The influence of orographic gravity waves on precipitation during an atmospheric river event at Davis, Antarctica

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Abstract

Intense snowfall sublimation was observed during a precipitation event over Davis in the Vestfold Hills, East Antarctica, from 08 to 10 January 2019. Radar observations and simulations from the Weather Research and Forecasting model revealed that orographic gravity waves (OGWs), generated by a north-easterly flow impinging on the ice ridge upstream of Davis, were responsible for snowfall sublimation through a Foehn effect. Despite the strong meridional moisture advection associated with an atmospheric river (AR) during this event, almost no precipitation reached the ground at Davis. We found that the direction of the synoptic flow with respect to the orography determined the intensity of OGWs over Davis, which in turn directly influenced the snowfall microphysics. Turbulence induced by the OGWs likely enhanced the aggregation process, as revealed by dual-polarization and dual-frequency radar observations. This study suggests that despite the intense AR, the precipitation distribution was determined by local processes tied to the orography. The mechanisms found in this case study could contribute to the extremely dry climate of the Vestfold Hills, one of the main Antarctic oasis.

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Key Points:

- Despite intense moisture advection by an atmospheric river, orographic gravity waves (OGWs) led to total sublimation of snowfall above Davis
- The flow direction determined the intensity of the OGWs and hence the temporal and spatial precipitation variability
- The event can be divided in three phases during which the features of the OGWs influenced the observed microphysics in distinct ways

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Abstract

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Plain Language Summary

A case study of a snowfall event over Davis, Antarctica is presented. Despite the strong precipitation, snowfall did not reach the ground due to intense sublimation (transition from solid to gas state). Meteorological radar observations and atmospheric model simulations revealed that a dry downslope wind was responsible for the sublimation of snowfall below the cloud base. Despite the intense transport of moisture associated with the low pressure system during this event, almost no precipitation reached the ground at Davis. We found that the wind direction with respect to the main ridge upstream of Davis determined the intensity of the sublimation. This study suggests that despite the perfect large-scale conditions for intense snowfall at Davis, local processes related to the topography determined how much precipitation reached the ground. The mechanisms found in this case study could contribute to the extremely dry climate of the Vestfold Hills, one of the main ice-free regions of Antarctica.

1 Introduction

Snowfall in Antarctica is the main input to ice sheet mass balance (King & Turner, 1997), which determines the contribution of the southernmost continent to sea level rise (Shepherd & Wingham, 2007). On the East Antarctic coast, most of the precipitation comes either from meridional moisture advection by extratropical cyclones or is induced by orographic forcing (King & Turner, 1997). The surface mass balance of the East Antarctic coastal ice sheets is hence heavily influenced by the frequency and intensity of maritime moisture intrusions from lower latitudes, which often result in high precipitation accumulations (Noone et al., 1999; Nuncio & Satheesan, 2014; Welker et al., 2014). A recent study by Turner et al. (2019) showed that extreme precipitation events (EPEs, defined as the largest 10% of daily totals) contribute to more than 40% of the annual precipitation over much of the continent. In particular, the greatest contribution from EPEs is found on the main ice shelves, especially on the Amery Ice Shelf (less than 10 days of the highest-ranked precipitation contributing to 50% of the annual total). Davis station (69°S, 78°E) is located on the coast of the Vestfold Hills, just north-east of the Amery Ice Shelf. The Vestfold Hills are one of the few ice-free regions in Antarctica, which makes it part of the Antarctic oasis (Pickard, 1986). This is due mostly to its precipitation climatology with only 70.9 mm mean annual precipitation and 7.5 mm in December–January–February (DJF, statistics computed over the period 1960–2021, `http://www.bom.gov.au/climate/averages/tables/cw_300000_All.shtml`). Davis station, with its 1.8 ° C mean daily maximum temperature and 8.3 h mean daily sunshine in DJF, is known as the 'Antarctic Riviera' (Summerson & Bishop, 2011), because it is both relatively warm and dry. According to Turner et al. (2019), EPEs contribute to about 55% of the annual total precipitation in the Vestfold Hills with more than 95% of the interannual variability explained by EPEs. This shows that in the dry climate of Davis, EPEs have a significant climatological impact. In Antarctica, EPEs are often associated with narrow corridors of enhanced integrated water vapor (IWV) and integrated vapor transport, called atmospheric rivers (ARs, Ralph et al., 2004; Zhu & Newell, 1998). Indeed, Gorodetskaya et al. (2014) showed that ARs were responsible for outstanding precipitation accumulations over coastal Dronning Maud land, East Antarctica. Moreover, Wille et al. (2021) concluded that ARs are responsible for at least 10% of accumulated snowfall over East Antarctica and a majority of EPEs. However, the fate of these intense meridional moisture advection events depends on the state of the coastal boundary layer. For instance, Grazioli et al. (2017) showed that snowfall sublimation by dry katabatic winds leads to a decrease of 17% of total snowfall on the continental scale and up to 35% on the margins of East Antarctica, consistent with the more recent study of Agosta et al. (2019). While this low-level sublimation is very effective for light snowfall events, Grazioli et al. (2017) showed that it can still lead to a decrease of about 20% for the most intense snowfall cases over Dumont d'Urville, East Antarctica. This shows that katabatic winds can substantially affect the total amount at ground level during EPEs. However, other atmospheric processes might contribute to low-level snowfall sublimation. For instance, Foehn winds, which are common in the Antarctic Peninsula (Elvidge et al., 2015; Grosvenor et al., 2014; Kirchgaessner et al., 2021) and in the McMurdo Dry Valleys (Speirs et al., 2010; Steinhoff et al., 2013), can lead to record-setting warming and drying of the air in the lee of a mountain (Bozkurt et al., 2018). While the impact of Foehn on melting and sublimation of ice shelves has been already studied (Cape et al., 2015; Zou et al., 2019), its effect on snowfall sublimation in Antarctica has, to our knowledge, never been investigated. Foehn winds are associated with orographic gravity waves (OGWs) (Damiens et al., 2018; Elvidge et al., 2016; Vosper et al., 2018), which, in East Antarctica, are generated when synoptic or katabatic winds impinge upon a mountain ridge or reach the coast (Valkonen et al., 2010; Watanabe et al., 2006) and they can be trapped downstream of a katabatic jump (Vignon et al., 2020). Alexander et al. (2017) studied a gravity wave event at Davis and found that the gravity waves were generated by the interaction between a strong north-easterly synoptic flow and the orography upstream of Davis. These OGWs were responsible for temperature fluctuations that affect the formation of cirrus clouds. While OGWs in East Antarctica have been the subject of investigations in the last two decades (Alexander & Murphy, 2015; Moffat-Griffin, 2019; Orr et al., 2014; Watanabe et al., 2006), their impact on precipitation remains to be determined.

The goal of this study is to investigate how the synoptic evolution of an intense precipitation event (08 to 10 January 2019) and the local orography influenced the precipitation distribution and microphysics over the Vestfold Hills. We use recent data collected during the Precipitation over Land And The Southern Ocean (PLATO) campaign at Davis. This includes scanning polarimetric and vertically pointing Doppler radar measurements at different frequencies, as well as radiosounding data and a Raman lidar. We also make use of simulations from the Weather Research and Forecasting (WRF) model. We address the following questions:

1. How does the synoptic flow constrain the presence of OGWs?
2. How do OGWs impact snowfall sublimation and the spatial distribution of precipitation during this event?
3. How do OGWs influence the snowfall microphysical evolution?

This paper is structured as follows. Section 2 describes the geography of Davis and the dataset. Section 3 presents the evolution of the synoptic conditions and the precipitation distribution of this case study. In Sect. 4 we analyze the dynamics and microphysics of the event during three distinct phases. The possible climatological relevance

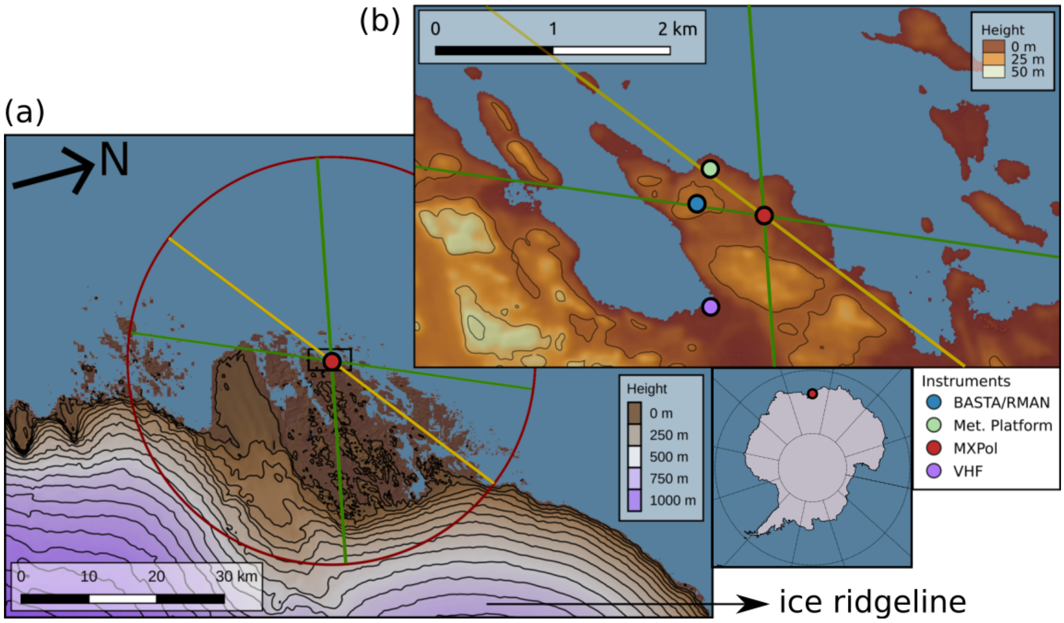

Figure 1. Topography of (a) the Vestfold Hills and (b) Davis station. The colored lines show the RHIs of MXPol, the yellow one correspond to the RHI at 52° azimuth. The red circle shows the extent of the PPI. The locations of the instruments are shown in (b). The colors correspond to altitude in m a.s.l. The altitude contours of (a) are shown every 100 m and of (b) every 20 m. The main ice ridgeline responsible for the generation of OGWs is shown with an arrow. The blue corresponds to altitudes smaller or equal to 0 m a.s.l.

of this case study is discussed in Sect. 5. We finally summarize and conclude this paper in Sect. 6.

