

Key Points:

- Atmospheric rivers (ARs) reaching East Antarctica show strong association with synoptic weather regimes
- ARs enhance the positive temperature and snowfall anomalies associated with the regimes
- ARs occur when the synoptic configuration is anomalously strong over the Southern Ocean

Supporting Information:

Supporting Information may be found in the online version of this article.

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Relationship Between Weather Regimes and Atmospheric Rivers in East Antarctica

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Abstract Here, we define weather regimes in the East Antarctica—Southern Ocean sector based on daily anomalies of 700 hPa geopotential height derived from ERA5 reanalysis during 1979–2018. Most regimes and their preferred transitions depict synoptic-scale disturbances propagating eastwards off the Antarctic coastline. While regime sequences are generally short, their interannual variability is strongly driven by the polarity of the Southern Annular Mode (SAM). Regime occurrences are then intersected with atmospheric rivers (ARs) detected over the same region and period. ARs are equiprobable throughout the year, but clearly concentrate during regimes associated with a strong atmospheric ridges/blockings on the eastern part of the domain, which act to channel meridional advection of heat and moisture from the lower latitudes towards Antarctica. Both regimes and ARs significantly shape climate variability in Antarctica. Regimes favorable to AR occurrences are associated with anomalously warm and humid conditions in coastal Antarctica and, to a lesser extent, the hinterland parts of the Antarctic plateau. These anomalies are strongly enhanced during AR events, with warmer anomalies and dramatically amplified snowfall amounts. Large-scale conditions favoring AR development are finally explored. They show weak dependency to the SAM, but particularly strong atmospheric ridges/blockings over the Southern Ocean appear as the most favorable pattern, in which ARs can be embedded, and to which they contribute.

1. Introduction

Although the Antarctic Ice Sheet (AIS) contribution to sea level rise is heavily influenced by ocean-driven mass loss (e.g., Edwards et al., 2019; Seroussi et al., 2020), the effects of sub-decadal to decadal precipitation variation on surface mass balance (SMB) dominate the overall mass balance variability of East Antarctica (IMBIE, 2018). A detailed understanding of SMB variability is therefore crucial to assess the future contribution of Antarctica to sea level rise (Seroussi et al., 2020). Uncertainties in future SMB changes contribute substantially to uncertainties in the projected Antarctic contribution to sea level rise, which varies between -7.8 and 43 cm sea level equivalent by 2100 under Representative Concentration Pathway (RCP) 8.5 scenario (Edwards et al., 2019, 2021; Seroussi et al., 2020). Estimates of regional scale SMB distribution and trends remain difficult to obtain as high-resolution data remain very scarce (e.g., Favier et al., 2017; Lenaerts et al., 2019). The strong variability of Antarctic SMB, both in time and space, further complicates this effort. Precipitation over most regions of Antarctica is controlled by a few high precipitation events (Turner et al., 2019). This characteristic has to be understood and correctly represented in models for accurate projections.

The strongly baroclinic Southern Ocean exhibits a high rate of cyclogenesis, and the southern Indian Ocean sector exhibits the highest frequency and strongest zone of cyclogenesis of the southern mid-latitudes (Simmonds et al., 2003). Yet, only a few of these cyclones actually reach the Antarctic coastline, and even fewer generate high precipitation events (Hoskins & Hodges, 2005; King & Turner, 2007; Simmonds et al., 2003; Turner et al., 2019; Uotila et al., 2013). These high precipitation events are generally recognized to occur when the mid-tropospheric jet configuration favors the development of atmospheric blocking ridges which direct heat and moisture transports further into the ice sheet (Hirasawa et al., 2013; Massom et al., 2004; Schlosser et al., 2010;

