 4a) and more frequent (Fig. 4b) than the relatively small sample of ERA5 suggests. For example, the 95th percentile of temperature is approximately 0.5 K higher than suggested in ERA5, and events with a 5% likelihood in ERA5 have a 6% (4.1%–9.4%) chance of occurring in UNSEEN. On the other hand, the higher percentiles of March WL Z500 anomaly appear to be better constrained by ERA5, as while record-breaking Z500 anomalies are possible according to UNSEEN [exceeding ERA5 by up to 102 m (Fig. 4c)], they are very unlikely [0.08% (0.00%–0.57%); Fig. 4d]. At slightly less-extreme percentiles of Z500 anomaly, the magnitude and chance of exceedance in the UNSEEN ensemble are similar to those in ERA5.

While the 2024 event in DML was the most extreme winter heat wave on record in the region, the UNSEEN ensemble suggests that T2m anomalies could potentially be even more extreme in August than already observed (Fig. 4e), with the record maxima being 16.7 and 17.4 K in ERA5 and UNSEEN,

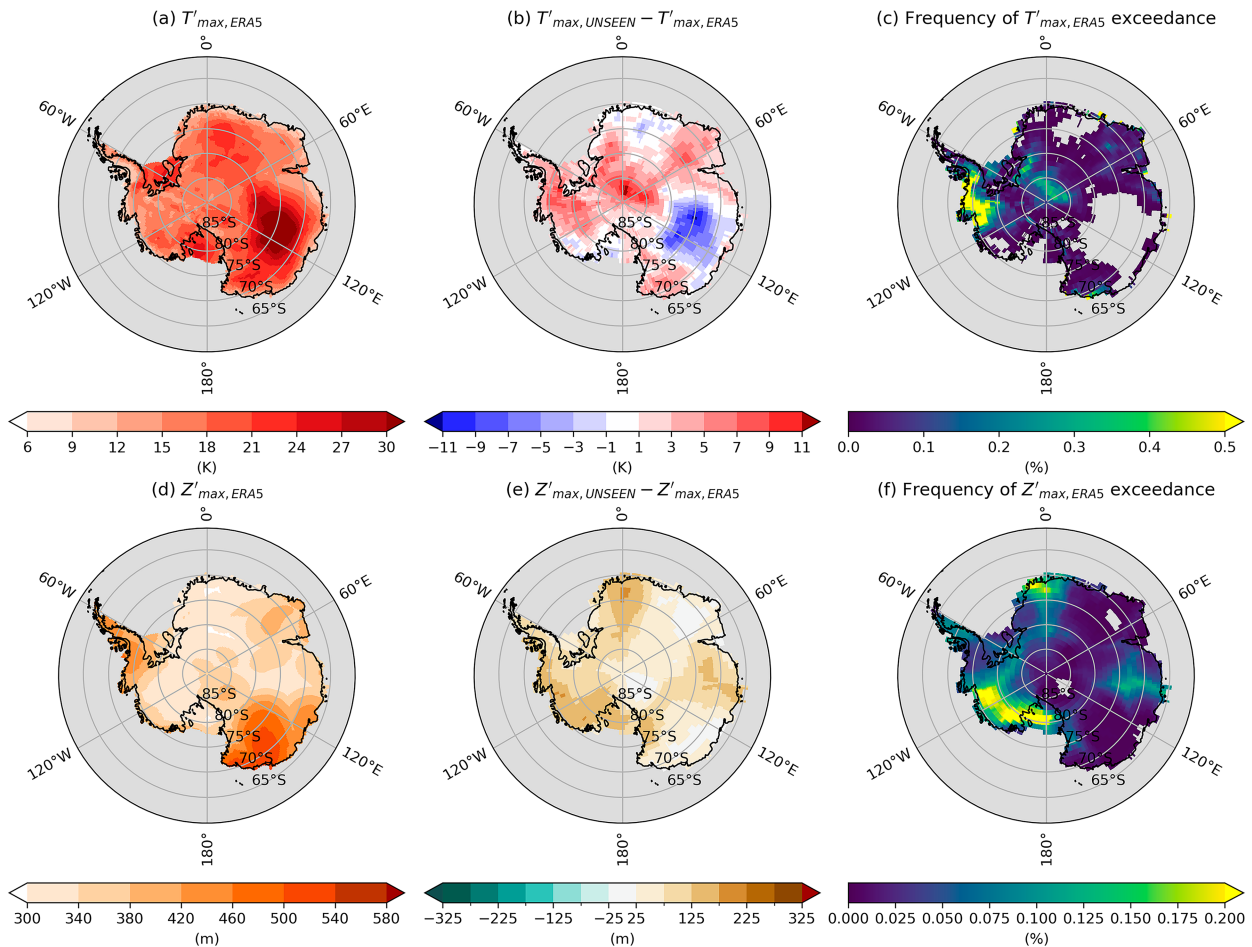


FIG. 5. Antarctic-wide record T2m and Z500 anomalies in ERA5 and the UNSEEN ensemble for March. (a) The maximum T2m anomaly at each grid point in the ERA5 record ($T'_{\max, \text{ERA5}}$) from 1979 to 2024, in March only. (b) The maximum T2m anomaly at each grid point in the UNSEEN ensemble ($T'_{\max, \text{UNSEEN}}$) compared to $T'_{\max, \text{ERA5}}$, with red shading indicating unprecedented heat in the UNSEEN ensemble. For this calculation, the ERA5 data have been regridded to the coarser grid of the UNSEEN ensemble. (c) The frequency at each grid point that $T'_{\max, \text{UNSEEN}}$ exceeds $T'_{\max, \text{ERA5}}$, with gray indicating either a grid point never exceeds $T'_{\max, \text{ERA5}}$ in the UNSEEN ensemble (i.e., frequency of exceedance is 0%) or it is outside of the ice shelf mask. (d)–(f) As in (a)–(c), but for the maximum Z500 anomalies in ERA5 ($Z'_{\max, \text{ERA5}}$) and UNSEEN ($Z'_{\max, \text{UNSEEN}}$). Note the different color bar scales in (c) and (f).

respectively. However, there is only a 0.01% (0.00%–0.29%) chance of exceeding the ERA5 record (Fig. 4f). This unprecedented T2m anomaly record is despite the 95th–99.9th percentiles of T2m anomaly magnitudes being smaller than ERA5 in DML by the ensemble (the ERA5 values being near the upper bound of the UNSEEN ensemble). This leads to estimations of frequencies of exceedance of the upper ERA5 percentiles being mostly smaller than those in ERA5 itself (e.g., only a 3.93% chance of exceeding the 95th percentile). A similar result is drawn for the August Z500 anomalies in DML, where it is possible that the record Z500 anomaly could be exceeded by a further 39 m in the current climate (Fig. 4g), despite it being a very low probability (up to 0.22% chance, Fig. 4h).

5. All Antarctic heat extremes

This section examines the record-maximum T2m and Z500 anomalies on a gridpoint level throughout the entire Antarctic

continent, and whether or not the UNSEEN method (using the corrected hindcasts) suggests even more extreme temperatures or circulation patterns could be realized in the current climate. The chances that any unprecedented temperatures or circulation patterns could be seen are also examined.

