Impacts of Atmospheric Dynamics on Winter-Spring Sea-Ice and Snow Thickness at a Coastal Site in East Antarctica

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Abstract:

Antarctic sea ice and its snow cover play a pivotal role in regulating the global climate system through feedback on both the atmospheric and the oceanic circulations. Understanding the intricate interplay between atmospheric dynamics, mixed-layer properties, and sea ice is essential for accurate future climate change estimates. This study investigates the relationship between the atmospheric conditions and sea-ice and snow characteristics at a coastal East Antarctic site using *in-situ* measurements in winter-spring 2022. The observed sea-ice thickness peaks at 1.16 m in mid-late October and drops to 0.06 m at the end of November, following the seasonal solar cycle. On the other hand,~~,~~ ~~while~~ the snow thickness variability is impacted by atmospheric forcing, with significant contributions from precipitation, Foehn effects, blowing snow, and episodic warm and moist air intrusions~~katabatic flows and atmospheric rivers (ARs)~~, which can lead to changes of up to 0.08 m within a day for a field that is in the range 0.02-0.18 m during July-November 2022. ~~The *in-situ* measurements highlight the substantial effects of warm and moist air intrusions on the sea-ice, snow and atmospheric state.~~ A high-resolution simulation with the Polar Weather Research and Forecasting model for the 14 July~~November~~ atmospheric river (AR), the only intense AR that occurred during the study period, reveals the presence of AR rapids and highlights the effects of ~~the~~ katabatic winds from the Antarctic Plateau in slowing down the low-latitude air masses as they approach the Antarctica coastline.~~, with~~ T~~t~~he resulting ~~low-level~~ convergence of the two air flows, with meridional wind speeds in excess of 45 m s^{-1}, leads~~ing~~ to precipitation rates above 3 mm hr^{-1} around coastal Antarctica~~.~~. The unsteady wind field in response to the passage of a deep low pressure system with a central pressure that dropped to 931 hPa triggers satellite-derived pack ice drift speeds in excess of 60 km day^{-1}, and promotes the opening up of a polynya in the Southern Ocean around 64°S,45°E from 14 to 22 July. ~~Including the observed sea-ice extent and a realistic SIT in the model does not yield more skillful predictions of surface/near-surface variables and atmospheric profiles. This suggests other factors such as boundary-layer dynamics and/or land/ice processes may play a more important role than sea ice concentration and thickness during AR events.~~ Our findings contribute to a better understanding of the complex interactions within the Antarctic climate system, providing valuable insights for climate modeling and future projections.

Keywords:

Sea Ice, Snow Thickness, PolarWRF, Atmospheric River, Katabatic winds, Foehn Effects, Antarctica

1. Introduction

Sea ice, which forms from the freezing of seawater and covers 3-6% of the total surface area of the planet ~~(depending on season)~~, plays multiple crucial roles in the Earth's climate system and high-latitude ecosystems (Thomas, 2017; Eayrs et al., 2019). Changes in the formation and melt rates, extent, seasonality and thickness of Antarctic sea ice - both in the form of drifting pack ice and less extensive stationary near-shore landfast ice (fast ice) attached to coastal margins, sea floor and grounded icebergs (Fraser et al., 2023) - substantially impact the heat and salinity content of the ocean, and hence the oceanic circulation (e.g., Haumann et al., 2016; Li and Fedorov, 2021). At the same time, breaks in the sea ice such as leads and recurrent and persistent polynyas (Barber and Massom, 2007; Francis et al. 2019, 2020; Fonseca et al., 2023) act as a thermal forcing, with the exposure of ice-free ocean water leading to sensible heat fluxes that can exceed 2000 W m^{-2} and heat up the atmosphere aloft (Guest, 2021), directly impacting the atmospheric flow (Trusel et al., 2023; Zhang and Screen, 2021). Both oceanic and atmospheric forcing directly affect~~impact~~ sea ice and its spatial extent, seasonality and thickness (Wang et al., 2020; Yang et al., 2021), within a finely-coupled interactive ocean-sea ice-atmosphere system. At the same time, decreases in sea-ice thickness (SIT), sea-ice extent (SIE), and its snow cover have strong potential to impact low-latitude weather patterns (England et al., 2020), disrupt the global surface energy balance (Riihelä et al., 2021), and amplify climate warming at high southern latitudes (Williams et al., 2023), leading to increased sea-ice loss that is likely to be further accelerated by poorly-understood ocean-ice-snow-atmosphere feedback mechanisms (Goosse et al., 2023).

The Antarctic sea ice-snow system is particularly impacted by two atmospheric processes: (1) strong katabatic winds that cascade seawards off the ice sheet and promote sublimation of the sea ice and its snow cover (Elvidge et al., 2020; Francis et al., 2023); and (2) a number of more ephemeral but influential extreme atmospheric events in the form of atmospheric rivers (ARs; Wille et al., 2025). Foehn effects are an important trigger of surface melting around Antarctica, as the adiabatic compression of the downslope flow can lead to a marked increase in surface temperature in excess of 15 K (Bozkurt et al., 2018), while the strong winds can promote iceberg calving events (Miles et al., 2017). An AR is a narrow and highly elongated band of moisture-rich air that originates in the tropics and subtropics and propagates polewards into the mid- and high-latitudes (Wille et al., 2019; Gorodetskaya et al., 2020). ARs are associated with increased humidity and cloudiness, leading to an enhancement of the downward longwave radiation flux while still allowing some of the Sun's shortwave radiation to reach the surface (Djouma and Holland, 2021). The resulting increase in the surface net radiation flux gives a warming tendency and promotes surface melting (Gorodetskaya et al., 2013; Francis et al., 2020; Ghiz et al., 2021).

There are several examples of ARs triggering ice and snow melt around Antarctica: e.g. in the Weddell Sea in 1973 and 2017 (Francis et al., 2020); off the Antarctic Peninsula in March 2015 (Bozkurt et al., 2018) and February 2022 (Gorodetskaya et al., 2023); around the Amery Ice Shelf in September 2019 (Francis et al., 2021), in West Antarctica (Francis et al., 2023); and in the Ross Sea (Fonseca et al., 2023). The recent study of Liang et al. (2023) highlights that the largest impact of ARs on sea ice is found on the marginal ice zone, where the SIE reduction may exceed 10% day^{-1}. Reduced coastal offshore SIE may also foster a deeper penetration of the low-latitude air onto the inland ice sheet, as is the case in the March 2022 "heat wave" in East Antarctica (Wille et al., 2024a,b). While ARs themselves are relatively rare and short-lived in coastal Antarctica, with a frequency of ~3 days year^{-1} at any given location, the warm and moist air masses they transport can make a substantial contribution to the surface mass balance (SMB) and are linked to extreme precipitation events (Massom et al., 2004; Wille et al. 2021, 2025). For example, in East Antarctica, a series of ARs delivered an estimated 44% of the total mean-annual snow accumulation to the high interior ice sheet over an 18-day period in the austral summer of 2001/2 (Massom et al., 2004), and AR-associated rainfall has exceeded 30% of the total annual precipitation (Mclennann et al. 2022, 2023). These studies highlight the impacts of extreme weather events on the coupled Antarctic ocean-ice-snow-atmosphere system and stress the need to better understand the role of low-latitude air incursions on the SMB and state of both the Antarctic Ice Sheet and its surrounding sea-ice cover - and how these may change in a warming climate.

~~Moreover, sea ice accumulates a highly reflective (high albedo) and insulative snow cover that then strongly modulates the physical and optical properties of the ice cover while also influencing its formation and melt rates (Sturm and Massom, 2017, and references therein). Decreases in the thickness and distribution of Antarctic sea ice and its snow cover have strong~~

~~potential to impact low-latitude weather patterns (England et al., 2020), disrupt the global surface energy balance (Riihelä et al., 2021) and amplify climate warming at high southern latitudes (Williams et al., 2023) - leading to further sea-ice loss that is likely to be further accelerated by poorly-understood ocean-ice-snow-atmosphere feedback mechanisms (Goosse et al., 2018).~~

Here, we investigate the impact of atmospheric dynamics on variability in both ~~sea-ice thickness (~~SIT~~)~~ and snow thickness (ST) state through analysis of high-resolution *in-situ* measurements obtained by an autonomous Snow Ice Mass Balance Array (SIMBA) buoy (Jackson et al., 2013), combined with atmospheric reanalysis and modeling products. The SIMBA buoy was deployed from July to November 2022 at a coastal fast ~~-~~ice site close to Mawson Station in East Antarctica (~~at~~ 67.5912°S, 62.8563°E), which will be denoted as "Khalifa SIMBA site on fast ~~-~~ice off ~~the~~ Mawson Station" throughout the manuscript. This station is selected as it has amongst the highest AR frequency in the continent, also with a statistically significant positive trend in AR frequency and intensity during 1980-2020 (Wille et al., 2025). The overall aim of this study is to further our understanding of the temporal evolution of the thickness and ~~the~~ vertical structure of coastal sea ice and its snow cover in~~around~~ East Antarctica, and over a six-month period spanning austral winter through late spring,~~early summer~~ when ARs are more frequent in the region (Wille et al., 2025). The motivation is to provide new observations and process information that will aid numerical-modelling efforts to more accurately simulate the annual cycle of the Southern Ocean sea ice, and observed trends and variability in its distribution (and ultimately thickness; ~~) (~~c.f. Eayrs et al., 2019). Such an advance is crucial to helping rectify present low confidence in model projections of future climate and Antarctic sea-ice conditions~~,~~ that currently diverge for different models and scenarios (Roach et al., 2020). This study is also ~~particularly~~ timely~~,~~ given the precipitous downward trend in Antarctic sea ice extent (SIE) since 2016 (Parkinson, 2019), an extraordinary record-low annual minimum in February 2023 and a sudden departure to major sea-ice deficits through the winters of 2023 and 2024 (Reid et al., 2024). This turn of events suggests that Antarctic sea ice has abruptly shifted into a new low-extent regime (Purich and Doddridge, 2023; Hobbs et al., 2024) due to complex changes in the coupled ocean-ice-snow-atmosphere system that are far from well understood. Much less well known - though no less important - are the thicknesses of the ice and its snow thickness (ST) and whether these are changing. Obtaining more accurate and complete information on the Antarctic SIT distribution and its ST and precipitation rates - and the factors and processes controlling them - is a critical high priority in climate science, particularly in light of climate variability and change (Webster et al., 2018; Meredith et al., 2021).

Accurate knowledge of SIT, SIE and concentration is needed to estimate sea-ice volume, a field that is more sensitive to climate change than SIE and SIT alone (Liu et al., 2020) and is also directly parameterized in numerical models (Massonnet et al., 2013; Zhang, 2014; Schroeter and Sandery, 2022). Current large uncertainties in these quantities prevent proper model evaluation and undermine confidence in model predictions of future Antarctic sea-ice conditions and global weather and climate (Maksym et al. 2008, 2012). Satellite radar and laser altimeters hold the key to large-scale estimation and monitoring of both ~~SIE/~~SIT (e.g., Fonseca et al., 2023) and ST (Kacimi and Kwok, 2020). Kurtz and Markus (2012) used the measurements collected by the Ice, Cloud, and land Elevation Satellite (ICESat) to estimate the ice thickness around Antarctica. A comparison with ship-based observations revealed a mean difference of 0.15 m for the period 2003-2008, with a typical SIT of 1-1.5 m. Kacimi and Kwok (2020), using both laser (ICESat-2) and radar (CryoSat-2) altimeter estimates for the period ~~0~~1 April to 16 November 2019, found the thickest sea ice in the western Weddell Sea sector (predominantly multi-year sea ice), with a mean thickness of 2 m, and the thinnest ice around polynyas in the Ross Sea and off the Ronne Ice Shelf. Coincident use of laser and radar altimetry also enables basin-scale estimates of ST. The thickest snow was again observed in the western Weddell Sea (0.228 ± 12.4 m in May) and the coastal region of the Amundsen-Bellingshausen seas sector (0.314 ± 23.1 m in September), while the thinnest was in the Ross Sea (0.0735 ± 4.30 m in April) and the eastern Weddell Sea (0.0821 ± 5.81 m in June) (Kacimi and Kwok, 2020). These studies focussed on pack ice, but a similar range of values has been estimated for the thickness of fast ~~-~~ice, such as off ~~the~~ Mawson (Li et al., 2022) and Davis (Heil, 2006) ~~S~~stations in East Antarctica. The SIMBA buoy provides high-resolution measurements at a given location of the vertical temperature profile through the air-snow-ice-upper ocean column, from which ST and SIT can be derived and monitored (Jackson et al., 2013). Time series of such point observations provide invaluable gap-filling information on the temporal evolution and state of the snow-sea ice system and its response to atmospheric and oceanic variability. They also provide crucial information with which to both (~~i~~1) calibrate the key satellite SIT and ST data products, and (~~ii~~2) evaluate and improve numerical idealized column and weather forecasting models (Hu et al., 2023; Plante et al., 2024; Sledd et al., 2024; Wang et al., 2024a).

~~In particular, In this study, and making use of the SIMBA observations, thewe here focus is on assessing the influence on the sea ice-snow system of: (1) strong katabatic winds that cascade seawards off the ice sheet and promote sublimation of the sea ice and its snow cover (Elvidge et al., 2020; Francis et al., 2023); and (2) a number of more ephemeral but influential extreme atmospheric events in the form of atmospheric rivers (ARs). An AR is a narrow and highly elongated band of moisture-rich air that originates in the tropics and subtropics and propagates polewards into the mid- and high-latitudes (Wille et al., 2019; Gorodetskaya et al., 2020). ARs are associated with increased humidity and cloudiness, leading to an enhancement of the downward longwave radiation flux while still allowing some of the Sun's shortwave radiation to reach the surface (Djouma and Holland, 2021). The resulting increase in the surface net radiation flux gives a warming tendency and promotes surface melting (Gorodetskaya et al., 2013; Francis et al., 2020; Ghiz et al., 2021). There are several examples of ARs triggering ice and snow melt around Antarctica e.g., in the Weddell Sea in 1973 and 2017 (Francis et al., 2020); off the Antarctic Peninsula in March 2015 (Bozkurt et al., 20108) and February 2022 (Gorodetskaya et al., 2023); around the Amery Ice Shelf in September 2019 (Francis et al., 2021), in West Antarctica (Francis et al., 2023); and in the Ross Sea (Fonseca et al., 2023).~~

The recent study of Liang et al. (2023) highlights that the largest impact of ARs on sea ice is found on the marginal ice zone e.g., where thea sea-ice extent reduction there that may exceed 10% day^{-1}. Reduced coastal offshore SIE may also foster a deeper penetration of the low-latitude air onto the inland ice sheet, as was the case in the March 2022 "heat wave" in East Antarctica (Wille et al., 2024a,b). While ARs themselves are relatively rare and short-lived in coastal Antarctica, with a frequency of ~3 days year^{-1} at any given location, the warm and moist air masses they transport can make a substantial contribution to the surface mass balance (SMB), and they are linked to extreme precipitation events (Massom et al., 2004; Wille et al., 2021, 2025). In East Antarctica, a series of ARs delivered an estimated 44% of the total mean annual snow accumulation to the high interior ice sheet (in the vicinity of Dome C) over an 18-day period in the austral summer of 2001/2 (Massom et al., 2004), and AR-associated rainfall has exceeded 30% of the total annual precipitation (Mclennnann et al., 2022, 2023). Moreover, and on Mac. Robertson Land (also in East Antarctica), which includes the Amery Ice Shelf and is the focal region of this study, more than half of the annual precipitation has been observed to fall in the 10 days of heaviest precipitation (Turner et al., 2019). This region also has some of the largest positive trends in AR frequency and AR-related snowfall occurrence in the period 1980-2018. These studies highlight the important impacts of extreme weather events on the coupled Antarctic ocean-ice-snow-atmosphere system, and stresses the need to better understand the role of low-latitude air incursions on the mass balance and state of both the Antarctic Ice Sheet and its surrounding sea-ice cover – and how these may change in a warming climate.

Continuous monitoring since 1978 of the circum-Antarctic spatial extent, concentration and seasonality of sea ice by satellite passive-microwave remote sensing (Parkinson, 2019) has revealed major losses around the continent since 2016 – not only in summer but also latterly through winter (Reid et al., 2024) and for reasons that are not fully understood. This abrupt and precipitous decline has been viewed as a possible regime shift in the coupled ocean-sea ice-atmosphere system (Hobbs et al., 2024). Much less well known – though no less important – are the thicknesses of the ice and its snow cover and whether these are changing. Obtaining more accurate and complete information on the thickness distributions of Antarctic sea ice and its snow cover (and precipitation rates) – and the factors and processes controlling them – is a critical high priority in climate science, particularly in light of climate change (and variability) (Webster et al., 2018; Meredith et al., 2021).

Accurate knowledge of SIT, SIE and concentration is needed to estimate sea-ice volume, a field that is more sensitive to climate change than SIE and SIT alone (Liu et al., 2020) and is also directly parameterized in numerical models (Massonnet et al., 2013; Zhang, 2014; Schroeter and Sandery, 2022). For climate modeling, sea-ice volume (modulated by ST) represents a key integrated measure of the total salinity and freshwater fluxes to the ocean in winter and summer, respectively, and total heat flux to the atmosphere. Current large uncertainties in these quantities prevent proper model evaluation and undermine confidence in model predictions of future Antarctic sea-ice conditions and global weather and climate (Maksym et al., 2012). An analysis of 10 models in the Coupled Model Intercomparison Project Phase 5 (CMIP5) revealed that, around the outer sea-ice zone, changes in sea-ice volume are largely driven by dynamic (wind-driven motion) processes during annual advance and thermodynamic (freeze and melt) processes during the retreat phase, while thermodynamic processes predominate deeper within the sea-ice zone (Schroeter et al., 2018). However, and for the trends, both dynamic and thermodynamic processes are at play, highlighting the sensitivity of sea-ice volume to changes in oceanic and atmospheric properties and circulation in response to anthropogenic forcing (Schroeter et al., 2018) and natural variability.

In addition to SIT, reliable large-scale information on the coincident ratio of snow-to-sea-ice thickness is required to determine the distribution of “snow ice” formation around Antarctica (Maksym and Markus, 2008). By this process, and where the snow is sufficiently thick to depress the sea-ice surface to below sea level, resultant flooding of the snow creates a slush layer that subsequently freezes onto the ice surface (Jeffries et al., 1998; Massom et al., 2001). In this way, snow makes a direct contribution to the sea-mass balance in the freezing season - in addition to its indirect contribution as a high-albedo insulative layer that moderates Antarctic sea-ice formation and melt rates (Sturm and Massom, 2017). These factors further underline the need for additional more accurate information on precipitation and accumulation rates over the sea-ice zone, including rainfall events (Webster et al., 2018).

Satellite radar and laser altimeters hold the key to large-scale estimation and monitoring of both SIT (e.g., Fons et al., 2023) and ST (Kacimi and Kwok, 2020). Kurtz and Markus (2012) used the measurements collected by the Ice, Cloud, and land Elevation Satellite (ICESat) to estimate the ice thickness around Antarctica. A comparison with ship-based observations revealed a mean difference of 0.15 m for the period 2003-2008, with a typical SIT of 1-1.5 m. Kacimi and Kwok (2020), using both laser (ICESat-2) and radar (CryoSat-2) altimeter estimates for the period 1 April to 16 November 2019, found the thickest sea ice in the western Weddell Sea sector (predominantly multi-year sea ice), with a mean thickness of 2 m, and the thinnest ice around polynyas in the Ross Sea and off the Ronne Ice Shelf. Coincident use of laser and radar altimetry also enables basin-scale estimates of ST. The thickest snow was again observed in the western Weddell Sea (22.8 ± 12.4 cm in May) and the coastal region of the Amundsen-Bellingshausen seas sector (31.4 ± 23.1 cm in September), while the thinnest was in the Ross Sea (7.35 ± 4.30 cm in April) and the eastern Weddell Sea (8.21 ± 5.81 cm in June) (Kacimi and Kwok, 2020). The studies mentioned above focus on pack ice, but a similar range of values has been estimated for the thickness of fast ice, such as off the Mawson Station (Li et al., 2022) and off the Davis Station (Heil, 2006) in East Antarctica. Validation of these and other satellite derived estimates of SIT, ST and sea-ice volume is a crucially important step towards improving their accuracy, yet remains a considerable challenge, given the lack of regionally- and seasonally-diverse *in situ* and near-surface observations with which to assess the satellite datasets (Kacimi and Kwok, 2020).