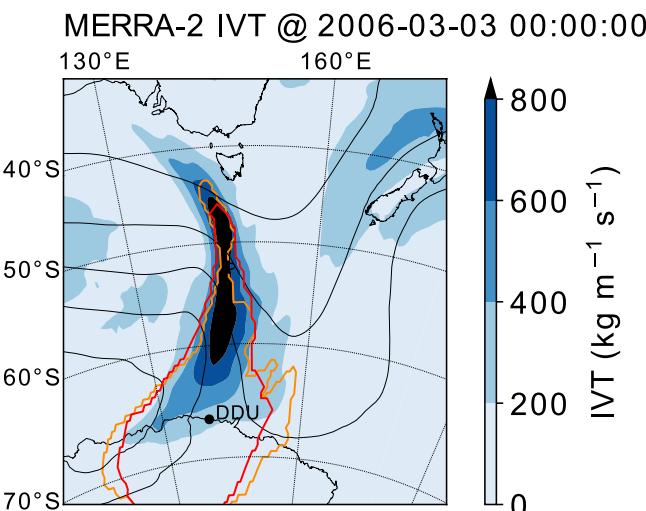


Figure 1. Example of an atmospheric river (AR) event detected by both vIVT and integrated water vapor (IWV) detection schemes on 3 March 2006. The red outline shows the delineation of the AR according to the vIVT scheme and the orange outline according to the IWV scheme. Colors represent the integrated vapor transport. Black contours show the corresponding Z700.

within the cyclone's warm conveyor belt (Dacre et al., 2019; Harrold, 1973; Madonna et al., 2014). Radiosonde observations during AR landfalls on the Antarctic coastline show extreme moisture, wind, and temperature values compared to the median state (Gorodetskaya et al., 2020). ARs have a distinctive integrated water vapor (IWV) profile on SSM/I (Special Sensor Microwave Imager) imagery (Ralph et al., 2017), but are more readily identified over polar regions using reanalysis IWV and integrated vapor transport (IVT) fields. The high moisture content within the AR is often related to moisture export from the lower latitudes, and is typically maintained through continuous and vigorous moisture convergence in the cyclone's warm conveyor belt and/or along the trailing cold front (Bao et al., 2006; Sodemann & Stohl, 2013). This connection with lower latitudes, along with atmospheric blocking or ridges directing the tropical moisture export poleward, contribute to differentiate ARs from non-AR related cyclones in regards to moisture transport.

While AR events are infrequent in Antarctica compared to other mid-latitude regions, they have a significant impact on SMB (Adusumilli et al., 2021; Gorodetskaya et al., 2014; Wille et al., 2019, 2021). Landfalls on the AIS occur between 1-3 times per year in a given region of Antarctica, yet are responsible for 10%–20% of the annual snowfall budget across large swaths of East Antarctica (Wille et al., 2021). The AR fingerprint is more pronounced in high precipitation events. ARs account for around 70% of the 1% most intense daily precipitation events (*ibid.*). Previous studies have demonstrated that high precipitation events control the interannual variability of surface snow accumulation (Gorodetskaya et al., 2014; Turner et al., 2019); annual AR frequency also controls the interannual variability of snow accumulation plus snowfall trends in many places of the AIS (Wille et al., 2021).

However, in addition to causing intense precipitation events, ARs can also cause strong melt events. They have triggered winter surface melt on the Antarctic Peninsula ice shelves along with being responsible for a majority of the summer melting events over Western Antarctic Ice sheet (WAIS) and the Ross ice shelf, especially in higher elevation regions (Adusumilli et al., 2021; Wille et al., 2019).

Overall, ARs have a predominantly positive impact on the AIS SMB and actively mitigate sea level rise driven from dynamic mass loss (Ligtenberg et al., 2013; Medley & Thomas, 2019; Wille et al., 2021). Mass gains from AR-related heavy snowfall occurrences across the AIS outweigh mass loss from sporadic AR-related melting events on the WAIS. How impacts from ARs on the AIS mass balance will change in the future is still uncertain. Indeed, any warming could increase melt and rain frequency over more areas of the continent (Kittel et al., 2021; Wille et al., 2019), with possible surface mass loss at lower elevations. Based on CMIP6 output, it is currently

Scott et al., 2019; Sinclair & Dacre, 2019). These blocking ridges have a particular prevalence in the Indo-Pacific sector due to a longitudinal SST gradient from the (colder) southeastern Indian Ocean to the (warmer) southwest Pacific sector (Pook, 1994; Pook et al., 2012). This region of blocking is of crucial importance to precipitation variability not only across East Antarctica (Massom et al., 2004), but also for the southern hemispheric nations of Australia and New Zealand (Pook et al., 2012, 2013; Risbey et al., 2009; Udy et al., 2021). Blocking ridges are among various synoptic weather types that influence moisture transport and precipitation in the southern Indian Ocean region (Cohen et al., 2013; Udy et al., 2021). Synoptic-typing efforts are useful in identifying discrete atmospheric circulation patterns (e.g., Pohl, Saucède, et al., 2021; Tozer et al., 2018) and of particular interest here, understanding which weather regimes provide the highest poleward moisture fluxes.