2 Vestfold Hills Geography and The PLATO Campaign at Davis

PLATO is a project coordinated and logistically supported by the Australian Antarctic Division that aims to characterize precipitation over the Southern Ocean and Antarctica, and evaluate the precipitation products obtained by satellites and atmospheric models. The central field campaign was organized at Davis with an intensive observation period from November 2018 to February 2019. Davis is located in the Vestfold Hills, one of the few ice-free regions of Antarctica, at the foot of a steep transition from the elevated ice sheet to the coast (Fig. 1). The Amery Ice Shelf starts at about 120 km to the south-west of Davis (Fig. 2). The main ice ridge responsible for the generation of OGWs (Alexander & Murphy, 2015; Alexander et al., 2017) is located about 80 km to the north-east of Davis and reach about 1000 m a.s.l. at the end of its steepest part (visible in Fig. 1 and 2). In January 2019 only scattered patches of sea-ice were present around Davis. At this time of the year, solar noon is at about 07:00 UTC. In this study, we focus on the data collected by an X-band Doppler dual-polarization (polarimetric) radar (hereafter MXPol), a W-band Doppler cloud profiler (hereafter BASTA), a Raman Lidar (hereafter RMAN), and a very-high frequency wind-profiling radar (hereafter VHF). In addition, we use radiosounding measurements (12-hourly resolution) and wind, temperature, pressure, and humidity measurements from an automatic weather station (AWS) located at Davis and managed by the Australian Bureau of Meteorology.

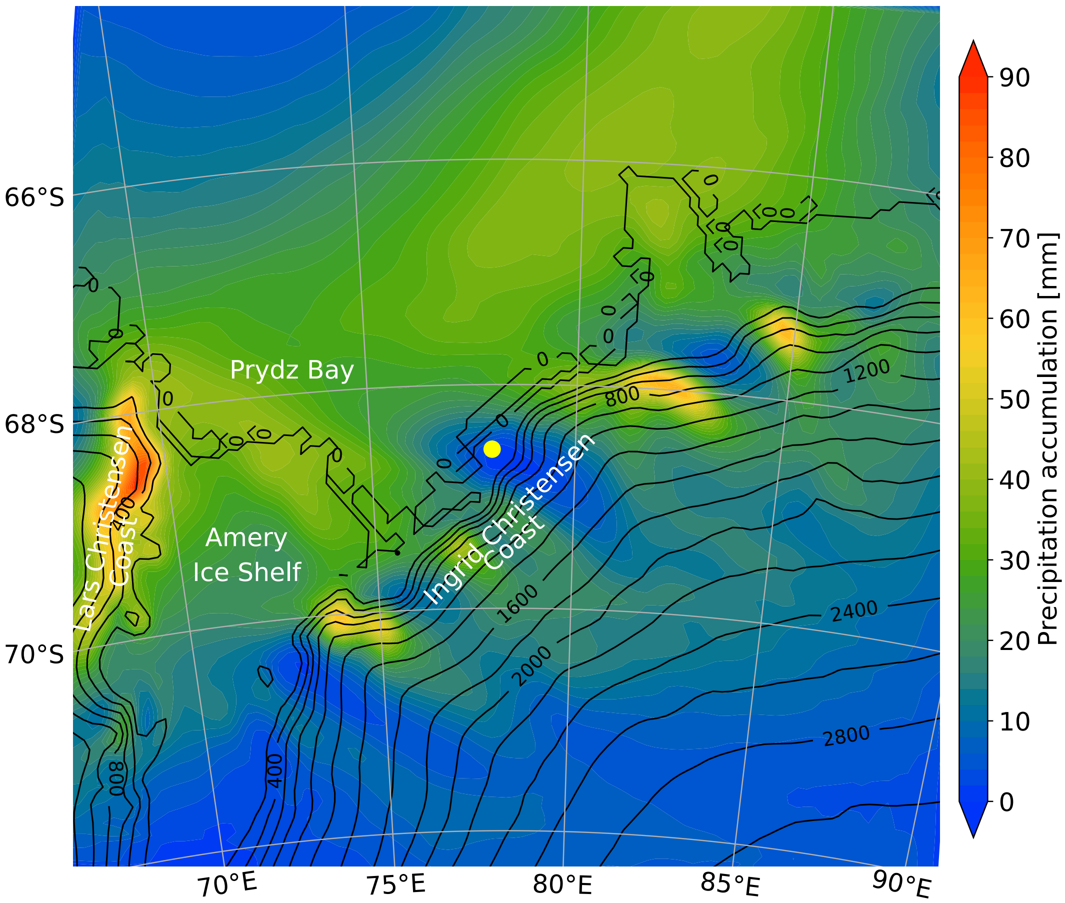

Figure 2. Precipitation accumulation (shading) from the WRF 9-km resolution domain from 00:00 UTC on 08 January to 12:00 UTC on 10 January 2019 and topography (black contours, labels in m a.s.l.). The yellow dot shows the location of Davis.

2.0.1 X-band polarimetric radar: MXPol

MXPol operates at 9.41 GHz with a typical angular sampling resolution of 1° and a range resolution of 75 m (see Schneebeli et al. (2013) for more details). Only the data up to about 28 km range are saved, since the decrease in sensitivity and increase in sampling volume make the further gates less relevant for microphysical studies. The scan cycle was composed of three hemispherical range height indicators (RHIs, i.e. a cross-section) at 23°, 52°, and 101° azimuth. The 23° RHI passes above the location of BASTA and RMAN, the 52° RHI (yellow line in Fig. 1) above a meteorological platform with other instruments not used in this study (Met. Platform in Fig. 1), and the 101° RHI is towards the ice sheet. The cycle was completed by one plan position indicator (PPI) at 4° elevation (red circle in Fig. 1) and one PPI at 90° elevation. The 52° and 101° RHIs, and the 4° PPI have an unambiguous Doppler velocity of 39 $\mathrm{m\,s^{-1}}$, while it is 11 $\mathrm{m\,s^{-1}}$ for the 23° RHI and the 90° PPI. The scan cycle had a 5 min duration and was repeated indefinitely. The main MXPol variables used in this study are the equivalent reflectivity factor (hereafter simply referred to as reflectivity) at horizontal polarization Z_H (dBZ), the differential reflectivity Z_{DR} (dB), and the Doppler velocity ($\mathrm{m\,s^{-1}}$).

Z_{DR} has been calibrated by subtracting a time-dependent offset from the original Z_{DR} field, according to the algorithm described in Ferrone and Berne (2021). Following the criteria described in the article, only the region between 1067 m and 3681 m above the radar has been extracted from the 90° PPIs (2932 over the whole campaign) and considered suitable for calibration purposes. The median Z_{DR} values from this vertical profile have been used as input for an ordinary Kriging interpolation. The median Z_{DR} offset of the 6495 scans (restricted to precipitation periods) is 0.53 dB and the interquartile range is 0.03 dB, showing that the Z_{DR} offset was stable in time.

During the 23° RHI and 90° PPI, the full Doppler spectrum at 0.17 $\mathrm{m\,s^{-1}}$ resolution was retrieved. A semi-supervised hydrometeor classification algorithm (Besic et al., 2018) was applied on the polarimetric variables. We use its de-mixing product, which estimates the proportions of hydrometeor classes within one radar volume, allowing us to study mixtures of hydrometeors. More specifically, we will show the de-mixing classification of all RHIs for horizontal distances greater than 6 km and excluding elevation angles between 45° and 135°.

2.0.2 W-band cloud profiler: BASTA

BASTA is a vertically-pointing, single-polarization, frequency modulated-continuous wave Doppler cloud radar operating at 95 GHz, with a beamwidth of 0.4° (Delanoë et al., 2016). The radar operates on a 12 s cycle, based on four 3 s modes using different range resolutions (ranging from 12.5 m to 100 m), corresponding to different Nyquist velocities and minimum detectable signal. The final product used in this study merges the four modes to provide 12 s resolution, 25 m vertical resolution profiles of reflectivity and Doppler velocity. BASTA has been calibrated following the procedure outlined in Protat et al. (2019), using statistical comparisons with T-matrix 95 GHz calculations from optical disdrometer observations (Klepp et al., 2018) and with a micro rain radar (MRR-PRO) 24 GHz vertically-pointing radar observations (Klugmann et al., 1996) collected during the second phase of the Clouds, Aerosols, Precipitation, Radiation, and atmospherIc Composition Over the southeRN ocean (CAPRICORN) experiment (Mace & Protat, 2018; McFarquhar et al., 2020), which took place just before the PLATO campaign. The consistency of all radar measurements of PLATO has also been established to be better than 1 dB by statistically comparing MXPol, MRR-PRO and BASTA observations collected during PLATO.

To compute the dual-frequency ratio (DFR) of reflectivity at X- and W-bands, vertical profiles of Z_H were extracted from MXPol's RHIs close to the location of BASTA (23° and 52 ° RHIs, respectively exactly over BASTA and 290 m away), at a horizontal distance between 480 and 680 m from MXPol. This timeseries of X-band reflectivity profiles (Z_X) can then be compared to the W-band reflectivity from BASTA (Z_W): both Z_X and Z_W profiles are binned to a common (time, height) grid with a timestep of 10 minutes and a height resolution of 50 m, which corresponds to two scan cycles of MXPol and two range gates of BASTA. The DFR is then computed as $Z_X - Z_W$, where Z_X and Z_W are in dBZ and hence the DFR is in dB. The principle of dual-frequency radar variables was introduced in Matrosov (1998). In essence, it is based on the fact that snow particles have different backscattering properties at the two frequencies: they behave as Rayleigh scatterers for one wavelength, but can enter the Mie oscillation regime for the other. In our case, snowflakes essentially remain in the Rayleigh regime at X-band, while they transition to the Mie regime at W-band as they grow in size, which in turn leads to a plateau or a decrease in Z_W. The DFR hence reflects snowflake median size and exhibits a sharp increase when processes, such as aggregation, lead to a rapid increase in snowflake size.

2.0.3 Raman lidar: RMAN

RMAN (Leosphere RMAN-511) is a vertically-pointing cloud-aerosol mini-Raman lidar measuring elastic backscatter and depolarization ratio at 355 nm, with a typical range resolution of 15 m and temporal resolution of 35 s (Royer et al., 2014). While the

RMAN system also includes a Raman scattering channel, the sensitivity of the system is such that long integration times in cloud-free tropospheric air are used for calibration (Alexander & Protat, 2019). From these lidar observations, cloud thermodynamic phase (liquid, ice, supercooled liquid water, and mixed-phase) is estimated first from the lidar backscatter and depolarization ratio using the algorithm described in Alexander and Protat (2018), then refined using cloud radar observations following Noh et al. (2019). In this study, we will only use the supercooled liquid water (SLW) category of this cloud classification.

2.0.4 Wind-profiling radar: VHF

The Davis VHF wind-profiling radar is a 55 MHz system consisting of 144-antenna main array with a one-way beamwidth of about 7°. Doppler radial velocities are obtained in the vertical, north, and east directions (with the off-vertical beams pointing at a 14° zenith angle), cycling every 6 min (Alexander et al., 2017). The vertical range resolution is 500 m and data are acquired from about 1500 m a.g.l. to the lower stratosphere.

