Strong Warming over the Antarctic Peninsula during Combined Atmospheric River and Foehn Events: Contribution of Shortwave Radiation and Turbulence

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Key Points:

- This study investigates the atmospheric river and foehn warming over the Antarctic Peninsula via observations and model simulations.
- Under the combined atmospheric rivers and foehn, shortwave radiation contributed to the ice surface warming, followed by sensible heat flux.
- Atmospheric rivers influence the foehn via extra moisture, which led to precipitation on the upwind side and cloud formation on the leeside.

Abstract

The Antarctica Peninsula (AP) has experienced more frequent and intense surface melting in recent years, jeopardizing the stability of ice shelves and ultimately leading to ice loss. Among the key phenomena that can initiate surface melting are atmospheric rivers (ARs) and leeside foehn; the combined impact of ARs and foehn led to moderate surface warming over the AP in December 2018 and record-breaking surface melting in February 2022. This study uses high-resolution Polar WRF simulations with advanced model configurations, Reference Elevation Model of Antarctica topography information, and surface observed albedo to improve our understanding of the relationship between ARs and foehn and their impacts on surface warming. With an intense AR (AR3) intrusion during the 2022 event, weak low-level blocking and heavy orographic precipitation on the upwind side resulted in latent heat release, which led to a more deep-foehn like case. On the leeside, sensible heat flux associated with the foehn magnitude was the major driver during the night and the secondary contributor during the day due to a stationary orographic gravity wave. Downward shortwave radiation was enhanced via cloud clearance, especially after the peak of the AR/foehn events, and dominated surface warming over the northeastern AP during the daytime. However, due to the complex terrain of the AP, ARs can complicate the foehn event by transporting extra moisture to the leeside via gap flows. During the peak of the 2022 foehn warming, cloud formation on the leeside hampered the downward shortwave radiation and slightly increased the downward longwave radiation.

Plain Language Summary

On the Antarctic Peninsula (AP), when ice shelves break up, glaciers flow faster from the land into the sea, leading to ice loss and increasing sea level rise. Surface warming may have led to ice shelf collapse and is projected to double by 2050 over Antarctica. Two phenomena that have enhanced surface warming are atmospheric rivers, (long corridors of moisture in the atmosphere) and leeside foehn effects (cooler and moist air advection on the upwind side and becomes warmer and drier when descending on the leeside). Here we study two combined atmospheric river and foehn events that led to surface warming on the AP, occurring in December 2018 and February 2022. The main warming mechanism in the northeastern AP during the nighttime was transfer of heat from the air to the ice surface (sensible heat flux), while the main mechanism during the daytime was intense sunlight, which was able to reach the surface because of clear skies on the opposite (lee) side caused by foehn. However, complicating the picture, there are gaps in the AP mountain range that let the atmospheric river through, allowing clouds to form on the other side, which then blocked some of the sunlight.

Key Words: Atmospheric River, Foehn Warming, Antarctic Peninsula, Polar AR Scale

1. Introduction

The Antarctica Peninsula (AP) is one of Earth's fastest warming regions and has been experiencing intense ice loss, especially since the early 2000s (Shepherd et al. 2018; Jones et al. 2019). Surface melting due to atmospheric warming is the major contributor to ice shelf break-up over the AP (e.g., van den Broeke 2005). In response to rapidly warming air temperatures, such as heat waves, surface melt is projected to increase in upcoming decades regardless of the emission scenario (Feron et al. 2021). Several Antarctic ice shelves have an increasing probability of reaching the record meltwater production that the Larsen A and Larsen B ice shelves exhibited before their collapse (Feron et al. 2021).

The rate of ice loss over the AP has tripled since the 1990s with an acceleration of 16 Gt yr^{-1} per decade (Rignot et al. 2019; Shepherd et al. 2018). Also, surface melting is projected to double by 2050 over Antarctica, especially over the AP, which can decrease the surface albedo and lead to the ice surface lowering and thinning (Tuckett et al. 2019; Paolo et al. 2015; Siegert et al. 2019). Surface meltwater produced during the warming will not only jeopardize the stability of ice shelves via hydrofracturing, but also release latent heat if the melting water in the perennial snowpack refreezes, and then lead to additional melting (Holland et al. 2011). In the past three decades, the northern AP has lost the Larsen A Ice Shelf in 1995 and the Larsen B Ice Shelf in 2002 (Rignot et al. 2004; Rott et al. 1996). Without the buttressing effect provided by ice shelves, ice loss over Antarctica will accelerate and contribute to global sea level rise. From 2003 to 2019, the floating and grounded ice loss over the AP has contributed 1.7mm to sea level rise and has the potential to increase the sea level by 0.5m if all ice melts (Smith et al. 2020).

The collapse of ice shelves over the AP is the consequence of multiple factors, including rapid regional atmospheric warming and an extended melting period (Mulvaney et al. 2012; Scambos et al. 2000). During the austral summer, warming over the northeast AP is strongly associated with strengthening westerly winds due to the positive Southern Annular Mode (SAM) trend (Clem et al. 2016, 2022; Marshall et al. 2006; Elvidge and Renfrew 2016). Stronger summer westerly winds (associated with a positive trend in the SAM) have led to a higher frequency of air masses being advected eastward over the orographic barrier of the northern Antarctic Peninsula (Marshall et al. 2006), contributing to foehn-induced surface melt of ice shelves on the Eastern side of the Peninsula (Bozkurt et al. 2018; González-Herrero et al. 2022). Also, deep convection in the central tropical Pacific often leads to prolonged cyclone activity over the South Pacific and blocking highs/anticyclones over the Drake Passage, which helps transport warm marine air towards the southwest AP (Clem et al. 2022). This circulation pattern may be associated with strong atmospheric rivers (ARs) and foehn warming on the leeside of the AP due to orographic lifting on the upwind side (Clem et al. 2022). However, the surface warming/melting pattern depends on the strength and landfall location of an AR, as well as its modification by the local topography.

Previous ice shelf break-ups have been influenced by ARs and foehn (Wille et al. 2022). Polar ARs are moisture from lower latitudes that travel to the polar region via a long narrow corridor of water vapor transport (Ralph et al. 2004; Wille et al. 2022; Gorodetskaya et al. 2020; Terpstra et al. 2021). Foehn wind is a warm and dry descending air on the leeside of the mountain barrier, which results from relatively cooler and moist air advection on the upwind side (WMO, 1992). ARs can trigger foehn warming and lead to record-breaking temperatures, such as the warm event (max 2m temperature of 17.5°C) observed at

Esperanza station in March 2015 (Bozkurt et al. 2018; Xu et al. 2021). Foehn warming in the polar regions triggered by ARs has been observed over the AP (e.g., Bozkurt et al. 2018; Wille et al. 2019), West Antarctica (eastern Ross Ice Shelf, Zou et al. 2021a), and Greenland (Mattingly et al. 2020). Standalone foehn events (without AR impacts) may generally have a smaller warming extent across the Larsen ice shelves than those associated with intense ARs (Wille et al. 2022)

A variety of mechanisms contribute to foehn warming, including latent heat release on the upwind side from orographic precipitation, adiabatic warming from the descending air, sensible heat transfer from upper foehn flow to the ice surface via turbulence, local topography, and enhanced radiative heating due to foehn clearance; in turn, these contribute to surface warming/melting on the leeside (Elvidge and Renfrew 2016). Larsen Ice Shelf is frequently under the impact of foehn warming, especially at the mountain base and the northern AP region (Turton et al. 2018). Extra moisture flux from ARs can amplify foehn warming due to increased latent heat release (Bozkurt et al. 2018). Thus, analysis of detailed mechanisms of surface warming under combined ARs and foehn can help us better understand the ice shelf stability and will benefit future projections of sea level rise.

Despite knowledge gains from previous studies, the detailed physical mechanism of surface melting on the AP under the combined impact of ARs and foehn is still unclear. First, with different circulation patterns, the water vapor flux or transport within the AR may or may not hit the mountain range over the AP perpendicularly, which significantly affects the formation of the foehn wind. Also, the northern tip of the AP tilts eastward, which indicates that the southern and northern AP might experience different magnitudes of warming under the same foehn event. Second, the strength of radiative heating depends both on cloudiness and on solar elevations, which are low over the AP. Previous studies have found radiative heating on the AP is relatively small in a deep-foehn case during early summer (Elvidge and Renfrew 2016); however, it is important to address whether this is always the case. Third, the topographic barrier over the AP has several gaps (or lower elevations), which can allow extra moisture from ARs to reach the leeside directly (e.g., foehn jets; Laffin et al. 2022). This can weaken the intensity of orographic precipitation on the upwind side and foster cloud formation from the extra moisture on the leeside, complicating the foehn-cloud clearance effect (Elvidge et al. 2020) by reducing the shortwave downward radiation (SWD), and thus the radiative heating. In addition, these foehn jets have contributed to surface melting due to enhanced sensible heat flux (SHF) transfer (Elvidge et al. 2015).

This work investigates two representative AR/foehn cases in 2018 and 2022 via high-resolution Polar Weather Research and Forecasting model (PWRF) simulations with advanced model configurations. Section 2 describes the data and PWRF model settings. Section 3 presents the evaluation of PWRF simulations by comparison to observations from weather stations and radiosondes, analyzes the regional circulation pattern, and investigates the contribution of AR/foehn to the leeside warming. Section 4 discusses the relationship between AR and foehn in the 2022 case, and their combined impact on the surface melting. A comparison of AR/foehn cases between the AP and West Antarctica (WA) is also presented. Section 5 summarizes the results from the previous analysis.

2. Data and Methods

2.1. ERA5 reanalysis data

This study uses the 5th major atmospheric reanalysis (ERA5) and the land dataset (ERA5 Land) produced by the European Centre for Medium-Range Weather Forecasts (ECMWF). By combining model simulations with observations, ERA5 provides hourly output with 31km horizontal resolution and 137 vertical levels. Compared to its predecessor, ERA-Interim, ERA5 significantly improved results in the troposphere with a shorter latency, including conservation of potential temperature (Hersbach et al. 2020; Hoffmann et al. 2019). Synoptic- and meso-scale features, such as cyclones, convective updrafts and gravity waves are better described in ERA5 (Hoffmann et al. 2019). Also, ERA5 outperforms other reanalysis products in describing stratospheric ozone depletion, which is critical for atmospheric changes in the high-latitude Southern hemisphere (Davis et al. 2017; Hersbach et al. 2020). Over the AP, ERA5 provides reliable information on surface temperature, wind speed, and humidity, especially at higher elevations (Tetzner et al. 2019). ERA5 Land with 9 km horizontal resolution is used to provide surface melting conditions for the case study. Driven by ERA5, ERA5 Land implements a correction in the thermodynamic near-surface state and reduces the error in skin temperature (Muñoz-Sabater et al. 2021).