Recent research has categorized some of these particularly intense poleward moisture fluxes as atmospheric rivers (ARs), and connected them to high precipitation events across the AIS (Adusumilli et al., 2021; Gorodetskaya et al., 2014, 2020; Wille et al., 2021). Most research on ARs has focused on the mid-latitudes, but these weather systems also occur in Antarctica (e.g., Bozkurt et al., 2018; Gorodetskaya et al., 2014, 2020; Wille et al., 2019, 2021). ARs are elongated bands of strong horizontal moisture transport (Figure 1) typically embedded within a low-level jet ahead of an extratropical cyclone's cold front (Ralph et al., 2004; Zhu & Newell, 1998) and

expected that the entire continent will warm between $1.3 \pm 0.5^\circ\text{C}$ (following the SSP1-2.6 forcing scenario) and $4.8 \pm 1.2^\circ\text{C}$ (SSP5-8.5) by the end of the 21st century (Bracegirdle et al., 2020).

In addition to further global warming increasing AR melt potential, there has been a general poleward shift in AR activity in conjunction with a poleward shift in the westerly jet over the past few decades (Espinoza et al., 2018; Ma et al., 2020). Meanwhile AR frequency has changed over certain regions of Antarctica during the satellite era with a decrease over parts of Adélie land, likely related to changes in atmospheric blocking occurrences around Antarctica (Wille et al., 2019, 2021). However, little is known on how AR tracks and impacts will change in a global warming context. This mainly stems from the lack of understanding of the synoptic weather regimes that transport these ARs towards the Antarctic coastline.

Here, we use a k-means clustering technique and an AR detection algorithm to analyze which synoptic weather regimes are most favorable for transporting ARs and their associated heat and moisture towards the East Antarctic coastline. Using both observations and reanalyses, we also assess the respective and combined influence of weather regimes and ARs on the climate of East Antarctica. Finally, we also attempt to separate, for each regime, the days associated with ARs from other ones, in order to identify possible factors that influence the development of AR events.

Section 2 gives a presentation of the climate conditions of East Antarctica and the data available to study it. Section 3 presents the methods used to define weather regimes and detect ARs. Section 4 characterizes synoptic-scale variability in the East Antarctica – Southern Ocean sector, and Section 5 presents the relationship between synoptic regimes and AR occurrence. The main results and their implications are finally summarized and discussed in Section 6.

2. Climate Settings and Available Data

2.1. Climate Settings

Long term meteorological surveys are available at the Dumont d'Urville (DDU) polar base ($66^\circ39'47''\text{S}$, $140^\circ00'03''\text{E}$) since January 1956. The base is located on an archipelago, less than 5 km from the ice sheet boundary, and is characterized by the typical climatic conditions of the East Antarctic Ice Sheet (EAIS) coast. The average weather conditions (temperature: -10.8°C , pressure: 987.3 hPa, wind speed: 9.5 m.s^{-1} , preferential wind direction: $120\text{--}160^\circ$: König-Langlo et al., 1998) and seasonal conditions at the edge of the ice sheet play a fundamental role in snow accumulation, melting and the extent of pack ice close to the continent. Seasonality is characterized by a long winter, from May to October, a short summer, from November to January, and extremely short inter-seasons (Périard & Pettré, 1993). The high seasonality of temperatures (-15°C in winter, -0.5°C in summer on average) implies that melting occurs only from December to February affecting snow conditions on the different nunataks as well as the break-up of sea ice around the archipelago. This is a direct result of the variations in solar radiation energy input, strong in summer, and the "night-time" radiative cooling on the Antarctic plateau responsible for the establishment of stable atmospheric layers leading to the development of katabatic winds (Gallée & Pettré, 1998; König-Langlo et al., 1998). The strong and persistent katabatic wind is a key characteristic of the climate of the region (Périard & Pettré, 1993). The area is nevertheless affected by frequent low-pressure systems from the northwest (King & Turner, 2007). More anticyclonic conditions are observed in summer and winter, but precipitation occurs throughout the year without a clear seasonal cycle (König-Langlo et al., 1998). Notable snow inputs are limited to a few heavy precipitation events that can occur at any time of the year (Turner et al., 2019). These are associated with warm and intense moisture transport from mid-latitudes, which can give rise to the rare rainfall events reported in the area (Favier et al., 2011). These events are expected to occur during atmospheric blocking conditions (Wille et al., 2021).