2.1 WRF simulations

We carried out numerical simulations using the version 4.1.1 of the WRF model with a parent domain of 27 km resolution containing three (one-way) nested domains (Fig. 3) with 9, 3, and 1 km resolution centered over Davis station. The boundary and initial conditions are from the ERA5 reanalysis (Hersbach et al., 2020). The nudging strategy, the 96-level vertical grid and the physical package employed are the same as in the so-called 'lINP-hr' simulation of Vignon et al. (2021). In particular, we used the Morrison 2-moment microphysical scheme with a new ice nucleation parameterization adapted to the low concentrations of ice nuclei particles observed in the atmosphere off the Antarctic coasts. The topography and land-use for the simulations are from the 1-km resolution Reference Elevation Model of Antarctica dataset (Howat et al., 2019) and from the AntarcticaLC2000 dataset respectively. The WRF-compatible files have been built by Gerber and Lehning (2020) and they show substantial improvements compared to the standard WRF forcing files used for Antarctica (which exhibited no topographical information over the Vestfold Hills).

3 Synoptic Evolution and Precipitation Distribution

At 00:00 UTC on 08 January 2019 a potential vorticity (PV) cutoff is located to the north of Davis (Fig. 4) and is associated with a surface cyclone. This system advects moisture polewards on its eastern flank, as can be seen by the large meridional moisture transport of around 500 $\mathrm{kg\,m^{-1}\,s^{-1}}$. This moisture advection is organized into a narrow filament of large integrated water vapor (IWV, up to 15 $\mathrm{kg\,m^{-2}}$) extending meridionally over several thousand of kilometers and resembling an AR. As explained in Gorodetskaya et al. (2014), the thresholds used to define ARs in the midlatitudes (e.g. Ralph et al., 2004, 2006) cannot be applied to the much drier and colder Antarctic environment. For this reason, Gorodetskaya et al. (2014) proposed a threshold on IWV based on the zonal mean saturated IWV, which is consistent with the idea that ARs are outstanding moisture transport compared to the zonal mean (Zhu & Newell, 1998). Taking the thresholds for the events described in Gorodetskaya et al. (2014), the IWV values of Fig. 4 south of 50°S along the longitude of Davis would correspond to an AR. Alternatively, Wille et al. (2019) proposed a definition of ARs based on temporal percentiles of IWV at each location. As our study does not focus on ARs and their climatological impact for Antarctic precipitation, it is out of the scope to show that this case satisfies specific ARs definitions. Nonetheless, it is noteworthy that the narrow corridor of large IWV of Fig. 4 qualitatively corresponds to an AR. We will therefore refer hereafter to this feature as an AR.

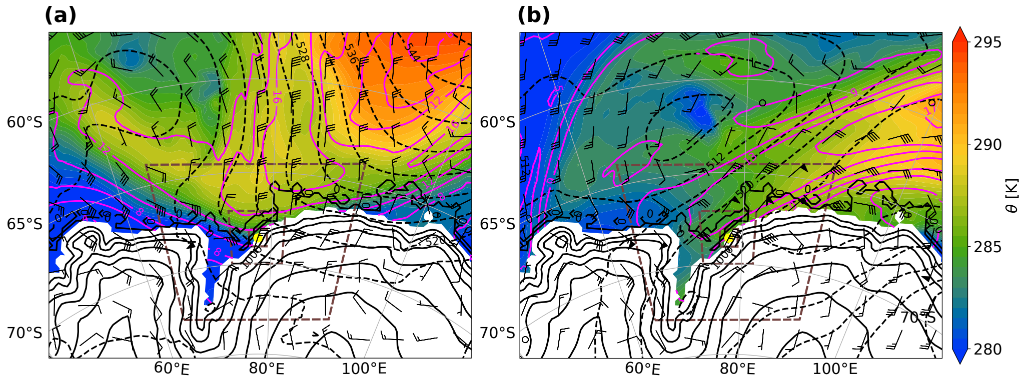

Figure 3. Synoptic map from the WRF domain at 27-km resolution at (a) 09:00 UTC 08 January 2019, and (b) 00:00 UTC 10 January 2019 of potential temperature (shading in K) and wind (barbs following meteorological standard notation) at 800 hPa, geopotential height at 500 hPa (dashed contours, labels in decameter), IWV (magenta contours, labels in $\mathrm{kg\,m^{-2}}$). The brown dashed boxes show the extent of the WRF domains at 9, 3, and 1 km resolution (from the largest to the smallest domain respectively). The yellow dot shows the location of Davis on the Ingrid Christensen Coast on the eastern side of Prydz Bay. The Lars Christensen Coast is on the western side of Prydz Bay.

The warm front of this extratropical cyclone is visible as a sharp temperature gradient to the north of Davis, while a cold air pool is located ahead over Prydz Bay (Fig. 3a). The thermal wind at this sharp temperature boundary leads to a barrier wind (van den Broeke & Gallée, 1996), which can be noticed in the wind fields of Figs 3a. Once the cold air pool has been eroded by advection and mixing of warm air associated with the passage of the warm front, the barrier wind is not present anymore (Fig. 3b). This together with a north-easterly flow at all heights (Fig. 5b and 6d) as the surface cyclone moves eastwards allows the atmospheric river to make landfall on the Lars Christensen Coast, discharging its moisture on the steep slopes of the ice sheet (IWV in Fig. 3b).

With the passage of a warm front and the presence of an AR, all the ingredients for intense precipitation over Prydz Bay are present, from a large-scale perspective. Figure 2 shows that there is indeed significant precipitation accumulation of up to 85 mm in 60 h. However, the spatial distribution of precipitation is very heterogeneous and shows two striking features. First, the largest accumulation is on the Lars Christensen Coast, where most of the AR makes landfall on the steep slope at the northenmost part of the coast. Second, on the Ingrid Christensen coast (i.e. where Davis is located) some wave patterns of precipitation accumulation appear with the maxima (minima) located windward (leeward) of the main ridges. Most of all, Davis is located in the broadest dry area in the lee of a ridge.

4 The Evolution of Snowfall and Orographic Gravity Waves Over Davis

In this section, we analyze the evolution of the local dynamics and snowfall microphysics over Davis to understand which processes led to the dry area over the Vestfold Hills, despite the intense large-scale moisture advection during this event. We divide the event into three distinct phases.

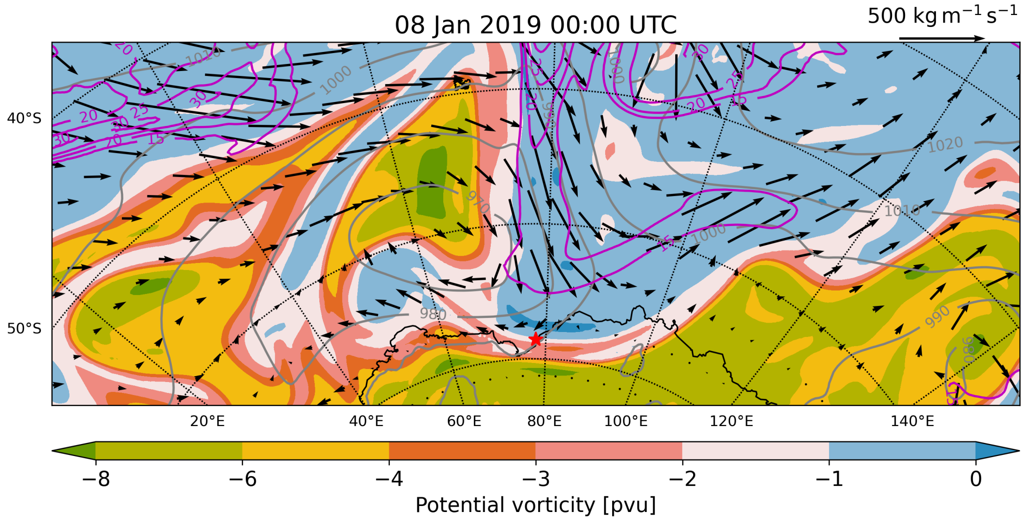

Figure 4. Synoptic situation at 00:00 UTC 08 January 2019 from ERA5 data. Potential vorticity (shading in potential vorticity unit (pvu) = $\mathrm{K\,m^2\,kg^{-1}\,s^{-1}}$) at the 315 K isentrope, mean sea level pressure (gray contours, labels in hPa), integrated water vapor (magenta contours, labels in $\mathrm{kg\,m^{-2}}$), and integrated vapor transport (arrows in $\mathrm{kg\,m^{-1}\,s^{-1}}$).

4.1 Phase I: Passage of the Warm Front and Trapped Orographic Gravity Waves, 02:00 to 15:00 UTC 08 January 2019

At 00:00 UTC on 08 January pre-frontal clouds are present over Davis and by 04:00 UTC a nimbostratus cloud with reflectivity values of up to 15 dBZ is extending to almost 8000 m (Fig. 5a). At 12:00 UTC the air is subsaturated w.r.t. ice below 1800 m a.s.l (blue dashed line in Fig. 6b) and snowfall sublimates completely before reaching the ground. In this dry layer, turbulence can be seen as a succession of intense up and downdrafts in BASTA mean Doppler velocity before 14:00 UTC below 2000 m. These large vertical velocities are qualitatively well represented by WRF (green contours in Fig. 5b), although the magnitude is underestimated. The passage of the warm front can be seen as a sharp increase of the -10 °C isotherm altitude at 10:00 UTC and is associated with strong turbulence, a faster decrease of pressure and increase in wind speed.

The sharp temperature gradient between the cold air pool over Prydz Bay and the warm front (Fig. 3a and 7a) causes a strong thermal wind which can be clearly seen before 10:00 UTC with backing winds with height (Fig. 5b), consistent with warm air advection in the Southern Hemisphere. The barrier wind (Fig. 3a) resulting from this temperature gradient deflects the moist flow such that the Lars Christensen Coast is protected from intense precipitation at this early stage of the event. The thermal wind provides the ideal orientation (north-easterly) for the generation of OGWs along the Ingrid Christensen Coast, while the warm front produces large-scale lifting and likely enhanced the updrafts in the OGWs (Fig. 7a). The flow-topography interaction leads to a Foehn effect in the lee of the ridge with clear isentropic drawdown (e.g. Damiens et al., 2018), negative vertical velocity, and a relatively dry air tongue extending even downstream of Davis station (Fig. 7b). An hydraulic jump at the base of the ice plateau is also evident in Fig. 7b and manifests as a strong updraft extending up to 3500 m. Note that the Vestfold Hills correspond to the dry zone directly in the lee of the ridge, while most of the precipitation fall upstream of the ridgeline and downstream of Davis (bars in Fig. 7).