~~The SIMBA buoy provides high-resolution measurements at a given location of the vertical temperature profile through the air-snow-ice-upper ocean column, from which snow and ice thickness can be derived and monitored (Jackson et al., 2013). Time series of such point observations provide invaluable gap-filling information on the temporal evolution and state of the snow-sea ice system and its response to atmospheric and oceanic variability. They also provide crucial information with which to both (i) calibrate the key satellite SIT and ST data products and (ii) evaluate and improve numerical idealized column and weather forecasting models (Hu et al., 2023; Plante et al., 2024; Sledd et al., 2024; Wang et al., 2024).~~

While there are a number of studies on *in-situ* SIT and ST measurements around Antarctica (e.g., Worby et al., 2011; Xie et al., 2011; Liao et al., 2022), the area of East Antarctica around Mawson Station, where extreme precipitation events in the form of ARs have become more frequent and intense in the recent decades (Wille et al., 2025), has not been sampled. In addition, these works do not delve deep into the processes responsible for the observed changes in SIT and ST, which is a necessary step for refining Antarctic climate projections. The objectives of this study are twofold: (~~i~~1) to identify the mechanisms behind the variability of the *in*-*situ* measured SIT and ST at ~~the~~ Mawson Station during July-November 2022, and compare the measured values with those estimated from remote sensing assets; and (~~ii~~2) to perform high-resolution numerical simulations for selected periods during the measurement campaign, in particular during extreme weather events, to gain further insight into the role of atmospheric forcing on the SIT and ST. This study will therefore contribute to further our understanding on the variability of the SIT and ST in coastal Antarctica and the respective driver processes.

This paper is structured as follows. The observational datasets and model outputs and products considered, and analysis techniques used, are described in Section 2. The measurements of SIT and ST, including their variability and the mechanisms behind them, are discussed in Section 3. Section 4 provides a case-study analysis of the period 11-16 July~~November~~ 2022, while in Section 5 the main findings of the work are outlined and discussed.

2. Methodology & Diagnostics

~~In this section, the datasets, numerical model, and diagnostics used in this study are described.~~

2.1. *In-Situ* Measurements at Khalifa SIMBA site off ~~the~~ Mawson Station

In-situ measurements of SIT and ST are obtained using a sea-ice mass-balance (~~[~~SIMBA)~~]~~ unit (Jackson et al., 2013). This SIMBA i~~wa~~s deployed on landfast ice offshore from Mawson Station at 67.5912°S, 62.8563°E (Fig. 1c) on ~~0~~7 July 2022, and remained *in-situ* until ~~0~~7 December 2022. The SIMBA unit consists of a 5 m-long thermistor string with a 0.02 m sensor~~s'~~ spacing, a barometer for surface air pressure, and an external sensor for near-surface ambient air temperature (Jackson et al., 2013). During deployment, manual measurements of SIT and ST, as well as freeboard, a~~we~~re recorded. The positions of the sensors relative to the interfaces a~~we~~re noted to establish the initial state (on ~~0~~7 July 2022). The measured SIT upon deployment i~~wa~~s 0.988 m, the ST on top of the sea ice i~~wa~~s 0.156 m, and the sea-ice freeboard i~~wa~~s 0.046 m. No manual validation or calibration is conducted during the measurement period of ~~0~~7 July - ~~0~~7 December 2022.

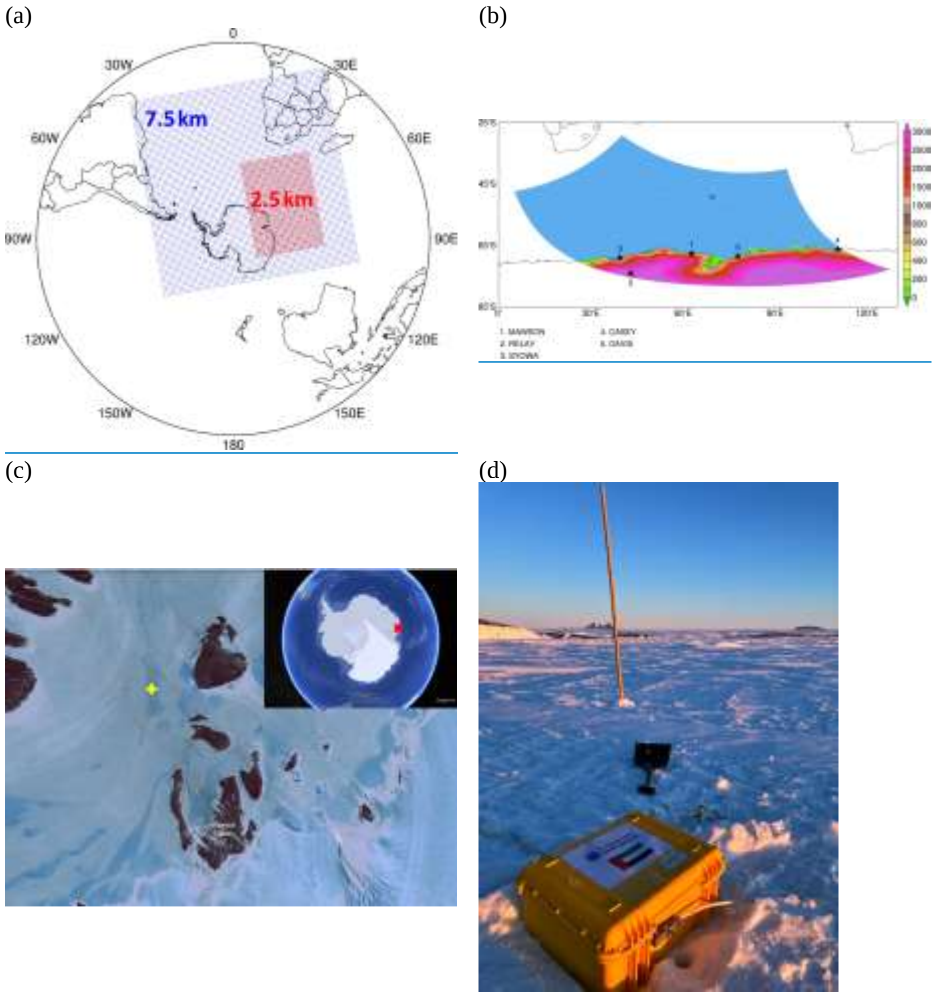


Figure 1: PolarWRF Simulation: (a) Spatial extent of the 7.5 km (blue) and 2.5 km (red) PWRF grids used in the numerical simulations. (b) Spatial extent and orography (m) of the 2.5 km PWRF grid. The stars highlight the location of the five weather stations considered in this work~~Zoom-in view around East Antarctica for the 2.5 km grid, with the location of the Mawson, Relay, Mizuho and Syowa weather stations highlighted by the stars. The shading gives the orography (m) as seen by the model~~. (c) SIMBA

deployment site (yellow cross) on the fast ice about 1.8 km off Mawson Station. Image source: Landsat 8 acquired on 19 November 2022. The red cross in the inset image, taken from Google Earth Pro, shows where ~~the~~ Mawson Station is located in Antarctica. (d) SIMBA instrument prior to deployment. Image credit: Peter Caithness.

The accuracy of the bus-addressable digital temperature sensing integrated circuit is ±0.0625 K. A resistor is mounted directly underneath each thermistor sensor. A low voltage power supply (8 V) is connected to each sensor, to gently heat the sensor and its immediate surroundings. In this study, heating is applied to the sensor chain for durations of 30 s and 120 s once per day, with four vertical temperature profiles without heating also recorded daily. In this study, SIMBA data from ~~0~~8 July to 30 November 2022 ~~is~~ are used to assess the evolution of SIT and ST at the site. The measurements are shown in Fig. 2. For the sensors 6 through 126, the actual temperature and the temperature rise after 120 s heating are given in Fig. 2a and 2b, respectively, with Fig. 2c showing the difference between the measurements of two adjacent temperature sensors after applying the heating.

The vertical temperature gradients in the air above the surface and in the water below the ice bottom are generally very small (Jackson et al., 2013; Hoppmann et al., 2015; Liao et al., 2018). After 120 s of heating, the rise in temperature is approximately 10 times higher in air than ~~it is~~ in ice and water (Jackson et al., 2013). For any two adjacent sensors in the ice, and following the algorithm detailed in Liao et al. (2018) based on a physical model applied to the SIMBA measurements, the temperature difference should be ≤ 0.1875 K, whereas for two adjacent sensors in snow, the temperature difference should be ≥ 0.4375 K. These thresholds are applied to the temperature differences between adjacent sensors in the heating profile to identify the air-snow and snow-ice interfaces (Jackson et al., 2013; Hoppmann et al., 2015; Liao et al., 2018). The ice-water interface is identified using a statistical approach based on Liao et al. (2018). A section of the thermistor string, spanning from the top of the sea ice to a few sensors below the water, is selected. The seawater temperature near the ice bottom remains stable around the freezing point (T_f). The temperature readings from this section are analyzed as a time series, and the most frequent value is identified as T_f. Scanning from bottom up, the last sensor close to T_f is identified as the ice bottom. The allowed temperature difference is 1.5 times the thermistor resolution of 0.0625 K. The t~~T~~emporal evolutions of the three interface locations are plotted in Figs. 2a-c.

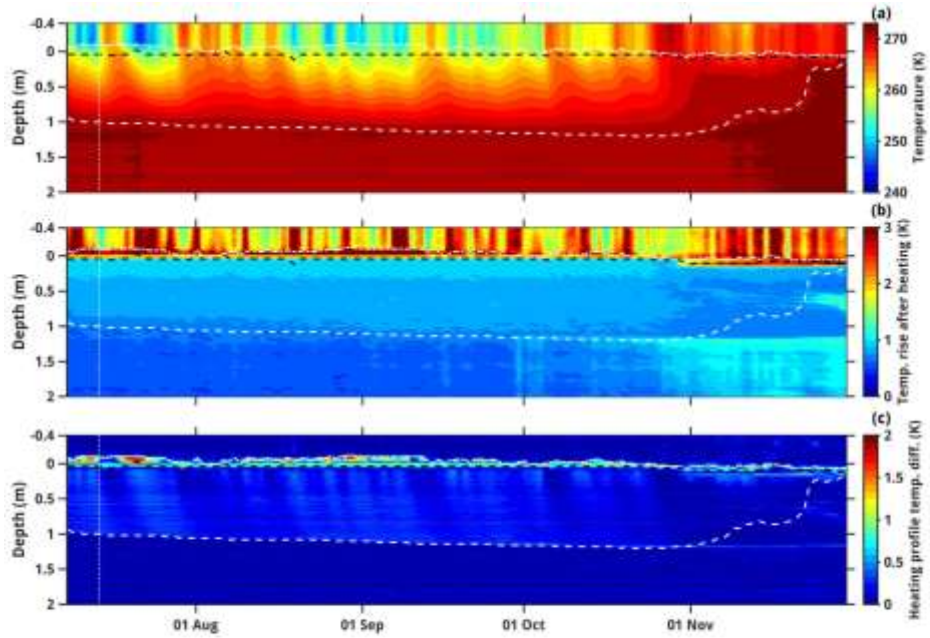


Figure 2: SIMBA measurements: (a) Temperature (K) evolution from the top of the chain through the ice down into the water (the zero line on the y-axis is at the snow-ice interface). (b) Temperature rise (K) after heating for 120 s. (c) Temperature difference (K) between adjacent sensors after applying the heating for 120 s. The vertical white dotted lines indicates the days of AR occurrence at the site, 14 July, according to Lapere et al. (2024). The horizontal dotted white line, black dashed line, and white dashed line giveindicate the air-snow (AS), snow-ice (SI), and ice-water (IW) interfaces, respectively.

2.2. Observational and Reanalysis Datasets

In addition to *in*-*situ* SIT and ST measurements, threefFour other observational datasets are considered in this work: (i) satellite-derived SIE and sea-ice velocity; (ii) daily true colour visible satellite images available at the National Aeronautics and Space Administration's (NASA's) WorldView website (Boller, 2024); (iii) ground-based observations at fivefour weather stations located in the target region (Fig. 1b), namely: at Mawson, Syowa, Relay, Mizuho, Casey, and DavisRelay stations (Fig. 1b); and (iiiv) twice daily sounding profiles at the Mawson, Syowa, Casey, and Davis stations (stations #1 and 3-5 in Fig. 1b) (Oolman, 2024). TheData from the fifth generation of the European Centre for Medium Range Weather Forecasting reanalysis (ERA-5);

~~reanalysis data (~~Hersbach et al., 2020) ~~is~~are used to investigate the large-scale circulation and SMB during the study period. ERA-5 is regarded as one of the best reanalysis products currently available over Antarctica and the Southern Ocean (Gossart et al., 2019; Dong et al., 2020). All of these products are listed in Table 1.

Dataset	**Specifications**
***In-situ* Sea-Ice Thickness and Snow Thickness**	SIT and ST measurements just offshore of ~~the~~ Mawson Station (67.5912°S, 62.8563°E) using a SIMBA unit; data available from ~~0~~7 July to ~~0~~7 December 2022
Sea-Ice Extent	Satellite-derived daily ~~sea-ice extent~~SIE at 3.125 km resolution; data available from June 2002 - ~~P~~present
Sea-Ice Velocity	Satellite-derived daily sea-ice velocity at 62.5 km resolution; data available from December 2009 - ~~P~~present
Weather Station Data	Ground-based observations at Mawson (67.6017ºS, 62.8753ºE; January 1954 - ~~P~~present), Relay (74.017ºS, 43.062ºE; November 2021 - ~~P~~present), Syowa (69.0053ºS, 39.5811ºE; January 1994 - ~~P~~present), Casey (66.2825ºS, 110.5231ºE; February 1989 - ~~P~~present), and Davis (68.5744ºS, 77.9672ºE; January 1957 - ~~P~~present) ~~S~~stations
Sounding Profiles	Twice daily at Mawson (67.6017ºS, 62.8753ºE; January 1954 - ~~P~~present), Syowa (69.0053ºS, 39.5811ºE; January 2021 - ~~P~~present), Casey (66.2825ºS, 110.5231ºE; February 1989 - ~~P~~present), and Davis (68.5744ºS, 77.9672ºE; January 1957 - ~~P~~present) ~~S~~stations
ERA-5 reanalysis	Hourly products at 0.25º × 0.25º (~27 km) spatial resolution; available from January 1940 - ~~P~~present

Table 1: Observational and Reanalysis Datasets: List of observational and reanalysis datasets used in this study.

Daily SIE ~~data are available at a resolution of 3.125 km and on a daily basis for the period June 2002 to present. It is estimated~~ is derived from the measurements of sea-ice concentration collected by the Advanced Microwave Scanning Radiometer for Earth Observing Systems (AMSR-E) ~~- Earth Observing Systems~~ onboard the National Aeronautics and Space Administration~~'s~~ (NASA~~'s~~) Aqua satellite from June 2002 to October 2011, and from the observations taken by the AMSR2 onboard Japan Aerospace and Exploration Agency's Global Change Observation Mission - Water (GCOM-W~~; "Shizuko"~~) satellite from July 2012 to present (Spreen et al., 2008). Sea-ice velocity vectors, on the other hand, are ~~available also daily at 62.5 km spatial resolution. This product is~~ obtained from the measurements collected by the Special Sensor Microwave

Imager/Sounder onboard the United States Air Force Defense Meteorological Satellite Program, the Advanced Scatterometer onboard the European Space Agency's Meteorological Operational Satellitesatellite, and the AMSR2 onboard the GCOM-W AMSR2 satellite, and is available from December 2009 to present (Lavergne et al., 2010). Warm and moist air intrusions impacting Antarctica can have substantial changes in SIE, with considerable sea-ice drift velocities that can exceed 50 km day^{-1} (e.g., Francis et al., 2021; Fonseca et al., 2023). Given this, BBoth the SIE and sea-ice velocity products are used to gain insight into the effects of the warm and moist air intrusions on the sea-ice state around the Mawson Station, during the measurements as performed in previous studies for other parts of Antarctica (e.g., Francis et al., 2021; Fonseca et al., 2023). Moderate Resolution Imaging Spectroradiometer (MODIS; (Xiong et al., 2006; Gumley et al., 2010) satellitetrue colour visible images are used to obtain additional high-resolution information on the SIE and its spatial variability (in the absence of clouds) including (this is only possible in the absence of clouds, as otherwise the sea-ice and other features near sea level will not be visible). They also provided information on the presence of polynyas and the fine structure within the ice pack, as the spatial resolution is no lower than 1 km.

In-situ observations at multiple Automatic Weather Stations (AWSs) are used in the analysis and model evaluation (Fig. 1b). These include: (i) 1-minute 2-m air temperature and humidity, 10-m horizontal wind velocity, and sea-level pressure (SLP) observations atfrom the Australian Antarctic stations of Mawson, Casey, and Davis Stations (67.6017ºS, 62.8753ºE); (ii) 1-minute measurements of meteorological parameters (2-m air temperature, SLP, 10-m horizontal wind velocity, and 2-m relative humidity) and radiation fluxes (surface upward and downward and shortwave and -longwave) at the coastal Syowa Station (69.0053ºS, 39.5811ºE); and (iii) 10-minute SLP, and horizontal wind velocity, and 2-m air temperature and relative humidity observations at the inland Mizuho Station (70.70ºS, 44.29ºE) and Relay Station (74.017ºS, 43.062ºE). Also analyzed awere data from atmospheric sounding profiles acquired twice daily (at 00 and 12 UTC) at the Mawson, Syowa, Casey, and Davis Sstations.

In addition, the fifth generation of the European Centre for Medium Range Weather Forecasting reanalysis (ERA-5) dataset (Hersbach et al., 2020) is used to investigate the large-scale atmospheric circulation during the measurements and to analyze the surface energy budget for the case study (11-16 JulyNovember 2022). At a spatial resolution of 0.25º × 0.25º (~27 km) and an hourly temporal resolution from 1940 to present, ERA-5 is regarded as one of the best reanalysis products currently available over Antarctica and the Southern Ocean (Gossart et al., 2019; Dong et al., 2020).

2.3. Numerical Models

Here we use version 4.3.3 of the Polar PWRF (Weather Research and Forecasting) model, a version of the WRF model (Skamarock et al., 2019) optimized for the polar regions (Bromwich et al., 2013; Hines et al., 2021; Xue et al., 2022; Zou et al., 2023), to simulate and investigate the AR that impacted the Mac Robertson Land region on 14 July~~November~~ 2022. The model is run in a nested configuration, with a 7.5 km horizontal resolution grid domain comprising Antarctica, the Southern Atlantic Ocean, southern Africa and the southwestern Indian Ocean, and a 2.5 km horizontal resolution grid domain extending from the Southern Ocean just south of South Africa around 30ºE into coastal East Antarctica ~~all the way to around~~as far east as approximately 120ºE~~around the Mawson Station~~ (Fig. 1a). The choice of resolution, in particular the 2.5 km grid that covers the bulk of the AR and associated warm and moist air intrusion into East Antarctica, reflects the findings of Box et al. (2023) and Francis et al. (2024). These studies stressed the need to properly resolve the fine-scale structure of an AR due to the possible presence of AR rapid-like features embedded in the convective region, which can generate copious amounts of precipitation and hence have a substantial impact on the SMB of the ice. AR rapids are narrow (5-15 km wide), elongated (100-200 km long) and shallow (~3 km deep) linear features within the AR that propagate at high speed (>30 $m\,s^{-1}$) and last for more than 24 h. They have been reported for an AR that impacted Greenland in September 2017 (Box et al., 2023) and another that wreaked havoc in the Middle East in April 2023 (Francis et al., 2024). AR rapids are distinct from mesoscale convective systems (MCSs; Houze, 2004; Feng et al., 2021; Nelli et al., 2021), which propagate at a slower speed (10-20 $m\,s^{-1}$), typically do not last as long (6-10 h), and generate broader (as opposed to linear) precipitation structures.