The weather conditions in the area are impacted by very high interannual climate variability which is expected to be related to large-scale atmospheric conditions (e.g., the intensity of the Southern Annular Mode [SAM]: Marshall et al., 2017). However, the link between regional variability and large-scale circulation has never been thoroughly studied at the DDU polar base.

2.2. Data

Atmospheric fields used in this study are taken from the ERA5 ensemble reanalysis (C3S, 2017; Hersbach et al., 2020). ERA5 is the fifth generation of atmospheric reanalysis released by the European Center for Medium-Range Weather Forecasts. It currently covers the period 1979 onwards (with planned extension to 1950 onwards) and includes a 10-member ensemble to quantify uncertainties associated with the density and quality of the assimilated data. In this work, we use regular $0.25^\circ \times 0.25^\circ$ grids of daily fields of the following variables: total water in the air column (kg.m^{-2}), air temperature at 2 m above the surface ($T_{2\text{m}}$: $^\circ\text{C}$), horizontal wind (m.s^{-1}), geopotential height (m) and specific humidity (g.kg^{-1}) at 700 hPa.

Global sea surface temperature fields (SST: $^\circ\text{C}$) are taken from the ERSST v5 database (Huang et al., 2017) available at a monthly time step on a $2^\circ \times 2^\circ$ global grid. This product is suited for long-term and large-scale studies and is used here to analyze global teleconnections with our regimes.

Snowfall rates from the regional climate model (RCM) MAR in its latest Antarctic configuration (version 3.11; Kittel et al., 2021) without drifting-snow physics (Amory et al., 2021) were used in this study. The model was forced at its lateral boundaries, at the top of the atmosphere and at the ocean surface by 6-hourly ERA5 reanalysis and run at 35 km horizontal resolution over the Antarctic with a 120 s time step and outputs every three hours. The details of the simulation setup are given in Amory et al. (2021), based on the model version presented in Kittel et al. (2021). MAR is a hydrostatic model specifically designed to represent climate features typical of high-latitude regions such as the stable atmospheric boundary layer and its interactions with the snow-covered surface. In particular, the model accounts for the sublimation of precipitation in the lower troposphere, a process particularly active over the coastal margins of East Antarctica (Grazioli et al., 2017). MAR has been evaluated across the continent near-surface meteorological data (Mottram et al., 2021) and SMB (Agosta et al., 2019; Kittel et al., 2021) observations from the GLACIOCLIM-SAMBA quality-controlled data set (Favier et al., 2013 updated by; Wang et al., 2016) and in particular in the study area where a 157 km transect is surveyed annually (Agosta et al., 2012; Amory et al., 2021). Precipitation rates modeled by MAR have been used to demonstrate that ARs control the interannual variability of precipitation across Antarctica (Wille et al., 2021).

These datasets are supported by in-situ observations performed in Adélie Land by Météo-France, the French weather forecasting services. Daily data measured at the synoptic station of the DDU polar base are available since January 1956 and are used here over the period 1979–2018. For the present study, we make use of the following variables: daily minimum (Tn) and maximum (Tx) air temperature ($^\circ\text{C}$), global surface radiation (RAD: J.cm^{-2}), mean sea-level pressure (SLP: hPa), wind speed (m.s^{-1}) and relative humidity (RH: %). Based on these series, diurnal thermal range (DTR, $^\circ\text{C}$) has been calculated as $Tx - Tn$, and specific humidity (Q: g.kg^{-1}) has been computed using the Goff-Gratch equation based on vapor pressure (Goff & Gratch, 1946). The number of available daily values for each variable is given in Section 5 below; from one variable to another, the fraction of missing values varies from 0.001% (for Tx) to 2.4% (for SLP and hence Q).