There is a layer with enhanced static stability between 3500 and 4000 m downstream of Davis (as indicated by the closer isentropes in Fig. 7b), the vertical wind shear below this layer is weak and the thermal wind is mostly present inside and above it, with wind shifting from east-northeasterly at 3000 m to northerly at 4000 m. This layer of enhanced static stability is partly due to the hydraulic jump and subsequent flow separation, which makes the isentrope downstream of the jump and below 1800 m move apart, leading to a boundary layer destabilization (Vignon et al., 2020). OGWs are trapped at low levels downstream of the jump (Fig. 7b), but extend vertically up to the layer of increased static stability ($\sim$3500 m). This corresponds to the case of waves propagating on a temperature inversion located close to the surface (i.e. $\sim$1000 m, Fig. 6a) as described in Sachsperger et al. (2017).

From a microphysical perspective, two main zones of aggregation can be identified during the event: (i) from 08:00 to 16:00 UTC on 08 January between 1000 and 4000 m, and (ii) from 20:00 UTC 09 January to 04:00 UTC 10 January between 2000 and 4000 m. While the latter belongs to Phase III and will be further discussed in Sect. 4.3, we discuss their common features here. In both cases the maxima of DFR are collocated with zones dominated by aggregates in MXPol hydromoteor classification and with maxima of mean particle mass diameter (D_{mean}) from WRF (Fig. 5c and d, respectively). Note that these aggregation zones are located at temperatures above -20 °C (Fig 5a), which represent favorable conditions for significant aggregation (Connolly et al., 2012; Hobbs et al., 1974; Phillips et al., 2015). Although the DFR and MXPol hydrometeor classification are not totally independent (they both use Z_X), the other variables used clearly point towards aggregation (minimum of Z_W due to Mie scattering regime, visible in Fig. 5a, which strongly contributes to the maximum of DFR, and low Z_{DR} in Fig. 8b interpreted as aggregates in MXPol classification). This spatio-temporal agreement between dual-polarization and dual-frequency variables makes our identification of aggregation robust. The simulation of D_{mean} from WRF is qualitatively consistent with the DFR in the aggregation layer (Fig. 5d) and shows that WRF is able to reproduce the zones of dominant aggregation.

Figure 8 shows a layer of enhanced Z_{DR} varying between 2000 and 4000 m during Phase I. This layer represents the end of depositional growth and the start of aggregation. Below this layer, Z_{DR} decreases drastically, while Z_H increases and reaches its maximum of 22 dBZ at 1500 m. This is due to intense aggregation taking place from 3000 to 1200 m, as can also be observed by the increase in aggregates' proportion in Fig. 5c and is consistent with DFR observation and D_{mean} simulation of WRF in Fig. 5d. Figure 9a shows an RHI representative of Phase I. The layers of enhanced Z_H and Z_{DR} are clearly visible at 2000 and 3000 m, respectively. The aggregation below 3000 m could be favored by the turbulence generated by the strong vertical motions within the OGWs (Fig. 7b) and then advected downstream to Davis. The Doppler spectrum shown in Fig. 9 supports our microphysical interpretation: the depositional growth above 3000 m leads to a slight increase in the magnitude of Doppler velocity and reflectivity, while the aggregation below 3000 m causes a sharp increase in the same variables. When the aggregates enter the updrafts within the OGWs at 2200 m, the magnitude of Doppler velocity decreases and the spectral width increases due to the turbulence. This favors continuous aggregation until 1200 m, where the snowflakes sublimate. The vertical extent of the updraft as shown in this Doppler spectrum is consistent with the OGWs simulated by WRF and shown in Fig. 7b.

In summary, the thermal wind enhanced by the cold air pool over Prydz Bay ahead of the warm front provides the ideal flow direction below 2000 m for the generation of OGWs. A Foehn effect manifesting as an isentropic drawdown in the lee of the ridge is followed by an hydraulic jump that favors the trapping of gravity waves downstream.

The relatively dry Foehn air that flows at low levels down to Davis station leads to total snowfall sublimation below about 1500 m above the station and explains the dry area extending over the Vestfold Hills. The OGWs also affect the snowfall microphysics by providing ideal conditions for aggregation through the generation of updrafts and turbulence.

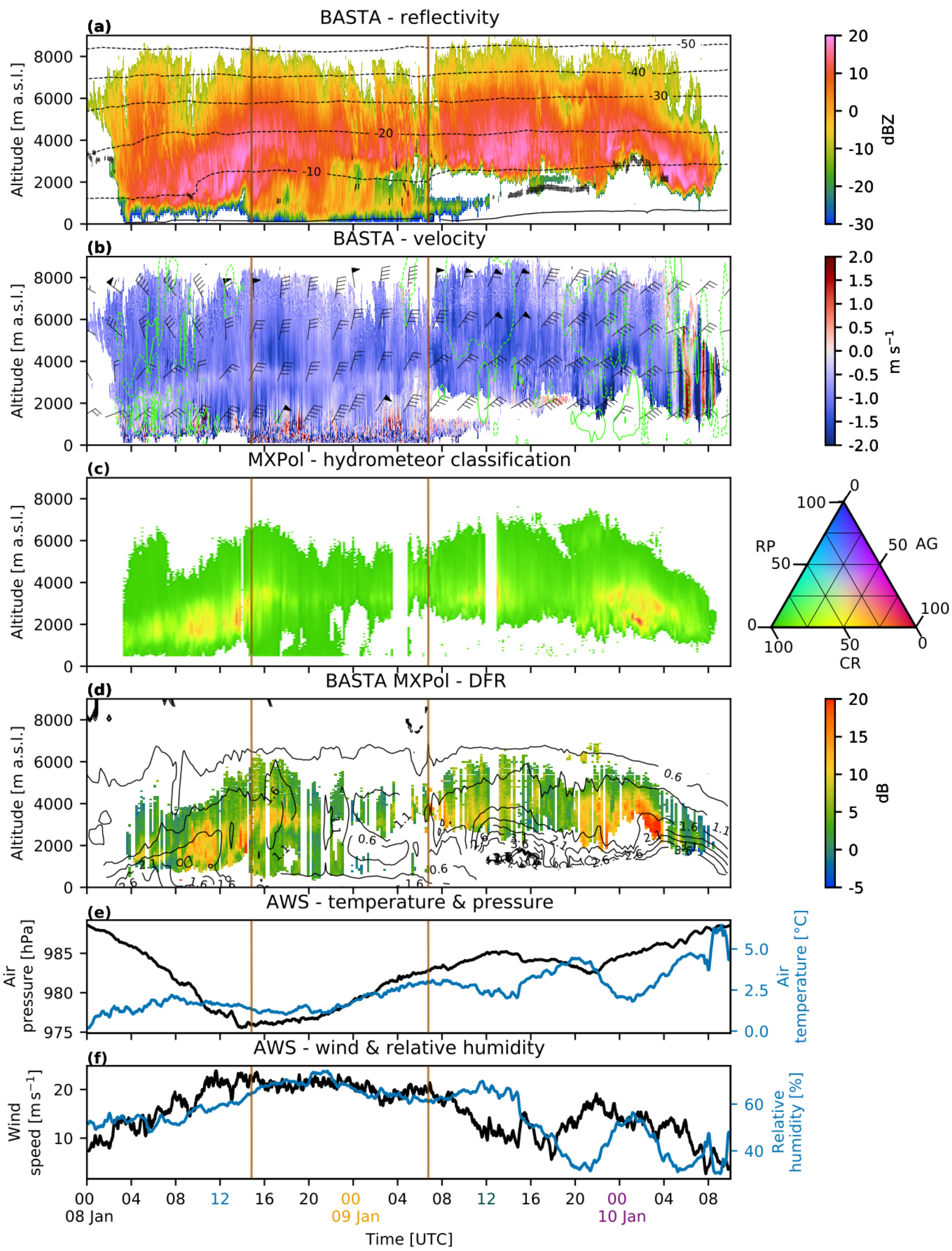

Figure 5. Time series from 00:00 UTC 08 January to 10:00 UTC 10 January 2019 of (a) reflectivity of BASTA (shading), isotherms of WRF (black contours, labels in °C) and SLW from RMAN cloud classification data (black shading), (b) mean Doppler velocity from BASTA (shading, defined positive upwards), horizontal wind from VHF (barbs following meteorological standard notation), and vertical wind speed from WRF (green contours every 0.4 m s^{-1}, continuous for upwards, dashed for downwards), (c) hydrometeor classification based on all MXPol RHIs (shading, see Sect. 2.0.1), (d) DFR from MXPol and BASTA (shading, see Sect. 2.0.2) and D_{mean} from WRF (contours, labels in mm), (e) air temperature and pressure from the AWS, and (f) wind speed and relative humidity with respect to liquid water from the AWS. The colors of the 00:00 and 12:00 UTC labels correspond to the radiosoundings shown in Fig. 6.