~~The physics schemes selected, listed in Table 2, reflect the optimal model configuration for Antarctica and the Southern Ocean (Zou et al. 2021a, 2021b, 2023).: the two-moment Morrison-Milbrandt P3 cloud microphysics scheme (Morrison and Milbrandt, 2015), with the Vignon adjustment to improve the simulation of mid-level mixed-phase clouds over the Southern Ocean (Hines et al., 2021; Vignon et al., 2021); the Mellor-Yamada-Nakanishi-Niino (MYNN) level 1.5 planetary boundary layer (PBL) scheme (Nakanishi and Niino, 2006); the Rapid Radiative Transfer Model for Global Circulation Models (RRTMG; Iacono et al., 2008) for shortwave and longwave radiation; the Noah Land Surface Model (Chen and Dudhia, 2001; Tewari et al., 2004);~~ t~~he Kain-Fritsch cumulus scheme (Kain, 1994) with subgrid-scale cloud feedbacks to radiation (Alapaty et al., 2012), switched on in the 7.5 km grid only; and the Zeng and Beljaars (2005) surface skin temperature scheme.~~ PWRF is run from 10 July~~November~~ 2022 at 00 UTC to 17 July~~November~~ 2022 at 00 UTC, comprising the only ~~strongest~~ AR that impacted the site during July-November 2022, with the first day regarded as spin-up and the output discarded. The hourly outputs of the 7.5 km and 2.5 km grids are used for analysis.~~ PWRF is driven by 6-hourly ERA-5 data, with the reanalysis' fractional SIE and ice concentration ingested into the model~~. The physics schemes selected, listed in Table 2, reflect the optimal model configuration for Antarctica and the Southern Ocean (Zou et al. 2021a, 2021b, 2023). In order to prevent the large-scales in the model from drifting from the forcing fields, spectral nudging (Attada et al., 2021) is employed in both grids for spatial scales ≳ 1,000 km above ~800 hPa and excluding the boundary layer. Fields nudged include the horizontal wind components, the potential temperature perturbation, and the geopotential height. In the vertical, 60 levels are considered, with the lowest level above the surface at ~27 m and roughly 20 levels in the range of ~1-6 km. The higher resolution in the low- to mid-troposphere is crucial to correctly representing the fine-scale variability of the warm and moist air masses impacting the site, and associated cloud processes (Rauber et al., 2020; Finlon et al., 2020).

Physics Scheme	**Option Selected**
Cloud Microphysics	Two-moment Morrison-Milbrandt P3 (Morrison and Milbrandt, 2015), with Vignon adjustment to improve the simulation of mid-level mixed-phase clouds over the Southern Ocean (Hines et al., 2021; Vignon et al., 2021)
Planetary Boundary Layer	Mellor-Yamada-Nakanishi-Niino level 1.5 (MYNN; Nakanishi and Niino, 2006)
Radiation	Rapid Radiative Transfer Model for Global Circulation Models (Iacono et al., 2008) for shortwave and longwave radiation
Cumulus	Kain-Fritsch (Kain, 2004) with subgrid-scale cloud feedbacks to radiation (Alapaty et al., 2012) only in 7.5 km grid
Land Surface Model (LSM)	Noah LSM (Chen and Dudhia, 2001; Tewari et al., 2004)
Sea Surface Temperature (SST)	6-hourly ERA-5 SSTs + Zeng and Beljaars (2005) surface skin temperature scheme

Table 2: WRF Experimental Setup: Physics scheme used in the WRF simulation.

PWRF is driven by 6-h ERA-5 data, with the SSTs and SIE used in the simulations taken from ERA-5. Due to the lack of availability of SIT in ERA-5, the model's default SIT value of 3 m is used in all sea-ice covered grid-boxes~~ in the PWRF simulations~~. The sea-ice albedo is parameterized as a function of air and skin temperature following Mills (2011), with the model explicitly predicting ST on sea ice. A sensitivity experiment is performed in which a more realistic representation of SIE and SIT is considered. In particular, satellite-derived values are used for SIE, extracted from the 3.125 km-resolution daily product available at the University of Bremen website (UoB, 2024), while the SIT estimates at Mawson are employed at all sea-ice covered pixels. A similar model performance is obtained with respect to the *in-situ* observations (not shown). Therefore, and for consistency with the atmospheric forcing, the ERA-5's SIE and the PWRF's default SIT values are used in the model runs. ~~This configuration is denoted as control simulation ("PWRF"). Given the order of magnitude difference between the spatial resolution of the innermost model grid (2.5 km) and that of ERA-5 (~27 km), and how important a realistic representation of the sea-ice may be in the model forecasts, an additional simulation is performed in which satellite-derived values are used for SIE, while the SIT estimates at Mawson are employed~~

at all sea-ice covered pixels. This run is denoted as “PWRF_SIE_SIT” throughout the manuscript. The SIE is extracted from is repeated using as sea-ice concentration boundary conditions for the full 7.5 km and 2.5 km PWRF domains the 3.125 km-resolution daily product available at the University of Bremen website (UoB, 2024). For the SIT, and to contrast with the excessively thick 3 m default value used in the control run, the range of values measured *in situ* at the Khalifa SIMBA site on fast-ice off the Mawson Station towards the end of November, which is about 0.18 m to 0.30 m (Fig. 3a), is ingested into the model at all sea-ice covered grid-boxes. This simulation will be denoted as “PWRF_SIE_SIT” throughout the manuscript. Satellite-derived measurements suggest an overall similar range of values for the thickness of pack ice and fast-ice at multiple sites around Antarctica (Heil, 2006; Kacimi and Kwokkw, 2020; Li et al., 2022), justifying the usage of the same value for all sea-ice pixels in the model domain.

In order to prevent the large scales in the model from drifting from the ERA-5 forcing fields, spectral nudging (Attada et al., 2021) is employed in both grids for spatial scales ≳ 1,000 km above ~800 hPa and excluding the boundary layer. Fields nudged include the horizontal wind components, the potential temperature perturbation, and the geopotential height. In the vertical, 60 levels are considered, with the lowest level above the surface at ~27 m and roughly 20 levels in the range of ~1-6 km. The higher resolution in the low- to mid-troposphere is crucial to correctly representing the fine-scale variability of the warm and moist air masses impacting the site, and associated cloud processes (Rauber et al., 2020; Finlon et al., 2020).

The moisture sources that contributed to the AR during 11-16 JulyNovember 2022 are diagnosed based on 96-h back-trajectories obtained with the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT; Stein et al., 2015) model driven by ERA-5 reanalysis data.

2.4. Diagnostics and Metrics

The performance of the PWRF model is assessed with the verification diagnostics proposed by Koh et al. (2012) outlined in Supplement Section S1. In addition to the model bias, the two key skill scores are the (i1) the normalized bias μ, defined as the ratio of the bias to the standard deviation of the discrepancy between the model forecasts and observations; and (2ii) the normalized error variance α, which accounts for both phase and amplitude errors. When $|\mu| < 0.5$ the model biases can be regarded as not significant, while when $\alpha < 1$, the model forecasts are deemed asto be practically useful. defined in Equations (1) to (5) below. These diagnostics are the (i) bias, $\underline{B}$, given by the mean discrepancy between the model forecasts, F, and the observations, O; (ii) normalized bias, μ, defined as the ratio of the bias to the standard deviation of the discrepancy B between F and O (following Koh et al. (2012), if $|\mu| < 0.5$, the bias makes a smaller contribution to the Root Mean Square Error than the error variance and can therefore can be regarded as not significant); (iii) correlation, ρ, which measures the phase agreement between the modelled and observed data; (iv) variance similarity, η, an indication of the amplitude agreement between the two signals; and (v) normalized error variance, α, a diagnostic that combines phase and amplitude errors. For a random forecast based on the climatological mean and variance $\alpha = 1$, the model predictions can be deemed as practically useful if $\alpha < 1$. The ρ, η and α skill scores are non-dimensional, symmetrical with respect to observations and forecasts, and applicable to scalar and vector fields – meaning that the model performance for scalars such as air temperature and vector quantities such as the wind vector can be directly compared. The verification diagnostics are:

$$B = F - O \quad (1)$$

$$\mu = \frac{<D>}{\sigma_D} \quad (2)$$

$$\rho = \frac{1}{\sigma_O \sigma_F} < (F - < F >) \cdot (O - < O >) >; \; -1 \leq \rho \leq 1 \quad (3)$$

$$\eta = \frac{\sigma_O \sigma_F}{\frac{1}{2}(\sigma_O^2 + \sigma_F^2)}; \; 0 \leq \eta \leq 1 \quad (4)$$

$$\alpha = 1 - \rho\eta = \frac{\sigma_D^2}{\sigma_O^2 + \sigma_F^2}; \; 0 \leq \alpha \leq 2 \quad (5)$$

ARs are identified based on the meridional Integrated Vapour Transport (vIVT; kg m^{-1} s^{-1}), which is the column integral of the water-vapour flux advected by the horizontalmeridional wind. This quantity is more appropriate for AR detection if the focus is on snowfall, which is the case here, whereas for surface melting IVT is a better metric (Wille et al., 2019). It is quantified as:

$$vIVT = -\frac{1}{g}\int_{1000\,hPa}^{200\,hPa} qv\,dp \quad (6)$$

$$IVT = \sqrt{\left(\frac{1}{g}\int_{1000\,hPa}^{200\,hPa} qu\,dp\right)^2 + \left(\frac{1}{g}\int_{1000\,hPa}^{200\,hPa} qv\,dp\right)^2} \quad (1)$$

In equation (16), where g is the gravitational acceleration (9.80665 m s^{-2}), q is the specific humidity (kg kg^{-1}), u is the zonal wind speed (m s^{-1}), v is the meridional wind speed (m s^{-1}), and dp is the pressure difference between adjacent vertical levels (hPa). The criteria of Wille et al. (2021) applied to ERA-5 data isare used here to identify ARs. In particular, IVT has to exceed The AR outer boundaries are taken from Lapere et al. (2024), who used the 3-hourly 987th percentile extracted for 1979-2022 at a given grid-box, of vIVT at a given grid box and a minimum latitudinal extent of 20° is required for the feature to be considered anto identify ARs, from the Modern Era Retrospective Analysis for Research and Applications Version 2 dataset (MERRA-2; Gelaro et al., 2017). The ARs in that study were extracted globally for the period 1980-2022, with the respective outlines made publicly available. The ARs for July-November 2022 are considered in this work. During the July to November 2022 study period, the Khalifa SIMBA site on fast- ice off the Mawson Station iwas affected by onethree AR,s: on 14 July, 04-05 October, 07 October,13 August and 14 November. The IVT and vIVT values around the Mawson Station, in particular the area averaged values in a 12º × 12º domain centred around the station and obtained with MERRA-2 data to be consistent with the AR outlines, are highest for the 14 JulyNovember AR. For this case, the maximum absolute IVT and vIVT values are 15161 kg m^{-1} s^{-1} and 78112 kg m^{-1} s^{-1}, respectively, compared to 8587 kg m^{-1} s^{-1} and 4639 kg m^{-1} s^{-1} for the 04-0513 OctoberAugust AR, 48 kg m-1 s-1 and 36 kg m-1 s-1 for 07 October AR, and 71148 kg m^{-1} s^{-1} and 4382 kg m^{-1} s^{-1} for the 14 NovemberJuly AR. Based on these findings, the 14 JulyNovember This event is selected for more in-depth analysis and modeling in Section 4. Large-scale circulation patterns that favour ARs, including the presence of blocking and interaction with tropopause polar vortices (TPVs), are also explored. Further details regarding the metrics used to diagnose them are given in Supplementary Sections S2-S3. Except for IVT and vIVT, for which MERRA-2 data are used as noted above, ERA-5 data are used to extract the other diagnostics outlined below.

For ARs to reach Antarctica, a large-scale circulation pattern that promotes the advection of warm and moist low-latitude air masses into the continent must be present. The leading mode of variability in the Southern Hemisphere extratropical atmospheric flow is the Southern Annular Mode (SAM; Marshall, 2003). This metric is based on the difference in mean sea-level pressure averaged over six stations at about 40ºS and six stations at about 65ºS, which are deemed representative of the zonal flow at the two latitudes. A positive index value indicates a stronger westerly flow in the Southern Hemisphere mid-latitudes, while a negative SAM phase is accompanied by an increase in blocking frequency (Oliveira et al., 2013). Atmospheric blocking promotes the development and propagation of ARs (Massom et al., 2004; Francis et al., 2021, 2022a; Wille et al., 2024). In this study, it is quantified using the blocking index (BI) proposed by Pook et al. (2013) and optimized over Antarctica by Wille et al. (2024c):

$$BI = 0.5\,(U_{35} + U_{40} + U_{65} + U_{70} - U_{50} - U_{60} - 2U_{55}) \quad (7)$$

where U_X is the geostrophic zonal wind computed from the 5-day running mean (in order to exclude temporary features) of the 500 hPa geopotential height at latitude XºS. Mid-latitude blocking events correspond therefore to higher values of BI, with values in excess of 40 m s^{-1} indicating a high degree of blocking.

The AR investigated in Section 4 originated over southern Africa, where tropical temperate troughs (TTTs), which arise from the interaction of mid-latitude baroclinic weather systems and tropical convection (Hart et al., 2013), are a regular occurrence. In order to assess whether a TTT event took place during the study period, we use the TTT index proposed by Ratna et al. (2023), which is based on Outgoing Longwave Radiation (OLR) and meridional wind speed as defined in equations (8a) and (8b), respectively:

$$OLR = \{[(OLR_{E1} + OLR_{E2})/2] \times 0.4 - [(OLR_{W1} + OLR_{W2})/2] \times 0.6\} \quad (8a)$$

In Equation (8a), E1 and E2 correspond to regions over Madagascar and southeastern Africa (E1: 37º-42ºE, 12º-17ºS; E2: 45º-50ºE, 23º-15ºS), with W1 and W2 located to the southwest of E1 and E2, the former over South Africa and the latter just offshore (W1: 22º-32ºE, 24º-18ºS; W2: 32º-42ºE, 36º-28ºS). In a TTT event, there are higher values of OLR ahead of the trough (E1 and E2) and lower values in the region where the trough is typically located (W1 and W2), with the placement of E1-E2 and W1-W2 reflecting the southeast-northwest orientation of the trough. The 0.4 and 0.6 factors in equation (8a) are indicative of the regional strength of the anomalies between the east and west regions, with the latter generally stronger than the former. The associated meridional wind index is defined as:

$$WIND = V_W - V_E \quad (8b)$$

The 850 hPa meridional wind speed is averaged over the western region (0º-15ºE, 38ºS-27ºS) to the southwest of South Africa, and the eastern region (34º-46ºE, 38º-27ºS) to the southeast of South Africa. If a trough is present, the associated clockwise circulation will lead to southerly winds to its west and northerly winds to its east, giving a positive value of the wind index. A TTT event requires the OLR and wind indices computed using the area-averaged anomalies to exceed their climatological standard deviations by 1.5 and 0.5, respectively.

Besides blocking and TTTs, the poleward transport of warm and moist low-latitude air is linked to the strength of the attendant cyclone, which is itself modulated by the presence of tropopause polar vortices (TPVs). As detailed in Wille et al. (2024c), TPVs are characterized by a minimum in potential temperature and a maximum in potential vorticity at the dynamic tropopause (PV = 2 $\times 10^{-6}$ m^2 K s^{-1} kg^{-1} = 2 PV Units = 2 PVU in the Northern Hemisphere and -2 PVU in the Southern Hemisphere). When co-located with increased low-level baroclinicity, they can trigger cyclogenesis, with a deeper low promoting an enhanced poleward propagation of the warm and moist low-latitude air mass. The TPVs are identified using the TPVTrack (v1.0) software described in Szapiro and Cavallo (2018), here driven by ERA-5 data.

The extratropical circulation can be modulated by tropical forcing, such as thermal (heating and cooling) anomalies (Hoskins and Karoly, 1981; Hoskins et al., 2012). In order to explore whether this occurs during the case study, the stationary wave activity flux that indicates the direction of the anomalous stationary Rossby wave propagation, defined in Takaya and Nakamura (2001), is derived in equations (2a-b), is derived (and and plotted.) as:

$$W_X = \frac{p\,cos(\phi)}{2|uU|}\left\{\frac{uU}{a^2cos(\phi)^2}\left[\left(\frac{\partial\psi'}{\partial\lambda}\right)^2 - \psi'\frac{\partial^2\psi'}{\partial\lambda^2}\right] + \frac{vV}{a^2cos(\phi)}\left[\frac{\partial\psi'}{\partial\lambda}\frac{\partial\psi'}{\partial\phi} - \psi'\frac{\partial^2\psi'}{\partial\lambda\partial\phi}\right]\right\} \quad (2a) \text{ and}$$

$$W_Y = \frac{p\,cos(\phi)}{2|uU|}\left\{\frac{uU}{a^2cos(\phi)}\left[\frac{\partial\psi'}{\partial\lambda}\frac{\partial\psi'}{\partial\phi} - \psi'\frac{\partial^2\psi'}{\partial\lambda\partial\phi}\right] + \frac{vV}{a^2}\left[\left(\frac{\partial\psi'}{\partial\phi}\right)^2 - \psi'\frac{\partial^2\psi'}{\partial\phi^2}\right]\right\} \quad (2b)$$

In equations (2a-b), ~~where~~ p is the ratio of the pressure level at which the W-vector is computed and 1000 hPa, ϕ is the latitude, λ is the longitude, U and V are the zonal and meridional climatological wind speeds, respectively, $|U|$ is the climatological mean wind speed, and ψ' is the streamfunction anomaly.

Variability in the ST, and perhaps to a lesser extent the SIT, is directly related to ~~by~~ the ~~surface mass balance (~~SMB~~)~~, which can be expressed as

$$SMB = P - Q_{sfc} - M - Q_{snow} - D \quad (3)$$

where P is the precipitation rate (mostly snowfall~~; mm w.e. day^{-1}~~), Q_{sfc} is the surface evaporation/sublimation rate, M is the surface melt and runoff rate, Q_{snow} is the blowing snow sublimation rate, and D is the blowing snow divergence rate term, all with units of mm w.e. hr^{-1}. Blowing snow refers to unconsolidated snow moved horizontally across the ice surface by winds above a certain threshold speed (Massom et al., 2001). As detailed in Francis et al. (2023), the P and M terms are directly extracted from ERA-5, for which the reanalysis values are in close agreement with satellite-derived estimates over Antarctica, while the remaining three (Q_{sfc}, Q_{snow}, D) are calculated using parameterization schemes, described in Supplement Section S4. The hourly PWRF output is also used to estimate the SMB for the 11-16 July 2022 case study, with M given by the decrease in ST when the air temperature is above freezing after accounting for the other processes. Positive values of SMB indicate an accumulation of snowfall at the site, while negative values represent a reduction due to melting, sublimation or wind erosion processes, or a combination of the three. It is also important to note that, following the convention of Dery and Yau (2002) adopted by Francis et al. (2023), positive values of Q_{sfc} indicate deposition while negative values indicate sublimation. For Q_{snow}, on the other hand, positive values indicate sublimation and negative values indicate deposition.