We also use the daily 2-m air temperature, surface pressure and wind speed data recorded by automated weather stations (AMRC-AWS) set up (a) on the D10 skyway, quite close to the DDU station (66.7°S , 139.8°E , 243 m asl, 5 km inland) available since January 1980, and (b) near Concordia station at Dome C (75.106°S , 123.346°E , 3,250 m asl) available since February 1980. The time series collected at D10 have 33% to 39% of missing data, and their equivalents at Dome C from 7% to 8% (see Section 5.2).

Finally, we use a series of indices to monitor the polarity of the main modes of climate variability that could influence both the climate of the region, and the properties of our regimes and ARs. The state of ENSO is monitored through a spatially averaged SST index computed over the Niño3.4 region (5°N – 5°S , 170°W – 120°W). The polarity of the SAM is derived from a daily index based on a Principal Component Analysis (PCA) of geopotential height anomalies south of 20°S . This index is mostly driven by geopotential height patterns over Antarctica (Pohl & Fauchereau, 2012; Spensberger et al., 2020) and assumes that anomalies over the Southern Ocean display some zonal symmetry in the mid-latitudes. Hence, it could prove less relevant to analyze and interpret atmospheric features (i.e., weather regimes and AR events) located over the Southern Ocean over a longitudinally bounded domain. Therefore, we also considered an alternative index, computed as the normalized difference of daily SLP between Hobart, Australia (42.9°S , 147.3°E), and DDU. This index can be seen as a regional equivalent to the more zonally symmetric, station-based SAM index proposed by Marshall (2003).

3. Methods

3.1. K-Means Clustering

Daily weather regimes are obtained through a k-means clustering (Cheng & Wallace, 1993; Michelangeli et al., 1995). This algorithm is often used in climate science and has already been successfully used to decompose synoptic-scale meteorology in the Southern Hemisphere at subtropical (Fauchereau et al., 2009; Pohl et al., 2018), middle (Pohl, Saucède, et al., 2021) and high latitudes (Pohl & Fauchereau, 2012; Richard et al., 2013). Alternative schemes of synoptic typing include self-organizing maps, as employed for a similar region by Udy et al. (2021), as well as PCA (Huth, 1996; Pohl et al., 2009), or, more recently, archetypal analyses (Risbey et al., 2021). In the Southern Hemisphere, Pook et al. (2014) also performed a synoptic typing leading to differentiate frontal systems, cold-cored lows often leading to cut-off lows and warm-cored lows associated with the development of atmospheric ridges and troughs. Numerous classifications and/or tracking studies also exist for individual synoptic weather features, including extratropical cyclones (Catto et al., 2015; Pezza et al., 2008; Simmonds & Keay, 2000; Uotila et al., 2011), anticyclones and blocking events (Jones & Simmonds, 1994; Liu et al., 2018; Pezza & Ambrizzi, 2003; Pepler, Dowdy, & Hope, 2019; Pepler, Hope, & Dowdy, 2019; Sinclair, 1996).

Here, because our focus is primarily on lower-layer advections of moisture and temperature, the k-means clustering is applied to Z700 anomalies (after removing the mean annual cycle) taken from ERA5 reanalysis on the period 1 January 1979 to 31 December 2018 (i.e., 40 years of daily regimes). Regimes are calculated over the domain 45°S-75°S, 110°E-170°E (corresponding to 121 x 241 grid-points), which is approximately centered on Adélie land. This domain is chosen to match the typical size of synoptic perturbations and thus encompasses most of the disturbances that propagate in this sector. However, most regime representations are on a wider domain (30°S-85°S, 70°E-220°E: 221 x 601 grid-points), in order to show possible larger-scale patterns in which they could be embedded.