Figure 5a shows the highest recorded March T2m anomaly in ERA5 ($T'_{\max, \text{ERA5}}$) from 1979 to 2024 at each grid point over Antarctica and its ice shelves. The most striking feature is the signature from the March 2022 event over WL, reiterating that it was the warmest March heat wave ever recorded in this region, with T2m anomalies widely exceeding 30 K. Other regions that have large anomalies are the Ross and Ronne–Filchner ice shelves and inland DML ($T'_{\max, \text{ERA5}} \approx 24$ K). When comparing the maximum T2m anomaly in the UNSEEN ensemble ($T'_{\max, \text{UNSEEN}}$) to $T'_{\max, \text{ERA5}}$ (Fig. 5b), the earlier result for WL from section 4 is also confirmed on a gridpoint level, in that the UNSEEN ensemble does not model events of the same magnitude as the 2022 event. Individual grid points in

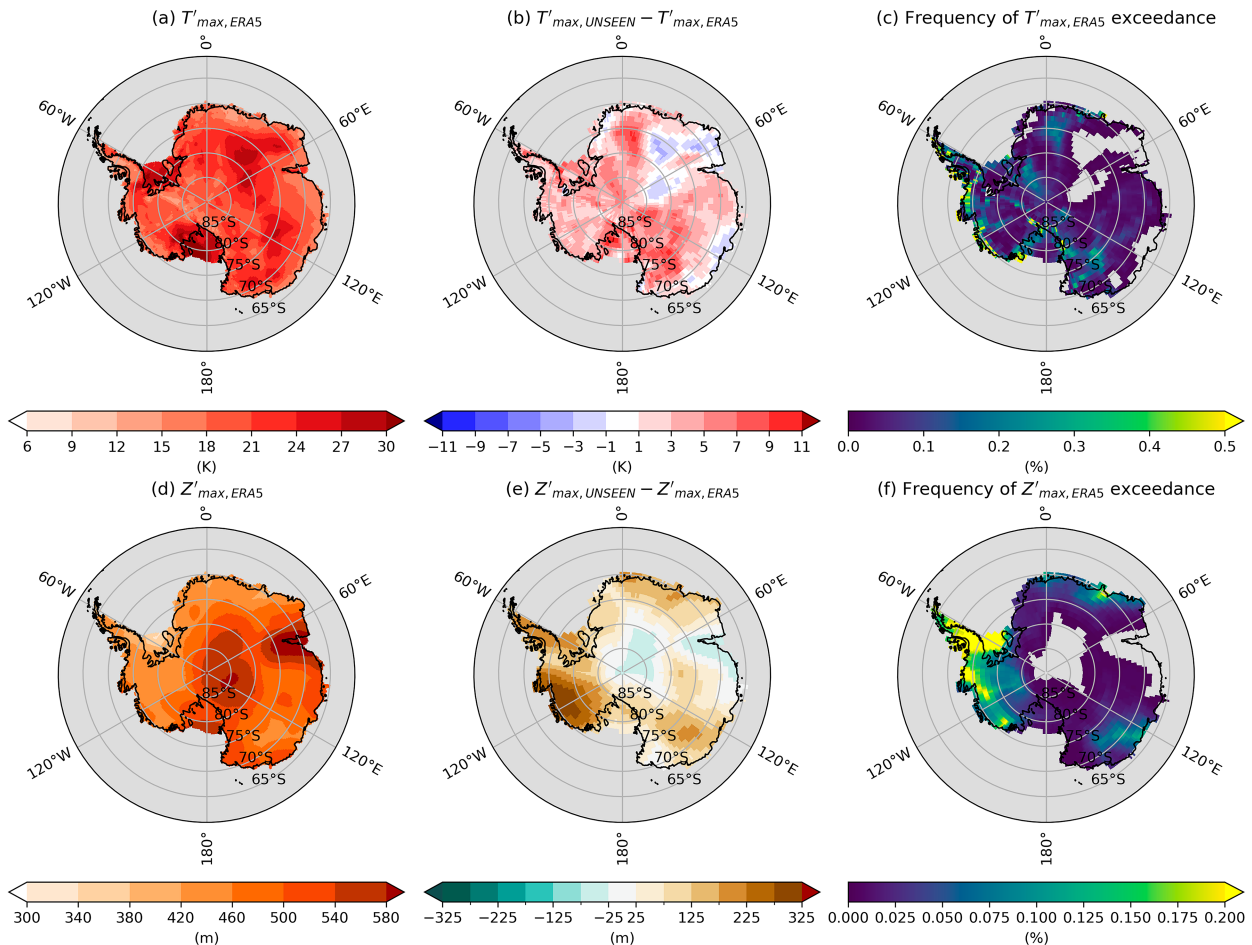


FIG. 6. Antarctic-wide record T2m and Z500 anomalies in ERA5 and the UNSEEN ensemble for August. As in Fig. 5, but showing the August records.

WL have their record-maximum T2m anomaly up to 11 K less than in ERA5, and as such, there is a 0% chance of exceeding the magnitude of the 2022 March heat wave here (Fig. 5c). The UNSEEN ensemble also does not contain examples of unprecedented March heat in some other places, like parts of DML, coastal Marie Byrd Land, and the western Ross ice shelf, though the differences between $T'_{\max,UNSEEN}$ and $T'_{\max,ERA5}$ are much smaller here than in WL. However, for the rest of the continent, unprecedented heat could occur, with $T'_{\max,UNSEEN}$ being several kelvins above $T'_{\max,ERA5}$, in particular near the pole and in Ellsworth Land. These are also the locations of the largest frequencies of $T'_{\max,ERA5}$ exceedance (Fig. 5c), with around 0.3% and 0.5%, respectively, of simulated March days in the UNSEEN ensemble surpassing the ERA5 records here. The chance of unprecedented heat around the rest of the continent is much lower (0.0%–0.1%).

The region with the highest recorded March Z500 anomaly in ERA5 ($Z'_{\max,ERA5}$) is eastern WL, at around 540 m (Fig. 5d). The UNSEEN ensemble suggests that an unprecedented strong ridge (by a further 25–75 m, Fig. 5e) is possible but extremely unlikely (less than 0.025%, Fig. 5f). The Peninsula contains the second largest $Z'_{\max,ERA5}$, though the difference

between $Z'_{\max,UNSEEN}$ and $Z'_{\max,ERA5}$ is larger than in WL (up to 125 m), and the likelihood of exceedance is slightly greater (around 0.15%). Even larger differences between $Z'_{\max,UNSEEN}$ and $Z'_{\max,ERA5}$ are found in Marie Byrd Land, the Ross ice shelf, western DML, and central WL, and the corresponding frequencies of $Z'_{\max,ERA5}$ exceedance in the UNSEEN ensemble are greatest but still low in magnitude here (e.g., over 0.2% over Marie Byrd Land and the Ross ice shelf).