3. Sea-Ice and Snow Thickness Variability

In ~~the bottom panels ofin~~ Figs. 3e-f~~a~~, the derived values of ST and SIT from ~~0~~8 July to 30 November 2022 at the Khalifa SIMBA site on fast ~~-~~ice off ~~the~~ Mawson Station are plotted. The uncertainty, which is estimated to be 7% for ST and 2% for SIT (Liao et al., 2018), is highlighted by the blue shading. The SIT exhibits a gradual increase starting on 08 July, peaking at 1.14-1.16 m from 19-24 October, followed by a steady decline to 0.06-0.10 m at the end of November. These values are comparable to those estimated for this region and time of ~~the~~ year using satellite-derived products, which are typically in the range 0.50-1.50 m (Kacimi and Kwok, 2020). The ST on top of the ice, on the other hand, exhibits pronounced day-to-day variations as high as 0.08 m, peaking in mid-August to early September, and with values not exceeding 0.10 m from mid-September to the end of November. These values are also in the range of those derived from satellite altimeter data for that coastal region (Kacimi and Kwok, 2020).

In order to explore whether atmospheric forcing could have played a role in the observed variability in SIT and ST, the local SMB is estimated around the Khalifa SIMBA site on fast -ice off the Mawson Station using ERA-5 data. An analysis of Figs. 2 and 3 reveals that tThe SIT appears to be mostly driven by the growth (increase in SIT) and melting (decrease in SIT) at the ice bottom which, on top of the oceanic heat flux (Heil et al., 1996; Haas, 2017), depends on the conductive heat flux driven by the atmospheric forcing.ocean forcing, and involving both ocean-driven fast ice deformation and thermodynamic growth (Heil et al., 1996; Haas, 2017), and Tto a lesser extent, the SIT is impacted by the seasonal solar cycle, with Tthe annual SIT decrease that initiates in late Octoberearly November coincidesing with the time when the air temperatures regularly climbs above 265 K (Fig. 2a; Fig. 3c) and there is increased solar insolation (note the strong diurnal variation in air temperature in Fig. 3c) at the site. The marked drop in SIT of 0.6 m from 20 November to 25 November seen in the bottom panel of Fig. 3fa corresponds to a period of warmer temperatures (>265 K; Figs. 2a and 3c) and increased solar insolation (note the strong diurnal variation in air temperature in Fig. 3c) at the sitewhen the surface and air temperature climbed above freezing at the site (Fig. 2a). On the other hand, a comparison of the ST observations and the sea ice SMB estimated from ERA-5 (eEquation 310) data reveals a good correspondence between the two (cf. Figs. 3a-b with 3e). In particular, instances of positive SMB values (based on ERA-5) are typically associated with and followed by an increase in the measured ST at the site (e.g., in early July, mid-August, early and mid-October and mid-November), while negative SMB values from ERA-5 are accompanied by a decrease in the observed ST (e.g., in late July-early August and in late September-early October). Besides precipitation (snowfall) events, which can lead to an increase in ST by up to 0.06 m, Foehn effectswinds also modulate ST. These correspond to episodes when the wind direction is offshore (typically southerly to southeasterly), with an increase in wind speed and air temperature and a decrease in relative humidity. Several of these occurrences are seen during the study period, such as in mid-July, early August, mid-September and late October, leading to a reduction in ST of up to 0.08 m in a day (cf. Figs. 3c-e). This is not surprising, as the Khalifa SIMBA site on fast -ice off the Mawson Station is exposed to katabatic winds flowing seaward off the interior plateau (Dare and Budd, 2001), which experience adiabatic compression as they descend towards coastal areas. Blowing snow, albeit less frequently, also affects the variability of ST: e.g., at the beginning of August, there is a 0.08 m decrease in ST during a blowing snow sublimation episode (Q_{snow} reaches 0.25 mm w.e. hr^{-1}) followed by a Foehn event (Figs. 3b-e). Blowing snow divergence, D, on the other hand, plays a much-reduced role in the SMB, being of a larger magnitude during the passage of the AR on 14 July that brought wind speeds in excess of 30 m s^{-1} (Figs. 3b-e). Surface melting is unlikely to be a major driver of ST, as evidenced by the zero values of M during the measurement period (Fig. 3b). This is because during July-November 2022, the surface and air temperatures at the site remained below freezing (Figs. 2a and 3c).

Figs. 3g-l zoom-in during 11-16 July, when an AR impacted the site. On 14 July, very heavy precipitation (>2 mm w.e. hr^{-1}) and strong easterly to southeasterly winds (> 30 m s^{-1}) occurred in association with the AR, with a steady increase in air temperature from around 245 K on 13 July to 256 K at the beginning of 15 July (Figs. 3g and 3i-j). On the following day, Foehn effects occurred, as evidenced by the decrease in relative humidity from ~83% to 60%, the increase in wind speed from 12 to 28 m s^{-1} with a shift from an easterly (96°) to a southeasterly (156°) direction, and a further 4 K increase in air temperature, Figs. 3i-j. The negative Q_{sfc}, which indicates surface sublimation, plays the largest role in the SMB during Foehn periods, Figs. 3g-h, in line with Francis et al. (2023). The 0.02 m drop in ST from 15 to 16 July, Fig. 3k, can be attributed to Foehn effects, while the absence of an increase in ST during the AR may be explained by the strong winds that blow the snow away and prevent it from accumulating at the instrument's location (note the positive blowing snow divergence, D, during the precipitation event, Fig. 3h). In fact, it has been reported that strong katabatic winds have blown the snow away as quickly as it falls on nearshore fast ice near the Mawson (Dare and Budd, 2001) and Syowa (Kawamura et al., 1995) ~~S~~stations, resulting in very low accumulation close to the coast. ERA-5 predicts some precipitation on 16 July, Fig. 3g, even though at much reduced levels compared to 14 July. However, the fact that the wind speed is much lower on this day, dropping below 2 m s^{-1}~~,~~ (Fig. 3j), allows for snow accumulation at the Khalifa SIMBA site on fast ~~-~~ice off ~~the~~ Mawson Station that~~,~~ contributes~~ing~~ to the observed 0.04 m increase in ST. The 0.02 m variations in SIT during 15-16 July~~,~~ (Fig. 3l)~~,~~ are within the uncertainty range and hence can be ascribed to uncertainties in the methodology used for its estimation. It is important to note that a longer measurement period that comprises multiple AR passages would be needed for a robust link between ARs and their effects on ST and SIT to be established~~. Foehn winds are unlikely to play a dominant role in the sea-ice SMB off the Mawson Station, even though the SIMBA site is exposed to katabatic winds flowing seaward off the interior plateau (Dare and Budd, 2001). This is evidenced in Fig. 3a, which shows that the sea-ice SMB is largely controlled by precipitation (P), while in Foehn wind events, surface sublimation (Q_{sfc}) is the predominant term (Francis et al., 2023). For the case study discussed in Section 4 (11-16 November; Fig. 3b), there is a 0.06 m increase in ST from 14-15 November while the observed SIT increases by 0.04 m from 0.74 m to 0.78 m at the same time, returning to the previous levels (0.74 m) on 19 November. The results in Fig. 3b show a clear link between the observed measurements and the reanalysis' SMB for 14 November AR. The increase in SIT, on the other hand, may be explained by the freezing of (some of) the snow on top of the sea ice, as the surface and air temperatures were below freezing, around 265 K (Fig. 2a), and/or by metamorphic processes that can transform snow into ice (Sturm and Massom, 2017). The possibility that the added snow would depress the sea-ice surface to below sea level, with the resulting flooding of the snow and subsequent freezing of the slush increasing SIT is unlikely. This is because the required conditions, namely a snow:ice thickness ratio in excess of 1:3, and an ocean water that is warm, with a temperature exceeding 268 K, and saline, with a bulk salinity higher than 5 psu (Sturm and Massom, 2017), are not met during this period~~.

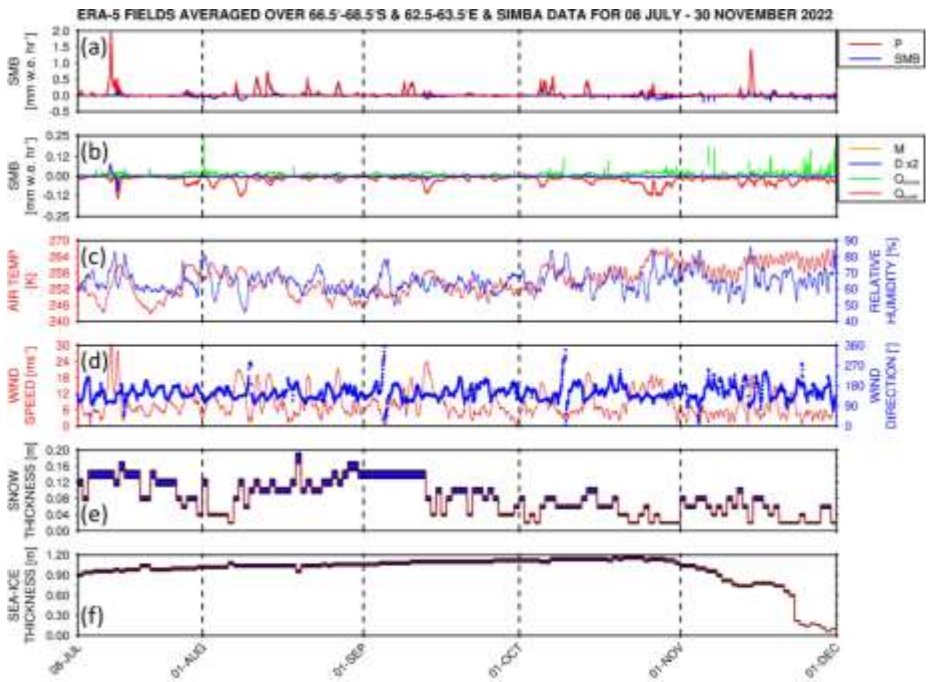
Figure 4a gives the Pook ~~b~~Blocking ~~i~~Index, defined in ~~e~~Equation ~~(~~S6~~)~~, for the study period. It ~~shows~~reveals ~~that~~ a few blocking ~~high~~ events ~~occurred around~~ east of the site ~~during the~~

~~measurements, in particular~~ around 120ºE in late July-early August, 150ºE in mid-~~late-~~September, and around the Dateline in mid- to late-November~~-early October, and 180ºE-120ºW in mid- to~~ late-November~~during the month of October, when the ST was decreasing (Fig. 3a)~~. Zoomed-in plots around the time of the Mawson~~each~~ AR passage highlight the occurrence of blocking around the Dateline and 60°W~~in particular in August~~ (Fig. 4d). The latter~~, which~~ actually coincided with the passage of three~~two~~ consecutive ARs west of the Antarctic Peninsula ~~during 10-12 and 13-15 August~~ (Fig. 4f), with the air temperature climbing above freezing (Fig. 4e). Wille et al. (2024c) and Maclennan et al. (2023) stressed that the occurrence of blocking can lead to the development of an “AR family” (or multi-AR) event, with the counterclockwise flow around the high-pressure and subsequent poleward advection of warm and moist low-latitude air masses leading to a marked rise in temperature. This is evident in particular around 120ºE in late July-early August and mid-September, and around 150ºE in late November (Figs. 4a-c). At the Khalifa SIMBA site on fast-~~-~~ice off ~~the~~ Mawson Station, on the other hand, blocking did not occur, as evidenced by the small values of the Pook ~~b~~Blocking ~~i~~Index (Fig. 4a). During the case study in mid-July (~~,~~Figs. 4d-f)~~.,~~ the presence of a ridge east of Mawson led to a second warm and moist air intrusion around 70°-90°E on 16 July. The passage of the AR at Mawson on 14 July~~two ARs also~~ coincided with an increase in air temperature by more than 15~~0~~ K in a couple of days (Fig. 4e), consistent with the observed rise in air temperature of ~18 K at the site (Fig. 2a)~~which is also noted for July~~. ~~It is explained by the counterclockwise flow around high-pressure systems and subsequent poleward advection of warm and moist low-latitude air masses. The most prominent such instance is around 150º-180ºE in late November 2022, when blocking around 180º led to an air temperature increase of more than 15 K to above freezing levels at some locations (cf. Figs. 4a-b).~~

~~In Fig. 2, the timings of AR passages at the site i.e., 14 July, 13 August and 14 November, are highlighted by vertical dashed lines. In particular and in the July and August events, during the polar night, there is a marked increase in air temperature of up to 18 K as the low latitude air mass reached the SIMBA site; this is also seen in the ERA-5 Hovmoeller diagrams (Fig. 4e). In the 14 November event, the increase is substantially reduced (by up to 3 K) as the air temperature is already much higher i.e., typically between 263-268 K. The ST increases by up to 0.06 m within 1-2 days of the AR event, returning to pre-AR levels in the following 2-4 days. The small magnitude effect may arise from an increase due to snowfall during the passage of the AR and a decrease before and after the event due to evaporation/sublimation in response to the drier and windier conditions or snow removal by katabatic winds (Fig. 3a). Other processes, such as snow metamorphism, by which snow changes to sea ice (Sturm and Massom, 2017), can also play a role. In fact, strong katabatic winds have been observed to blow the snow away as quickly as it falls on nearshore fast ice near the Syowa Station, resulting in very low accumulation close to the coast (Kawamura et al., 1995), and off the Mawson Station as well (Dare and Budd, 2001). The SIT does not show a clear response to the passage of the ARs, except for the 14 November AR where a 0.04 m increase may arise from snow-ice interactions as noted before (Sturm and Massom,~~

2017). It is important to note that a longer measurement period would be needed for a robust link between ARs and their effects on ST and SIT to be established.

The results in Figure 4 stress highlight the role of atmospheric dynamics in modulating the ST at the Khalifa SIMBA site on fast -ice off the Mawson Station-, with the SIT largely controlled by the oceanic and conductive heat flux- dynamics (ocean-driven fast-ice deformation and thermodynamic growth) and the seasonal variability in the incoming solar radiation.



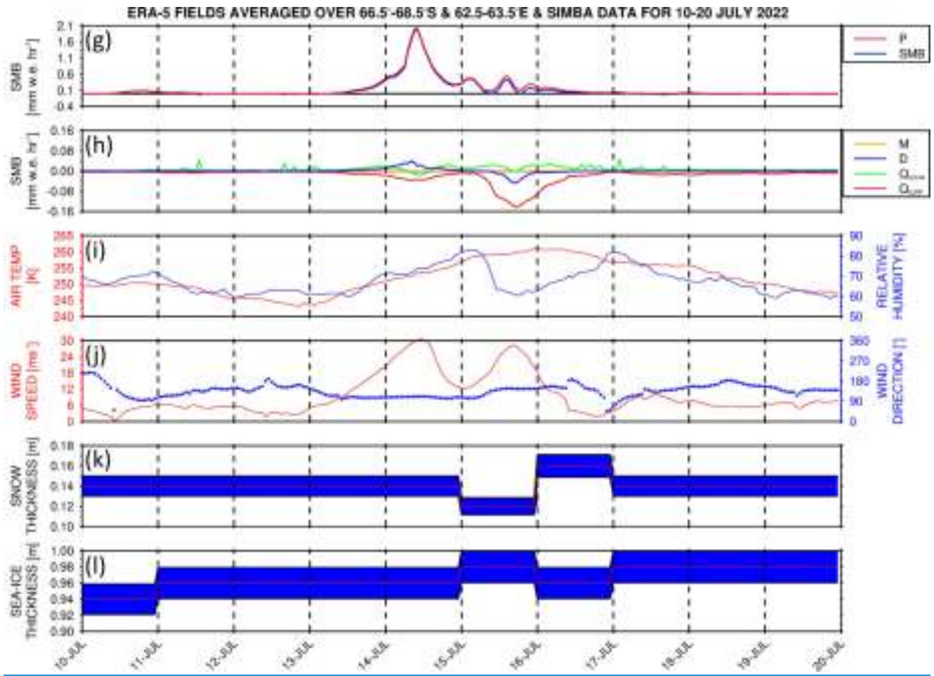


Figure 3: Surface Mass Balance and SIMBA Observations: ERA-5 hourly (a)-(b) s~~S~~urface mass balance (mm w.e. hr^{-1}) ~~from ERA-5 (top two plots)~~, (c) air temperature (red; K) and relative humidity (blue; %), and (d) horizontal wind speed (red; m s^{-1}) and direction (blue; º) averaged over 66.5º-68.5ºS and 62.5º-63.5ºE for the period 08 July and 30 November 2022. The local SMB terms plotted are the SMB (blue) and precipitation (red; P) in (a), and the snowmelt (orange; M), surface sublimation (red; Q_{sfc}), blowing snow sublimation (green; Q_{snow}), and blowing snow divergence (blue; D) in (b). No snowmelt occurred during the measurement period, and the D term is multiplied by two for visualization purposes. (e)-(f) give the ~~and~~ ST (m) and ~~sea-ice thickness (~~SIT~~;~~ (m) from the SIMBA measurements, respectively ~~(bottom two plots) for the period 8 July to 30 November 2022~~. The red line shows the observed value while the blue shading gives the uncertainty, which is estimated as 7% for ST and 2% for SIT (Liao et al., 2018). ~~(b) is as (a) but for 10-20 JulyNovember 2022. The local SMB terms plotted are the SMB, precipitation (P), snowmelt (M), surface sublimation (Qsfc), blowing snow sublimation (Qsnow), and blowing snow divergence (D).~~ (g)-(l) are as (a)-(f) but for 10-20 July 2022. No scaling is applied to the D term.

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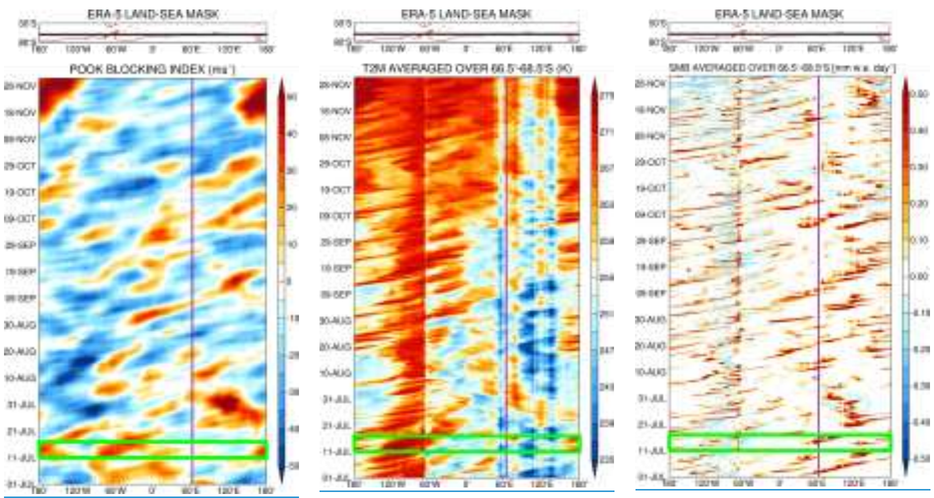
(a) (b) (c)



(d) (e) (f)

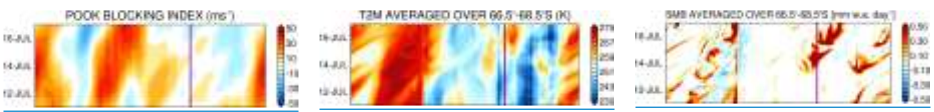


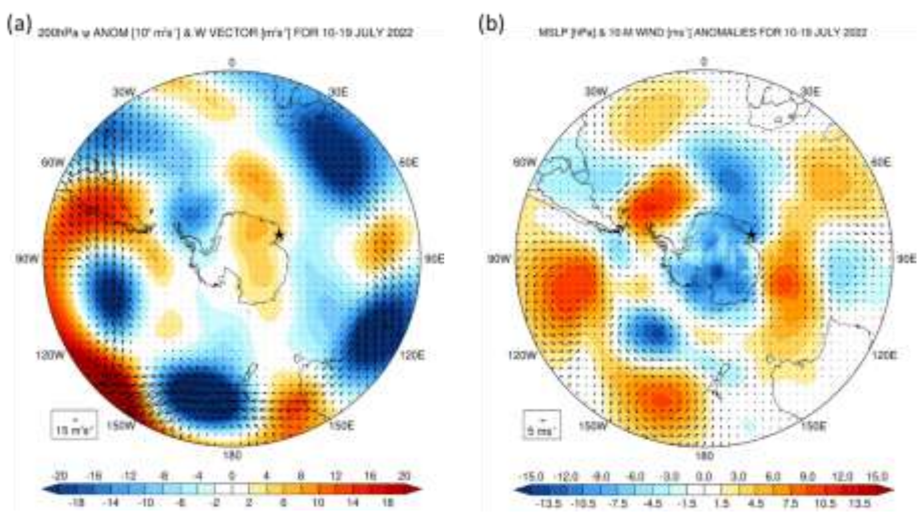
Figure 4: Atmospheric dynamics and thermodynamics during the Observational Period: (a) Pook blocking index ($m\,s^{-1}$) for July-November 2022. The vertical purple line gives the approximate longitude of the measuring site. Regions where the index exceeds 40 $m\,s^{-1}$, an indication of a high degree of blocking, are stippled. The green rectangles indicate the period~~s~~ when an AR impacted the site,~~:~~ 11-16 July~~, 10-15 August, and 11-16 November. The latter is considered for modeling and is highlighted with a thick line.~~ Above the Hovmoeller plot, the land-sea mask as seen by ERA-5 is plotted in red and the averaging region is highlighted with a black rectangle. (b) and (c) are~~is~~ as (a) but for air temperature (K) and the SMB, defined in equation (3), respectively, averaged over 68.5º-66.5ºS. The sharp transition in the temperature field around 60ºW arises due to the presence of the Antarctic Peninsula (landmass), while~~.~~ t~~T~~he stipple in (b) indicates regions and times when the temperature is above freezing (273.15 K). ~~(c) is as (b) but for the SMB defined in equation (310).~~ (d)-(f) are as (a)-(c) but zooming in for 11-16 July 2022~~each of the three periods~~.