A PCA is applied to these Z700 anomalies prior to the k-means clustering to filter out atmospheric noise (i.e., smaller-scale features, or specificities of instantaneous fields that could make them deviate from the main atmospheric features most recurrently associated with similar synoptic contexts). The PCA-filtered Z700 anomalies account for 80% of the original variance in 5 eigenvectors. Following Michelangeli et al. (1995), the optimal number of clusters k is determined using a red-noise test, which compares the “classifiability” of real input data against Markov-generated red-noise data having the same covariance matrix. Results (Figure S1 in Supporting Information S1) reveal that a partition into 15 regimes is the best possible choice.

3.2. AR Detection Scheme

To detect ARs in the Adélie land region, we employ the AR detection algorithm described in Wille et al. (2021). To summarize, this algorithm searches for grid cells between 37.5°S and 80°S where the meridional (v) component of integrated vapor transport (vIVT) exceeds the 98th percentile of all monthly vIVT values. The same is then done using IWV to create a second catalog of AR detections. Using a relative threshold takes into account the progressive reduction of atmospheric saturation capacity moving poleward. Consecutive grid points above this relative threshold that extend at least 20° in the meridional direction are classified as ARs. Here, vIVT and IWV are defined as

$$vIVT = -\frac{1}{g} \int_{\text{surface}}^{\text{TOA}} qvdp, \quad (1)$$

$$IWV = -\frac{1}{g} \int_{\text{surface}}^{\text{TOA}} qdp, \quad (2)$$

where g (m.s^{-2}) is the gravitational acceleration, q ($\text{kg} \cdot \text{kg}^{-1}$) is the specific humidity, v is the meridional wind velocity (m.s^{-1}), and p is the atmospheric pressure (hPa). vIVT and IWV are calculated on all reanalysis levels, from the surface to the top of atmosphere. The two detection schemes are used to retrieve ARs that make landfall along the coastline around DDU between 138°E and 142°E. The data used to initialize the AR detection is provided by the Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2), which has a $0.5^\circ \times 0.625^\circ$ horizontal resolution (Gelaro et al., 2017). Using MERRA-2 (i) is standard for all AR detection algorithms that are part of the Atmospheric River Tracking Method Intercomparison Project (Rutz et al., 2019),

and (ii) ensure independence between the weather and AR definitions, both in terms of algorithms but also input data set. Nonetheless, previous analysis has shown that when the AR detection algorithm is initialized with data from the ERA5 reanalysis, there is very little difference in AR detection frequency compared against MERRA-2 (Wille et al., 2021). The criteria for AR detection are stricter in this algorithm compared to global algorithms like Guan and Waliser (2015), as evidenced by the lower annual frequency of AR detections around the Antarctic coastline (1.2% and ~6% respectively; Wille et al., 2021). For a more detailed explanation of the AR detection algorithm, see Wille et al. (2021). An illustration of a typical AR event as detected by both IWV and vIWT schemes is given in Figure 1.

4. Characterization of the Weather Regimes Over East Antarctica

4.1. Synoptic Configurations

Figures 2 and 3 present the spatial anomaly patterns associated with the 15 weather regimes for selected mid-tropospheric, surface and vertically integrated variables. The regimes have been ordered by increasing longitude of associated positive 700 hPa geopotential height anomalies (Figure 2). All regimes have quite similar sizes (from 795 days for regime #7 to 1213 days for #9). This is least partly attributable to the formulation of the k-means algorithm (Huth, 1996). The regime occurrences tend to show weak seasonality but large interannual variability (Figure S2 in Supporting Information S1), a result similar to Pohl, Saucède, et al. (2021) and Udy et al. (2021) over the Southern Ocean sector. The Z700 field, used as an input of the clustering analysis, is by construction well differentiated from one regime to another, especially on the inner region used for regime definition. All regimes tend to show wave-like alternations of positive and negative geopotential anomalies that strongly influence regional circulation anomalies in the troposphere. A few regimes show opposite-sign anomalies between Antarctica and the Southern Ocean (e.g., regimes # 5, 13 or 15), thereby suggesting potential interactions with the SAM (see Section 4.2) and/or strong associations with the SOM3 node of Udy et al. (2021; see also Table S2 and Figures S21–S23 in Supporting Information S1). However, most regimes correspond to wave patterns located over the Southern Ocean, north of the Antarctic coastline, with zonal extensions reminiscent of wavenumber 4–6 structures. This is fairly consistent with Udy et al. (2021). Regime sequences are generally short (generally less than 2 days, except for rare sequences exceeding 7 days and persisting up to 15 days; Figure S3 in Supporting Information S1). Preferential transitions between regimes (Table 1) depict a clear tendency for eastward propagation of atmospheric configurations, most regimes being followed by regimes with quite similar patterns shifted to the east (Pohl, Saucède, et al., 2021; Scarchilli et al., 2011; Udy et al., 2021). Taken together, these results suggest that these regimes mostly characterize synoptic-scale transient perturbations embedded in mid-latitude westerly circulation.