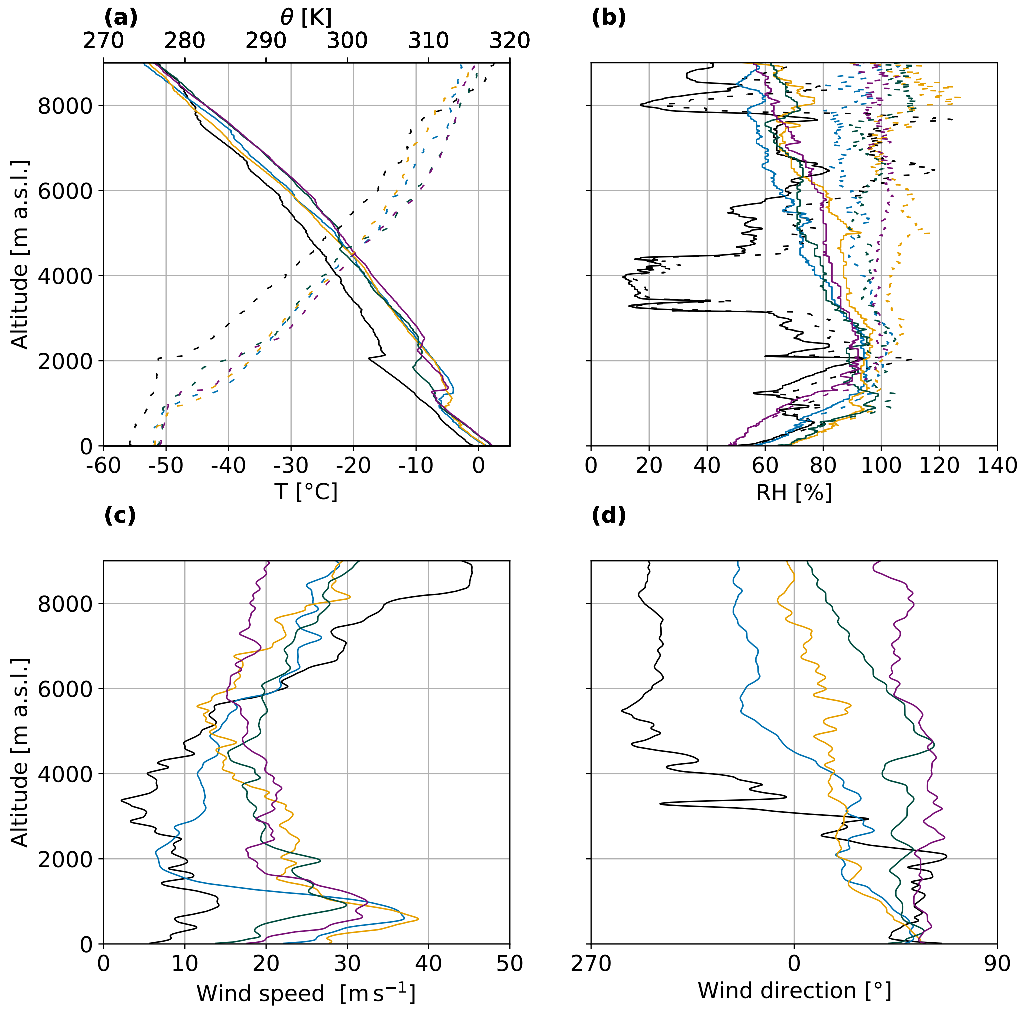

Figure 6. Radiosoundings launched at Davis station on 08 January at 00:00 UTC (black) and 12:00 UTC (blue), on 09 January at 00:UTC (yellow) and 12:00 UTC (dark green), and on 10 January at 00:00 UTC (purple) of (a) temperature (T, solid lines) and potential temperature (θ, dashed lines), (b) relative humidity with respect to liquid (solid lines) and ice (dashed lines), (c) wind speed, and (d) wind direction.

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4.2 Phase II: Northerly Flow and Light Precipitation at Davis, 14:00 UTC 08 January to 07:00 UTC 09 January 2019

As the warm front passes, the stable layer at around 4000 m dissipates, the thermal wind weakens, and the synoptic flow becomes north-northeasterly (Fig. 10a). As a consequence, winds are oriented more northerly at all heights (Fig. 5b at 16:00 UTC 08 January). As can be seen in Fig.10a, a north-northeasterly flow will not impinge perpendicularly to the ridge located to the north-east of Davis, but rather to the ridge located further south where the strongest OGWs are present. The collocation of the warm front with these intense OGWs, as during Phase I, suggests that it provides large-scale

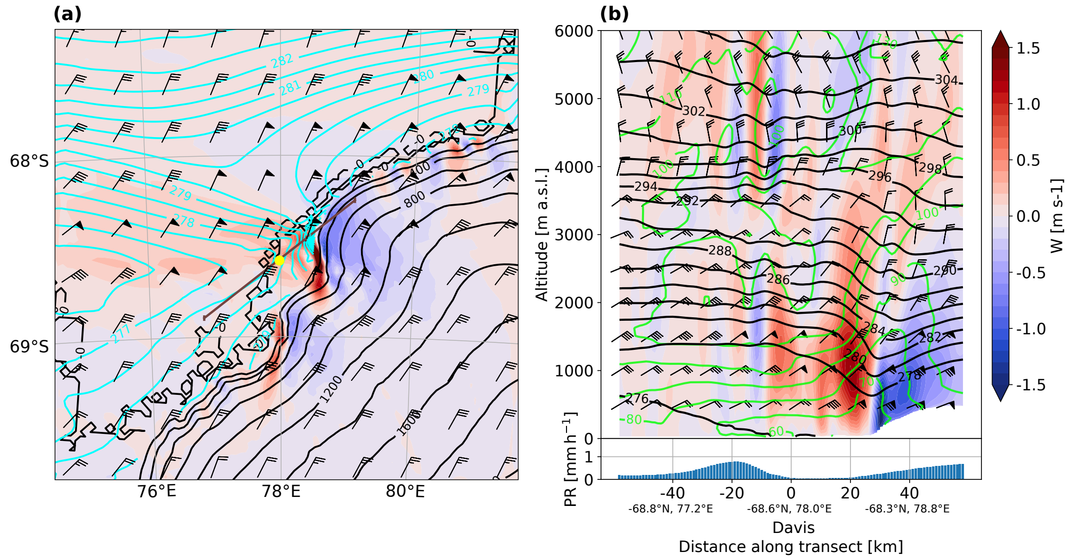

Figure 7. WRF output on 08 January 2019 at 09:00 UTC. (a) map of the 3-km resolution domain of vertical wind velocity (shading in $\mathrm{m\,s^{-1}}$), horizontal wind (barbs following meteorological standard notation), and potential temperature (cyan contours) at 850 hPa (about 1200 m a.s.l.). The black contours show the topography (labels in m a.s.l.). (b) cross-section of the 1-km resolution domain, corresponding to the brown line in (a), of vertical wind velocity (shading in $\mathrm{m\,s^{-1}}$), potential temperature (black contours, labels in K), RHi (green contours, labels in %) and horizontal wind (barbs following meteorological standard notation) and precipitation rate along the cross-section (blue bars in mm^{-1}).

lifting enhancing the updrafts. Along with the absence of intense low-level OGWs over Davis, the Foehn effect weakens (relative humidity increases and air temperature decreases, Fig. 5e-f). The increase in relative humidity can be seen in the whole boundary layer (Fig. 6b). It allows light precipitation to reach Davis between 14:00 UTC 08 January and 06:00 UTC 09 January. The absence of low-level trapped OGWs during Phase II coincides with much less aggregation than during Phase I. Indeed, the layer of aggregation is less intense and confined between 3000 and 4000 m before disappearing completely after 20:00 UTC 08 January (Fig. 5c-d). The reflectivity values at both X- and W-bands are also weaker (Fig. 5a and d). Although reflectivity is significantly lower during this period, snowfall reaches the ground since sublimation is less intense. While the Foehn effect is less pronounced during Phase II, it is enough to cause partial snowfall sublimation below about 2000 m (Fig. 5a).

The most intriguing radar signature during Phase II is the minimum of Doppler velocity observed around 3000 m, in particular between 14:00 and 20:00 UTC on 08 January (Fig. 5b). A careful investigation of the spectrograms from MXPol PPIs at 90° elevation revealed that this minimum is due to an updraft varying between 0.5 and 1 $\mathrm{m\,s^{-1}}$. Figure 11b shows an example of such a spectrogram, where a bimodality is present just above the updraft layer. Almost all spectrograms during the period where this minimum in Doppler velocity is observed featured both a decrease in the magnitude of the mean Doppler velocity and a bimodality. To ensure that this minimum in Doppler velocity is due to an updraft and not only to the contribution of the secondary mode in decreasing the magnitude of the mean Doppler velocity, we computed the velocity of the primary mode only (not shown), which revealed the same behavior as the mean Doppler velocity showed in Fig. 5b. This updraft tends to broaden the spectrum and skew the

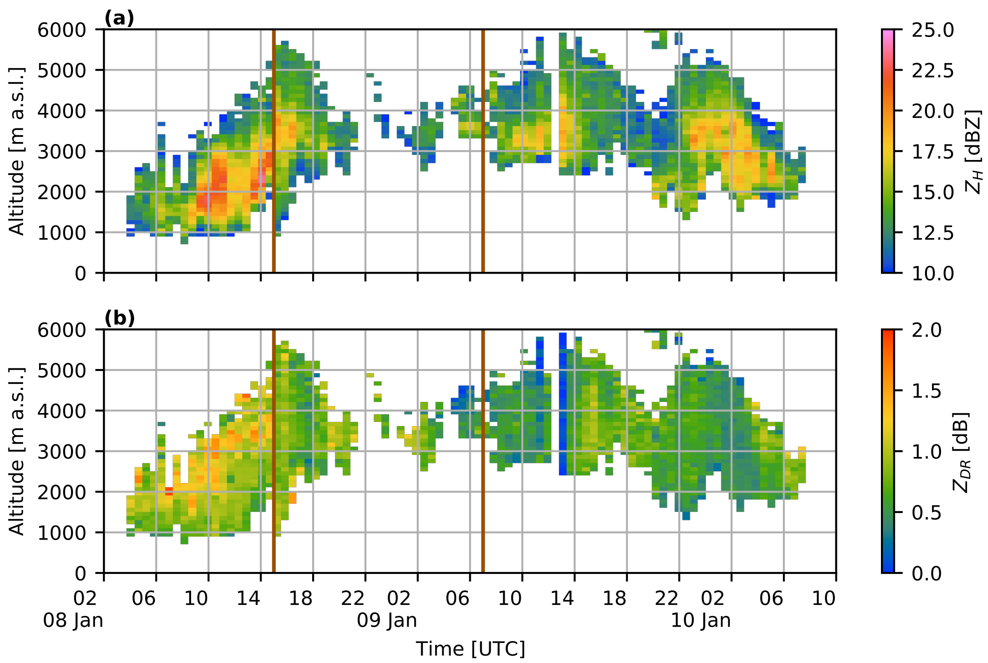

Figure 8. Time series of MXPol Z_H (a) and Z_{DR} (b) from 02:00 UTC 08 January to 10:00 UTC 10 January. The profiles were extracted from the RHIs at 23° and 52° elevation from 6000 to 10000 m range and for elevation angles greater than 135°.

distribution towards smaller magnitudes of Doppler velocity (Fig. 11). The increase in spectral width is due to the turbulence in the updraft, similar to turbulence present in other summertime cloud systems which were observed by ship-based remote sensors near Davis and Mawson (650 km west of Davis, Alexander et al., 2021). Note that it is much lighter than the turbulence observed in the boundary layer below 1000 m. The increase in skewness could be due to a size sorting effect by the updraft. The size sorting cannot however totally explain the bimodality, since it is unlikely to create such a discontinuity in the Doppler spectrum. We hypothesize that the bimodality is due to secondary ice production through collisional breakup of ice crystals (Takahashi et al., 1995; Vardiman, 1978) at the top of the updraft. A recent study by Sotiropoulou et al. (2021) showed that breakup could account for the enhanced number concentration of ice crystals often measured in Antarctic clouds (Young et al., 2019). They also showed that a minimum concentration as low as $\sim$0.1 L^{-1} of primary ice crystals is sufficient. Considering the measured reflectivity during this event, the primary ice concentration is probably much above this threshold. Furthermore, for secondary ice production through breakup to be efficient, snowflakes have to be partially rimed. Despite the lidar signal being almost totally attenuated, some regions of SLW (black shading in Fig. 5a) at around 3000 m are visible during Phase II, suggesting that riming can at least partially occur. The MXPol hydrometeor classification however does not show significant occurrences of rimed particles during Phase II, likely due to its sensitivity to large rimed particles, which are not present here considering the low reflectivity values. Also, it requires a certain degree of riming for particles to be classified as rimed, which means that the crystals category can contain some rime. Moreover, photographs of snowflakes (only nine due to the strong wind) taken by a snowflake imager (not shown) during Phase II revealed the presence of small graupel particles, which confirm that SLW must have been present. Finally, Takahashi et al. (1995) showed that breakup was the most efficient at -16 °C, which corresponds