2.2. Observations

PWRF surface simulations, including surface pressure, 2m temperature, and 10m wind speed were compared to station observations (Escudero; upwind side) and observations from Automatic Weather Stations (AWS) or manual stations on the upwind side (Vernadsky and Rothera) and on the lee side (Esperanza, Marambio, and Larsen C). Weather station data were obtained from the Antarctic Meteorological Research and Data Center (AMRDC; https://amrdcdata.ssec.wisc.edu/) at the University of Wisconsin-Madison (Lazzara et al.

2012), and from the QGIMET website (https://www.ogimet.com/). Three-hourly observations were used.

In addition, this study uses Antarctic composite infrared satellite imagery data for both 2018 and 2022 cases from the AMRDC at the University of Wisconsin-Madison. The Worldview tool from NASA's Earth Observing System Data and Information System (EOSDIS) provides additional satellite imagery on cloud conditions over the AP. Daily cloud conditions are observed from Moderate Resolution Imaging Spectroradiometer (MODIS) Corrected Reflectance (utilized from MODIS Level 1B data) on the Aqua and Terra satellites.

PWRF atmospheric profiles of temperature, humidity, and winds are compared to all available radiosonde measurements from three Antarctic stations: Escudero, Rothera and Marambio for the two case study periods (see columns 1-3 of Table 3 for 2022 and Table S1 for 2018). At Rothera, radiosondes were launched almost daily at 12UTC during 2018-2022. Unfortunately, only one radiosonde was launched at Rothera during the 2022 case study. At Marambio, radiosondes were launched less frequently, and only one radiosonde is available for each case study. By contrast, intensive extra observing activities were conducted at Escudero during the two case study time periods (including launching 7 radiosondes in 2018 and 5 radiosondes in 2022) as part of the Polar Prediction Project (PPP), a 10-yr (2013–22) initiative of the World Meteorological Organization’s (WMO) World Weather Research Programme (WWRP) (Bromwich et al. 2020; Gorodetskaya et al., 2022).

The AP ice shelves experience persistent summer melt ponds, and surface melting and refreezing reduce the surface albedo, leading to a positive snowmelt-albedo feedback and accelerating melting (Jakobs et al. 2021; Feron et al. 2021). Thus an accurate model surface description in PWRF is critical for the estimation of surface warming/melting (Luckman et al. 2014; Turton et al. 2018). Instead of the arbitrary default albedo in WRF, we use observed daily surface albedo from MODIS as an initial field in model simulations (hereafter referred to as MODIS albedo; Wang et al. 2015; Figs. S1a and b). The MODIS albedo is produced by the National Aeronautics and Space Administration (NASA) based on 16 days of Terra and Aqua MODIS observational data. The MODIS albedo has been tested in the surface melting study over West Antarctica, where it was shown to lead improvements in the surface temperature estimation (Zou et al. 2021a). Also, the systematic cold bias over the Tibetan Plateau in WRF has been reduced by including the MODIS albedo. Created from stereophotogrammetry and satellite imagery, the Reference Elevation Model of Antarctica (REMA) provides a high-resolution surface elevation dataset with a spatial resolution of up to 8m (Howat et al. 2019; Gerber and Lehning 2020). REMA surface elevation at 1km resolution is introduced in PWRF simulations to better describe the modifications of the airflows by the local topography.

2.3. Polar WRF and Antarctic Mesoscale Prediction System (AMPS)

Developed and maintained by the Polar Meteorology Group of the Byrd Polar and Climate Research Center at The Ohio State University (Hines and Bromwich 2008; Bromwich et al. 2013; Listowski and Lachlan-Cope 2017; Hines et al. 2019), PWRF is a regional numerical prediction model based on WRF. This study used PWRF V4.3.3 to produce hourly output with a downscaling method, which includes 30-km-resolution domain 1, 6-km resolution domain 2, and a 1.2 km high-resolution domain 3 covering the AP region

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(Fig. 1). All PWRF outputs used in this paper are initialized at 00UTC, discarding the first 24h as spin-up time.

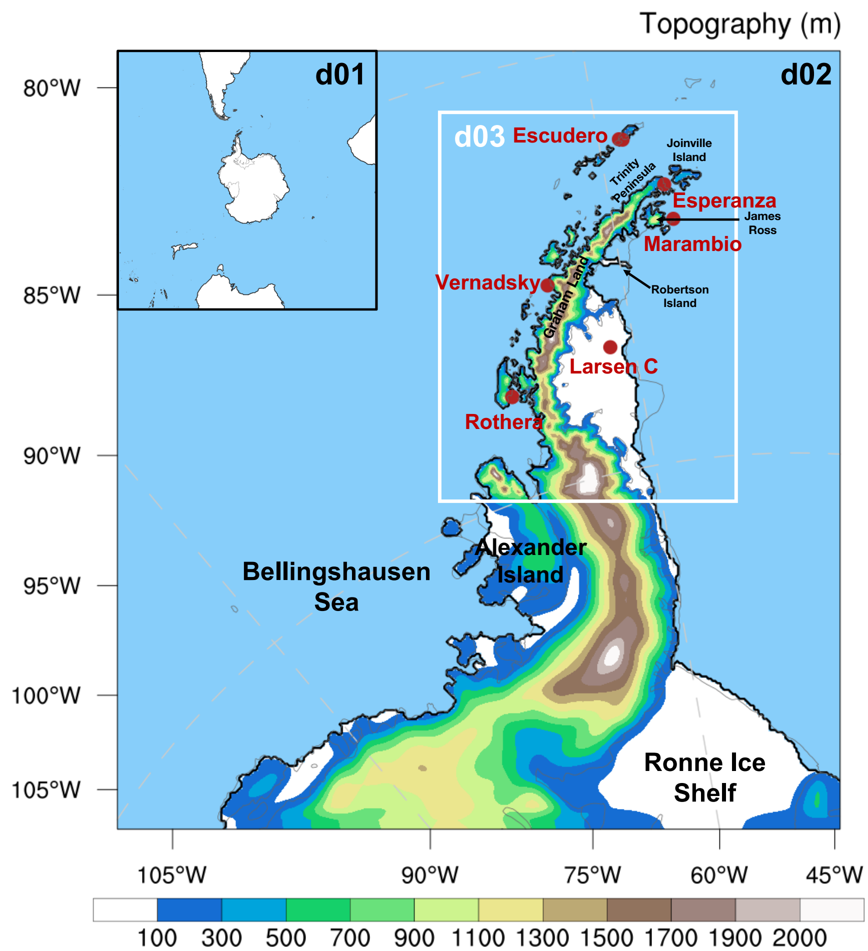

Figure 1. PWRF domain with Reference Elevation Model of Antarctica (REMA) topography. Red dots indicate locations of available surface stations.

Table 1 shows the input data and physical parameterization settings in PWRF. Supercooled water in clouds is always challenging to predict in the numerical weather models over the Southern Ocean (e.g., Bodas-Salcedo et al. 2016; Listowski et al. 2019). More advanced microphysics schemes provide more realistic cloud liquid water simulations, which is critical for estimation of the surface energy balance (Hines et al. 2019; Listowski et al. 2019). Instead of using an arbitrary categorization of frozen hydrometers, the two-moment

Morrison-Milbrandt P3 (P3) adopts a continuum of particle properties for clouds (Hines et al. 2019, 2021). P3 provides the best estimation of liquid water path and longwave radiation from clouds compared to two other advanced schemes, Morrison two moment and Thompson (Hines et al. 2019). Thus, P3 is selected for the microphysics scheme, and the Mellor–Yamada–Nakanishi–Niino (MYNN; Nakanishi and Niino 2006) is used for the atmospheric boundary layer scheme. Both longwave and shortwave radiation use the Rapid Radiative Transfer Model (RRTMG; Clough et al. 2005) or Global Climate/Circulation Models. We also use the Kain–Fritsch scheme for cumulus parameterization and Noah-MP for the land surface model (Kain 2004; Niu et al. 2011). Most importantly, REMA 1km topography information and MODIS surface observed albedo, described previously, are included in the input data to provide a better surface description (Howat et al. 2019; Corbea-Pérez et al. 2021; Fig. S1). To avoid model instabilities, topographic smoothing has been applied to PWRF simulations. Adopting several PWRF settings, the Antarctic Mesoscale Prediction System (AMPS) outputs are used in this paper to provide default albedo and landmass in PWRF. AMPS, developed by the National Center for Atmospheric Research (NCAR), provides high-resolution weather forecasts to support the operations of the US Antarctic Program (Powers et al. 2012).

Table 1. PWRF model setting.

	PWRF V4.3.3
Input data	ECMWF reanalysis data (ERA5)
Horizontal resolution	30 km / 6 km / 1.2km
Vertical levels	71 levels (lowest level 4m above the surface)
Temporal resolution	hourly
Spin-up	24h
Microphysics	P3
PBL scheme	MYNN
Shortwave and longwave	Both RRTMG

Land surface options	Noah MP
Surface layer options	MYNN
Surface albedo	MODIS (MODIS/Terra+Aqua BRDF/Albedo Albedo Daily L3 Global 0.05 Deg; black-sky albedo)
High-resolution topography	REMA 1km topography
Nudging	Every 6 hours; nudging to u, v wind, temperature, and water vapor from ERA5 for model level 40 (~ 400 hPa) and above.

2.4. Polar Atmospheric River Scale

Compared to the mid- and low-latitudes, Antarctica has a colder, drier, and more pristine environment. Thus, the Center for Western Weather and Water Extremes (CW3E) group developed an AR scale specific to the polar regions, the Polar AR scale (7 rankings from AR A1 to AR5; Fig. S2), to rank ARs over the AP at a given geographic location (Fig. S2). The Polar AR scale was widely tested during the Year of Polar Prediction in the Southern Hemisphere (YOPP-SH) Winter Targeted Observing Periods, and has been proven to reflect the strength and duration of ARs accurately, which benefits both forecast operations and research (Bromwich et al. 2020; Ralph et al. 2019; Zhenhai et al., 2023).