The August record temperature and Z500 anomalies in ERA5 and the UNSEEN ensemble are compared in Fig. 6. The largest $T'_{\max,ERA5}$ is found over the Ross and Ronne–Filchner ice shelves, where the gridpoint maxima exceed 30 K in places (Fig. 6a). In general, $T'_{\max,ERA5}$ at each grid point is larger in August than in March, with other local maxima found in DML and WL. The UNSEEN ensemble widely models $T'_{\max,UNSEEN}$ that are larger than $T'_{\max,ERA5}$, and this difference is largest in magnitude on the Ross ice shelf, Victoria Land, and western DML (up to 11 K, Fig. 6b). However, the likelihood that the existing ERA5 T2m extremes are exceeded is small throughout, peaking at around 0.5% in some coastal areas in West Antarctica (Fig. 6c). In Coates Land, western DML, and Victoria Land, the frequency of exceedance is

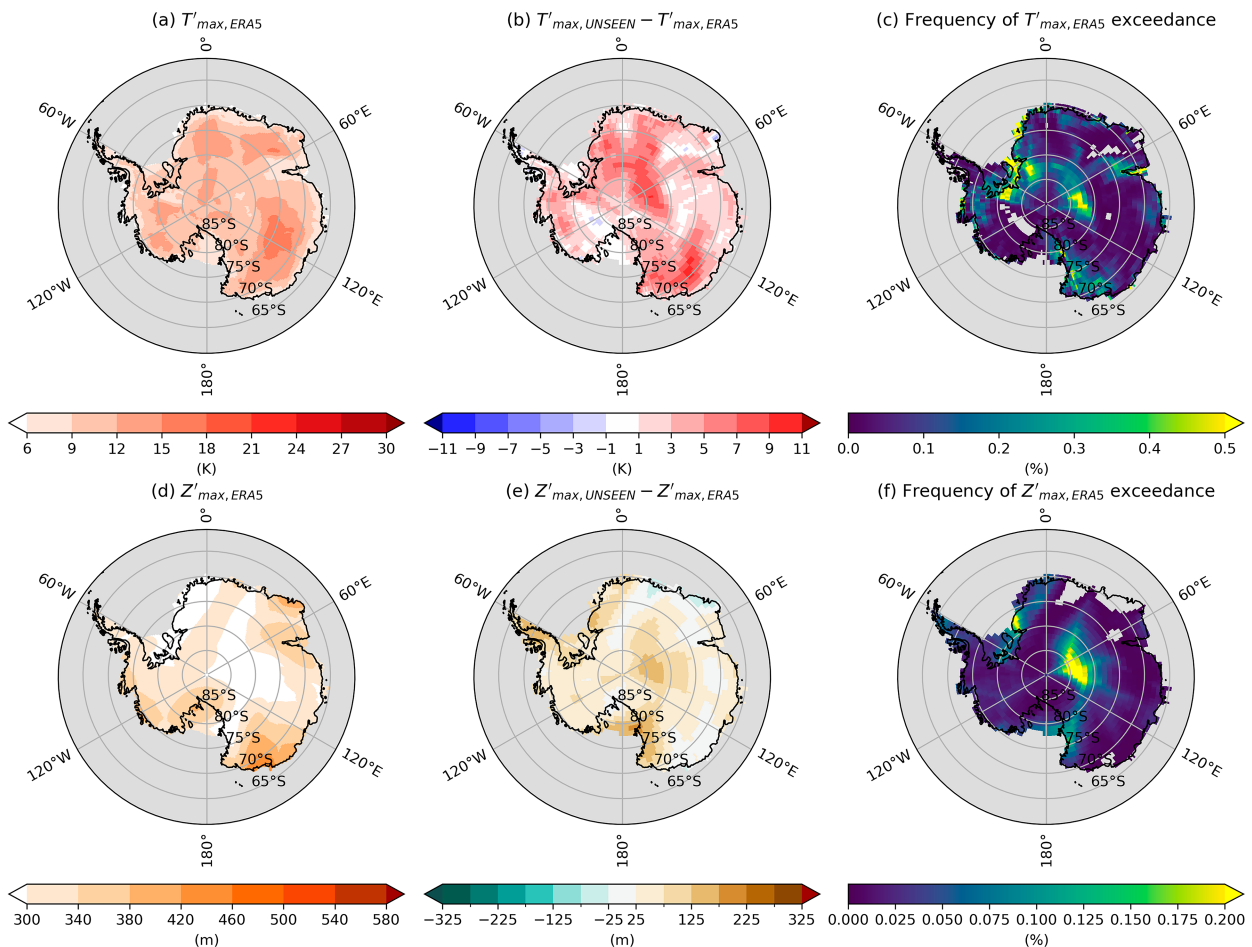


FIG. 7. Antarctic-wide record T2m and Z500 anomalies in ERA5 and the UNSEEN ensemble for January. As in Fig. 5, but showing the January records.

lower, around 0.3%–0.4%. In eastern DML and coastal WL, $T'_{\max, \text{UNSEEN}}$ is smaller than $T'_{\max, \text{ERA5}}$ by approximately 3 K (Fig. 6b), and as a result, the likelihood of exceedance here in the UNSEEN ensemble is 0% (Fig. 6c).

The record-strongest ridging over Antarctica in August, where $Z'_{\max, \text{ERA5}}$ exceeds 580 m, is near the South Pole and the Amery ice shelf (Fig. 6d). The UNSEEN ensemble does not simulate events of this magnitude in these two areas (Fig. 6e), and as a result, the frequency of $Z'_{\max, \text{ERA5}}$ is 0% (Fig. 6f). Conversely, the ensemble models much stronger record-breaking ridges than ERA5 over the rest of Antarctica. This is particularly notable over Marie Byrd Land ($Z'_{\max, \text{UNSEEN}} - Z'_{\max, \text{ERA5}} \approx 300$ m) and the Peninsula/Ronne ice shelf (around 200 m). These regions are also where the highest likelihoods of exceedance are found, though yet again they are still small (about 0.2%).

Similar results are presented for the Antarctic continent in January (Fig. 7). Although there are no recently observed January heat waves considered in this study for comparison to UNSEEN extremes, January is climatologically the warmest time of the year in Antarctica (Gossart et al. 2019) and thus the month where melting of ice sheets and ice shelves is most

likely. Therefore, it is interesting to compare observed January maximum temperatures to UNSEEN January temperatures to determine whether the continent could experience even warmer conditions in the current climate (the effect that any UNSEEN temperature extremes would have on the frequency of ice melt is examined in section 6).

The $T'_{\max, \text{ERA5}}$ is smaller in January compared to March and August, with the record-highest gridpoint T2m anomalies peaking at approximately 18 K over DML (Fig. 7a). Inland areas have the largest $T'_{\max, \text{ERA5}}$, while around the coasts and large ice shelves, $T'_{\max, \text{ERA5}}$ is smaller in magnitude. The UNSEEN ensemble contains larger maximum T2m anomalies almost everywhere in Antarctica (Fig. 7b), with $T'_{\max, \text{UNSEEN}} - T'_{\max, \text{ERA5}}$ being largest, at around 9 K, over Victoria Land, eastern WL, and DML near the South Pole. These areas are also the most likely to exceed current ERA5 records, with frequencies of occurrence approaching 0.5% (Fig. 7c). Additionally, similar magnitudes of frequency of exceedance are also found along the grounding line of the Ronne-Filchner and the Amery ice shelf, and the west coast of DML. There are only a small number of grid points where $T'_{\max, \text{ERA5}}$ exceeds $T'_{\max, \text{UNSEEN}}$, most notably over both the eastern and western coasts of the Peninsula, which

could have an impact on the frequency of melting in the UNSEEN ensemble (more details are given in section 6). Additionally, the maximum January ERA5 temperatures are larger than in UNSEEN for parts of Marie Byrd Land, which was associated with the 2016 record-breaking heat wave and AR event here (Nicolas et al. 2017; Wille et al. 2019).