Regional atmospheric circulation adjusts to geopotential height anomalies through quasi-geostrophic lower-layer flux anomalies (Figure 2). Anomalies of specific humidity at 700 hPa (contours in Figure 2), and total water content of the air column (contours in Figure 3), are strongly coherent and directly modulated by meridional wind anomalies, with northerly fluxes advecting moist air from the lower latitudes while southerly fluxes advect dry air from the higher latitudes. There is also a very strong link with lower-layer air temperature anomalies, with northerly fluxes favoring anomalously warm conditions and southerly fluxes favoring anomalously cold conditions (colors in Figure 3). Hence, the regimes are key for controlling mass, momentum and energy exchanges between the middle-latitudes of the Indo-Pacific sector and East Antarctica, a result confirming that of Udy et al. (2021).

To sum up, the 15 regimes identified here characterize the short-lived weather systems embedded in the mid-latitude westerlies that tend to propagate eastwards off the East Antarctica coast. By modulating meridional advections they strongly control exchanges between lower (subtropical to middle) and higher (polar) latitudes, resulting either in the ventilation of the polar air mass by warmer and moister air originating from the Southern Ocean, or symmetrically, intrusion of cold, dry air from the polar air mass in the middle latitudes.

4.2. Teleconnections With Large-Scale Variability

The regimes defined here characterize the mid- to high-latitudes that connect the polar and tropical air masses. As a result, their occurrence and variability from one year to another could either relate to tropical or high-latitude modes of climate variability. Figures S4–S9 in Supporting Information S1 aim to assess the large-scale background conditions favoring regime occurrences, considering a 5% false discovery rate (Benjamini &