After using PWRF domain 3 outputs to identify AR intrusions, the hourly integrated vapor transport (IVT) is calculated as follows:

$$IVT = \sqrt{\left(\frac{1}{g}\int_{1000}^{10} qu\mathrm{d}p\right)^2 + \left(\frac{1}{g}\int_{1000}^{10} qv\mathrm{d}p\right)^2} \quad (1),$$

where g is the gravity acceleration constant (m s^{-2}), q is specific humidity (kg kg^{-1}), u and v are zonal and meridional wind (m s^{-1}), and dp is the differential pressure (hPa).

3. Results

3.1. Evaluation of PWRF results

PWRF simulation outputs were compared to station and AWS 3-hourly observations and ERA5 reanalysis data. Overall, PWRF was found to reliably simulate the synoptic circulation pattern (not shown) and surface conditions compared to ERA5. Figure 2 shows the comparison of 3 basic surface variables between weather station observations and PWRF domain 3 outputs at Rothera (upwind) and Larsen C (leeside) during the 2022 case. PWRF simulations have a weak negative bias (-0.2 °C) in temperature and a moderate positive bias in wind speed (1.9 m/s) at the Larsen C Ice shelf. At Rothera, where the topography is complex, PWRF has a larger bias in all variables, especially for the 10m wind speed during the peak of the foehn warming. The 1.2 km horizontal resolution might be insufficient to capture the complex terrain on the upwind side. Thus, PWRF performs better in general at stations with a smoother surface. In addition, the average bias of 2m relative humidity is 5% at Marambio and 1.3% at Escudero. On average, PWRF biases (Table 2) were found to be 0.82 hPa in surface pressure, -1.22 °C in 2m temperature, and a 4.38 m/s in 10 m wind speed (2.6 m/s on the leeside and 6.2 m/s on the upwind side) at the selected AWS stations. In addition, compared with ERA5, PWRF simulations show a stronger barrier jet on the upwind side; further investigation into this result is needed.

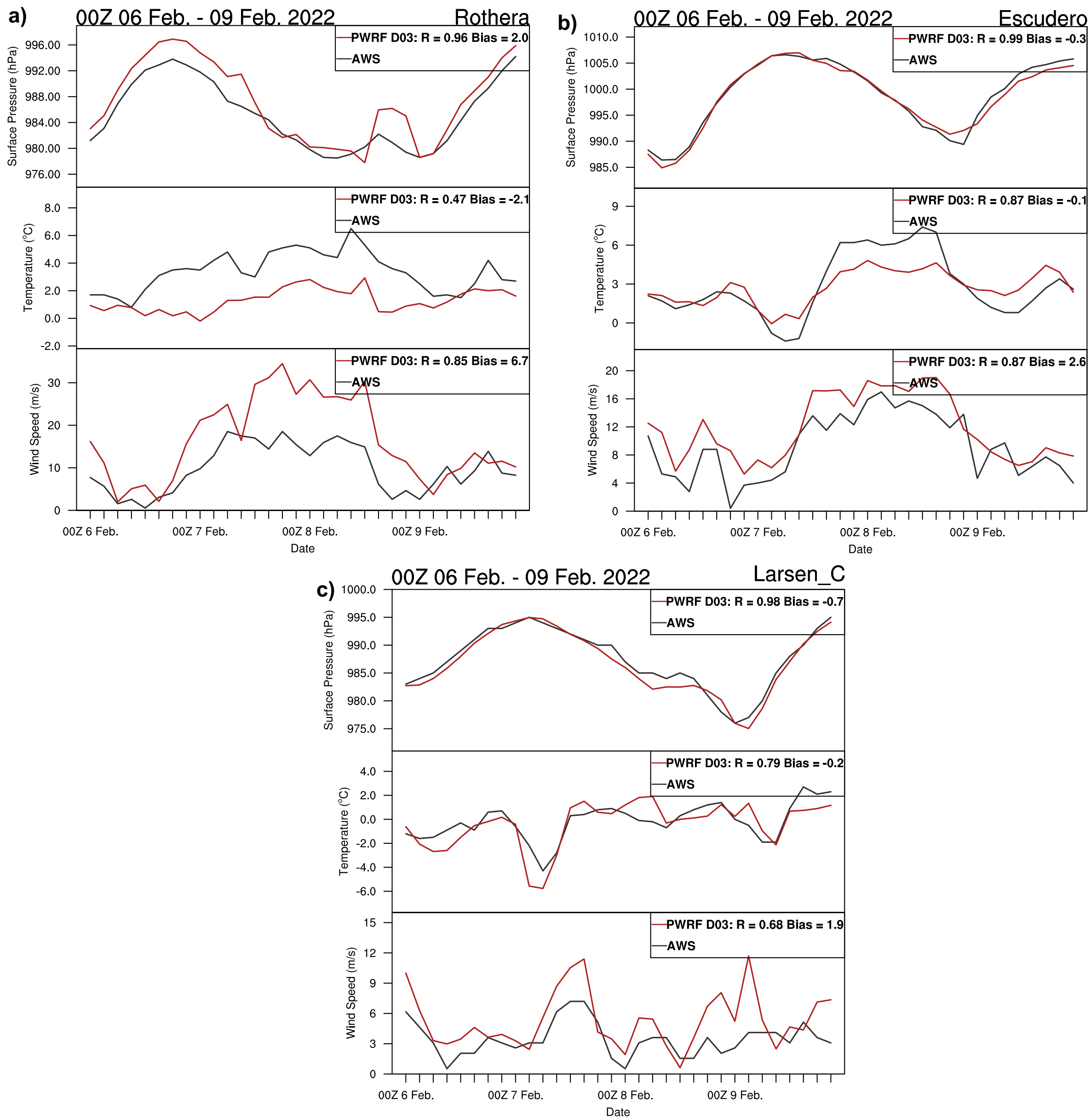

Figure 2. Evaluation of PWRF simulations based on observations at Rothera, Escudero, and Larsen C weather stations every 3 hours.

Table 2. PWRF correlation coefficient (R) and bias at several weather stations based 3hrly data from 0000UTC 6 February to 2100UTC 9 February 2022.

Stations	Surface pressure (hPa)		Temperature (°C)		Wind speed (m/s)	
	R	Bias	R	Bias	R	Bias
Rothera	0.96	2.0	0.47	-2.1	0.85	6.7
Vernadsky	0.96	-0.3	0.78	0	0.54	9.2
Escudero	0.99	-0.3	0.87	-0.1	0.87	2.6

Marambio	0.99	2.2	0.53	-3.3	0.74	1.2
Larsen C	0.96	-0.7	0.79	-0.2	0.68	1.9
Esperanza	0.94	2.0	0.27	-1.6	0.25	4.7
Average	**0.97**	**0.82**	**0.62**	**-1.22**	**0.66**	**4.38**

*Gray shadow indicates stations located on the upwind side.

PWRF temperatures, relative humidities, and wind speeds in the troposphere were compared to station radiosonde measurements (Figs. S3a and S3b). Absolute maximum, mean, and root mean square differences for temperature and wind speed are summarized in Table 3 for 2022 (and in Table S2 for 2018). In 2022, the root-mean-square (RMS) difference in tropospheric temperature was 1.1 ℃ (absolute maximum of 3.3 °C and mean bias of -0.2 ℃), and the RMS difference in tropospheric wind speed was 3.7 m/s (absolute maximum of 10 m/s and mean bias of 0.9 m/s). Differences in 2018 (Table S1) were similar. Differences for relative humidity (RH) are complicated by high variability and occasional low biases in the radiosonde RH measurements they are given in tables S2 and S3. The overall good performance discussed above provides high confidence for us to use the PWRF simulation to analyze the two surface warming events over the AP.

Table 3. PWRF maximum (max; absolute) differences, mean biases (Mean) and root mean square differences (RMS) in tropospheric temperature and wind speed, relative humidity (RH) and wind speed at several stations during the 2022 case study.

Stations	**Date**	**Time**	**Temperature (ºC)**			**Wind speed (m/s)**		
			Max	**Mean**	**RMS**	**Max**	**Mean**	**RMS**
Escudero	2022/2/7	0	2.6	-0.1	0.7	6.7	0.9	2.0
	2022/2/7	12	2.1	-0.1	0.6	9.5	0.6	4.3
	2022/2/8	0	3.5	-0.3	1.2	20.0	2.5	5.1
	2022/2/8	23	4.2	0.2	1.5	7.4	-0.9	2.9
	2022/2/9	12	2.0	-0.2	0.9	8.0	0.8	3.3
Rothera	2022/2/9	12	5.8	-0.2	1.6	8.4	1.3	4.5
Marambio	2022/2/7	12	2.9	-0.8	1.3	10.8	0.8	3.5
Average			**3.3**	**-0.2**	**1.1**	**10.1**	**0.9**	**3.7**

*Gray shadow indicates stations located on the upwind side. The absolute bias, mean bias, and RMS are the average values of 27 pressure levels, from 100hPa to 1000hPa by 25hPa.

3.2. December 2018 and February 2022 surface melt events over the Antarctic Peninsula

Two surface melting events that were triggered by the combined impact of ARs and foehn warming are studied, occurring on the northern AP in December 2018 and February 2022. In December 2018, a high precipitation amount (up to 5.7mm/day) was observed at Vernadsky (Chyhareva et al. 2021), and surface melting also detected on the leeside based on National Snow and Ice Data Center (NSIDC) daily surface melt extent (not shown). At the beginning of January 2022, a large expanse of sea ice (about 2,000 km^2), which had persisted in the Larsen B embayment since 2011 and that can bond and stabilize the ice shelves, began to break up between 17 and 19 January 2022 (NASA, 2022). In the following February, under the La Niña condition and positive SAM (SAM index 1.92; Marshall 2003), an unprecedented warming caused major surface melt over both western and eastern AP (Gorodetskaya et al, 2022). On 7-8 February 2022, several Antarctic stations observed record high temperatures, such as +12.7 °C at Vernadsky, +13,6°C at Carlini, and +13.7 °C at King Sejong (Gorodetskaya et al, 2022). The air temperature at Escudero remained above +6 °C from 18UTC 7 February until 15UTC on 8 February.