Like with the T2m anomalies, $Z'_{\max, \text{ERA5}}$ is more modest in January compared to the other two months examined here and is largest over Victoria Land at around 400 m (Fig. 7d). Once again, the UNSEEN ensemble contains examples of much stronger Z500 ridges than ERA5, particularly along the western Ross Sea coast, the South Pole, the eastern Weddell Sea coast, and the Peninsula (Fig. 7e). Frequencies of $Z'_{\max, \text{ERA5}}$ exceedance are especially low throughout most of the continent, however (around 0%), except for around 60°E, 80°–85°S and the Weddell Sea coast, where it exceeds 0.2%.

6. Melt potential index in ERA5 and UNSEEN

This section describes how the extreme temperatures, both observed in ERA5 and as yet unrealized in the hindcasts, could translate to impacts for the Antarctic ice sheet. The MPI metric (Orr et al. 2023), adapted slightly in this study (section 2d), is used to illustrate regions within the ice sheet that are most vulnerable to melting, and therefore potential hydrofracture and collapse due to extreme warmth. Figures 8 and 9 show the record-maximum ERA5 MPI-freq and MPI-int, respectively; a comparison between this and the maximum MPI determined from the UNSEEN ensemble; and the frequency of maximum ERA5 MPI exceedance by the UNSEEN ensemble, for the AP where MPI-freq is highest (Orr et al. 2023). Results for the whole continent are shown in Figs. A2 and A3. The results for ERA5 and the UNSEEN ensemble are from their whole time series; however, the same qualitative results are drawn when only using data from the common time period of 1993–2016 (not shown).

Record-high MPI-freq of 1 day or more in ERA5 is confined only to the coasts of East Antarctica, the large ice shelves, the Peninsula, and a small region of Marie Byrd Land. This is even the case in January (Figs. 8a and A2a), when the continent is climatologically warmest. Inland regions are simply too cold, even in summer, to experience any melting due to any of the extreme observed temperature anomalies (cf. Fig. 7a), meaning that, here, the record MPI-freq is zero. The highest record MPI-freq values are found over the Peninsula (Fig. 8a) and exceed 20 days over the Larsen C, George VI, and Wilkins ice shelves in January. In March (Fig. 8d), the record-highest MPI-freq over these areas is lower at around 5–15 days. In August (Fig. 8g), melting over the Peninsula is rarer still, and the record-highest MPI-freq is only a couple of days, mostly on the windward western side. Over the Amery ice shelf, parts of the DML coast, and other East Antarctic coastal areas, January record MPI-freq is mostly less than 15 days (Fig. A2a). The maximum January MPI-freq over Marie Byrd Land and the Ross and Ronne-Filchner ice shelves is on the order of a few days, signifying that melting events here are rare even in summer (Fig. A2a). Maximum MPI-freq

is zero in all inland areas and almost all other coastal regions in March and August (Figs. A2d,g).

The UNSEEN ensemble suggests that unprecedented January melt frequencies are possible over all AP ice shelves, with the potential for the existing record to be broken by 10 or more days over the George VI ice shelf (Fig. 8b), parts of the Amery, and WL ice shelves (Fig. A2b). On the eastern side of the Peninsula, melting could occur on all 31 days of the month, exceeding the approximately 25-day maximum melt frequency shown in ERA5 (Fig. 8a), as shown by the positive difference between the record January MPI-freq in UNSEEN and ERA5 (Fig. 8b). However, the likelihood of exceeding the ERA5 MPI-freq records throughout is low, maximizing at about 0.3%, approximately a 1 in 300 chance in every January (Figs. 8c and A2c). Unprecedented March melt frequency is almost exclusive to the AP, and differences between UNSEEN and ERA5 are of a similar magnitude to those in January (but from a lower record value) while also being slightly more likely to be achieved (0.5% chance in parts of the west; Figs. 8e,f, and A2e,f). Strikingly, UNSEEN suggests that melting could extend further inland on the AP in the most extreme cases than ERA5 in both January and March, albeit highly unlikely. Unprecedented August melt frequency is exclusive to the AP and is smaller in magnitude than the other months, but it is noteworthy that some ice shelves, like Larsen C, could experience August melting (likelihood of around 0.3% every August) where it has not been recorded before (Figs. 8g–i).

Since, in this study, the threshold for MPI-int is the 100th percentile of daily mean T2m, it can be used to assess the impact of the record-breaking temperatures examined in Figs. 5–7 on melting. In the 3 months examined here, MPI-int in ERA5 is largest over the AP, particularly over the Larsen C ice shelf, where MPI-int exceeds 5°C in January and March (Figs. 9a,d,g). In August, only the AP has regions where the record MPI-int is above zero (consistent with where MPI-freq is also above zero), but values are much smaller than earlier in the year (Figs. 9a,d,g and A3a,d,g). The maximum MPI-int is larger in UNSEEN than in ERA5 almost everywhere there is melting (Figs. 9b,e,h and A3b,e,h), except for Larsen C in January and March, and the western Peninsula in January. This indicates that the record-highest temperature in UNSEEN is smaller than that in ERA5 in these regions (cf. Figs. 5b and 7b). However, elsewhere, UNSEEN MPI-int is larger than ERA5 MPI-int, which implies that there is the potential for unprecedented ice shelf melt intensity as well as the frequency of melt. Once again, however, the likelihood of achieving unprecedented melt intensity in any given month is low (Figs. 9c,f,i) and most likely on the west of the AP in March.

7. Discussion and conclusions

In this study, the UNSEEN methodology is applied to severe weather in Antarctica for the first time to contextualize the recent March 2022 and winter 2024 heat waves. The results demonstrate that the magnitude of the March 2022 event in the WL was exceptional, with regionally averaged daily mean temperature anomalies being markedly larger than in