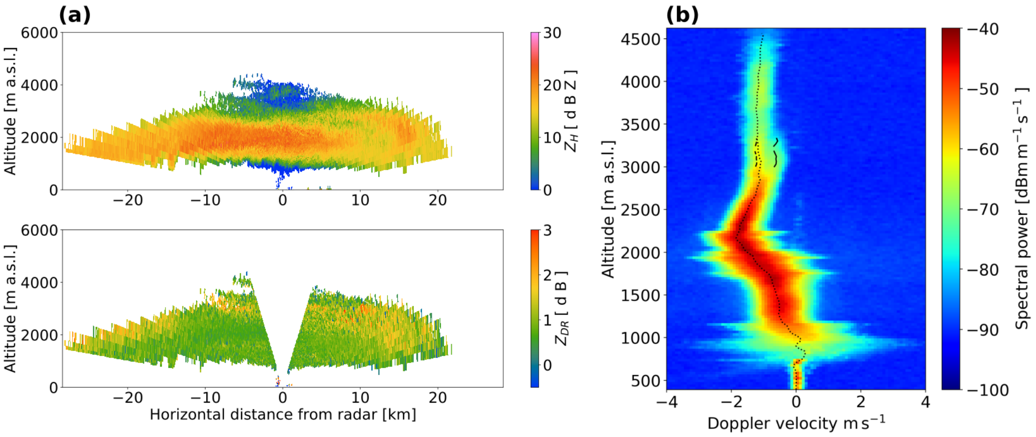

Figure 9. (a) MXPol RHI at 52° azimuth (yellow line in Fig. 1) at 09:27 UTC 08 January of Z_H, and Z_{DR}. (b) MXPol Doppler spectrogram averaged over a PPI at 90° elevation at 09:24 UTC 08 January. The dotted line shows the mean Doppler velocity, the dashed and solid lines show, if present, the velocity of the first and second mode, respectively.

to the temperature at which we observe this bimodality (Figs 5a and 6a). Other secondary ice generation processes involving significant SLW amounts, such as rime splintering (so-called Hallett-Mossop process, Hallett and Mossop (1974)) and droplet shattering (Korolev & Leisner, 2020), are less likely to dominate here, since we have no evidence for the required SLW amounts at this height. In particular, the Hallett-Mossop process operates at temperatures between -3 and -8 °C whereas we observe this bimodality at a temperature of -15 °C.

As to the origin of this updraft observed between about 3000 and 4000 m from 12:00 to 20:00 UTC, Fig. 10b shows that a gravity wave train propagating downstream of the ice-ridge is present between 3000 and 5000 m above Davis. In particular, a maximum of vertical wind speed is observed above the Vestfold Hills at 3500 m, which corresponds to the altitude at which the updraft is observed in the radar data (Fig. 5b and 11b). This feature is quasi-stationary in the WRF simulation during the whole period where we observe the minimum in Doppler velocity in Fig. 5b, suggesting that this updraft is probably due to the gravity wave train between 3000 and 5000 m shown in Fig. 10.

In summary, Phase II is characterized by a north-northeasterly flow at all heights, which prevents the formation of intense low-level OGWs as during Phase I and consequently the Foehn effect is weaker and snowfall only partially sublimates. Nonetheless, quasi-stationary OGWs are present between 3000 and 5000 m and lead to a minimum in the magnitude of mean Doppler velocity and possibly secondary ice production.

4.3 Phase III: North-Easterly Flow and Nonstationary Orographic Gravity Waves, 07:00 UTC 09 January to 10:00 UTC 10 January 2019

Starting from 07:00 UTC on 09 January OGWs, which propagate vertically further than the low-level trapped gravity waves of Phase I, formed at the base of the ice plateau 20 km upstream from Davis (not shown). At around 14:00 UTC temperature rises, while relative humidity decreases as the Foehn effect intensifies again (Fig. 5f). This coincides with winds below 4000 m becoming increasingly easterlies (Fig. 5b) due to the configuration of the upper-level low (Fig. 3b). This north-easterly flow impinges the ridge

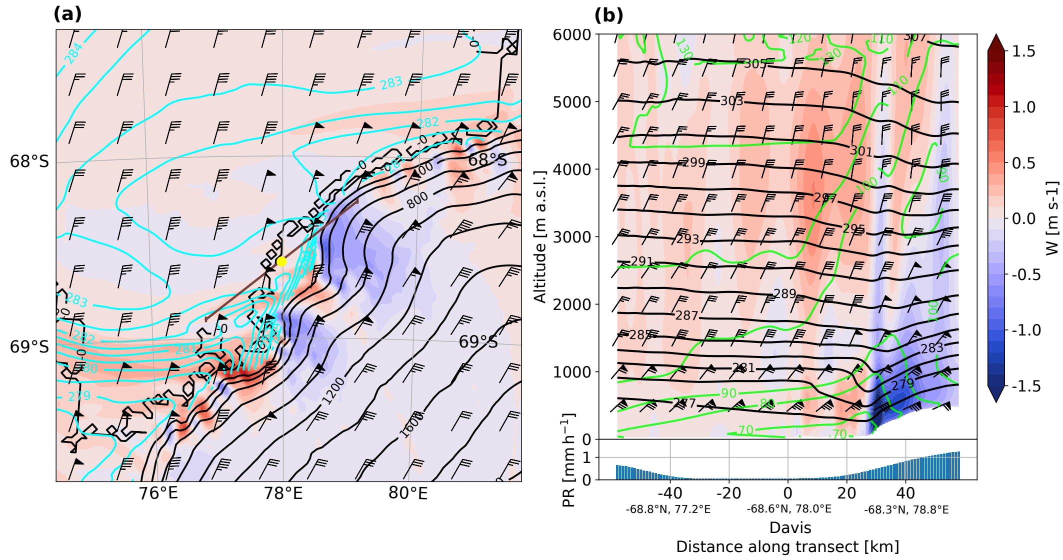

Figure 10. As for Fig. 7 except at 18:00 UTC 08 January 2019.

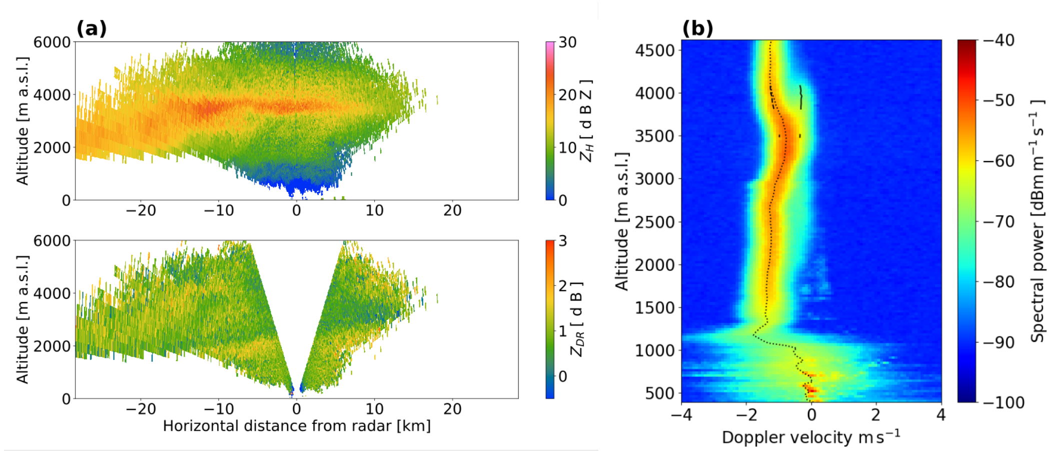

Figure 11. As for Fig. 9 except at (a) 16:03 and (b) 16:10 UTC 08 January.

upstream of Davis perpendicularly and generates a band of updrafts oriented along the ridge line (Fig. 12a).

After 14:00 UTC, the air temperature is anti-correlated with the relative humidity (Fig. 5e-f), which supports our hypothesis of a Foehn wind event. Indeed, Kirchgaessner et al. (2021) showed that temperature and relative humidity are in antiphase during Foehn events in the Antarctic Peninsula. The overall increase in temperature during the event is a combination of the passage of the warm front and of a Foehn wind. The shorter phases of temperature and relative humidity oscillations at the end of the event are due to the rapid successions of up and downdrafts that brought the temperature up to 6 °C.

From about 20:00 UTC 09 January to 04:00 UTC 10 January a zone of intense aggregation is present (Fig. 5c-d). The high values of D_{mean} simulated by WRF is once again qualitatively consistent with the high values of DFR, especially between 22:00 UTC 09 January and 00:00 UTC 10 January. The zone of dominating aggregates in MXPol classification corresponds well to the high values of DFR and shows also some rimed particles (red-magenta shading in Fig. 5c). The lidar also detected SLW just above this mixture of aggregates and rimed particles. Note that the presence of hydrometeors further down in MXPol classification compared to BASTA is because all RHIs at an horizontal range greater than 6 km have been considered in MXPol classification, showing that the height of sublimation significantly varies spatially. Unlike during Phase I, where the zone of aggregation was topped by a layer of intense depositional growth leading to high Z_{DR} values, during Phase III the layer of aggregation is topped by smaller Z_{DR} values (Fig. 8) and aggregation is identified solely by the increase in Z_H and DFR.