3.3. Regional circulation and Atmospheric River

The regional circulation significantly affects the strength and direction of ARs, and local topography impacts the orographic precipitation. Figure 3 shows 500hPa geopotential height, horizontal wind from PWRF and the surface melting map from ERA5 Land for both 2018 and 2022 cases (e.g., 00UTC 6 December and 00UTC 8 February). Although both cases featured the development and propagation of two low-pressure centers, location of the lows varied, as well as the circulation pattern. In the 2018 case, the first low-pressure center developed over Pine Island Glacier at ~00UTC on 6 December (Fig. 3a), and the secondary low developed over the Weddell Sea at ~03UTC on 7 December (not shown). These two lows covered the entire AP region, which led to zonal marine air advection over the northern tip of the AP for ~24 hours. In the 2022 case, the first low was located at coastal Pine Island Glacier (Fig. 3b) and the second low migrated from the Bellingshausen Sea towards Alexander Island (not shown). Unlike the 2018 case, the 2022 case had a blocking high over the Weddell Sea (blue dashed line, Fig. 3b). This low-high coupled pattern not only led to a stronger pressure gradient and marine air intrusion but also resulted in a stationary northerly flow lasting for 3 days, which transported extra moisture and heat from lower latitudes to Antarctica (e.g., Hirasawa et al. 2013). Using two polar-specific AR detection algorithms (see Wille et al. 2021; Zhang et al. 2023), an AR was briefly detected northwest of the AP for the 2018 case, while in 2022, a prolonged AR was detected over the AP from 7-9 February following a shorter AR landfall on 5 February.

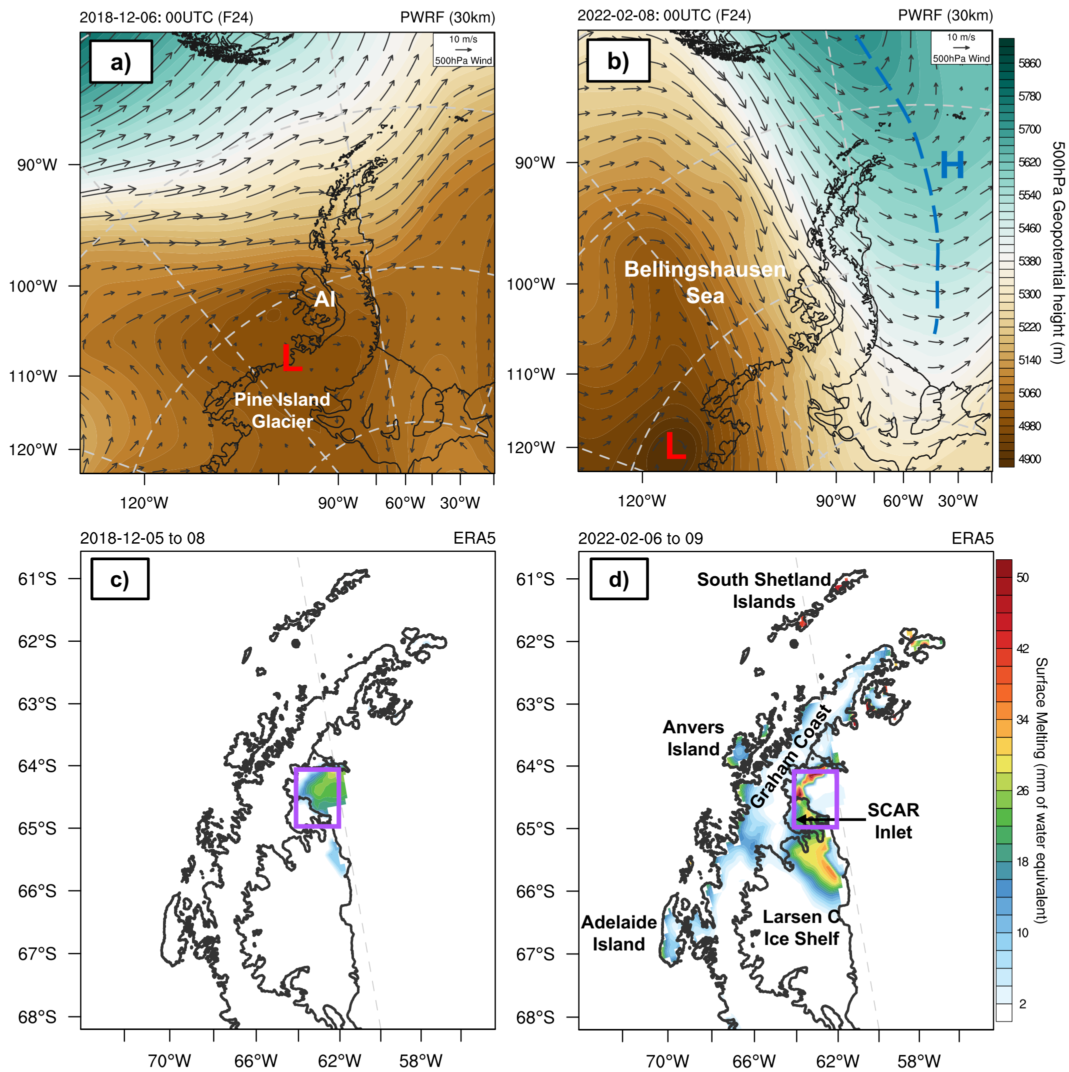

Figure 3. Circulation pattern and surface melting for the 2018 and 2022 cases. a) and b) 500hPa geopotential height (contours) and wind field (black arrows) from PWRF d01 (30km) at 0000UTC 06 December 2018 and 08 February 2022. Blue "H" and dashed blue line represent the blocking high, and red "L" represents the low-pressure center. c) and d) show the 3-day accumulated surface melting of water equivalent based on hourly ERA5 Land (9km) reanalysis data. AI: Alexander Island. The purple box in d) represents the AR/foehn "hotspot".

Compared to the 2018 case, the melting in the 2022 case impacts a broader area. In the 2018 case, the surface melting was mainly over the remaining Larsen B Ice Shelf (max ~30 mm of water equivalent; see Fig. 3c). By contrast, in the 2022 case, surface melting affected the whole northern AP (Fig. 3d), including the upwind side (e.g., Anvers Island, Graham Coast, and Adelaide Island; see also Gorodetskaya et al., 2022). The South Shetland Islands also experienced strong melting, whereas no melting was detected there in the 2018 case. On the leeside of the AP in the 2022 case, the intense melting (max >50 mm of water equivalent) covered the remaining Larsen B embayment, SCAR inlet, and the northern edge of the Larsen C Ice shelf, which are the focus areas of this research. The warming event in early February 2022 may have also contributed to the significant negative anomalies in sea ice extent observed in austral summer 2021-22. In late February 2022, sea-ice extent hit its annual minimum at 1.9 million km^2, the absolute record low Antarctic sea-ice extent since the beginning of continuous satellite monitoring in 1979 (Wang et al. 2022a). Sea-ice extent remained close to record low levels during most of the summer 2021-22.

Using PWRF simulations, the maximum AR scale was found to be a moderate AR2 (Fig. 4a), according to the Polar AR scale (Fig. S2). Consistent with the regional circulation, in 2018 the AR only affected the northern tip of the AP, as indicated by the IVT (Fig. 4c). During the 2022 event, the entire AP region, coastal Pine Island Glacier, and the Filchner–Ronne Ice Shelf were all under the strong impact of AR3 with a max AR4 over Adelaide Island (Figs. 4b and d; Table 4).

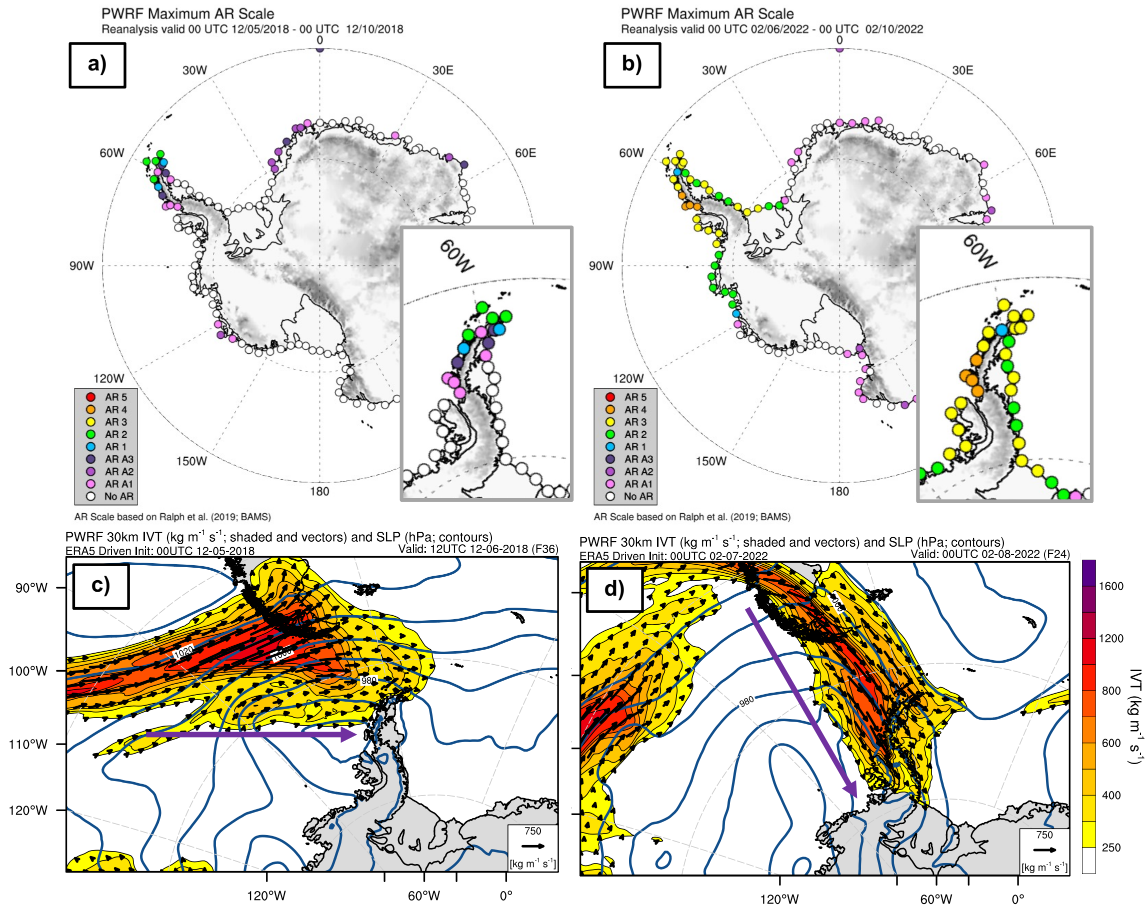

Figure 4. The Atmospheric River (AR) cases in 2018 and 2022 over the Antarctic Peninsula (AP). a), b) The adaption of CW3E Polar AR Scale for both cases. c), d) Integrated vapor transport (IVT) from PWRF d01 for both cases. Navy lines represent the mean sea level pressure (interval: 10 hPa).