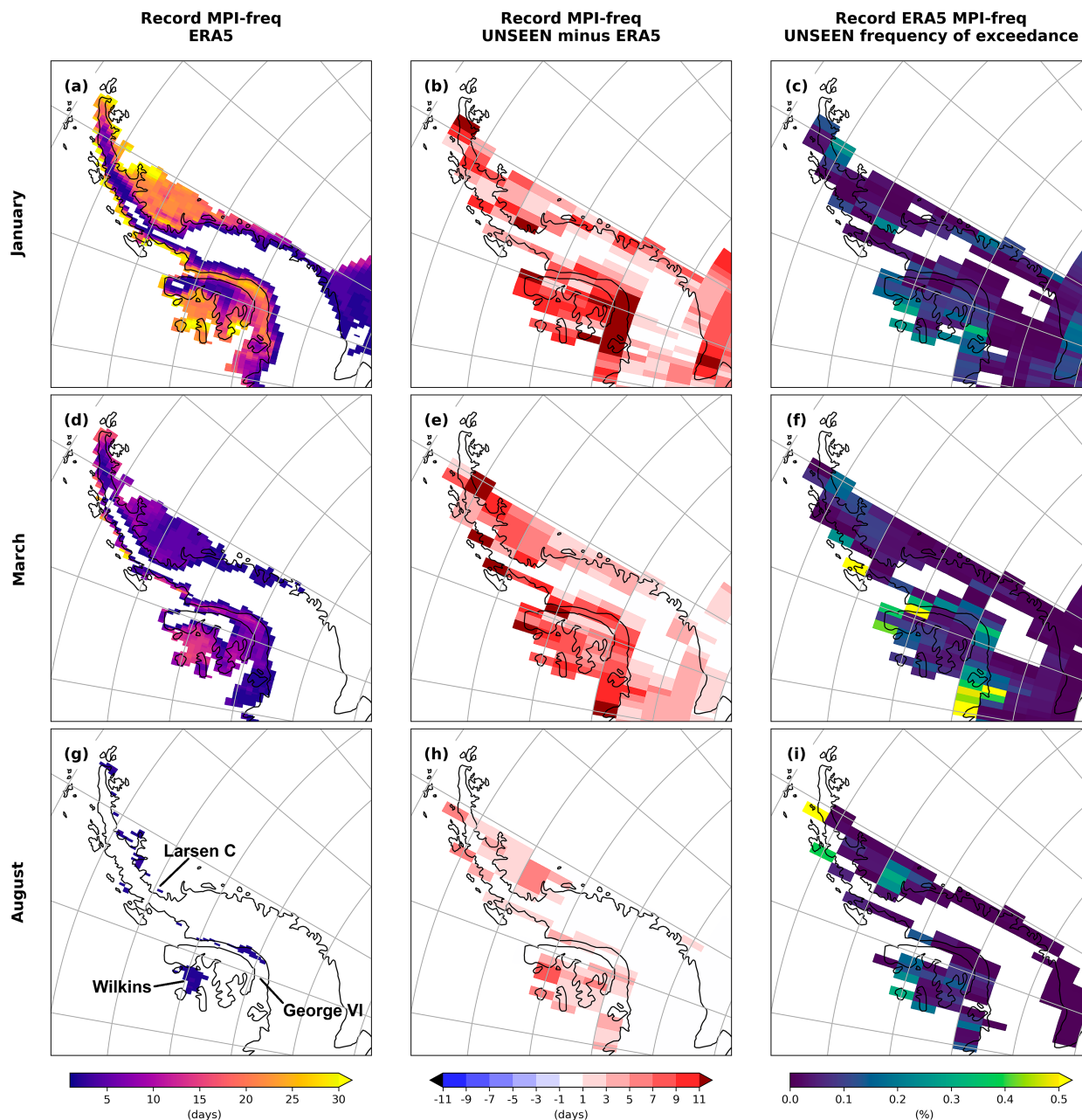


FIG. 8. Maximum MPI-freq over the AP in ERA5 and UNSEEN. (a),(d),(g) Record maximum MPI-freq in ERA5, (b),(e),(h) UNSEEN record maximum minus ERA5 record maximum MPI-freq, and (c),(f),(i) frequency of ERA5 record MPI-freq exceedance in the UNSEEN ensemble for (a)–(c) January, (d)–(f) March, and (g)–(i) August. Selected ice shelves are labeled in (g).

any other observed event and at least 7.5 K higher than the warmest events simulated in the UNSEEN ensemble. Conversely, it is found in both regions and months that unprecedented high Z500 anomalies are possible but unlikely. While the DML winter 2024 event was also the event with the highest temperatures in the region for that month, the UNSEEN analysis suggests that both regionally and on a gridpoint level, higher temperature anomalies are possible, though highly unlikely, in the current climate.

Across Antarctica as a whole for the 3 months examined (January, March, and August), unprecedented temperature extremes are also possible in the current climate. The largest possible temperature anomaly exceedances and probabilities in these months are primarily around parts of coastal West Antarctica and the South Pole (exceeding existing records by over 7 K in many places but with likelihoods much smaller than 1%). Although ERA5 is known to have a bias in near-surface temperature compared to individual AWSs,

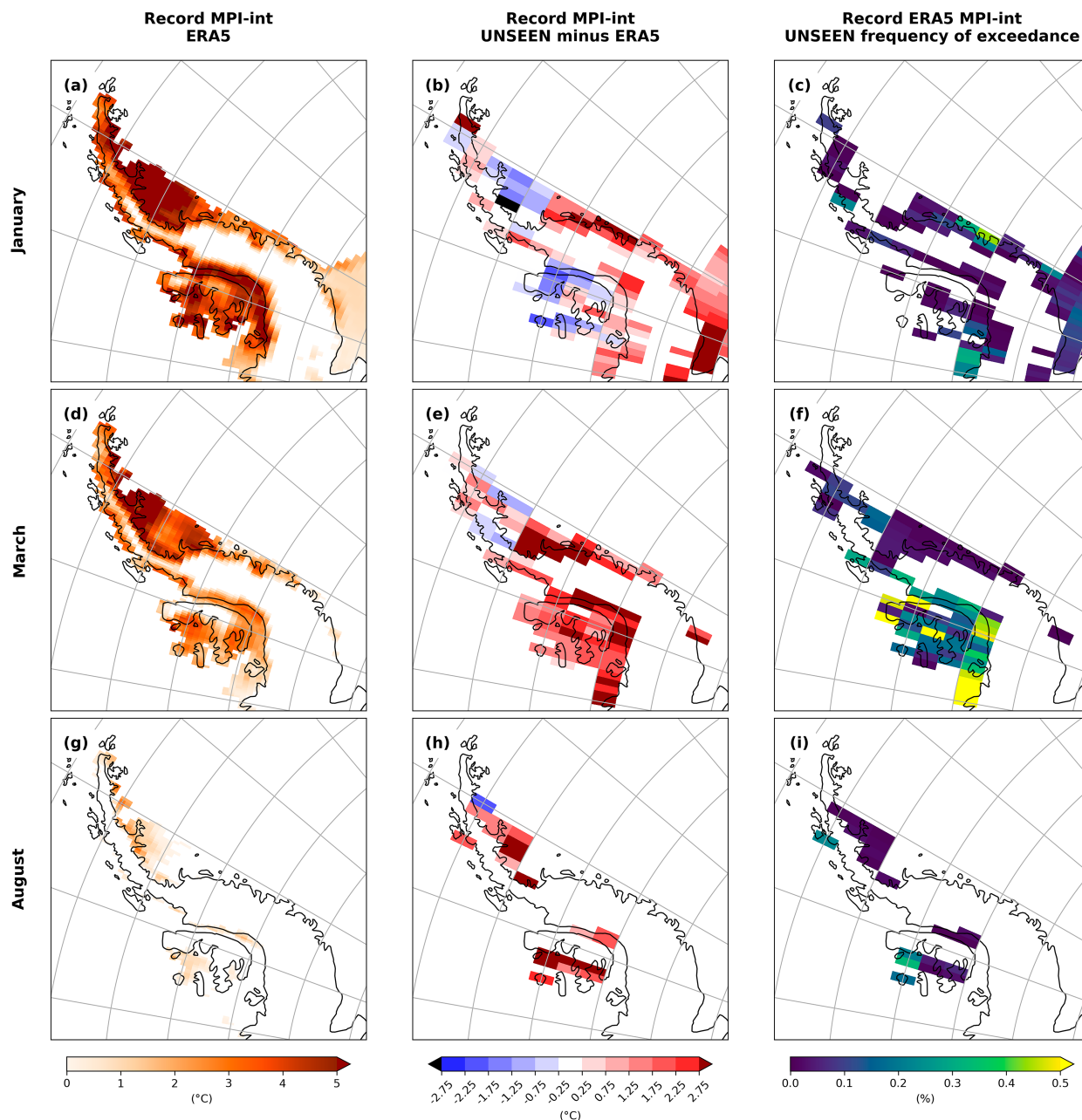


FIG. 9. Maximum MPI-int over the AP in ERA5 and UNSEEN. As in Fig. 8, but for record MPI-int.