On 10 January between 04:00 and 09:00 UTC, nonstationary OGWs trapped in the low- and mid-troposphere can be seen as a succession of intense up and downdrafts with Doppler velocities of more than 2 $\mathrm{m\,s^{-1}}$ and a periodicity of about an hour (Fig. 5b). The nonstationary nature of these OGWs likely owes to the decrease in wind speed upstream of the ridge (compare Fig. 10a and 12a). WRF simulations revealed that the OGWs are propagating upstream (not shown). We hypothesize that this upstream propagation is a consequence of the the gravity wave train adapting to the weaker forcing, which leads to nonstationary OGWs (Nance & Durran, 1997). These OGWs are qualitatively well represented by WRF (Fig. 5b): one can see a succession of up and downdrafts with similar vertical extent and phase than in the Doppler velocity, although the magnitude is underestimated and the phase shifted. These vertical motions strongly affect the vertical structure of the cloud as can be seen by the fluctuating level of maximum reflectivity (Fig. 5a). This can also be seen in MXPol measurements (Fig. 13), where the OGWs lead to an oscillation of the height of sublimation and to a shift of the whole Doppler spectrum. The mean Doppler velocity at cloud top is of about -2 $\mathrm{m\,s^{-1}}$ and its magnitude increases with decreasing height as the hydrometeors likely become denser and fall faster. The rapid change from about -3 to -4 $\mathrm{m\,s^{-1}}$ at 2000 m is probably due to an increase in the magnitude of the downdraft. The horizontal wavelength of the OGWs is about 10 km and is consistent between MXPol measurements and WRF simulation (Figs 13b and 12b). The OGWs are also associated with rapid fluctuations of temperature and relative humidity (Fig. 5f). These OGWs become visible (compared to earlier phases) in a time-series of vertical Doppler velocity above Davis because (i) they are nonstationnary, (ii) they are present far enough downstream of the ice plateau and (iii) they are sufficiently strong to lift the hydrometeors and hence lead to positive vertical Doppler velocities. Note that these strong OGWs coincide with winds shifting to easterlies for the first time during the event around 3000 m, showing again that their generation depends on the wind direction.

In summary, Phase III is characterised by a north-easterly flow generating nonstationnary OGWs, which are evident in vertical Doppler velocity measurements and lead to a fluctuation of the level of sublimation.

4.4 Summary of the three phases

Figure 14 shows a conceptual model of the three phases of the event. During Phase I, Davis is located just ahead of the warm front and the low-level flow is north-easterly. The cold front is directing the AR meridionally to the coast with precipitation maxima on the windward slopes ahead of the warm front (Fig. 14a, orange shading). Due to the sharp horizontal temperature gradient between the cold air pool over Prydz Bay and the warm sector of the cyclone, the thermal wind is directed to the east and leads to backing winds with height. This thermal wind leads to a barrier wind over Prydz Bay, which protects the Amery Ice Shelf from the large-scale flow. The north-easterly flow provides the ideal conditions for the generation of trapped OGWs, which are excited at the temperature inversion at the top of the boundary layer. The turbulence at the top of the OGWs enhances aggregation, which is visible in the hydrometeor classification (Fig. 5c), the maxima of DFR (Fig. 5d), and the polarimetric variables (Fig. 8). Despite the advection of moisture by the AR and the intense aggregation, the Foehn effect creates a

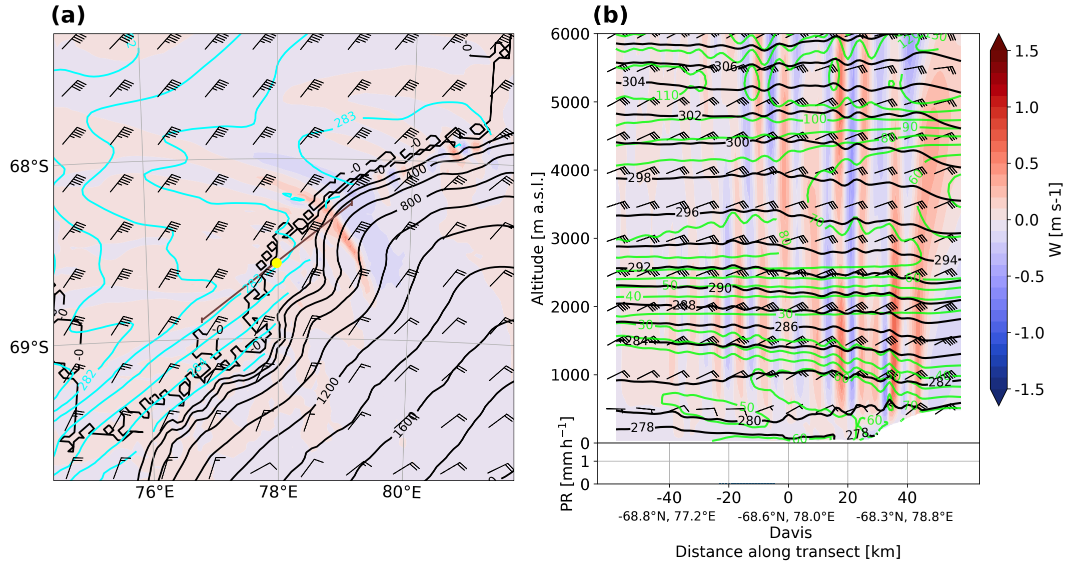

Figure 12. As for Fig. 7 except at 07:00 UTC 10 January 2019.

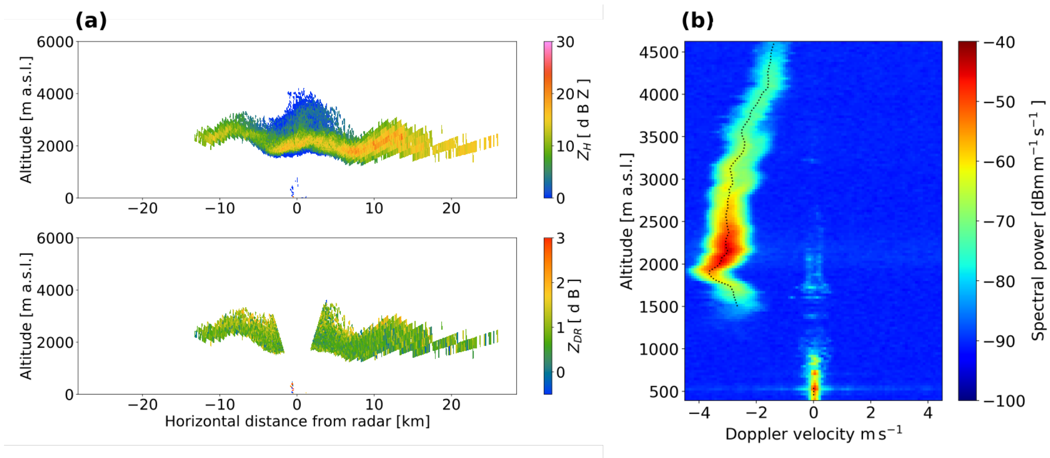

Figure 13. As for Fig. 9 except at (a) 07:02 and (b) 07:00 UTC 10 January.

tongue of relatively dry air that spreads over the Vestfold Hills leading to sublimation of snowfall below 1000 m a.s.l., as can be seen in the reflectivity profiles (Fig. 5a).

During Phase II, the surface cyclone has moved eastwards. Davis is in the warm sector, the cold air pool has been eroded, which allows the moisture advected by the AR to enter Prydz Bay, leading to precipitation maxima on the windward slopes of the Ingrid Christensen Coast. Another consequence after the passage of the warm front is the weaker horizontal temperature gradient over Davis, which reduces the thermal wind, such that the flow is north-northeasterly at all heights (Fig. 14e). Since the flow is north-northeasterly, it does not impinge on the orography upstream of Davis, which prevents the generation of low-level OGWs above Davis. As a result, the boundary layer is moister, the sublimation is less intense and snowfall does reach the ground at Davis. The absence of low-level OGWs coincides with the lack of intense aggregation, which leads to overall smaller reflectivity values than during Phase I. A layer of moderate updrafts ($\sim 1\,\mathrm{m\,s^{-1}}$) between about 3000 m and 4000 m could be identified in Doppler velocity measurements and the WRF simulation and is attributed to a gravity wave train located downstream of the ridge

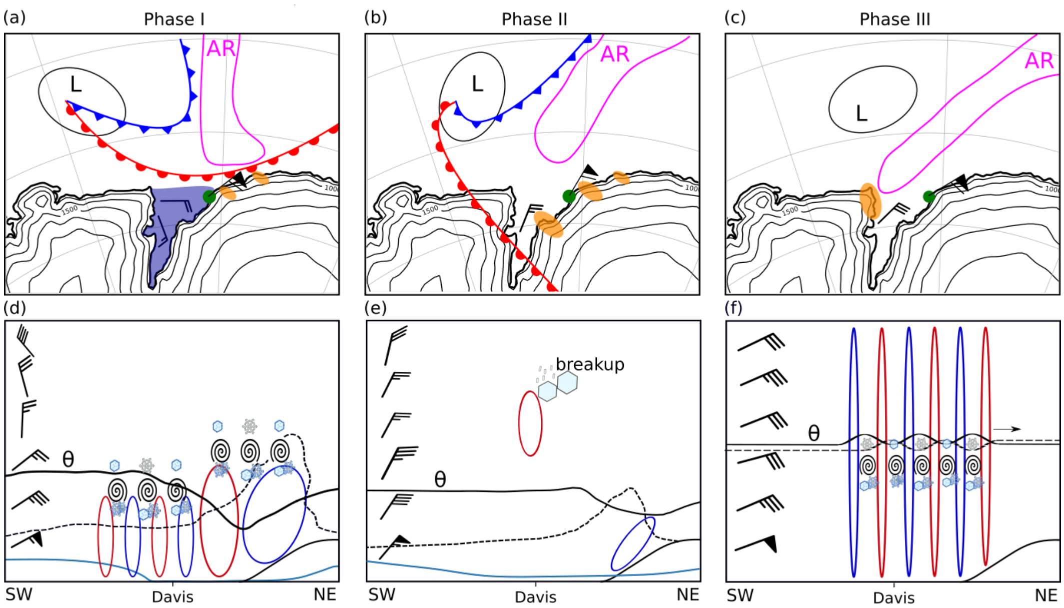

Figure 14. Conceptual model of the three phases of the event. (a)-(c) maps as in Fig. 3. "L" represents the low pressure system, the blue area the cold air pool. The orange shapes represent precipitation maxima, the green dot Davis. (d)-(f) cross-sections as in Fig. 7b. The blue and red shapes show downdrafts and updrafts respectively. The black line in the bottom panels show an isentrope, the dashed line the height of saturation with respect to ice, and the blue line the qualitative variation of precipitation rate along the cross-section. Only the main microphysical processes are represented.

to the north-east of Davis. This moderate updraft is also associated with a bimodality in radar Doppler spectra, which is likely due to secondary ice production by collisional breakup of ice crystals.

During Phase III, the low pressure system has split in two, the fronts have moved eastward with one of them, while the other one is directing the AR to the north of the Lars Christensen Coast, leading to the largest precipitation accumulation over the whole event (Fig. 2). The flow is oriented north-easterly at all heights providing the ideal conditions for the generation of OGWs. As opposed to the OGWs during Phase I, they are nonstationnary and lead to a succession of strong up and downdrafts with a period of about 1 h visible in Doppler velocity measurements (Fig. 5b). The vertical gradient of relative humidity below 2000 m is the largest of the event (Fig. 6b) and lead to total sublimation within about 200 m of cloud base. Phase III marks the end of the event, before the PV cutoff and associated low pressure decays and a high-pressure ridge directs a dry flow to Prydz Bay (not shown).