Table 4. Overview of 2018 and 2022 cases.

	2018	**2022**
Maximum AR detected	AR2 (ERA5)	AR3 (ERA5) and AR4 (PWRF)
AR duration	1 day	3 days
AR impact area	Upwind side of the northern tip of the AP	Entire AP region, coastal Pine Island Glacier and Ronne Ice Shelf.
AR direction	AR hits the AP via southwesterly wind	AR hits the AP via northwesterly wind
AR peak	2018-12-06 ~06UTC	2022-02-07 ~00UTC @Palmer land region

		2022-02-07 ~12UTC @upwind side of the AP
Foehn peak	2018-12-06 ~12UTC	00UTC 02-08-2022 – 00UTC 02-09 2022
Max. temp on the leeside	11 ºC	18 ºC

ERA5 generally agrees with PWRF on the AR scale, except for a few spots adjacent to Adelaide Island where ERA5 indicates AR3 (not shown). The IVT pattern clearly shows the difference between these two cases. With a more zonal wind during the 2018 event (Fig. S4a grey arrow, e.g., 06UTC 6 December 2018), southern Graham Land experienced nearly perpendicular moist air advection (Fig. S4a solid brown box). Under this circumstance, the Larsen C Ice Shelf was most likely under foehn warming. Over Trinity Peninsula, where the topographic barrier tilts eastward, the marine air intrusion approached the coast at a ~45° angle (Fig. S4a blue dashed box). Thus, the foehn warming was weaker over the original Larsen A and B Ice Shelves (hereafter referred to as Larsen A and Larsen B). However, in the 2018 case, upcoming wind is not strong enough to trigger widespread foehn warming over the Larsen C Ice shelf, and Larsen A and B experienced moderate surface warming. By contrast, the 2022 case had a perpendicular airflow over the Trinity Peninsula due to a northerly wind pattern (Fig. S4b, grey arrow, e.g., 00UTC 8 February 2022), and the northern AP was under a stronger foehn warming (Fig. S4b solid blue box). The direction, strength, and duration of the noted ARs are important because they affect the magnitude of the foehn warming on the leeside.

3.4. Foehn warming and AR impacts

Both the 2018 and 2022 case experience foehn warming on the leeside, however this study focuses on the 2022 event due to its broader impact (Figs. 3c, 3d and 4). For the 2018 case, the surface warming mainly occurs along the mountain base and then expands to the Larsen ice shelves, which only last for ~24 hours. Over the Larsen B region (indicated previously with a purple box in Fig. 3d), the average 2m temperature increased ~3°C within 12 hours (from 00UTC 6 to 12UTC 6 December 2018) and above freezing point 2m temperature lasted for ~10 hours (Fig. S5a). The skin temperature (over land only) confirms a moderate surface melting that lasted ~6 hours during the foehn period. On the leeside of the AP, there are two warming spots during the 2022 foehn case. One is over the Larsen B embayment (including the SCAR Inlet) and the other is adjacent to James Ross Island (Fig. 5). The Larsen C Ice shelf did not experience widespread warming, except for the northern edge. Over the Larsen B region (purple box in Fig. 3d), the average 2m temperature increased more than 5°C and the average 10m wind speed increased ~8m s^{-1} within 24 hours (from 00UTC 7 to 00UTC 8 February 2022, second foehn period; Fig. S5b). The average 2m relative humidity dropped by 20% after the peak of AR/foehn impact (Fig. S5b). The above freezing point 2m temperature lasted for ~30 hours during the second foehn period, which was 3 times longer to the 2018 case. The skin temperature over ice shelves reached 0°C for 29 hours and remained high even after the foehn warming. The barrier jets on the upwind side indicate weak low-level blocking (e.g., Figs. 5f and 5h). While both ERA5 and PWRF captured the two warming hotspots (Fig. 5), the 2m temperature in ERA5 was sometimes 4 °C warmer than PWRF over Larsen B, especially at the beginning of this warming event (e.g., compare panels a and b in Fig. 5). Larsen B is a mixture of open water and floating ice during the 2022 case. ERA5 indicates this area as land/ice shelves based on its land-sea mask variable, and PWRF has updated this area as open water via REMA dataset. Further analysis is needed to explain this difference.

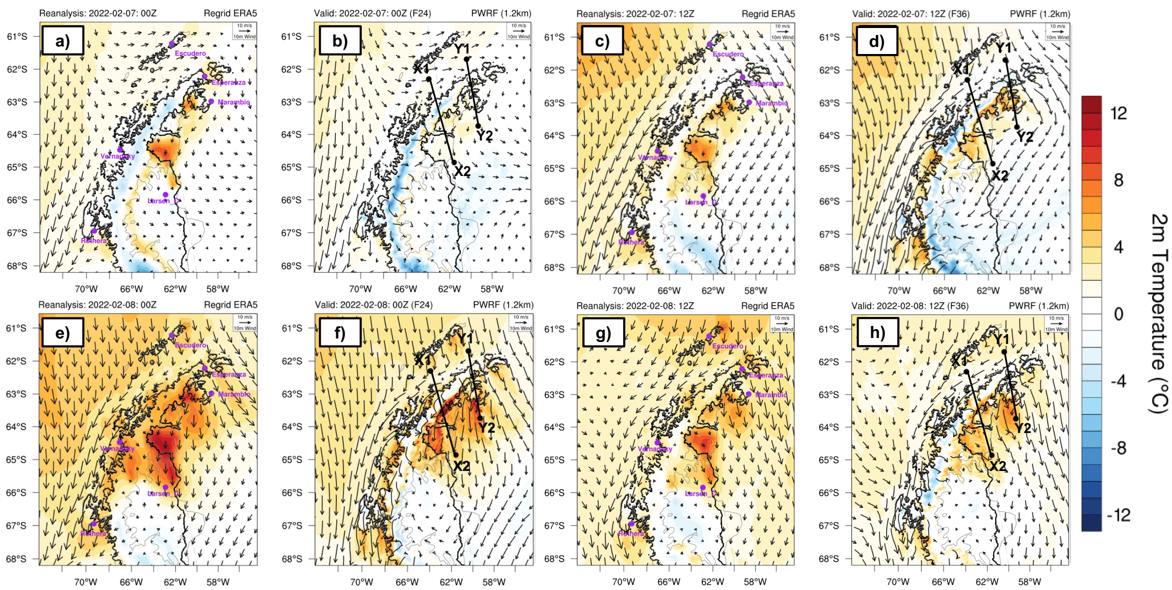

Figure 5. 2m temperature and 10m wind field from ERA5 reanalysis data and PWRF simulations at 0000UTC 07 February 2022 (a, b); 1200UTC 07 February 2022 (c, d); 0000UTC 08 February 2022 (e, f); and 1200UTC 08 February 2022 (g, h). All coastline information is from the REMA topography dataset. ERA5 land-sea mask contains the fraction of land within every grid box. Over Antarctica, it is defined by RAMP-2 dataset, which does not include the 2002 Larsen B Ice Shelf collapse (https://confluence.ecmwf.int/pages/viewpage.action?pageId=208482147).

The cross-section of temperature and wind speed confirms the strong foehn warming (Figs. 6, S7b and S7d). Temperature inversions were observed on the upwind side, with a warm core ~700m above the surface, and intense mountain waves were captured on the leeside (e.g., Fig. 6g). Such temperature inversions reflect a more-stratified atmosphere in the 2022 case, which could enhance low-level blocking on the upwind side, and adiabatic warming on the leeside (Elvidge et al. 2015). However, the strong incoming wind brought by ARs can force the low-level air to pass over the mountain peak (compensate for the low-level blocking) and enhance the latent heat release on the upwind side. Furthermore, the strong mountain waves on the leeside transfer sensible heat from the upper warm foehn flow to the leeside surface of SCAR Inlet. The short-lived 2018 case, by contrast, has much weaker mountain waves and more moderate foehn warming on the leeside (Figs. S5a, S6 and S7). The foehn warming mainly affects the leeside of the James Ross Island and the mountain base in the northern AP.