the magnitude by which UNSEEN exceeds ERA5 temperature records is often larger than this (up to 4 K; Zhai et al. 2025). These gridpoint temperature extremes are larger in magnitude than in other studies that utilized the UNSEEN method for heat events [e.g., China (Thompson et al. 2019) and the United Kingdom (Kay et al. 2020)] but with much smaller likelihoods. It is unknown whether these discrepancies are due to the unique meteorology of Antarctica, uncertainties in the ERA5 occurrences due to its small sample size, or UNSEEN ensemble model deficiencies, or a combination of the three. Strikingly, gridpoint maximum T2m anomalies in the UNSEEN ensemble are lower

than those in ERA5 in March over WL and parts of DML in August, reiterating the extraordinary observed heat waves of 2022 and 2024, respectively.

Reasonable confidence should be given toward the reliability of the data in the UNSEEN ensemble. In this study, it was possible to correct for biased temperature and Z500 means and standard deviations within the ensemble (when compared to ERA5), so that to leading order, the distributions of ERA5 and UNSEEN ensemble data are statistically indistinguishable. Differences between the higher-order moments of the UNSEEN ensemble and ERA5 distributions are harder to

correct for and risk artificial manipulation of the model data, and in about half of the instances, the corrected UNSEEN ensemble data fail the traditional fidelity tests for these moments. However, it should also be noted that the true distribution of the observed T2m is also uncertain, so it is impossible to suggest which dataset (ERA5 or UNSEEN) has skewness and kurtosis that is closest to the real distribution. Furthermore, confidence is gained in the ensemble from the fact that two-tailed Kolmogorov–Smirnov tests confirm that the model distributions are statistically similar to ERA5 and the fact that the same synoptic conditions are responsible for extreme heat in both datasets.

In both WL and DML, temperature extremes are brought about by anomalously anticyclonic conditions, with a blocking anticyclone situated slightly to the east. This promotes strong northerly advection of warm air from lower latitudes, which can combine with local processes such as the foehn effect, to elevate surface temperatures. The UNSEEN ensemble models a similar relationship between Z500 and T2m anomalies to ERA5, but the WL March 2022 and DML August 2024 events contain days where T2m cannot entirely be explained by a linear relationship with the large-scale circulation (Fig. A1). In these cases, the ERA5 T2m is up to 15 K larger than expected from the linear fit, and it is likely that local processes are amplifying the magnitude of the T2m anomaly in ERA5 that are not modeled by the UNSEEN ensemble. The fact that these events (especially for the WL 2022 event) are outliers even in ERA5 implies that the midlevel circulation pattern cannot be used to accurately predict T2m in these cases, and thus, it is perhaps to be expected that the UNSEEN ensemble does not contain events of this magnitude. If the analysis was performed on 500-hPa temperature (T500) instead of T2m, we consider it likely that similar conclusions could be made to that for Z500, namely that unprecedented T500 could occur at WL in March, just as it could for Z500. However, these unprecedented T500 events would also be unlikely to result in the extreme near-surface temperatures observed in 2022 because the lower-level drivers in this event would not be reflected in T500 (or Z500) patterns aloft.

Furthermore, Blanchard-Wrigglesworth et al. (2023) showed that the magnitude of the WL March 2022 heat wave was underestimated at the surface, by both forecasts and a general circulation model, by a similar amount to that in the UNSEEN ensemble presented here. The surface cold bias reported in Blanchard-Wrigglesworth et al. (2023) was due to an underestimation of the weakening of the surface inversion layer (which was also present in ERA5 to a lesser extent, when compared to in situ observations), meaning that the warm air aloft did not reach the surface in these forecasts and ERA5. This process would be modeled more accurately in a high-resolution model that is able to resolve more local-scale processes in the boundary layer. Thus, it is perhaps not surprising that the UNSEEN ensemble does not contain such extreme outliers such as those in ERA5 in WL in March 2022, due to its coarse resolution that is unable to resolve finescale dynamics. However, were the same subgrid-scale or unresolved processes in the UNSEEN ensemble to occur during the days of unprecedented Z500 anomalies, the associated extra warming associated with higher geopotential height means that it is feasible that the March 2022 and August 2024 events could be exceeded in magnitude in the current climate.

Though the same synoptic pattern is responsible for the extreme temperatures in both ERA5 and the UNSEEN ensemble, this study does not ascertain whether the same large-scale drivers and tropical teleconnections make these synoptic patterns and thus heat extremes more likely in the two datasets. There are many known relationships between Antarctic temperatures and these patterns of variability (Li et al. 2021), for example, the SAM (Marshall 2007; Clem et al. 2016), El Niño–Southern Oscillation (ENSO; Clem et al. 2016; Welhouse et al. 2016), Amundsen Sea low (ASL; Raphael et al. 2016), and sudden stratospheric warmings (SSWs; Zi et al. 2025). Future work will establish the role of large-scale drivers such as these of promoting Antarctic temperature extremes in both ERA5 and the UNSEEN ensemble.

Further evidence of the UNSEEN ensemble's relatively coarse resolution impacting the results in this study is found when computing the MPI. Local-scale meteorology plays an important role in coastal Antarctic temperatures and melting events (e.g., Elvidge et al. 2016; Zou et al. 2021; Gilbert and Kittel 2021), and processes such as the foehn effect require high-resolution modeling to provide an accurate magnitude of downslope warming. The 1° resolution of the hindcasts in the UNSEEN ensemble is too coarse to model the complex orography of coastal Antarctica, and thus, coastal temperatures in the UNSEEN ensemble are likely to be underestimated. The effect of foehn warming can even dominate synoptic warming in some cases (Bozkurt et al. 2018), so the melting frequencies in the UNSEEN ensemble (and regridded ERA5 data for the comparisons) are likely to be underestimates. The foehn effect is well known to produce strong warming over the AP (e.g., Elvidge et al. 2016; Datta et al. 2019; Gilbert et al. 2022), which potentially means that the magnitude of melting frequency and intensity could be underestimated here. Nevertheless, it is striking that certain regions of Antarctica in this analysis could break existing monthly melt duration frequencies by 10 or more days, and break intensity records by several kelvins. Furthermore, it should be noted that unprecedented melting could occur further inland than it ever has before. If this melting frequency and intensity on the continent is realized, it could have lasting effects on the surface mass balance of the Antarctic ice sheet and global sea levels.