4. Case Study: 11-16 July~~November~~ 2022

An~~The strongest~~ AR ~~to~~ impacted the site during July-November 2022 ~~occurred~~ on 14 July~~November~~. In Section 4.1, the large- and regional-scale environment that promoted the development of the AR is investigated, while in Section 4.2 the results of the PWRF simulations are discussed.

4.1 Large-Scale Atmospheric Patterns

The period 10-19 July~~November~~ 2022 is characterized by a strong wavenumber #3 pattern along~~in~~ the Southern Hemisphere polar jet at about 60ºS~~mid-latitudes~~ and a wavenumber #5 pattern along the subtropical jet at about 30ºS (Fig. 5a), projecting onto the ~~in association with a~~ positive phase of SAM (Fig. 5b) ~~phase~~. ~~In fact, the SAM index for November 2022 is the third highest since 1979, and is more than 1.5 standard deviations above the 1979-2021 climatological mean (Fig. S1a).~~ The stationary wave activity flux vectors in Fig. 5a show little wave propagation from the tropics into the Southern Hemisphere mid-latitudes, with a prevailing zonal propagation within the wavenumber #5~~3~~ pattern. This is also evidenced by the strong westerly flow around Antarctica (Figs. 5~~c~~-d). One of the reasons for the positive SAM is the La Niña that was taking place at the time, the third consecutive La Niña year after the 2018-2019 El Niño (NOAA/NWS, 2024). ~~La Niña events favour a stronger than normal Amundsen Sea Low (Raphael et al., 2016), as was the case during November 2022 (Fig. 5b). In the previous month (October) it was even deeper, with a cyclone in the South Pacific Ocean reaching a sea-level pressure of 900 hPa, making it the strongest extratropical cyclone since the start of the satellite era in 1980 to date (Lin et al., 2023).~~



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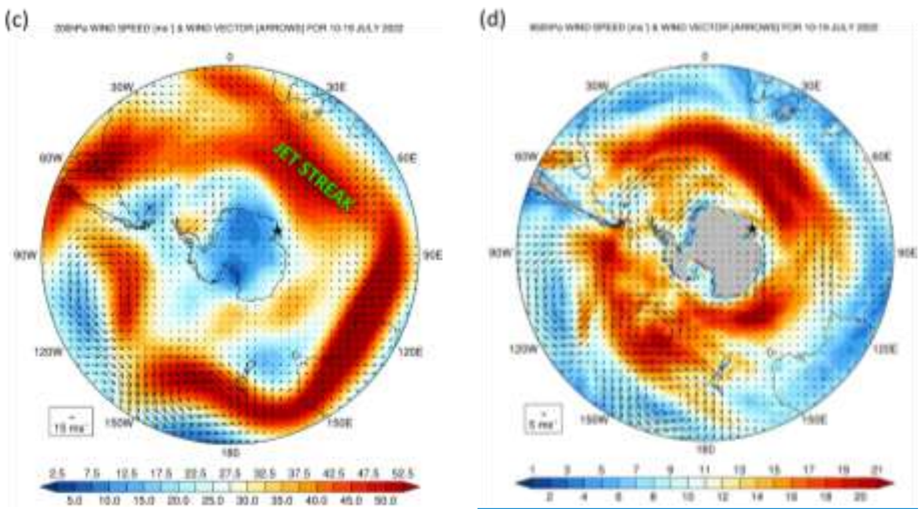

Figure 5: Large-Scale Circulation during 10-19 JulyNovember 2022: (a) 200 hPa stream-function anomalies (shading; 10^6 m^2 s^{-1}), with respect to the hourly 1979-2021 climatology, and the stationary W vectors (Takaya and Nakamura, 2001; equations (2a) and (2b); arrows; m^2 s^{-2}) averaged over 10-19 JulyNovember 2022. (b) Sea-level pressure (shading; hPa) and 10-m wind vectors (arrows; m s^{-1}) anomalies for the same period. (c) and (d) show the 200 hPa and 850 hPa wind speed (shading; m s^{-1}) and vectors (arrows) averaged over the same period. The jet streak referred to in the text is highlighted in (c). In all panels, tThe star gives the location of the Mawson Station (67.5912ºS, 62.8563ºE).

North of Mawson Station, a pressure dipole is present around 40º-65ºS (Figs. 5-b), with a ridge to the east and a trough to the west, with both features more than onetwo standard deviations away from the climatological mean (not shownFig. 6e). This pattern favours the poleward propagation of warm and moist low-latitude air into the Khalifa SIMBA site on fast -ice off the Mawson Station in East Antarctica, and is conducive to the development of ARs (Francis et al., 2022b; Gorodetskaya et al., 2023). The interaction between the subtropical jet and polar jet (Fig. 5c) led to the development of a jet streak, (Fig. 5c), a localized maximum in the strength of the flow., with The low pressure associated with the AR (Fig. 5a) is located to the south of the jet entrance, in an area favourable for cyclogenesis (Wallace and Hobbs, 2006) on 13-14 November that promoted an intensification of the low. Despite its slow eastward movement and anomalous high strength, the meridional extent of the ridge from East Antarctica to southeastern Madagascar may explain why it is not detected by the Pook blocking Blocking indexIndex, Fig. 4a and eEEquation (S67), as the westerly flow at 35º-40ºSN and 65º-7040ºSN is also weaker. In any case, this pressure dipole fosters the transport of warm and moist low-latitude air across the SIMBA site and is conducive to the development of ARs (Francis et al., 2022b; Gorodetskaya et al., 2023). The ARone that developed on 14 JulyNovember 2022 is particularly remarkable, extending from the southwestern

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Indian Oceantropical Africa into the Southern Ocean and East Antarctica, and having its primary origin in South America (Figs. 6a-b). The wavetrain extending from South America to the southeastern Pacific Ocean to South America comprises a ridge over southern parts of Chile and Argentina, and a low over northern Argentina to the west of South Atlantic subtropical high (Figs. S1b, S1d and S1f). The pressure gradient between the latter two systems leads to a strengthening of the South American low-level jet (Marengo et al., 2004; Montini et al., 2019), which advects moisture from equatorial South America into the subtropics and helps to feed convection east of the Andes (Figs. S1a, S1c, and S1e). The moist outflow coming out of South America and the latent heat release from the convection strengthen the low pressure to the southwest of South Africa that is tracking southeastwards, and promote the development of the AR that impacted the Khalifa SIMBA site on fast -ice off the Mawson Station on 14 July. After a first landfall on 14 July around Mawson Station, Fig. 6a, the AR made a second landfall around 75º-90ºE, Fig. 6b, impacting a wide swath of East Antarctica from about 45ºE to 100ºE. Here, the air temperature anomalies generally exceeded 10 K, with some parts of East Antarctica having near-surface temperatures in the top 1% of the 1979-2021 climatological distribution (Fig. 6d). The IVT anomalies at 06 UTC on 14 JulyNovember exceeds 1560 kg m^{-1} s^{-1} around the Khalifa SIMBA site on fast -ice off the Mawson Station and 8400 kg m^{-1} s^{-1} further north along the AR (Fig. 6b), with the hourly IVT on this day being in the top 0.51% of the climatological distribution (Fig. 6cb), an attestation to the extreme nature of this event. The air temperature anomalies are also noteworthy, exceeding 108 K in parts of East Antarctica around andjust eastwest of the SIMBA site (Fig. 6d), where in some parts they are in the top 1% ofmore than two standard deviations above the 1979-2021 climatological distributionmean (not shown). A back-trajectory analysis performed with HYSPLIT forced with ERA-5 data revealed tropical and subtropical moisture sources contributed to the 14 July 2022 AR (Fig. S2a). While at lower levels the moisture came from the Southern Ocean, with specific humidity values generally below 2 g kg^{-1} and air temperatures generally below freezing, at 2250 m it originated in the subtropics just south of South Africa with specific humidity values in excess of 6 g kg^{-1} and air temperatures around 280-290 K (Figs. S2b-e). The latter air mass ascended from roughly 200 m to 2250 m just north of the Mawson Station, when it encountered the colder and drier katabatic airflow (Fig. S2a). Several studies report on ARs impacting Antarctica being fed by subtropical moisture, such as the February 2011 (Terpstra et al., 2021) and the November-December 2018 (Gorodetskaya et al., 2020) ARs over East Antarctica, and the February 2022 AR over the Antarctica Peninsula (Gorodetskaya et al., 2023).

Theis AR and attendancet cyclone alsoand associated warm and moist air intrusion left a considerable imprint on the weather conditions over East Antarctica around and to the west of the Mawson Station. Furthermore, it had an important effect on the sea ice in the region. As seen in Figs. S3a-b, there was a considerable reduction in SIE from 124 to 167 JulyNovember both around coastal Antarctica and upstream, with an open-ocean polynya developing well northwest of the Mawson Station around 64°S,45°E on 14 July and disappearing on 22 July. The role of ARs and the surface divergent flow associated with the attendant cyclone in opening up polynyas has been

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reported at multiple sites around Antarctica (Francis et al. 2019, 2020). The low-pressure system northwest of Mawson reached a minimum value of 944 hPa on 12 July over the Southern Ocean, with the secondary low that formed on 14 July reaching 933 hPa on this day at 06 UTC just off the Khalifa SIMBA site on fast ~~-~~ice off ~~the~~ Mawson Station (Fig. 6a), and deepening further to 931 hPa late on 15 July just to the northeast of the site (Fig. 6b). These systems are stronger than those that played a role in the opening up of the Weddell Sea ~~p~~Polynya in September 1973 and 2017 (Francis et al., 2020), and the Maud Rise ~~p~~Polynya in September 2017 (Francis et al., 2019). The sea-ice vectors in Figs. S3c-d show an equatorward movement north of Mawson Station from 12~~1~~-14~~3~~ July~~November~~ (prior to the event) at speeds in excess of 40 km day^{-1}, and a southward movement from 14-16 July~~November~~ (post event) at speeds in excess of 20~~5~~ km day^{-1}~~, the latter an order of magnitude larger than that estimated during 12-14 November at the same site~~. These sea-ice drift velocities, which are associated with the changing wind field in response to the shift in the position of the mid-latitude weather systems in the region (Figs. 6a-b, 6d and 7), are higher than~~comparable to~~ those observed in the western Ross Sea in late April 2017 (Fonseca et al., 2023), and comparable to those estimated in the region in September 2017 (Francis et al., 2019). ~~They,~~ and ~~are associated with the changing wind field in response to the shift in the position of the mid-latitude weather systems in the region~~ (Figs. 6a-b, 6d and ~~7).~~

~~The southeast-northwest convective band over southern Africa is a potential TTT event, resulting from the interaction of mid-latitude weather systems with tropical convection. Such TTTs are known to precondition the environment for the development of ARs, as in the March 2022 East Antarctica "heat" wave (Wille et al. 2024a,b). In order to quantify its strength and check whether a TTT event took place during the study period, the TTT index put forward by Ratna et al. (20123), which is based on OLR and meridional wind (equations S7-S88a,b), is utilized (Fig. S1b). While the meridional wind index does exceed half of its climatological standard deviation during 12-13 November, the OLR index does not meet its condition of being higher than 1.5 the climatological standard deviation. Hence, no TTT event occurred during 10-20 November 2022. Having said this, tropical and subtropical moisture contributed to the warm and moist air intrusion that impacted East Antarctica. This is evident in the back-trajectories obtained with HYSPLIT forced with ERA-5 data (Fig. S2). While at lower levels (500 m and 1500 m) the moisture came from the Southern Ocean, at 2500 m it originated in the subtropics just south of South Africa before rising just north of the Mawson Station when this moist air mass encountered the colder and drier katabatic airflow. Even at 500 m, the dry air parcels descending the Antarctic plateau into the Southern Ocean are moistened over the water before turning back to Antarctica and reaching the site (Figs. S2b-e). Several studies report on ARs impacting Antarctica being fed by subtropical moisture, such as the February 2011 (Terpstra et al., 2021) and the November-December 2018 (Gorodetskaya et al., 2020) ARs over East Antarctica, and the February 2022 AR over the Antarctica Peninsula (Gorodetskaya et al., 2023).~~

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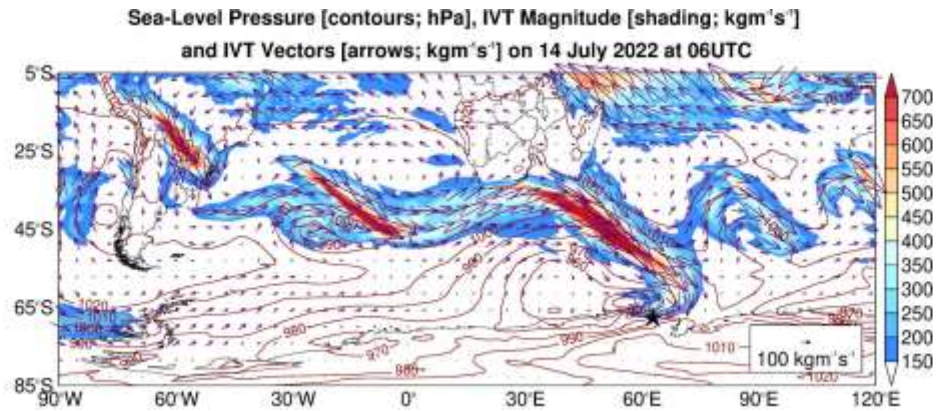
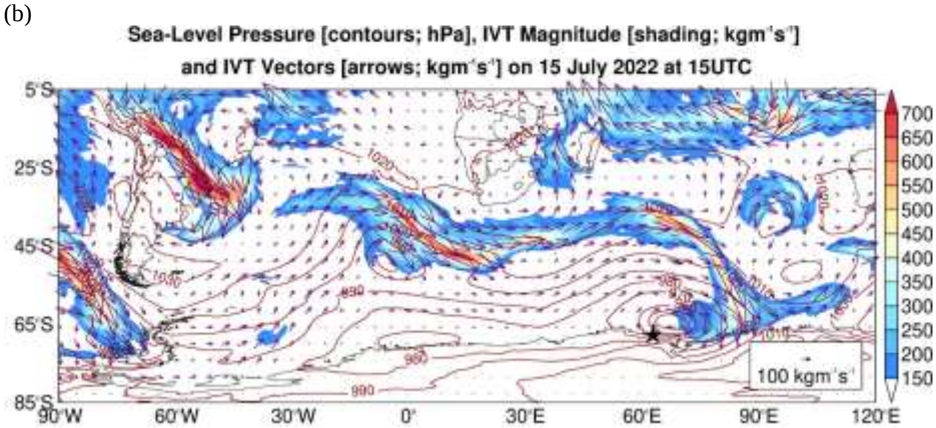

Sea-Level Pressure [contours; hPa], IVT Magnitude [shading; kgm⁻¹s⁻¹]
and IVT Vectors [arrows; kgm⁻¹s⁻¹] on 14 July 2022 at 06UTC
5°S
25°S
45°S
65°S
85°S
90°W
60°W
30°W
0°
30°E
60°E
90°E
120°E
100 kgm⁻¹s⁻¹
700
650
600
550
500
450
400
350
300
250
200
150

(b)


Sea-Level Pressure [contours; hPa], IVT Magnitude [shading; kgm⁻¹s⁻¹]
and IVT Vectors [arrows; kgm⁻¹s⁻¹] on 15 July 2022 at 15UTC
5°S
25°S
45°S
65°S
85°S
90°W
60°W
30°W
0°
30°E
60°E
90°E
120°E
100 kgm⁻¹s⁻¹
700
650
600
550
500
450
400
350
300
250
200
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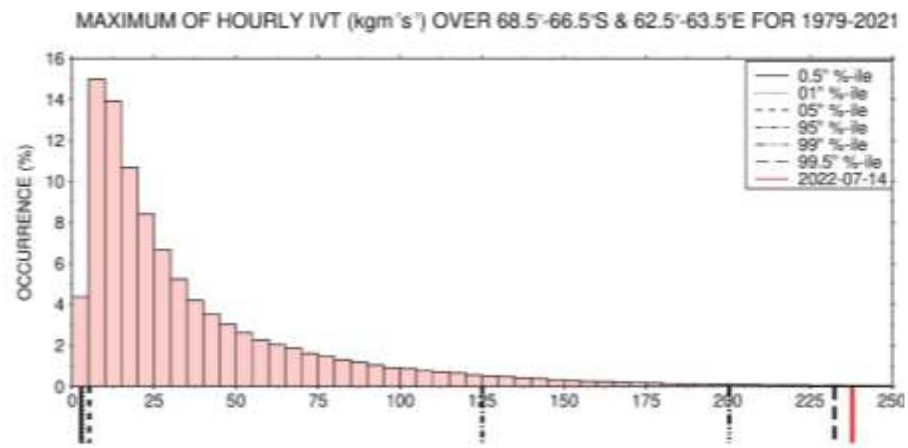
(c)



(d)

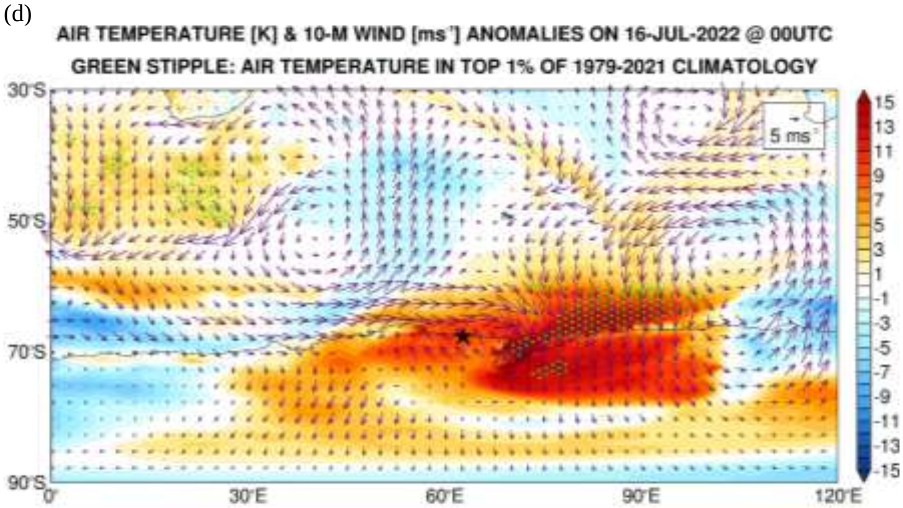


Figure 6: Atmospheric River on 14 July~~November~~ 2022: (a) Sea-level pressure (contours; every 10 hPa), Integrated Vapour Transport (IVT) magnitude (shading; kg m^{-1} s^{-1}) and vectors (arrows; kg m^{-1} s^{-1}) on (a) 14 July 2022 at 06 UTC and (b) 15 July 2022 at 15 UTC from ERA-5. The star gives the location of the Mawson station. ~~MODIS visible image on 14 November 2022 over the domain 10ºW-90ºE and 5ºN-75ºS. The location of the Atmospheric River, Mawson Station (star) and a coastal polynya to the east of the station are highlighted. Image Credits: NASA WorldView. (b) Integrated Vapour Pressure (IVT; kg m-1 s-1) anomalies, the shading gives the magnitude and the arrows the vectors, on 14 November 2022 at 06 UTC with respect to the hourly 1979-2021 climatology from ERA-5.~~ (c) Histogram of the maximum~~edian~~ hourly IVT around the Mawson station (~~for the domain~~ 68.5º-66.5ºS and 62.5º-63.5ºE)~~, black box in (b),~~ for 1979-2021. The solid, dotted, dashed, dotted-dashed~~, and~~ dashed-dotted-dotted and long dashed lines give the 0.5th, 1st, 5th, 95th~~, and~~ 99th and 99.5th percentiles, respectively, while the red~~,~~

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Formatted: Not Superscript/ Subscript green and blue lines indicates the minimum, mean and maximum hourly values on 14 JulyNovember 2022. (d) is as (b) but for the air temperature (shading; K) and 10-m wind vectors (arrows; $m\ s^{-1}$) anomalies with respect to 1979-2021 climatology on 16 July 2022 at 00 UTC. The green stipple indicates regions where the air temperatures are in the top 1% of the 1979-2021 climatological distribution., while in (e) the shading gives the sea level pressure and the arrows give the 10-m wind vector standardized anomalies.