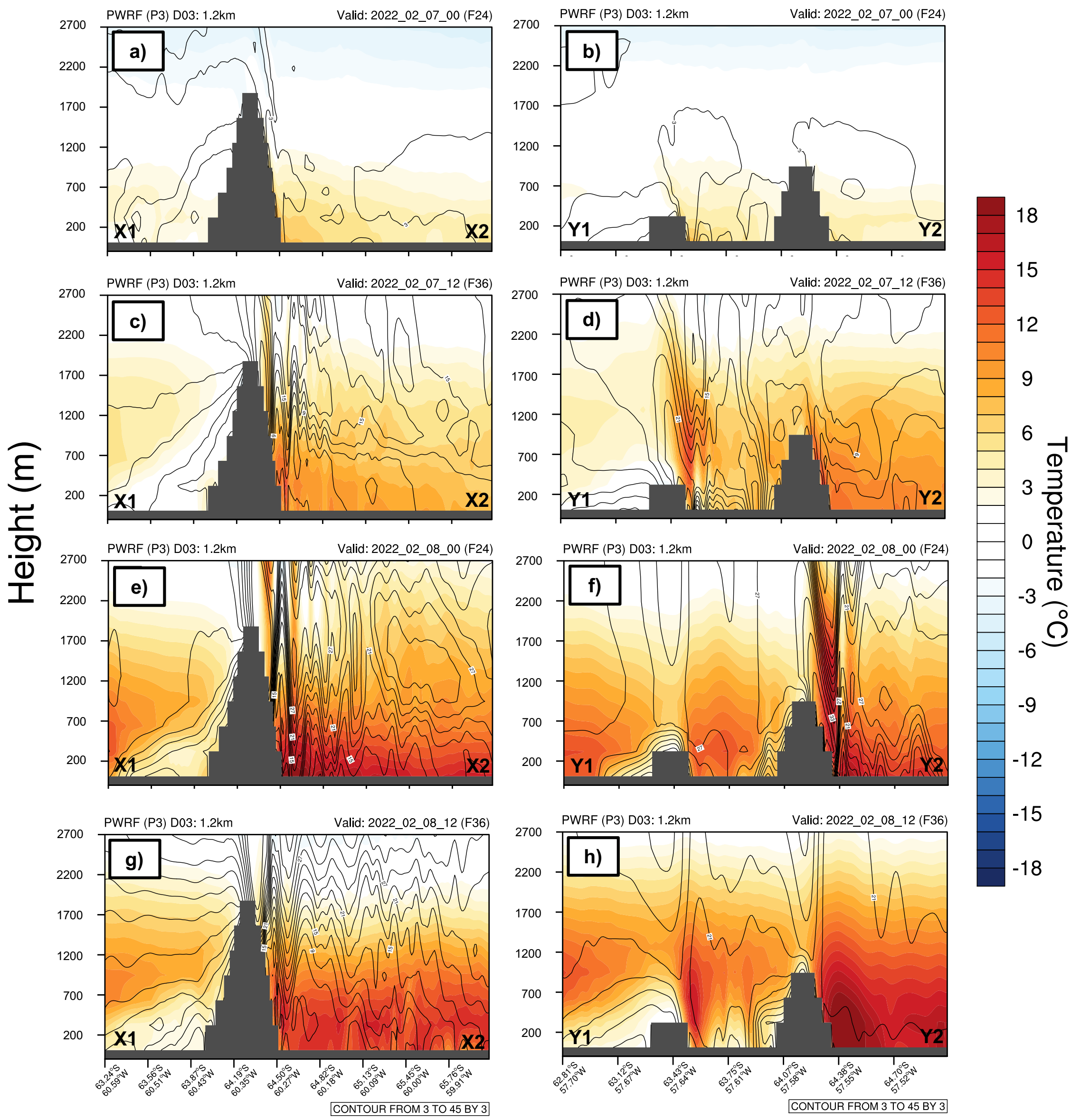

Figure 6. Vertical profiles of horizontal wind speed (horizontal only, u and v) and physical temperature along cross-sections X1X2 (a, c, e, g) and Y1Y2 (b, d, f, h), at 0000UTC 07 February, 1200UTC 07 February, 0000UTC 08 February, and 1200UTC 08 February, 2022. Cross-section X1X2 runs across the Graham Land, while cross-section Y1Y2 runs across the Trinity Peninsula (Fig. 5).

The two major drivers of surface melting over SCAR Inlet were found to be strong SWD during reduced cloudiness due to foehn clearance and SHF transferred to the surface by the mountain waves. However, the main driver of surface melting was found to differ between daytime and nighttime. During the day, net shortwave radiation (SW_{net}) is the leading contributor, ranging from 400 to 700 Wm^{-2}. Sensible heat flux, as the secondary factor during the daytime, can reach up to 300 Wm^{-2} (Fig. 7). During the night (Fig. 8), SHF maintains its strength, while the net shortwave radiation drops to 0 Wm^{-2} (not shown). The SHF is strongly correlated with the magnitude of the foehn, while the SW_{net} is considerably more complicated. Also, the SHF exhibits a wave pattern for multiple time steps during the 2022 event, especially closer to the mountain base (e.g., Figs. 7d and 8d). This pattern is consistent with mountain waves captured in the cross-section (Fig. 6) and cloud conditions from the Antarctic infrared composite (Fig. 7a) and MODIS corrected reflectance image (Figs. S8c and S8d).

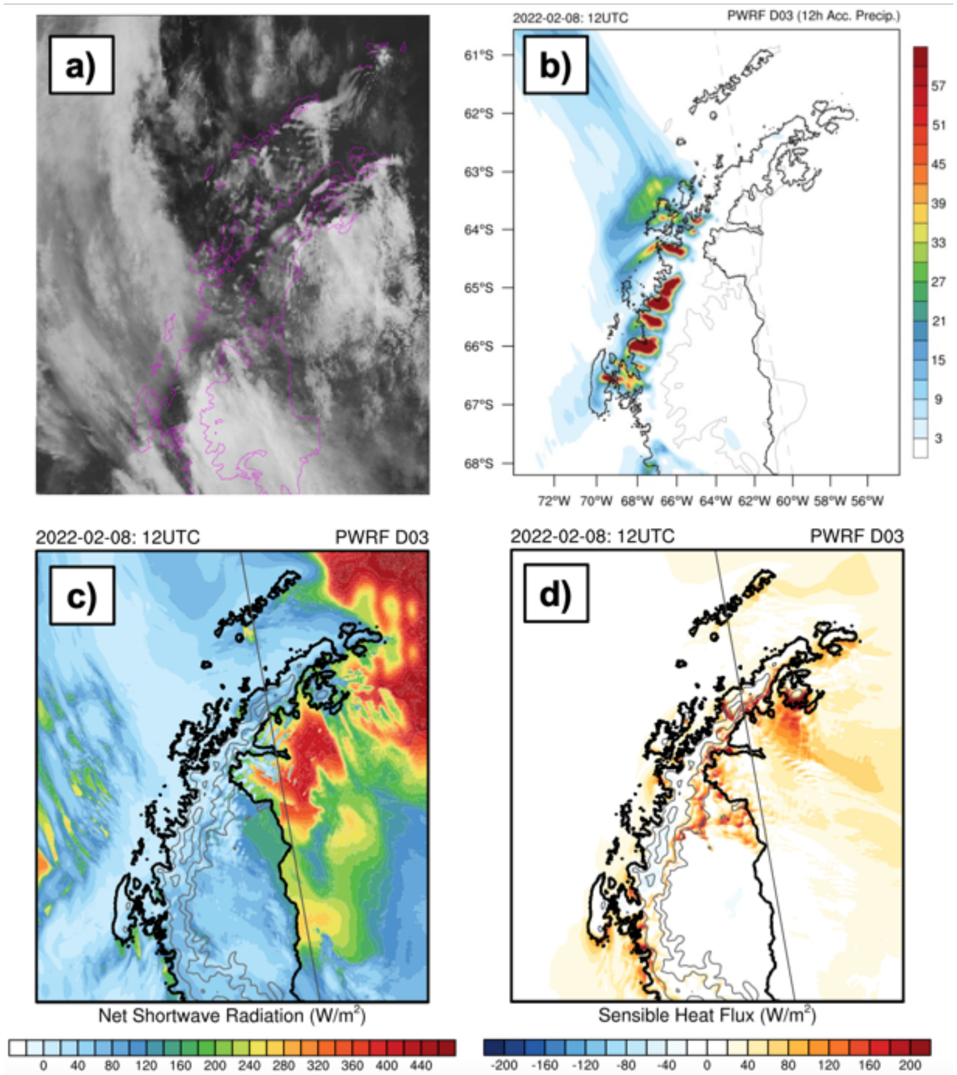

Figure 7. Clouds, precipitation, and the surface energy balance during the daytime, at 12UTC on 2022/02/08. a) Cloud cover from Antarctic composite infrared data. b) 12-h accumulated precipitation (00UTC - 12UTC) from PWRF d03. c) Net shortwave radiation from PWRF D03. d) Sensible heat flux from PWRF d03. Grey lines are meridians.

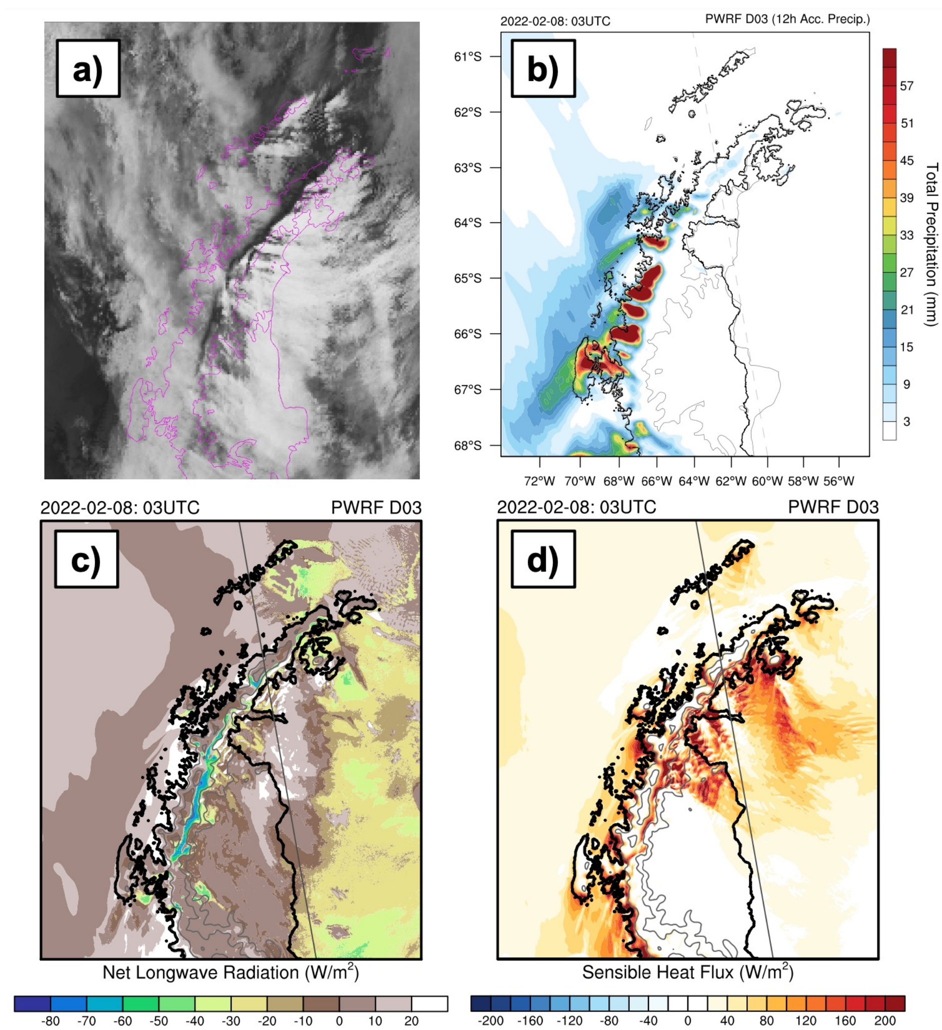

Figure 8. Surface energy balance pattern and cloud condition during the nighttime. a) Cloud cover from Antarctic composite infrared data b) 12-h accumulated precipitation (1500UTC 07 - 0300UTC 08 February 2022) from PWRF d03. c) Net longwave radiation at 0300UTC 08 February 2022 from PWRF d03. d) Sensible heat flux at 0300UTC 08 February 2022 from PWRF d03.