The results presented here suggest that unprecedented warm events are possible throughout the Antarctic continent in the current climate; however, the climate of Antarctica is not stationary. The mean temperature in West Antarctica in particular has increased in recent decades (Nicolas and Bromwich 2014; Jones et al. 2016, 2019), and the entire continent is expected to warm by the end of the century due to anthropogenic climate change (Bracegirdle et al. 2008; Feron et al. 2021), though the magnitude to which it warms is uncertain due to large natural interannual variability (Jones et al. 2016, 2019). If the unprecedented T2m anomaly events found in this study were superimposed on a climate with a higher mean temperature, then the absolute temperatures reached during the UNSEEN heat waves would be higher and closer to the melting point, which leaves much of the coastal ice shelves even more vulnerable to melting and/or collapse (Gilbert and Kittel 2021; van Wessem et al. 2023).

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Data availability statement. The reanalysis and seasonal hindcasts used in this study are obtainable from the online Copernicus Climate Data Store (CDS) at <https://cds.climate.copernicus.eu/>. The mask for the continental ice shelves around Antarctica is sourced from the National Snow and Ice Data Center (<https://nsidc.org/data/nsidc-0709/versions/2>).

APPENDIX

Additional Information

Moments tests for all regions

The results of the moments tests for WL and DML in March and August respectively are shown in Table A1.

TABLE A1. Summary of moments for ERA5, and moments fidelity test results for the UNSEEN ensemble. “C” = corrected. Bold numbers from the UNSEEN moments indicate a significantly different value from ERA5, i.e., the ERA5 moment is outside of the ensemble 95% confidence interval and the ensemble has therefore failed that particular aspect of the fidelity test. Corrected UNSEEN means and std devs are omitted because they always pass the fidelity test by construction. Raw UNSEEN skewnesses and kurtosis are also omitted since they are not accounted for in the correction process (and the uncorrected ensemble is not used in further analysis) Results are only shown for the common period between the three models, i.e., 1993–2016.

	WL March T2m	WL March Z500	DML August T2m	DML August Z500
ERA5 mean	231.22 K	5008 m	231.73 K	4907 m
UNSEEN mean	231.74 K	5019 m	230.73 K	4905 m
ERA5 std dev	3.81 K	80 m	3.80 K	98 m
UNSEEN std dev	4.50 K	87 m	4.73 K	105 m
ERA5 skewness	0.14	0.18	0.53	0.74
UNSEEN (C) skewness	0.39	0.29	0.39	0.36
ERA5 kurtosis	−0.37	0.07	−0.10	1.00
UNSEEN (C) kurtosis	0.19	0.31	0.09	0.17

T2m–Z500 relationships

The relationship between anomalies in Z500 and T2m for March in WL and August in DML for ERA5 and the UNSEEN ensemble is shown in Fig. A1. A positive correlation is found in all four examples, with the temperature response ranging from 0.025 to 0.033 K m^{−1}, meaning that a larger Z500 anomaly leads to a larger T2m anomaly. However, the T2m anomalies during the March 2022 event (and to a lesser extent, the August 2024 event) are markedly higher for a given Z500 anomaly, suggesting that, during these events, other processes are also responsible for increasing surface temperature anomalies.

Continent-wide MPI

In addition to the MPI results focused on the AP in the main text, results for the continent as a whole are presented in Figs. A2 and A3.

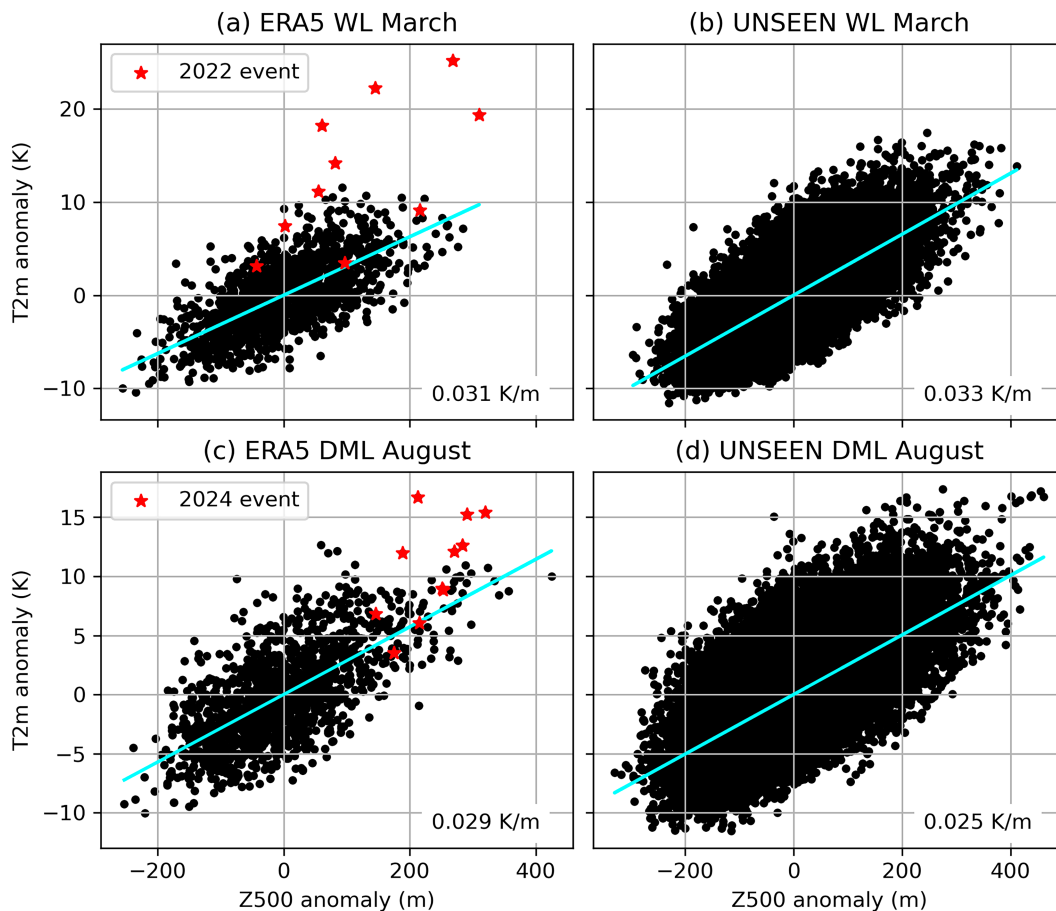


FIG. A1. Relationships between daily mean Z500 and T2m anomalies. Relationships are shown for (a),(b) WL in March and (c),(d) DML in August in (a),(c) ERA5 from 1979 to 2024 and (b),(d) the UNSEEN ensemble 1981–2016. The line of best fit, from linear regression, is shown in cyan, and the numerical value of the slope is shown in the bottom right of each panel. The days highlighted by the red stars indicate dates during the extreme (a) March 2022 WL and (c) the August 2024 WL events, defined by the red shading in Fig. 1.