Figures 5-6 provide a summary of the weather conditions during 10-1920 JulyNovember 2022, with Fig.ure 6 focusing on the AR event that impacted the Mawson Stationpeaked on 14 JulyNovember. In order to gain insight into this AR event, it is important to assess the temporal evolution of the atmospheric circulation prior to and during the event itself. This is achieved in Fig.ure 7, which shows multiple fields every 12 h from 13 JulyNovember at 0618 UTC to 15 JulyNovember at 1806 UTC. At 0618 UTC on 13 JulyNovember (Fig. 7a), a broad low-pressure system is centered northwest of the site, coincident with a TPV (highlighted in the figure), which came from the Antarctic plateau (full track shown in Fig. S1c), withand a ridge to its east. The TPV helps the surface low to intensify, together with the jet streak at upper levels (Fig. 5c), with the central pressure dropping to around 944 hPa on 12 July at 12 UTC. The pressure dipole promotes the southward advection of a warmer and moist low-latitude air mass into the Southern Ocean, as noted by the hatching that highlights regions where the IVT exceeds 250 $kg\ m^{-1}\ s^{-1}$. A secondary low, which develops laterearly on 134 JulyNovember (highlighted in Fig. 7cb, also also noted by the additional sea-level pressure contour), is not co-located with a TPV. Instead, the secondary low it is driven by the interaction of the warm and moist air mass from the west and northwest around the low pressure with that from the northeast around the ridge. Closer – and also closer to the Antarctic coast, the aforementioned low-level convergence is reinforced by also with the drier and colder katabatic flow blowing from the continent. The maximum EeEady growth rate, a measure of baroclinicity (Hoskins and Valdes, 1990), at 850 hPa exceeded 3 day^{-1} on 14 JulyNovember (not shown), indicating a highly baroclinic environment.

Figures 7b-de show cyclonic Rossby wave breaking, with the secondary low exhibiting little eastward movement owing to the presence of a strong ridge to the east (Figs. 6a-be), and instead shifting southwards towards Antarctica. The incursion of the higher low-latitude potential temperature values into East Antarctica (Figs. 7b-d) is consistent with the warmer (Fig. 6d) and more moister (Figs. 6ab-c) conditions in the region. The flow became westerly and the warm and moist air intrusion weakened and shifted eastwards from 14 to 15 JulyNovember (Figs. 7c-d) and penetrated deeper into East Antarctica on 15-16 July (Figs. 7d and 6d), with air temperatures more than 15 K above climatology in some parts (Fig. 6d), with another warm and moist air intrusion (albeit weaker) developing to the northwest of the site (Fig. 7d) later impacting the area on 16-17 November (not shown). Fig. 7 shows more than one episode of intrusion of low-latitude air masses into Antarctica. For example, on 14-16 NJulyovember a warm and moist air intrusion reached the Antarctic PeninsulaVictoria Land just to the west of the Ross Sea (Figs. 7c-d). Such occurrences are more common in an amplified pattern and can be aided by TPVs that act to strengthen the attendant cyclone (Wille et al., 2024c).

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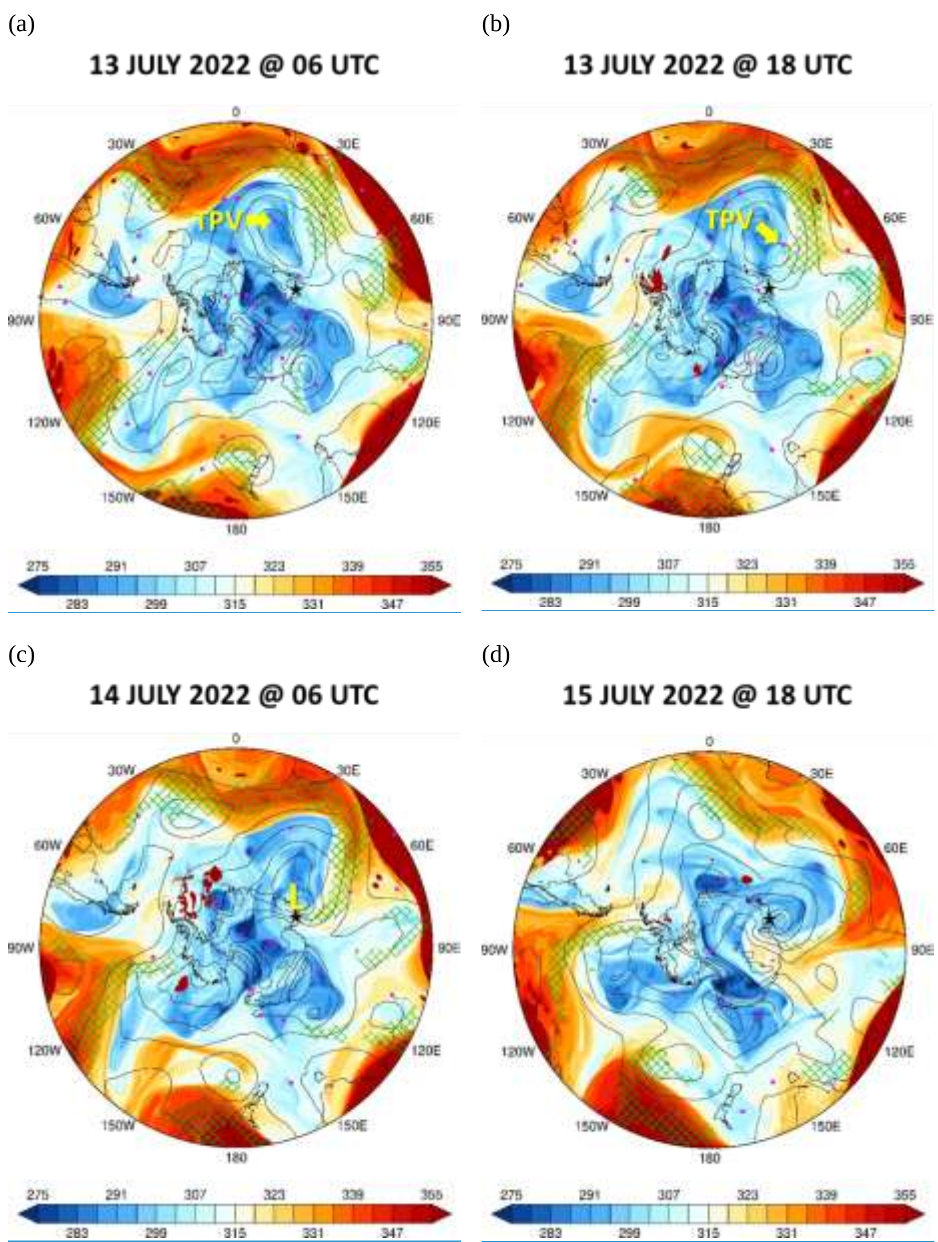
(a)
13 JULY 2022 @ 06 UTC
TPV
(b)
13 JULY 2022 @ 18 UTC
TPV
(c)
14 JULY 2022 @ 06 UTC
(d)
15 JULY 2022 @ 18 UTC
0
30W
30E
60W
60E
90W
90E
120W
120E
150W
150E
180
275
291
307
323
339
355
283
299
315
331
347

Figure 7: Evolution of Atmospheric State during 13-15 July~~November~~ 2022: Potential temperature (θ; shading; K) on the dynamical tropopause (PV = -2 PVU), sea-level pressure (black contours; every 15 hPa starting at 900 hPa) and integrated vapour transport (IVT; hatching if > 250 kg m^{-1} s^{-1}) on ~~(a)~~ 13 July~~November~~ at (a) 06~~18~~ UTC and (b) 18 UTC, ~~,~~ (c) 14 July~~November~~ at ~~(b)~~ 06 UTC, and (d~~c~~) 15 July at 18 UTC~~, and (d) 15 November at 06 UTC~~. The purple dots indicate the location of tropopause polar vortices (TPV) at the respective times. The TPV and the secondary low pressure discussed in the text are highlighted in panels (a)~~, and~~ (b) and (c), respectively.

4.2 PolarWRF Simulation

In this subsection, the focus is on the modeling experiments. In Section 4.2.1, the PWRF predictions are evaluated against *in-situ* measurements at the five~~**four**~~ stations in East Antarctica given in Fig. 1b, while in Section 4.2.2 the emphasis is on the additional insight the higher-resolution model data gives on the mid-July~~**November**~~ 2022 AR event.

4.2.1 Evaluation of PolarWRF

The PWRF simulations for 11-16 July~~November~~ 2022 are evaluated against *in-situ* meteorological observations at the Mawson, Syowa, ~~Mizuho and~~ Relay, Davis and Casey stations, in addition to surface radiation fields at Syowa Station. Fig. 8 shows the time-series of hourly data for the Mawson and Syowa stations, with the corresponding time series for the other two stations given in Fig. S4. A quantitative assessment of the model performance for all stations and variables is presented in Table 3~~1~~.

~~The~~ PWRF simulates the weather conditions well at the Mawson (Figs. 8a-f), Syowa (Figs. 8g-l~~b~~ and S4a-f), ~~Mizuho (Fig. S4a) and~~ Relay (Fig. S4g-l~~b~~), Davis (Fig. S4m-r) and Casey (Fig. S4s-x) stations for 11-16 July~~November~~ 2022. In particular, ~~(i)~~ the observed variability in sea-level pressure is well replicated, with the model correctly capturing the time of passage and strength of the secondary cyclone on 14-15 July~~November~~ at Mawson (Figs. 7c-d~~b-c~~; Fig. 8c) and on 15 July at the Davis (Fig. 7d; Fig. S4p) ~~S~~stations~~at all sites~~.~~;~~ Moreover,~~(ii)~~ the warmer, more moist and windier conditions on 12-14 July at Syowa Station (Figs. S4a-c and S4f), on 14~~3~~-15 July~~November~~ at Mawson (Fig. 8a-c and 8e) and Relay (Fig. S4g-i and S4l) Stations, and on 15-16 July at Davis (Fig. S4m-o and S4r) and Casey (Fig. S4s-u and S4x) Stations are predicted by the model~~at all sites;~~ ~~and (iii) it~~. Also, the model captures the ~~reduction in the surface downward shortwave radiation flux by about 200 W m-2, or a third of its value, and the~~ increase in the downward long-wave radiation flux by up to 8~~9~~0 W m^{-2} at Syowa Station (Fig. 8k) in association with the warm and moist air intrusion on 13-14 July. An inspection of Table 3~~1~~ reveals that, and except m~~ostly~~ainly for the air temperature and surface pressure~~by and large~~, the normalized bias μ is smaller than 0.5, indicating the ~~(small magnitude)~~ biases can be regarded as not significant, while the normalized error variance α does not exceed 1 for all fields and stations (except for the wind

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vector at the higher-elevation Relay and coastal Davis Stations), indicating that the PWRF predictions can be regarded as trustful. The performance of PWRF for this site and event is comparable to that for the McMurdo Station in early January 2016 (Hines et al., 2019), for West Antarctica in early to mid-January 2019 (Bromwich et al., 2022), and for the Antarctic Peninsula for May-June 2019 and January 2020 (Matejka et al., 2021). This reflects the improvements made to PWRF by the model developers, with the aim of optimizing its performance and skill over Antarctica (e.g., Hines et al., 2021).

A closer inspection of Figs. 8 and S45 and Table 3 reveals some discrepancies in the PWRF predictions. For example, at Syowa Station, the model has a tendency to over-predict the air temperature by ~1-32 K. This may explain the overestimation of the upward longwave radiation flux by about 14.3 W m^{-2} (,Fig. 8l), which can also arise from an overprediction of the observed surface emissivity. The downward longwave radiation flux (,Fig. 8k),, on the other hand, is underestimated by roughly 7.7 W m^{-2}, likely related to the reduced atmospheric moisture content in the model by about ~0.16 g kg^{-1}. While the downward shortwave radiation flux is generally well captured by the model, the upward shortwave flux has a significant negative bias of ~68 W m-2, which can arise e.g. from an underestimation of the observed surface albedo by around 10% (roughly 0.84 for observations and 0.75 for PWRF for 11-16 November). This suggests the need to properly represent land surface properties in the model, which has been highlighted by other studies (e.g., Hines et al., 2019). The lower albedo in PWRF leads to a positive bias in the net shortwave radiation flux, which is consistent with the warmer air temperatures and the enhanced upward longwave radiation flux biases of ~11 W m-2. At all four coastal Antarctica stations, the predicted wind direction is generally shifted clockwise by 45º-90º compared to that observed (Figs. 8d, S4e, S4q and S4w), with this mismatch at times reaching 180ºbeing more evident at the Relay Station (Fig. S4k) located on the Antarctic plateau more than 3,000 m above sea-level (Fig. 12b). This discrepancy can be attributed to an incorrect representation of the surface topography which, as for surface properties such as the albedo, exhibits a complex spatial heterogeneity in the region (Lea et al., 2024). Despite these issues, both the magnitude and variability of the observed wind speed are generally well represented by PWRF (Figs. 8e, S4f, S4l, S4r, and S4x3). The more offshore wind direction at the coastal AntarcticaMawson and Syowa stations reflect a stronger katabatic wind regime that acts to slow the poleward movement of the warm and moist low-latitude air mass, which is consistent with the dry bias of up to 0.11 0.216 g kg^{-1}. The positive mixing ratio bias at the Relay Station occurs primarily on 15-16 July, (Fig. S4h), and is associated with increased (but still rather low, (generally below 0.1 g kg^{-1}) moisture levels advected from the interior of Antarctica. At all stations except Mawson, PWRF exhibits a warm bias (Figs. 8a, 8g, S4g, S4m, and S4s), with the near-surface wind speed being underestimated at Mawson (Fig. 8e) and overestimated at the other stations (Figs. S4f, S4l, S4r, and S4x). Together with the dry bias, this suggests a tendency for excessive boundary layer mixing in the model compared to observations, whichIn fact, and in particular at the Mawson Station, when the model overpredicts the strength of the near-surface wind (e.g., around 00 UTC on 12 and 16 November and between 18-24 UTC on 13 November) from an offshore direction, there is a cold and dry bias, confirming

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the occurrence of an enhanced katabatic airflow.Table 1 also reveals that the control and model simulation with updated SIE and SIT yield similar skill scores, a fact that is confirmed by the time-series in Figs. 8 and S4. This suggests that a more realistic representation of the sea-ice state, and at least for this particular event and model configuration, does not translate into more accurate predictions. By and large, the results in Figs. 8 and S4 indicate a tendency for drier and windier conditions compared to observations. This has been reported in a number of PWRF studies (e.g., Wille et al. 2016, 2017; Vignon et al., 2019), and has been attributed to excessivetoo much boundary layer mixing in the model. An optimized PBL scheme, which at least partially corrects for the excessive mixing, and/or a more sophisticated land surface model that more accurately represents the boundary layer and surface processes, have to be considered to address the aforementioned biases. Despite this, PWRF captures the effects of the AR as seen in observations, most notably the increase in air temperature and water vapour mixing ratio, and the strengthening of the near-surface wind in particular at the more impacted Mawson (Figs. 8a-e) and Davis (Figs. S4m-r) Stations. The SMB analysis performed using ERA-5 data is repeated using the hourly PWRF predictions. PWRF gives a similar estimate of the different terms of the SMB with respect to the reanalysis dataset (cf. Figs. S5a-b with 3g-h), with the roughly 30% higher surface sublimation on 15 July arising from the drier (~10% lower relative humidity; cf. Figs. S5c with 3i) and windier (~10% higher wind speed; cf. Figs. S5d with 3j) near-surface conditions in the model. The fact that ERA-5 can capturecaptures Foehn effects at this site and for this event, at least for this one, suggests that it can be used for the studywider analysis of Foehn events inaround East Antarctica, as has been done over West Antarctica (Francis et al., 2023) and the Antarctica Peninsula (Laffin et al., 2021). The up to ~2 mm w.e. hr^{-1} precipitation rate (Figs. S5a and 3g), ~5 K air temperature increase (Fig. S5c and 3i), and 30 m s^{-1} wind speeds (Fig. S5d and 3j) associated with the passage of the AR on 14 July are simulated by PWRF, with the cold bias in the model also seen in comparison with *in-situ* measurements at Mawson Station (Table 3).

Fig. 8f shows a comparison of the observed and simulated snow depth at the Khalifa SIMBA site on fast -ice off the Mawson Station. The ST in PWRF is initialized to zero, and hence the discrepancy with respect to the observed values during 11-13 July (the observed ST is equal to 0.14 m during 10-14 July). PWRF predicts around 0.24 m of snowfall in association with the passage of the AR on 14 July and: the weaker wind speeds in the model, at times by more than 20 m s-1, likely allow for snow to accumulate at the site instead of it being blown away by the wind. The model fails to capture the observed decrease of 0.02 m in ST on 15 July in response to Foehn effects, which can be attributed to less favourable conditions for Foehn events in the model, both with respect to the wind direction (west-southwesterly in PWRF as opposed to southeasterly in observations) and speed (lower by as much as 20 m s^{-1}). A higher spatial resolution of at least 1 km would probably be needed for a more accurate simulation of the interaction of the AR with the complex Antarctic topography including the Foehn effects (Gilbert et al., 2025). The increase in ST on 16 July due to falling precipitationsnowfall is simulated by PWRF, even though its magnitude is underestimated by the model (0.01 m in PWRF as opposed to 0.04 m in observations), possibly because of the drier environment brought on by a more offshore wind direction (Figs. 8b, 8d-e, and S5b-d).