5 Climatological perspective

A question that arises from the results of this case study is: how representative is it in the climatology? We consider this question in this section, by discussing the possible climatological implications of our results using ERA5 reanalysis. Figure 2 indicated that orography played a major role in the distribution of precipitation during this event. This is supported by the results shown in Sect. 4 and we showed that the direction of the large-scale flow with respect to the orography dictates the precipitation accumulation pattern. Given that north-easterly is the most frequent flow direction during precipitation events over Davis (Fig. 4 of Vignon et al., 2019), one might suspect that the precipitation accumulation shown in Fig. 2 could be climatologically representative. This is supported by the ERA5 climatology (Fig. 15a), which shows a maximum on the Lars Christensen Coast, in particular in its northernmost part, while the Ingrid Christensen Coast is much dryer, especially the region around the Vestfold Hills. This distribution is remarkably similar to the one of this event (Fig. 2), suggesting it is representative of the January climatology in terms of spatial distribution. The contribution of this event to the annual total precipitation of 2019 is up to 8% in the interior of the Lars Christensen Coast and around 2 % in the Vestfold Hills (Fig. 15b). By comparing Fig. 15a with Fig. 2, we note that this event exceeds the January precipitation climatology over the northern part of the Lars Christensen Coast. This shows that this event can be qualified as extreme for the Lars Christensen Coast.

Figure 15 only allows us to compare the precipitation distribution of our case study with the climatology, but does not make it possible to ascertain the main synoptic configurations associated with intense precipitation over Prydz Bay. Some recent studies however allow us to bring the large-scale features of our case study in a climatological perspective. Yu et al. (2018) studied the synoptic patterns associated with extreme precipitation at Progress station, which is located 110 km to the south-west of Davis on the Ingrid Christensen Coast. They found out that a dipole structure with a low (high) geopotential height anomaly to the north-west (north-east) of Prydz Bay together with a northeasterly advection of moisture is the dominant synoptic pattern associated with extreme precipitation at Progress station. They also mention that the ascending motions over Progress station provides favorable conditions for extreme precipitation. This synoptic description resembles the one presented in Sect. 3, suggesting that the synoptic conditions of our case study can be representative of extreme precipitation over Prydz Bay. Further recent studies showed that Prydz Bay is prone to intense precipitation events by enhanced meridional moisture advections. First, Turner et al. (2019) showed that 50% of the annual precipitation is received in less than 10 days of the heaviest precipitation over the Amery Ice Shelf. They attribute this to quasi-stationary depressions, which can occasionally transport moisture far into the Amery Ice Shelf in regions normally sheltered by the orography. The quasi-stationary nature of the PV cutoff described in Sect. 3 and the fact that it directs an increasingly more easterly flow (ideal for orographic enhancement on the the Lars Christensen Coast) explains the relatively high contribution to the 2019 annual precipitation on the Lars Christensen coast (Fig. 15b). Second, Portmann et al. (2020) showed that Prydz Bay is located poleward of the band of high frequency of PV cutoffs around Antarctica (their Fig. 3). Furthermore, Ch. 3 of Portmann (2020) investigated the relevance of PV cutoffs for precipitation. They found that cutoffs involving enhanced meridional moisture transport contribute the most to extreme precipitation events. Since our case both features a PV cutoff to the north of Prydz Bay and intense meridional moisture transport, it suggests that similar synoptic configurations are common and do contribute to extreme precipitation over Prydz Bay. Wille et al. (2021) studied the precipitation impact of ARs in Antarctica. They showed that the frequency of ARs above Prydz Bay was about 2 days per year. They also investigated the attribution of extreme precipitation events to ARs. Their Fig. 4c shows a strong dipole over the Ingrid Christensen Coast, with the Vestfold Hills being located in a region with less than 10% of EPEs attributed to ARs, while further north-east on the coast up to 50% of EPEs are attributed to ARs. This suggests that the contribution of ARs to EPEs over Prydz Bay is highly variable, consistent with Fig. 2 and 15b. We showed that local processes can be determinant in how much an AR event contribute to the annual precipitation accumulation. Furthermore, Fig. 3b of Wille et al. (2021) shows large AR-related snowfall on the eastern sides of ice ridgelines, including the one to the north-east of Davis. The Vestfold Hills also appear as a minimum of total AR-related snowfall. This suggests that our case study is representative of large snowfall accumulation from ARs around East Antarctica. Finally, it also confirms our finding that local processes related to the orography, such as a Foehn wind, can determine the fate of large-scale moisture advec-

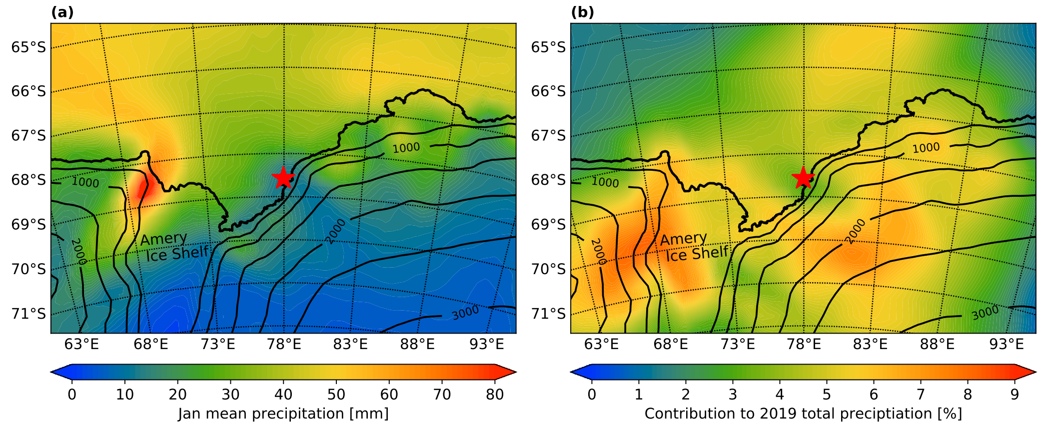

Figure 15. (a) Precipitation climatology for January computed from 1969 to 2020. Davis is marked with the red star. (b) Ratio of the precipitation accumulated from 07 January 19 UTC to 10 January 19 UTC to the 2019 annual precipitation. All data are from the ERA5 reanalysis. The black contours show the ERA5 topography in m a.s.l. The thicker contour shows the coast and the ice-edge.

tions from ARs. The study of Grazioli et al. (2017) shows that the Vestfold Hills are in a region of maximum ratio of sublimated snowfall with up to 48% of total snowfall sublimating before reaching the ground. They attribute low-level sublimation to dry katabatic winds, but they also mention that Foehn winds can play an important role in the Antarctic Peninsula. Our study shows that Foehn winds can lead to total snowfall sublimation also in East Antarctica and be as efficient as katabatics in doing so, at least at the scale of one event. While the Foehn effect is a local process, the dynamical triggering comes more often from the large-scale flow. As stated by Bozkurt et al. (2018), it is hence difficult to totally disentangle the role of local versus large-scale processes during Foehn events. In the end the interactions between the synoptic flow, the orography, and the regional-scale circulation determine the impact on precipitation.

Overall, the ERA5 climatology shown in Fig. 15 and the studies of Portmann et al. (2020), Turner et al. (2019),and Wille et al. (2021) show that we can expect the synoptic configuration of our case study to be representative of EPEs over Prydz Bay, at least in austral summer. In this view, we can hypothesize that the processes at play for snowfall sublimation over Davis shown in Sect. 4 might substantially contribute to the precipitation climatology of the Vestfold Hills.

6 Conclusions

In this study, we analyzed the precipitation distribution and microphysics associated with an intense meridional moisture transport affected by OGWs over Prydz Bay, Antarctica. The complementary nature of remote-sensing instruments and WRF simulation allowed us to link local observations with the complex dynamics of this event. We divided the event into three distinct phases. Our findings can be summarized as follows:

1. The direction of the synoptic flow was the dominant factor driving the occurrence of OGWs over Davis, with an easterly to north-easterly flow favoring the development of low-level OGWs, while a north-northeasterly flow inhibited such low-level OGWs. The presence of a statically stable layer favored the trapping of the OGWs below 2000 m during Phase I.
2. A Foehn effect produced a dry air flow that spread over the Vestfold Hills and led to total snowfall sublimation during Phase I and Phase III. During Phase II, the wind backed to north-northeasterly inhibiting the formation of low-level OGWs above Davis and hence reducing the dryness of the boundary layer, which led to light snowfall reaching the ground.
3. The turbulence generated at the top of the trapped OGWs during Phase I led to intense aggregation, which was observable in dual-polarization and dual-frequency radar variables. During Phase II, a persistent updraft associated with a mid-level stationary gravity wave train was visible in the radar Doppler velocity. Analyses of the Doppler spectrograms showed that this updraft was associated with a bimodality, which we attributed to the production of secondary ice by collisional breakup of ice particles. During Phase III, nonstationary OGWs can be clearly seen in vertical Doppler velocity measurements and lead to a fluctuation of the level of maximum reflectivity. Those OGWs are qualitatively well represented by WRF, although the magnitude is underestimated and the phase shifted.

This study showed that despite the intense meridional moisture advection by an AR, local processes tied to the orography determined the spatial and temporal distribution of precipitation over Prydz Bay. This stresses the importance of studying local effects when interpreting the impact of ARs in terms of surface precipitation at the regional scale. Moreover, it suggests that climate models projections and satellite measurements over regions where local processes dictate the precipitation patterns should be interpreted with care. Similarly to the study of Grazioli et al. (2017), we showed that the fate of precipitation in Antarctica often comes down to complex interactions between the large-scale flow, the orography, and regional circulations, such as Foehn and katabatic winds. Future studies should concentrate on the synoptic configurations during precipitation and sublimation events over Prydz Bay to determine whether the mechanisms proposed here can explain the rather peculiar precipitation climatology of Prydz Bay, and in particular of the Vestfold Hills.

Acronyms

AR Atmospheric river
AWS Automatic weather station
DFR Dual-frequency ratio
EPE Extreme precipitation event
IWV Integrated water vapor
OGWs Orographic gravity waves
PLATO Precipitation over Land And The Southern Ocean
PPI Plan position indicator
PV Potential vorticity
RHI Range height indicator
SLW Supercooled liquid water
VHF Very high frequency
WRF Weather Research and Forecasting

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JG, EV, AB, and SPA designed the experiment. JG and AF operated the instruments and processed the observational data. EV ran the WRF simulations. ACBR processed the dual-frequency and spectral radar data. SPA and AP processed the lidar and cloud radar data, respectively. JG, EV, AB, ACBR, SPA, and AP interpreted the data. JG, with contributions from all authors, prepared the manuscript.

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