During the 2022 case, weak low-level blocking and intense precipitation on the upwind side can lead to clear sky and stronger foehn warming on the leeside (e.g., Figs. 7a, and S8d). However, there is a gap between Trinity Peninsula and Joinville Island, which allows moist marine air to reach the leeside and form clouds, especially low- and mid-level liquid clouds (e.g., Figs. 7a and S9a). The foehn jets going through the lower elevation in Graham Land can also transport extra moisture. When foehn warming is powered by the AR, the moisture transport can be strong through those gaps. Thus, the foehn clearance can be compensated for by clouds formed from the moisture in the gap flows; given that cloud conditions can vary significantly with time (Fig. S8), the resulting SWD can be highly varying. Similar enhanced cloud impacts on the leeside were observed for the 2018 case. Taking SCAR Inlet as an example, the SW_{net} (average 69 Wm^{-2}) contributes ~1.3 times as much as the SHF (average 54 Wm^{-2}) to the surface melting/warming from 00UTC 6 February to 23UTC 9 February (Fig. 9). The maximum of the SHF occurs on 03UTC 8 February, which is around the foehn peak (Fig. 9c). Orographic lee waves on the leeside transfer the sensible heat from upper foehn flow to the surface.

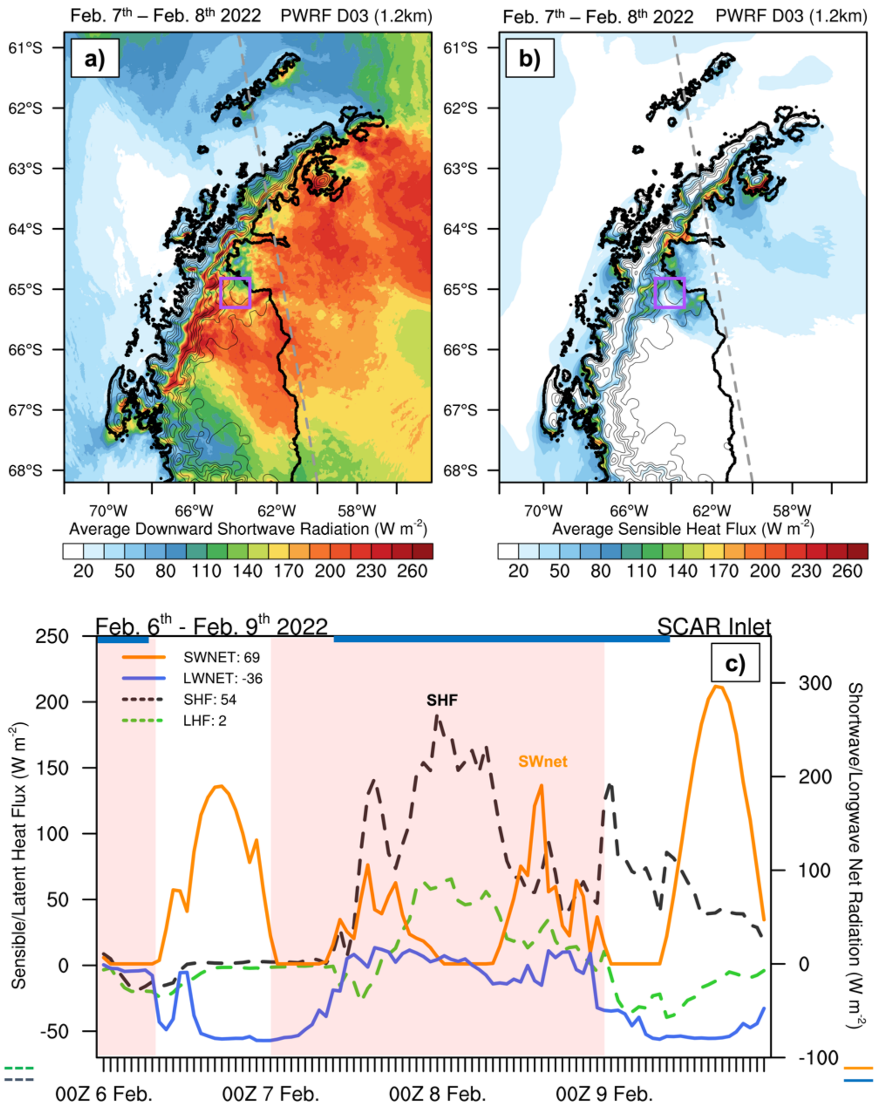

Figure 9. Surface energy balance during the peak of 2022 foehn event over the SCAR Inlet. a) average downward shortwave radiation from hourly PWRF d03 simulations. a) average sensible heat flux from hourly PWRF d03 simulations. c) time series of net shortwave/longwave radiation and sensible/latent heat flux within the purple box in a) and b). Pink shadow indicates the foehn period and navy lines at the top of c) indicate the atmospheric river effects over the SCAR Inlet.

Overall, SW_{net} is the major contributor to the surface warming over most of the ice surface on the leeside, except the mountain base or areas strongly affected by the cloud formation, where the SHF has an equal impact as SW_{net} (both ~140 Wm^{-2}; Fig. 9). The dominant contribution of SW_{net} after the foehn event mainly comes from stronger SWD with time due to clear sky conditions (Fig. S8e). The combined AR/Foehn event can be more complicated due to the extra moisture input via dampened foehn effect over lower elevation regions (e.g., foehn jets) and potential cloud formation accordingly (Figs. S8 and S10).

Consistent with Laffin et al. (2022), two foehn jets were found over Larsen A and B in high-resolution PWRF outputs during the 2022 event (LA jet and LB jet, Fig. 10a). With faster wind speed, lower temperature, and higher relative humidity during the foehn jets (purple boxes in Figs. 10b - d) compared to the background air, the two jets created a cooling gap between the two warming spots mentioned before (Fig. 5). The maximum wind speed of the jets occurs at ~700m above the surface (Fig. 10b). Because the direction of the marine air advection varies with time, the locations of the jets shift slightly. For instance, the LB jet can affect either the Larsen B or SCAR Inlet depending on the incoming flow. Within the jets, a larger vertical potential temperature gradient indicates stronger sensible heat transfer from upper-level air to the surface (Fig. 10b). While temperatures and SW_{net} (due to the potential cloud formation) may be lower within foehn jets, the strong accompanying winds could accelerate the ice shelf disintegration via pushing ice to the ocean and enhancing SHF (Laffin et al. 2022; Elvidge et al. 2015). However, unlike Elvidge et al. (2015)'s foehn jet study over the Larsen C Ice shelf, where the surface was relatively smooth ice, both the LA and LB jets in 2022 blow over a surface that is a mixture of open water and floating ice (Fig. S8). Further research, such as trajectory analysis, is necessary to distinguish all the mechanisms that lead to surface warming.

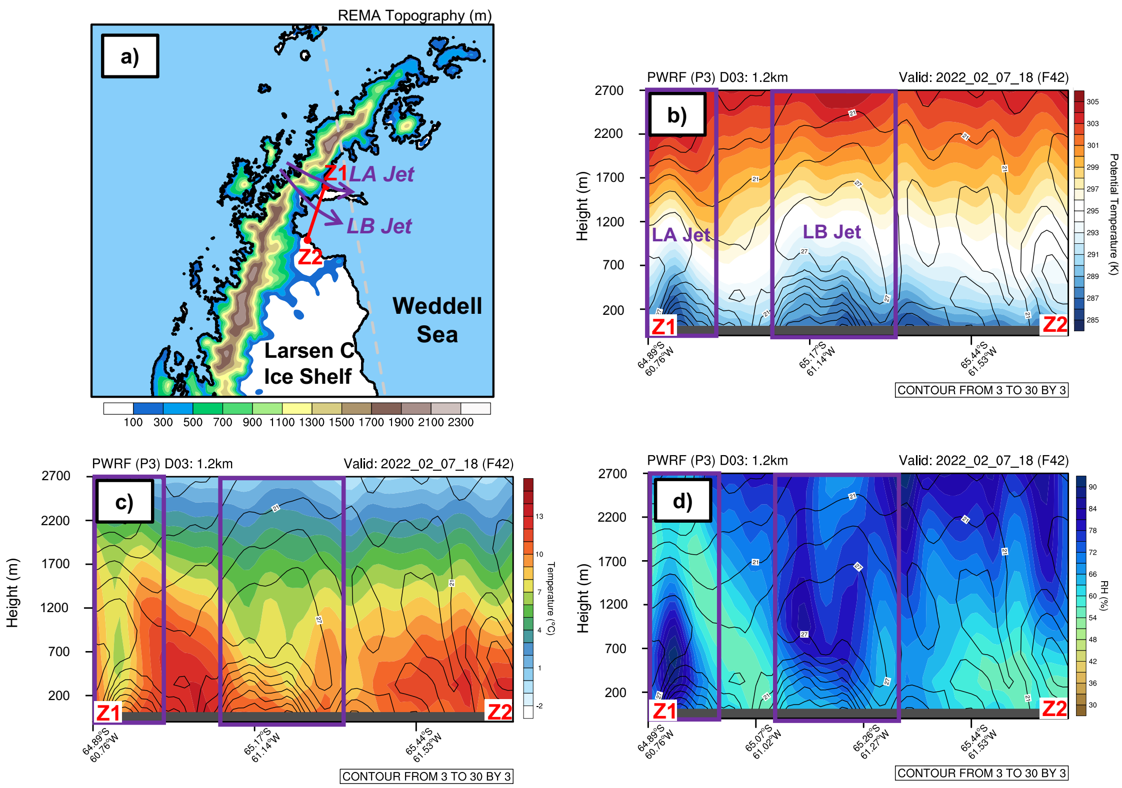

Figure 10. Larsen A and B jet during the 2022 foehn case. a) illustrates the location of the jets and the cross section (Z1Z2). b), c), d) Cross section of potential temperature, temperature, and relative humidity (RH) with wind speed at 1800UTC 07 February 2022. (LA jet: Larsen A jet. LB jet: Larsen B jet).