Besides ground-based observations, sounding data are available at the Mawson, Syowa, Davis, and Casey ~~s~~Stations every 12 h ~~(Figs. S5a)~~ and can be compared with the hourly PWRF predictions (Figs. S6 and S7~~5b-c~~). The model captures the timing of the arrival of the warm and moist air mass at Mawson on 14~~-~~15 July~~November well~~, as evidenced by the higher values of θ_E (27~~8~~0-28~~9~~0 K; Figs. S6a and S6e) and relative humidity (6~~9~~0-9~~10~~0%; Figs. S6b and S6f). However, the katabatic wind flow is stronger in the model as seen by the offshore wind direction (Fig. S6h) and drier conditions (Figs. S6b and S6f), and also evident in the ground-based observations (Figs. 8d and 8b), with a strong low-level jet (mostly below 700 hPa) on 14 and 16 July (Fig. S6g). At Syowa, the PWRF and observed profiles are in closer agreement than at the Mawson ~~s~~Station (cf. Figs. S6a-h with S6i-p). Here, the main discrepancy between the observed and modelled profiles is the dry bias (Figs. S6j and S6n), which is more pronounced on 13-14 July, and is also evident in the near-surface data (Fig. 8i). The arrival of the low-latitude air mass at Davis on 15 July is seen in both the PWRF and observed profiles (Figs. S7a-h), with a less pronounced katabatic regime in the model compared to that at ~~the~~ Mawson Station (cf. Figs. S6e-h with S7e-h). At Casey (Figs. S7i-p), PWRF simulates the more moist conditions on 14 July and the drier conditions on 15-16 July. The analysis of the sounding profiles reveals, however, that PWRF tends to overestimate the strength of the katabatic flow over coastal East Antarctica during 11-16 July. ~~This has been noted by~~ Vignon et al. (2019)~~, who~~ attribute such overestimates~~it~~ to more stable boundary layers over the Antarctic Plateau and, to a ~~smaller~~lesser extent, steeper synoptic land-ocean pressure gradients in the model. ~~The northwesterly flow between 750 and 950 hPa late on 14 November is also simulated by PWRF, even though the wind direction in the model tends to be more from an easterly component compared to observations.~~

The results in Figs. 8, S4-S7, ~~and S64 S75~~, and Table 3~~1~~ reveal a reasonably good PWRF performance in the study area for the period 11-16 July~~November~~ 2022. In the next subsection, the model simulations are used to gain further insight into the dynamics of the 14 July AR~~for this~~ event. ~~The simulation with the updated SIE and SIT was used for this purpose.~~

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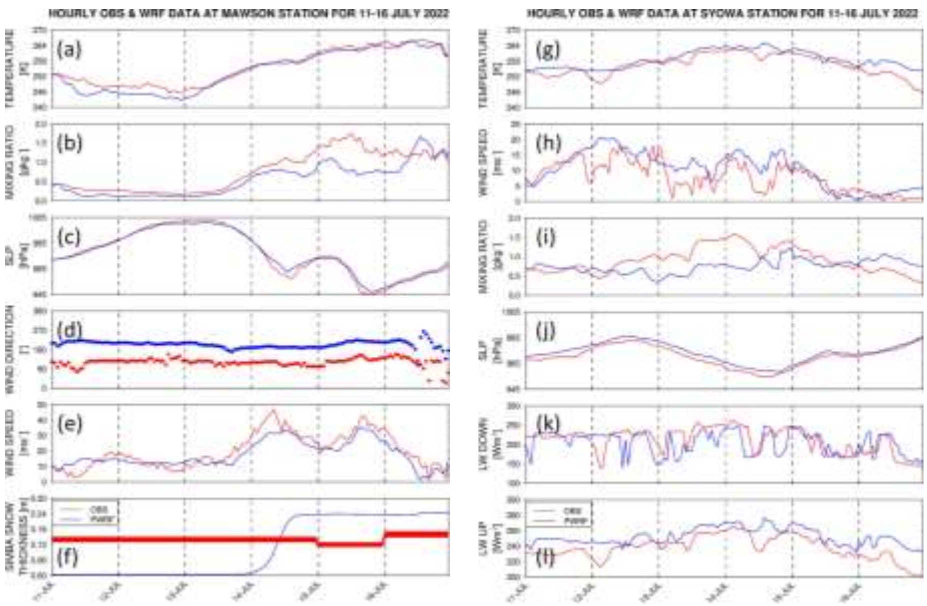

Figure 8: Evaluation of PolarWRF against ground-based observations: (a) Hourly (a) air temperature (°C), (b) water vapour mixing ratio (g kg^{-1}), relative humidity (RH; %), (c) sea-level pressure (SLP; hPa), and horizontal wind (d) direction (°) and (e) speed (m s^{-1}) from observations (red) and for the PWRF simulationcontrol (bluegreen), PWRF simulation and the one with updated SIE and SIT (blue) for 11-16 JulyNovember 2022 at the Mawson Station. (f) shows the daily observed (red) and hourly PWRF-predicted (blue) ST (m) at the Khalifa SIMBA site on fast -ice off the Mawson Station, the former with the estimated 7% uncertainty. (gb)-(l) is as (a)-(f) but for the hourly air temperature (K), horizontal wind speed (m s^{-1}), water vapour mixing ratio (g kg^{-1}), sea-level pressure (SLP; hPa), and surface downward and upward shortwave and longwave radiation fluxes (W m^{-2}), respectively at the Syowa Station. The wind fields at Syowa Station are shown in Figs. S4e-f. The location of the stations is given in Fig. 1b.

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Variable	**Station**	Bias	μ	ρ	η	α
Air Temperature	Mawson	-1.420.04 K	-0.9201	0.9881	~1.00.90	0.0227
	Syowa	2.151.89 K	1.0877	0.8777	0.98~1.0	0.124
	Relay	2.511.13 K	0.6532	0.9081	~1.00.99	0.109

	Davis	3.11 K	1.30	0.98	0.97	0.05
	Casey	2.66 K	1.22	0.75	0.97	0.27
Water Vapour Mixing Ratio	Mawson	-0.21~~16~~ g kg^{-1}	-0.8~~5~~2	0.86~~77~~	0.98~~~1.0~~	0.16~~24~~
	Syowa	-0.16~~1~~ g kg^{-1}	-0.45~~34~~	0.05~~83~~	0.82~~98~~	0.96~~19~~
	Relay	0.01~~2~~ g kg-1	0.69~~28~~	0.75~~3~~	0.99	0.25~~8~~
	Davis	-0.09 g kg^{-1}	-0.28	0.97	0.94	0.08
	Casey	-0.02 g kg^{-1}	-0.12	0.61	0.92	0.43
Wind Vector (Bias and μ are for wind speed)	Mawson	-2.39~~1.24~~ m s^{-1}	-0.48~~23~~	0.27~~35~~	0.96~~7~~	0.74~~66~~
	Syowa	2.36~~0.13~~ m s^{-1}	0.61~~04~~	0.39~~62~~	~1.00~~0.99~~	0.61~~39~~
	Relay	2.02~~0.41~~ m s^{-1}	1.82~~0.25~~	-0.60~~73~~	~1.00~~0.98~~	1.60~~72~~
	Davis	1.40 m s^{-1}	0.36	-0.30	0.99	1.29
	Casey	0.79 m s^{-1}	0.24	0.08	0.98	0.93
Surface Pressure	Mawson	-3.78~~4.22~~ hPa	-1.72~~2.75~~	0.99~~8~~	~1.0	0.01~~3~~
	Syowa	3.08~~4.03~~ hPa	2.3~~7~~5	0.99	~1.0	0.01~~2~~
	Relay	2.53~~24~~ hPa	3.16~~20~~	0.99	0.99~~~1.0~~	0.02~~1~~
	Davis	-0.74 hPa	-0.50	~1.0	~1.0	0.01
	Casey	-2.48 hPa	-2.16	~1.0	0.99	0.01
Downward LW	Syowa	-7.71~~4.40~~ W	-0.24~~19~~	0.47~~63~~	~1.00~~0.9~~	0.53~~3~~

		m^{-2}			~~8~~	~~8~~
Upward LW		14.26~~0.71~~ W m^{-2}	1.54~~69~~	0.79~~3~~	0.95~~~1.0~~	0.25~~7~~

Table 3~~1~~: Verification diagnostics with respect to station data: Bias, normalized bias (μ), correlation (ρ), variance similarity (η), and normalized error variance (α) for air temperature, water vapour mixing ratio, horizontal wind vector and sea-level pressure for ~~the~~ Mawson, Syowa, ~~Mizuho and~~ Relay, Davis, and Casey S~~s~~tations for 11-16 July~~November~~ 2022. For ~~the~~ Syowa Station, the scores are also given for the surface downward and upward ~~shortwave and~~ longwave radiation fluxes at the bottom of the table. ~~Humidity measurements are not available at the Mizuho Station for this period. The first value gives the score for the control simulation, while the one in parenthesis is for the simulation with updated SIE and SIT.~~ The model values are those at the closest ~~model~~ grid-point to the location of the station, and the evaluation is performed for hourly data. The correspondent time-series are given in Figs. 8~~7~~ and S4~~3~~.

4.2.2 Insights into the Dynamics and Effects of the AR

One of the motivations for implementing the high-resolution (2.5 km) innermost grid is to check for the presence of AR rapids (Box et al., 2023; Francis et al., 2024). Figs. 9a-d~~c~~ show a hovmoeller plot of the vertical velocity at 700 hPa, 10-m meridional wind speed, ~~the~~ 850 hPa equivalent potential temperature (θ_E), and precipitation rate averaged over 40º-50ºE, a latitude band that comprises the bulk of the AR (Figs. 6a~~7a-b and~~, 7a-c~~10a~~ and 9i). It reveals AR rapids, in particular one on 13-14 July between 40º-60ºS (pink arrows in Figs. 9a and 9d), which is embedded within the AR, as seen on 13 July at 12 UTC when it is located at 40º-50ºS (Fig. 9i). No AR rapids are seen ~~in all fields as well as~~ in the vertical profiles at the coastal Antarctic stations (Figs. S6 and S7~~5b~~), suggesting they are confined to the Southern Ocean. The linear structure propagating from ~55ºS late on 11 July to 65ºS early on 13 July does not correspond to an AR rapid. Instead, the heavy precipitation (>1 mm hr^{-1}; Fig. 9d) arises ~~Instead and from 12 UTC on 13 November to 12 UTC on 14 November, the AR exhibits mesoscale frontal wave structures between 50º-60ºS, with an increase in precipitation just off the Antarctica coast at ~65º-67.5ºS, Fig. 9c, likely arising~~ from the interaction of the low-latitude air mass with the katabatic wind regime~~flow~~ originating from the Antarctic Plateau, as it is placed at the interface between the two flows (cf. Figs. 9a-b with 9d). The low-level convergence of these two air masses can be seen in Fig. 9i around 65ºS. The katabatic flow is characterized by southerly winds (Fig. 9b) and low θ_E values (260-270 K, compared to 290-300 K for the low-latitude air mass; Fig. 9c), extending from the Antarctic Plateau to the Southern Ocean. ~~At about 50ºS at 18 UTC on 13 November, there are two propagating atmospheric structures: one moving southwards and reaching Antarctica on 14 November, and another moving northwards, reaching 40ºS at about the same time (Figs. 9a-c). The initial AR band breaks into two pieces, with one moving southwards into Antarctica, the one discussed here, while the counter-clockwise circulation associated with a ridge moving in from the west slows down and gradually pushes the northern part equatorwards (cf. Figs. 10a and 10c). A~~

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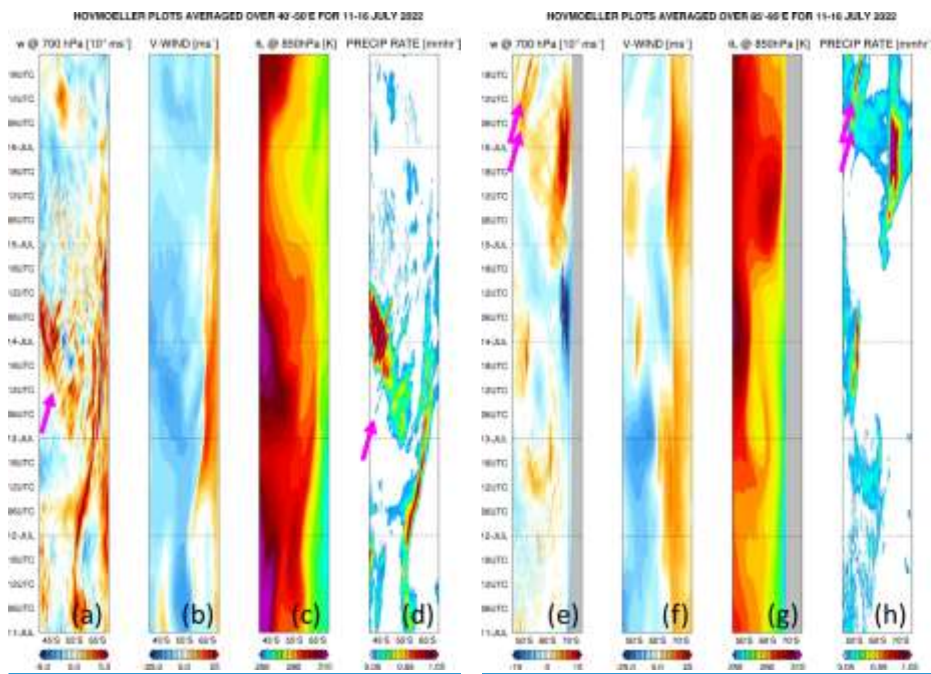
~~similar contrasting poleward and equatorward propagation is seen on 15-16 November at about 65ºS, here driven by the interaction of the katabatic winds off Antarctica with the flow around the ridge to the east (Figs. 5b and 6e).~~ Figs. 9e-h are as Figs. 9a-d but the fields are averaged over 85º-95ºE. The low-latitude air mass reaches this part of East Antarctica on 15-16 July, when precipitation rates exceed 1.8 mm w.e. hr^{-1}. The maximum precipitation rate ~~at~~in coastal Antarctica and averaged over 85º-95ºE is about 66% higher than that averaged over 40º-50ºE (1.81 vs. 1.09 mm w.e. hr^{-1}). This can be explained by ~~the~~ (1~~i~~) the higher moisture levels (maximum longitudinally-averaged θE values of 297.9 K vs. 289.7 K), as the low-latitude air mass penetrates further polewards due to a more favourable synoptic pressure pattern, and (~~ii~~2) a stronger katabatic flow off the Antarctic Plateau (maximum longitudinally-averaged meridional wind speed of 22 m s^{-1} vs. 19 m s^{-1}). Around 45º-55ºS on 16 July, AR rapids are present in the plots averaged over 85º-95ºE (pink arrows in Figs. 9e and 9h), when the low-level air intrusion was in the area (Fig. 9j). The fact that these structures have been identified in modelling products in the Southern Ocean in this study, around Greenland in Box et al. (2023), and in the Middle East in Francis et al. (2024), stresses the need for high spatial and temporal resolution three-dimensional radar observations along the ARs to check whether they actually exist or are just model artefacts.


V-WIND
PRECIP RATE
V-WIND
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(a)
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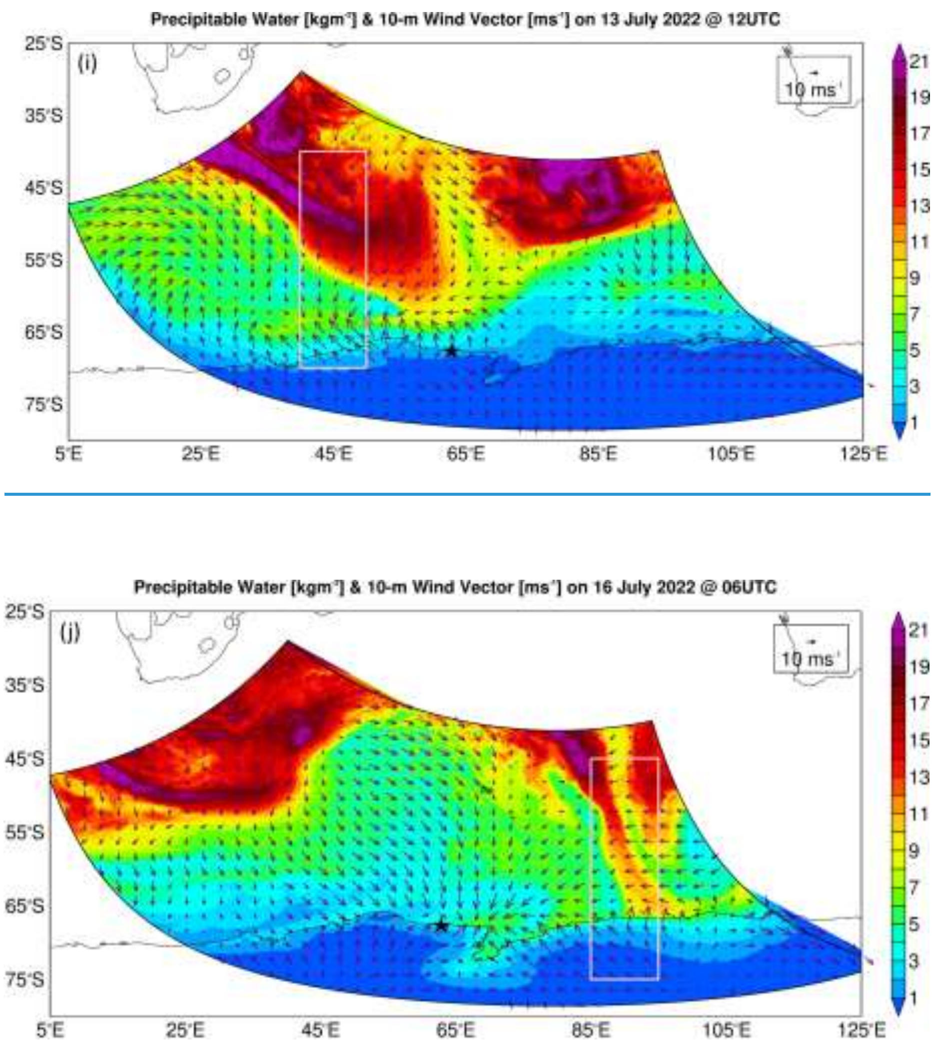

Figure 9: Hovmoeller Plots: Hovmoeller of hourly (a) 700 hPa vertical velocity (10^{-2} m s^{-1}), (b) 10-m meridional wind speed (m s^{-1}), (c~~b~~) 850 hPa equivalent potential temperature (θ_E; K), and (d~~c~~) precipitation rate (mm hr^{-1}) for 11-16 July~~November~~ 2022 averaged over 40º-50ºE~~, the core of the AR~~. The pink arrows highlight AR rapids. (e~~d~~)-(h~~f~~) are as (a)-(d~~c~~) but ~~for the (d) 10-m meridional wind speed (m s^{-1}), (e) 850 hPa equivalent potential temperature (K) and (f) precipitation rate (mm hr^{-1})~~ averaged over 8~~5~~5º-9~~6~~5ºE~~, where there is a strong interaction between the low-latitude air mass and the katabatic wind~~

~~flow. The thick blue line in (f) indicates the latitude of the SIMBA site~~. The grey shading in (e) and (g) highlights latitudes for which the 700 hPa and 850 hPa pressure levels, respectively, are~~is~~ below topography. (i) Precipitable water (shading; kg m^{-2}) and 10-m wind vector (arrows; m s^{-1}) at 12 UTC on 13 July. The star indicates the location of Mawson Station. The fields given in (a)-(d) are averaged over the longitude band of the pink box (40º-50ºE) and plotted over its latitude range. (j) is as (i) but at 06 UTC on 16 July, with the pink box also giving the latitude range over which the fields in (e)-(h) are plotted, and its longitude band (85º-95ºE) that used for averaging to generate the hovmoeller plots.