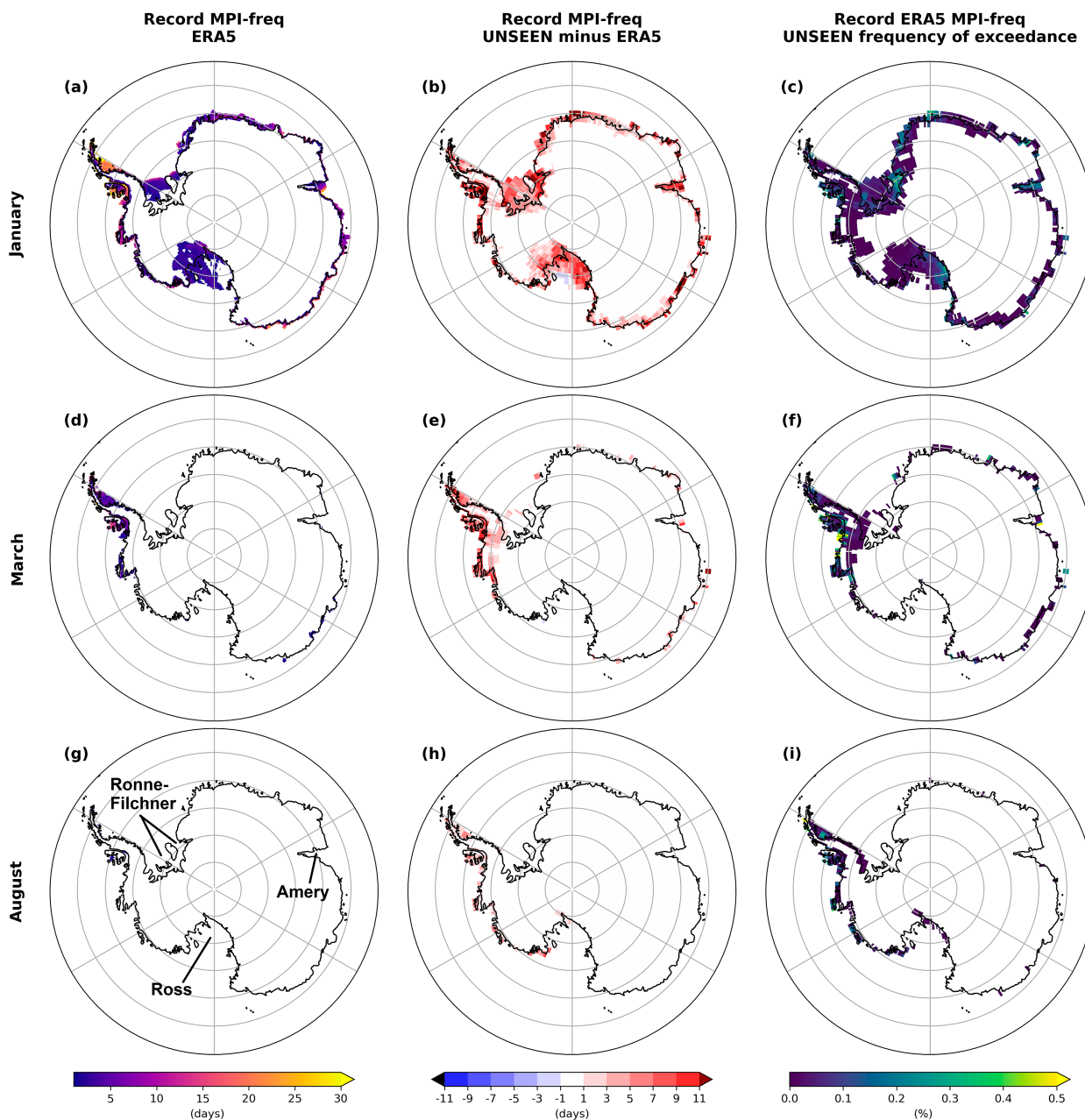


FIG. A2. MPI-freq for the whole Antarctic continent. As in Fig. 8, but for the whole Antarctic continent.

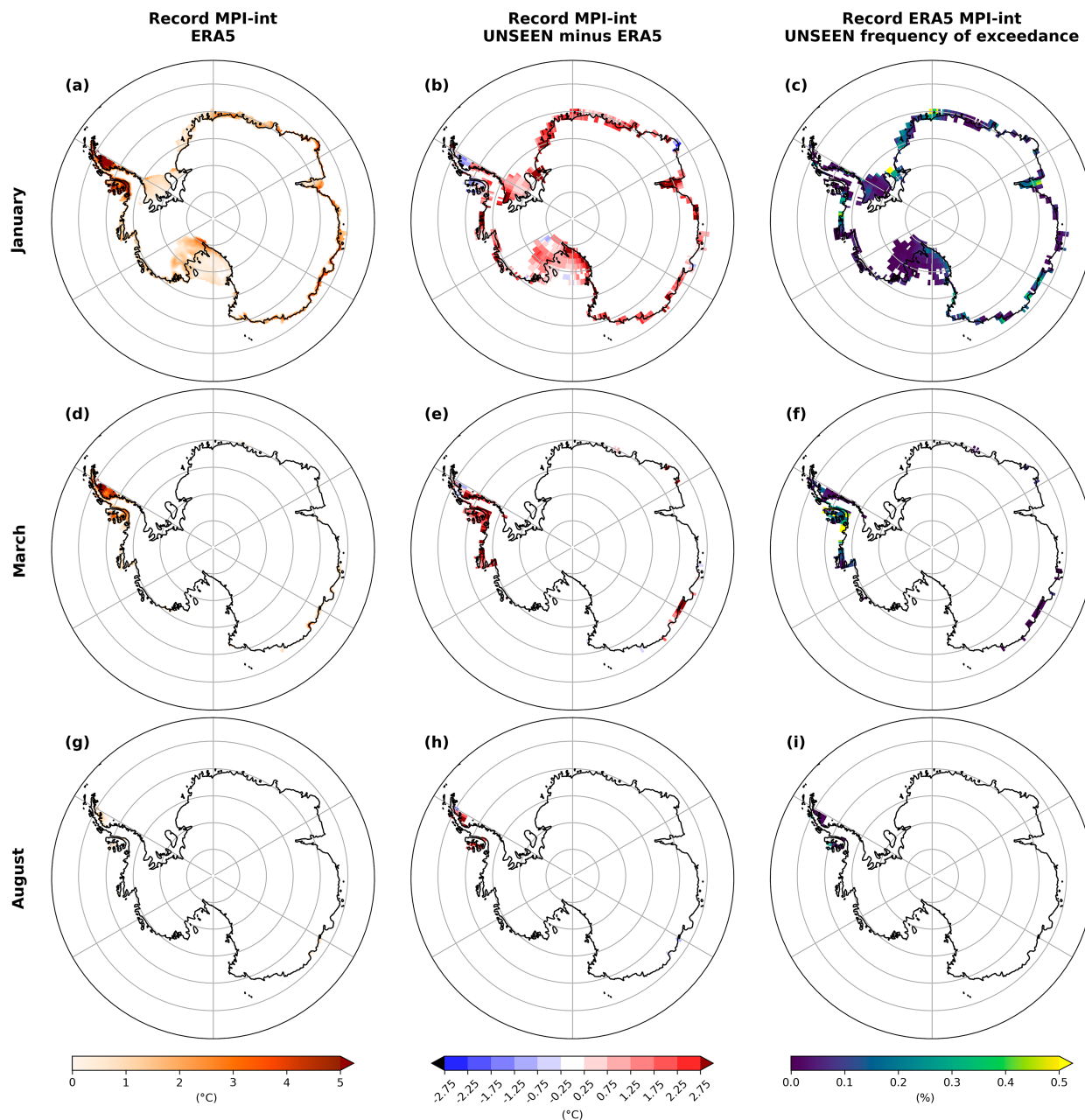


FIG. A3. MPI-int for the whole Antarctic continent. As in Fig. 9, but for the whole Antarctic continent.

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