4. Discussion

The maximum impact of foehn warming is expected to occur when the incoming wind approaches the topographic barrier perpendicularly (e.g., during a zonal wind). Most of the AP region, especially the southern area, will have a stronger foehn warming under the zonal wind (Bozkurt et al. 2018). However, when there is a low over the Bellingshausen Sea and a nearby blocking high over the Weddell Sea, the AP is more likely to experience meridional warm air advection. Given that the northern tip of the AP tilts eastward, it will experience a stronger foehn under a meridional (northerly) wind (Fig. S4). In other words, the northern AP is more vulnerable to the combined impact from foehn and AR under a persistent meridional wind, such as the 2022 case instead of the 2018 case. Also, the vertical structure of the atmosphere on the upwind side also affects the foehn warming. A more stratified atmosphere with slow wind speed will result in a shallow foehn condition, which has low-level blocking on the upwind side and possible hydraulic jumps on the leeside (Durran 1990). For example, the topographic blocking for the northerly meridional wind at 850hPa persisted for 11 months during 2002-03 (Orr et al. 2004). In contrast, strong vertical wind shear and unstable atmosphere usually lead to intense orographic lifting on the upwind side and stationary orographic gravity wave on the leeside (Elvidge et al. 2015).

For the 2022 case, the strong AR brings faster and warmer moist air from the lower latitudes over the relatively colder ocean and propagates to the northern AP perpendicularly. On the upwind side, a temperature inversion is observed, as well as strong vertical wind shear due to the low-level jet (~700m above the surface; not shown). Thus, the 2022 case was characterized by weak low-level blocking and strong mountain waves on the leeside, which made this case closer to a deep foehn scenario. PWRF simulations show a weak-to-moderate hydraulic jump near the mountain peak and stationary mountain waves covering most of the leeside (e.g., Fig. 6g). By contrast, the 2015 case study conducted by Bozkurt et al. (2018) has strong low-level blocking on the upwind side (shallow foehn). Instead of the stationary orographic gravity wave, the leeside has a sharp and large hydraulic jump, which leads to the formation of “foehn gaps” (cloud-free zone) along the mountain base. Although shallow foehn often leads to a larger positive temperature anomaly via adiabatic warming (isentropic drawdown) and intensive SHF at the mountain base, deep foehn is more likely to result in extensive surface warming/melting via SHF from stationary orographic waves (Elvidge et al. 2015). The direction and magnitude of AR can complicate the foehn warming via contributing extra moisture and also affect the atmospheric structure on the upwind side, which is related to the development of mountain waves on the leeside. This will impact the SHF and cloud conditions, and the surface warming consequently.

Similar to the AP region, the eastern Ross Ice Shelf over WA experienced the combined impact of AR and foehn in a few historic surface melting events. With a blocking high (over the Bellingshausen/Amundsen Sea) and a nearby low-pressure system (over the Amundsen/Ross Sea), coastal WA is more likely to have strong warm marine air advection or ARs (Scott et al. 2019; Zou et al. 2021a). The eastern RIS on the leeside can have foehn warming subsequently. The local topography over the AP is different from WA. Instead of two relatively gentle mountain ranges (over Marie Byrd Land and Edward VII Land), the AP has one sharp topographic barrier along Graham Land. Thus, the AP usually has stronger foehn warming. In addition, both the AP and eastern RIS can experience foehn clearance and have direct moisture input that potentially led to cloud formation simultaneously. For example, during a 2015 melt event (Ghiz et al. 2021), Siple Dome had a descending warm and dry air mass that might have reduced the optical thickness of the clouds and enhanced all-wave radiation. In the 2022 case, cloud formation on the leeside triggered by the extra moisture via AR and gap flows hampers the SWD at the mountain base but increases the LWD slightly. Although the LA and LB jets reduce temperatures and the impacts from SW_{net}, they could accelerate the ice shelf disintegration via pushing ice to the ocean and enhancing SHF (Fig. 10). The occurrence of AR and complicated local topography introduce more uncertainties to foehn studies over the AP.

The detailed mechanisms of foehn for both regions need to be analyzed case by case. With a colder background temperature, the RIS is at a lower risk of collapsing or intense surface melting. The RIS might experience moderate surface melting during a foehn event in austral summer, and no melt ponding has been reported over the Siple Coast region (Ghiz et al. 2021; Zou et al. 2021b). In contrast, foehn/AR events contributed to the collapse of Larsen A Ice shelf in 1995 and Larsen B Ice Shelf in 2002 (Wille et al. 2022). An increasing AR frequency over the AP may occur in the future under climate change, as well as the positive SAM trend (Wille et al. 2021; Espinoza et al. 2018). Consequently, more intense and complicated foehn cases may occur, which can lead to extreme weather, such as record-breaking temperature and intense precipitation (e.g., Bozkurt et al. 2018; Gorodetskaya et al., 2022; González-Herrero et al. 2022). In addition, the fast-changing surface due to the melting and ice loss challenges the ability of numerical weather models to accurately describe surface condition, such as temperature. A more advanced land surface model that can accurately represent the changing surface dynamically (e.g., albedo and land mass) should be included in PWRF, especially for simulations over the AP region (e.g., Fig. S1). Field observations of cloud properties are needed to help validate model cloud microphysics, as well as its impact on surface warming.

5. Summary

The AP region experienced a combined impact from AR and foehn warming during both 2018 and 2022 cases. With a blocking high located at the Weddell Sea during the 2022 case, the northern tip of the AP is hit by a northwesterly AR perpendicularly for three days. Thus, compared to the 2018 case, the 2022 case was characterized by stronger and longer-lasting foehn warming. Over the Larsen B embayment during the 2022 foehn case, there was an average 2m temperature increase of 5 °C within 24 hours. A low-pressure center to the west of the AP with a blocking high to the east often leads to a stationary circulation pattern, which contributes to poleward moisture transport (Wang et al. 2022b). The importance of the blocking high to the regional circulation over the AP as well as the rest of the Antarctic continent has been highlighted in multiple research papers. It not only enhances the pressure gradient and accelerates the marine air advection (AR related), but the blocking high also creates a more persistent pattern that results in a longer-lasting event, especially for the northern AP (e.g., Hirasawa et al. 2013; Nicolas et al. 2017; Xu et al. 2021).

The persistent impact of the AR can lead to strong foehn warming along the leeside of the AP, especially from the latent heat release on the upwind side (Bozkurt et al. 2018; Wille et al. 2022). Both 2018 (ENSO-neutral) and 2022 (La Niña) cases have intense precipitation on the western AP, and warm downslope wind on the eastern side. As a deep-foehn like case, the 2022 event has strong stationary orographic gravity waves on the leeside, which enhances heat transfer between the upper foehn flow and the surface (Fig. 6). The 2022 case has two warming spots, one over the Larsen B embayment and the other on the leeside of James Ross Island (Fig. 5). Between these two spots, there is a relatively cooler gap close to Robertson Island, which is indicative of a strong foehn jet (the LB jet).

During the austral summer, the AP region experiences a strong diurnal cycle. Thus, the lead driver of surface warming is different between daytime and nighttime (Figs. 7 and 8). During the daytime, SW_{net} significantly contributes to the surface warming/melting over the SCAR Inlet, followed by the SHF. During the nighttime, SHF is the major driver. Shortwave radiation is associated with foehn clearance, which can be amplified by the AR intrusion. However, in the 2022 case, gap flows/foehn jets significantly contribute to moisture transports on the leeside and reduce SW_{net}, especially at the mountain base. On the other hand, SHF continuously contributes to surface warming, which is highly correlated with the magnitude of the foehn. Overall, SW_{net} is the major contributor to surface warming/melting over the ice surface during the 2022 foehn period, except for the mountain base where SHF has an equal contribution or areas with cloud formation due to the gap flows/foehn jets.

In general, the AR intrusion complicates the foehn warming over the AP region, and usually amplifies the surface warming/melting. First, ARs with longer duration usually propagate towards the AP in a meridional direction, which moves perpendicular to the northern tip but not to the southern AP. Thus, the Larsen C ice shelf will have less foehn warming, but Larsen A and B (including SCAR Inlet) will be under greater impact. Second, there are several gaps along the topographic barrier over the AP, especially over the northern tip. Foehn jets via the low-elevation gap can compensate for the increased SWD resulting from foehn clearance and enhance the SHF. Third, for the 2022 case, SWD is the leading driver for the surface warming over the ice surface with SHF playing a significant role. However, the mechanisms of AR/foehn warming events over the AP vary case by case. ARs can amplify the leeside foehn warming via increased latent heat release on the upwind but can also hamper the foehn clearance via potential cloud formation. Depending on the phase, height, and thickness of clouds on the leeside, the net radiation can be different. All cases need to be analyzed independently and trajectory analysis will help distinguish the impact of each driver. Our future research will 1) continue to improve the high-resolution simulations over the AP region; 2) improve our understanding of the relationship of AR and foehn under different synoptic circulation patterns; 3) quantify the contribution of each driver to surface warming in order to build a better understanding of surface melting over the AP under the influence of climate change.

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Open Research

ERA5 and ERA5 Land reanalysis data are available at Copernicus Climate Change Service (C3S) Climate Date Store. Surface station observations and Antarctic composite infrared satellite imagery data are available at Antarctic Meteorological Research and Data Center (AMRDC) (https://amrdcdata.ssec.wisc.edu/). The Worldview tool from NASA's Earth Observing System Data and Information System (EOSDIS) provides additional satellite imagery (https://worldview.earthdata.nasa.gov/). Moderate Resolution Imaging Spectroradiometer (MODIS) albedo is produced by the National Aeronautics and Space Administration (NASA; https://lpdaac.usgs.gov/products/mcd43c3v006/). Reference Elevation Model of Antarctica (REMA) topography used in PWRF is available at https://www.envidat.ch/dataset/rema-topography-and-antarcticalc2000-for-wrf. PWRF model is available upon request at Polar Meteorology Group, Byrd Polar and Climate Research Center, The Ohio State University.

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