On top of surface evaporation from the subtropics (Fig. S2), the convergence of the flow around the low-pressure system to the west and the ridge to the east helped feed the AR and associated warm and moist air mass (Fig. 7). This can be seen in Figs. 10a-c~~b~~. The zonal moisture transport in Fig. 10b highlights the convergence of the westerly flow at 5~~10~~-10~~5~~ m s^{-1} associated with ~~equivalent potential temperature (~~θ_E~~)~~ values of 29~~8~~0-29~~8~~5 K, with the~~and the more moist~~ easterly flow around the high with zonal wind speeds ~~in excess~~ of 20-25 m s^{-1} and θ_E values of~~∼~~ 300~~290~~-305~~0~~ K, as this air mass comes directly from the tropics. At about 65ºE, where the AR is located (Fig. 10a), the vertical velocity peaks in the mid-troposphere around 600-800 hPa with speeds up to 0.3 m s^{-1} (Fig. 10c). The vertical structure of the updrafts, with a peak in the low-to-mid troposphere, and the updraft~~ir~~ speeds are comparable to the AR rapids reported by Box et al. (2023) over Greenland on 14 September 2017. Precipitation rates in excess of 3 mm hr^{-1} are simulated by the model at 12 UTC on 14~~3~~ July~~November~~ (Fig. 10d) and at 00 UTC on 15 July (Fig. 10a) along the AR~~ (Fig. 10a)~~. As the moisture plume moved closer to the Antarctic coast, it interacted with the katabatic wind regime. This is evident in Figs. 10e-f~~d~~, with the colder, drier (θ_E ~ 260~~75~~-265~~80~~ K) and strong (meridional wind speeds in excess of 45~~0~~ m s^{-1}) airflow from Antarctica, which descends the steep slopes with downward vertical velocities ~~down~~ up to -0.6 m s^{-1}, converging with the slower (35~~20~~-4~~3~~0 m s^{-1}) and more moist (θ_E ~ 275~~80~~-28~~9~~0 K) flow from lower-latitudes with vertical velocities in the bottom 5 km reaching +0.3 m s^{-1}. This convergence led to precipitation rates in excess of 3 mm hr^{-1} around~~just north of~~ ~~the~~ Mawson Station (Fig. 10d~~e~~). ~~The pattern of the precipitation field (Figs. 10a and 10c), which has a gap-core structure, reflects the complex topography of the region (Fig. 1b). The evolution of the interaction between the warm and moist southward-moving and the colder and drier northward-moving air masses is displayed in Figs. 9d-f, where the meridional wind speed,~~ ~~θ_E~~ ~~and precipitation rate are averaged over 55º-65ºE; the band of strong convergence (Fig. 10c). On 12 November, and in particular on 14-15 November, the strong southerly winds with speeds in excess of 20 m s~~~~$^{-1}$~~ ~~converged with, at times, an equally strong northerly flow, Fig. 9d, with precipitation around the convergence line, Fig. 9f, where~~ ~~θ_E~~ ~~values exhibit steep meridional gradients that can exceed 25 K, Fig. 9e. The katabatic winds on 12 and 14-15 November led to the opening up of a polynya east of the site (Fig. 6a). Coastal polynyas are a regular and persistent feature at certain locations around Antarctica owing to the steep coastal terrain and topographic channeling of katabatic winds (Barber and Massom, 2007), with warm and moist air intrusions also playing a role in their spatial extent (Fonseca et al., 2023).~~

The results in Figs. 9~~d~~ and 10~~c-d~~ suggest that it can be difficult for ARs and associated warm and moist air intrusions to reach this region of East Antarctica owing to the interaction with the strong katabatic flow. This factor has been highlighted for other regions of East Antarctica (e.g., Terpstra et al., 2021; Gehring et al., 2022).

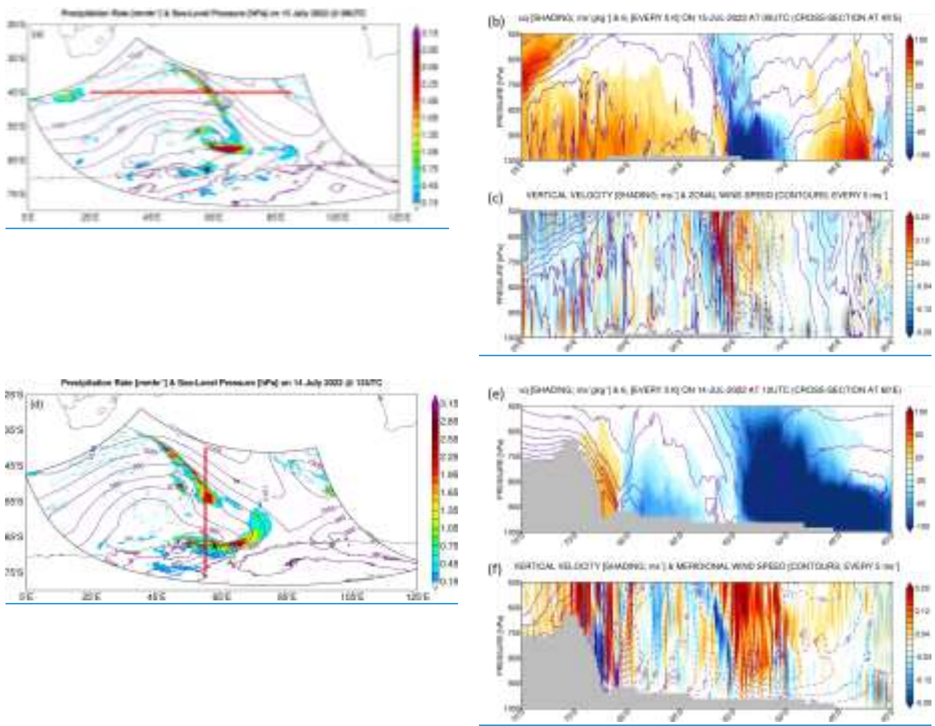

Figure 10: Precipitation mechanisms in the Southern Ocean: (a) Precipitation (shading; mm hr^{-1}) and sea-level pressure (contours; hPa) at 00~~18~~ UTC on 15~~3~~ July~~November~~ 2022, from PWRF's 2.5 km grid. ~~(b)~~ Vertical cross-section at 45~~50~~°S, red line in (a), of (b) zonal mass transport (shading; m s^{-1} g kg^{-1}) and equivalent potential temperature (θ_E; contours; every 5 K)~~ in the top plot~~, and (c) vertical velocity (shading; 10^{-2} m s^{-1}) and zonal wind speed (contours; every 5 m s^{-1})~~ in the bottom plot~~, at the same time. Regions below the orography are shaded in grey. (d~~c~~)-(f~~d~~) are as (a)-(c~~b~~) but at 12~~8~~ UTC on 14 July~~November~~. The cross-section is at 60°E, with the meridional mass transport and meridional wind speed in (e) and (f)~~the top and bottom plots~~ plotted instead of their zonal counterparts, respectively.

5. Discussion and Conclusions

Sea ice is a critically important component of the climate system, modulating atmosphere-ocean interactions and ultimately the global climate (Raphael et al., 2011; Goosse et al., 2023). The Antarctic SIE has abruptly dropped from 2016 to 2019 (Eayrs et al., 2021; Yang et al., 2021) with an all time-record low in 2023, driven by a complex and as yet poorly-understood combination of oceanic and atmospheric processes (Wang et al., 2024b). Climate model projections indicate major changes in the atmospheric circulation driven by the projected reduction in Antarctic sea ice in a warming climate: the Polar Cell and the katabatic flow off the coast of Antarctica are projected to strengthen, with a marginal weakening of the Ferrel and Hadley cells, and an equatorward shift in the position of the Polar Jet (Tewari et al., 2023). This stresses the need for a much -improved understanding of the observed variability of sea-ice properties, such as the SIE and SIT that are highly heterogeneous around Antarctica, in order to increase confidence in future climate-change projections.

The SIT at the Khalifa SIMBA site on fast -ice off the Mawson Station largely follows the annual solar (seasonal) cycle, with a gradual increase during winter to mid-to-late October followed by a steady decline in late spring. The maximum values of ~1.1-1.2 m are in the 0.50-1.50 m range estimated from satellite altimeter products for fast -ice in the region around the Mawson Station (Li et al., 2022) and are also comparable to the thickness of pack ice around Antarctica (Kurtz and Markus, 2012; Kacimi and Kwokw, 2020). The ST, on the other hand, is highly variable, with values in the range 0.02-0.18 m; these are also consistent with the estimates from the satellite altimetry. In contrast to SIT, the temporal variability of ST is strongly linked to atmospheric forcing, and in particular to precipitation (snowfall), Foehn effects, blowing snow, and episodic warm and moist air intrusions, which can lead to variations of up to ±0.08 m in a day. During July-November 2022, anthree ARs impacted the site i.e., on 14 July. It led, 13 August and 14 November to an 18 K increase in air temperature within 24 h,. A comparison of reanalysis data with in-situ observations revealed and a variation of up to 0.046 m in ST due to Foehn effects and snowfall (the 0.02 m change in and SIT is within the estimated uncertainty range) in response to the ARs in both July and August ARs. The warm and moist air masses associated with ARs have a larger impact on sea ice in the colder months, as in the summer the increases in the heat fluxes are partially offset by a decrease in the downward shortwave radiation flux (Liang et al., 2023). These changes ST and SIT response to the AR occurred within one12 days of the AR'sits arrival, followed by a recovery to pre-AR levels in the following 12-24 days. However, it is important to stress that a longer observational period (than the current 5-month record) would be needed to establish more robust and statistically significant links between atmospheric phenomena such as Foehn effects, blowing snow, and incursions of warm and moist low-latitude air from low-latitudes and the coastal SIT and ST (and potentially SIT). In addition, having measurements for at least a full year would also allow for the quantification of the potential role of surface melting in ST and SIT, which is more likely in the summer months but may occur at other times in a warming climate. Simulations with coupled ocean-atmosphere-sea-ice models should also be considered to further explore the role of atmospheric forcing in ST and SIT. In addition, refined methods to extract SIT and ST are desirable, as in particular for SIT, the variation during weather events such as the passage of the AR is within the uncertainty range, preventing a clear signal from being extracted from the data. The air temperature exhibited a marked increase of up to 18 K within 24 h at the site in the case of the 14 July AR, with a less pronounced effect in the summer months (3 K). The in-situ snow, sea-ice and temperature observations highlight the, at times, strong response in particular to ARs impacting the site.

The 14 JulyNovember AR iwas particularly intense, with the highest IVT around the Khalifa SIMBA site on fast -ice off the Mawson Station of of ~15661 kg m^{-1} s^{-1}, which is in the top 0.5% of the climatological distribution. From 14 to 15 November, there is a 0.06 m increase in ST and 0.04 m increase in SIT, followed by a return to pre-AR levels on 19 November for SIT and 20 November for ST. The increase in SIT can be explained by the freezing of (some of) the snow on top of the sea-ice, during a time when the surface and air temperatures were below freezing at the site. This AR has its origins in South America, where a wavetrain coming from the Pacific Ocean leads to an intensification of the South American Low Level Jet and increased moisture outflow into the South Atlantic Ocean. The period 10-19 JulyNovember 2022 is characterized by a wavenumber #5 pattern along the subtropical jet and a wavenumber #3 along the polar jet in the Southern Hemisphere, the latter projecting into the strong positive SAM phase, with the SAM index being more than 1.5 standard deviations above the 1979-2021 climatological mean, in line with which is expected given thean ongoing La Niña. A pressure dipole, with a low to the west and a ridge to the east, promotes the advection of warm and moist low-latitude air across the Mawson Station, with the IVT values in the top 1% of the 1979-2021 climatological distribution and air temperature anomalies in excess of 8 K or more than two standard deviations above the 1979-2021 mean in parts of East Antarctica between 0º and 70ºE. A back-trajectory analysis indicates that contributions from evaporation both in the subtropics and the Southern Ocean contributed to the precipitation event on 14 JulyNovember 2022. A mMore in-depth analysis reveals that a secondary low formed just northwest of the site on 134 JulyNovember, driven by highly baroclinicity arising from the interaction of the warmer low-latitude air masses with the cold katabatic winds that prevail around the Mawson Station. At the same time, a TPV and a jet streak at upper-levels contributed to the an intensification of the primary low to the west. The changing wind field in response to the passage of the deep cyclone, which had a central pressure as low as 931 hPa, also has an impact on the sea-ice dynamics. In particular, in the region, with maximum pack-ice drift velocities north of Mawson Station exceededin excess of 4025 km day^{-1} north of the Mawson Station from 124-146 July and 20 km day^{-1} from 14-16 JulyNovember, with the opening of a polynya in the Southern Ocean northwest of Mawson Station around 65°S,45°E from 14 to 22 July. These pack-ice drift speeds are comparable to those estimated during the opening of the Maud Rise pPolynya in September 2017 (Francis et al., 2019).an order of magnitude larger than the 2.5 km day^{-1} during 12-14 November 2022.

A high-resolution simulation with PWRF down to 2.5 km is conducted to gain further insight into this event. An evaluation against *in-situ* observations indicates~~d~~ a good performance for both coastal and inland stations in the target region. A dry bias at coastal sites is attributed to an excessive offshore wind direction in the model and/or too much boundary layer mixing. An evaluation of the simulated vertical profiles against those observed at four coastal sites reveals a stronger katabatic flow in PWRF, which is consistent with the drier near-surface conditions.~~, as~~ This is reported by other studies (e.g., Vignon et al., 2019), which attributed it to more stable boundary layers over the Antarctic Plateau and steeper land-sea synoptic pressure gradients. T~~while~~ ~~the~~~~at Syowa Station, for which surface radiation fields are available for evaluation, an~~ over~~under~~estimation of the surface upward longwave~~shortwave~~ radiation flux may be a reflection of higher surface temperatures and/or a too high~~a higher~~~~lower~~ surface emissivity~~albedo~~ in PWRF.~~the model. Regarding the latter, and for 11-16 November 2022, the surface albedo in PWRF is typically 10% lower than that observed.~~ This suggests the need to optimize the land surface properties in the model~~PWRF~~, as has been highlighted by other studies ~~(such as~~ Hines et al., ~~(~~2019)~~, which will be left for future work~~. Ingesting a more realistic representation of the SIE and SIT does not translate into higher skill scores for this particular event. This indicates~~suggests~~ that improvements to the boundary layer dynamics and/or land/ice processes, noted~~highlighted~~ by ~~studies such as~~ Wille et al. (2016, 2017) and Vignon et al. (2019), and at least for this~~e~~ case study ~~considered here~~, are probably more important than having a more accurate sea-ice representation in the model. Besides calibrating surface parameters, future PWRF studies should explore other physics schemes and/or optimize the tunable parameters defined inside the selected ones, in particular in the PBL and land surface model as done for other regions (e.g., Quan et al., 2016; Chinta and Balaji, 2020), in an attempt to improve the model performance. ~~In contrast to a September 2017 AR over Greenland (Box et al., 2023) and an April 2023 AR in the Arabian Peninsula (Francis et al., 2024), AR rapids are not seen for this particular event.~~ The high-resolution PWRF~~model~~ simulation~~s~~ revealed the presence of AR rapids, with a similar vertical structure and propagation speed as those reported in Box et al. (2023) over Greenland in September 2017. The model simulation also highlighted ~~the strong interaction between the air masses around the low to the west and the high to the east in the Southern Ocean, as well as~~ the effects of the katabatic wind regime in slowing down and weakening the low~~er~~-latitude warm and moist air incursions as they approach the Antarctic coast. It is this~~e latter~~ interaction that triggers precipitation rates in excess of 3 mm hr^{-1} around ~~the~~ Mawson Station during 14 July~~November~~ AR~~, with the precipitation spatial pattern reflecting the complex topography of the region~~.

The SIMBA deployment at a fast-ice site off ~~the~~ Mawson Station during July-November 2022 enabled a better understanding of the spatial and temporal variability of SIT and ST in that part of coastal East Antarctica. Such measurements should also be conducted at other sites given the marked regional differences in sea-ice properties in the Southern Ocean (Parkinson and Cavalieri, 2012). This will also help to evaluate and improve the ST, SIE and SIT estimates derived ~~and key products~~ from satellite remote sensing ~~assets~~ and numerical models. Besides ocean dynamics and thermodynamics, the findings of the study stress the role of atmospheric forcing in driving ~~in particular the ST~~the variability of ST in particular. Long-term measurements are needed to further explore and quantify how Foehn effects, blowing snow, ~~-~~warm and moist air intrusions, and surface melting modulate ~~the~~ SIT ~~(not just the SIE)~~ and ST, and how they respond to seasonal and inter-annual variations in the atmospheric and oceanic state. This is a crucial step to improvinge the quality and confidence of future ~~climate~~ climate-change projections and medium- and long-range weather forecasts owing to the global ~~effects~~ influence of sea-ice variability on the climate system.

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Code/Data availability

The sea-ice and snow thickness measurements at the Khalifa SIMBA site on fast ~~-~~ice off ~~the~~ Mawson Station for July-November 2022 are available upon request from the corresponding author (Diana Francis; diana.francis@ku.ac.ae). The remaining observational and the reanalysis datasets used in this study are freely available online: (i) ERA-5 reanalysis data were downloaded from the Copernicus Climate Data Store website (Hersbach et al., 2023a,b); (ii) Automatic Weather Station (AWS) data at the Mawson, Davis, and Casey Stations can be requested at the Australian Antarctic Data Center website (AADC, 2022); (iii) AWS and surface radiation data for Syowa Station were obtained from the World Radiation Monitoring Center - Baseline Surface Radiation Network website (AWI, 2024); (iv) AWS data for the ~~Mizuho and~~ Relay S~~s~~tation~~s~~ w~~ere~~as extracted from the Antarctic Meteorological Research Center & Automatic Weather Stations Project (Lazzara, 2024); ~~(v) true colour visible daily satellite images from the measurements collected by the Moderate Resolution Imaging Spectroradiometer instrument onboard the Terra satellite were accessed on the National Aeronautics and Space Administration's Worldview website (Boller, 2024)~~; (v~~i~~) sea-ice velocity vectors from the low resolution sea-ice drift product are available at the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT) Ocean and Sea Ice Satellite Application Facility (EUMETSAT, 2024); (vi~~i~~) sea-ice concentration maps derived from the measurements collected by the Advanced Microwave Scanning Radiometer (AMSR) for Earth Observing Systems instrument onboard the National Aeronautics and Space Administrations (NASA) Aqua satellite and the AMSR-2 instrument onboard the Japan Aerospace and Exploration Agency ~~by the Advanced Microwave Scanning Radiometer 2 instrument onboard the Japan Aerospace and Exploration Agency~~ Global Change Observation Mission 1st-Water "Shizuku" satellite from January 2013 to present, were obtained from the University of Bremen website (UoB; 2024); (vii~~i~~) twice daily atmospheric sounding profiles at the~~from~~ Mawson, Syowa, Davis, and Casey s~~S~~tations were accessed at the University of Wyoming website (Oolman, 2025~~4~~). The Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) transport and dispersion model is downloaded from the National Aeronautic and Space Administration Air Resources Laboratory website (NOAA ARL, 2024). The PolarWRF model version 4.3.3 is available at the Byrd Polar and Climate Research Center at The Ohio State University website (PWRF, 2024). The figures presented in this manuscript have been generated with the Interactive Data Language (IDL; Bowman, 2005) and MATLAB (Mathworks, 2024) software.

Competing interests

One co-author is a member of The Cryosphere editorial board.

Author Contributions: CRediT

DF: Conceptualization of the study, Interpretation and validation of the results, Writing the draft, Funding Acquisition; **RF**: Formal analysis, Data processing and analysis of the results, Writing the draft; **NN**: Data acquisition, processing and analysis, Interpretation of the results, Inputs to the manuscript; **PH**: Interpretation of the results, Inputs to the manuscript; **JDW**: Interpretation of the results, Inputs to the manuscript; **IVG**: Interpretation of the results, Inputs to the manuscript; **RAM**: Interpretation of the results, Inputs to the manuscript. All authors interpreted the results and provided input to the final manuscript.

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