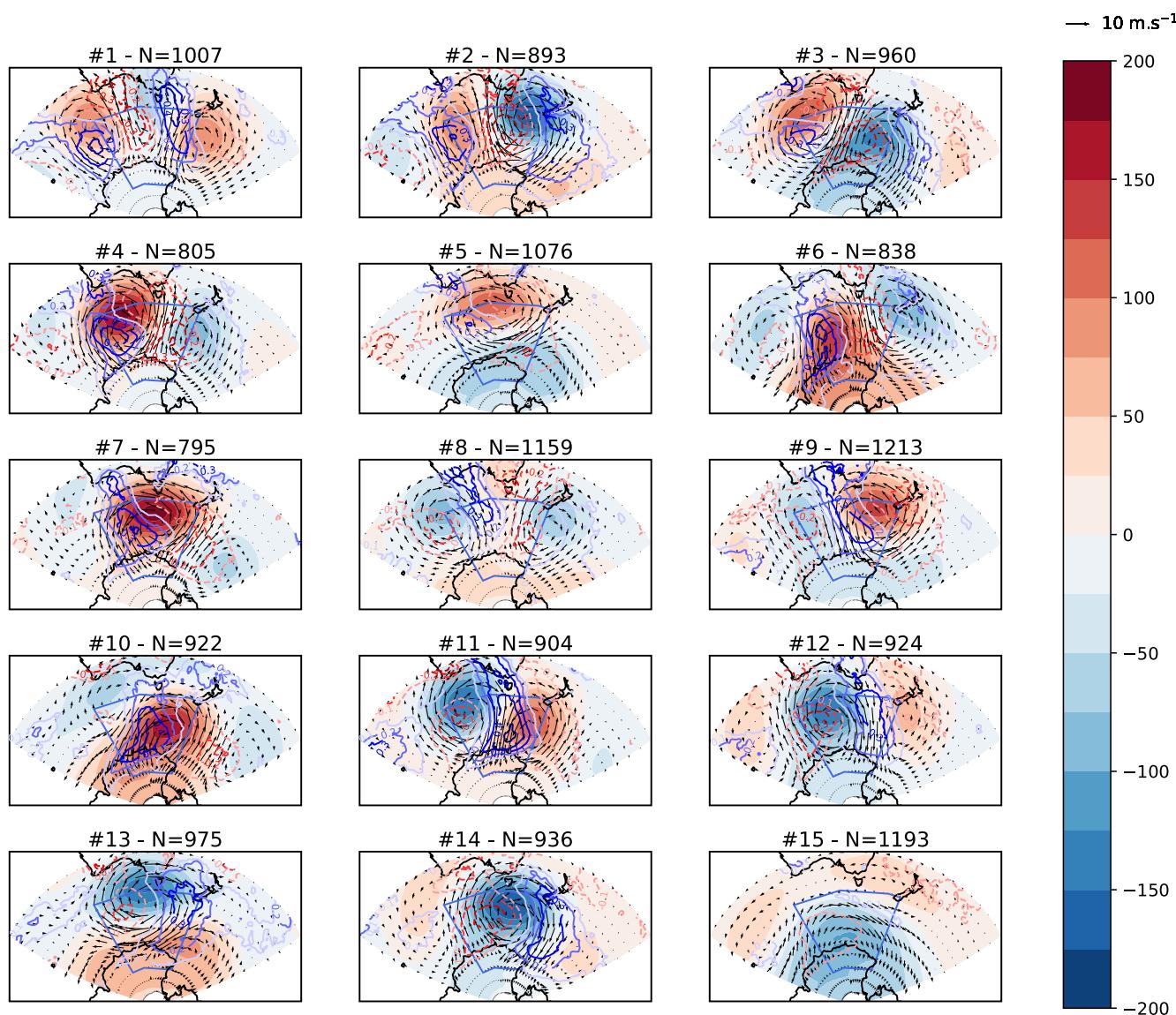


Figure 2. Anomaly patterns associated with the 15 weather regimes, period 1979–2018. Colors: Z700 anomalies (m, see color legend). Vectors: anomalies of the horizontal wind at 700 hPa (m.s^{-1} , see arrow key for vector scales). Contours: synchronous specific humidity anomalies at 700 hPa (g.kg^{-1}). Contour interval is 0.05 g.kg^{-1} , with solid blue (dashed red) contours corresponding to positive (negative) humidity anomalies. For all variables, anomalies that are not significantly different from the mean climatology according to a t-test at the 95% confidence level are shaded white or omitted. The domain used for regime definition is shown by the inner blue polygon. N = number of days in each regime.

Yekutieli, 2001) for field significance assessment. These results are summarized in Table 2 for the two leading modes of climate variability in the tropical and polar latitudes of the Southern Hemisphere, that is, El Niño Southern Oscillation (ENSO: McPhaden et al., 2006) and the SAM (e.g., Marshall, 2003). No significant relationships were found with the Indian Ocean Dipole (not shown). As no significant trend is found in regime occurrences, the time series were not detrended in the following analyses. Preliminary tests (not shown) reveal that this does not qualitatively modify our results, and none of the conclusions reached below is sensitive to this choice. This may be the case as the study period is too short to detect the low-frequency changes in the SH over the 20th century which were notably dominated by stratospheric ozone depletion (e.g., Marshall, 2003; Pohl & Fauchereau, 2012, among many others; Renwick, 2004; Thompson et al., 2011).

Interannual correlations between seasonal regime occurrence and indices monitoring the polarity of these modes of variability (Table 2) reveal (a) a weak relationship with ENSO, a result that holds more generally for the whole SST field at tropical and middle latitudes (Figures S8 and S9 in Supporting Information S1); (b) a significant

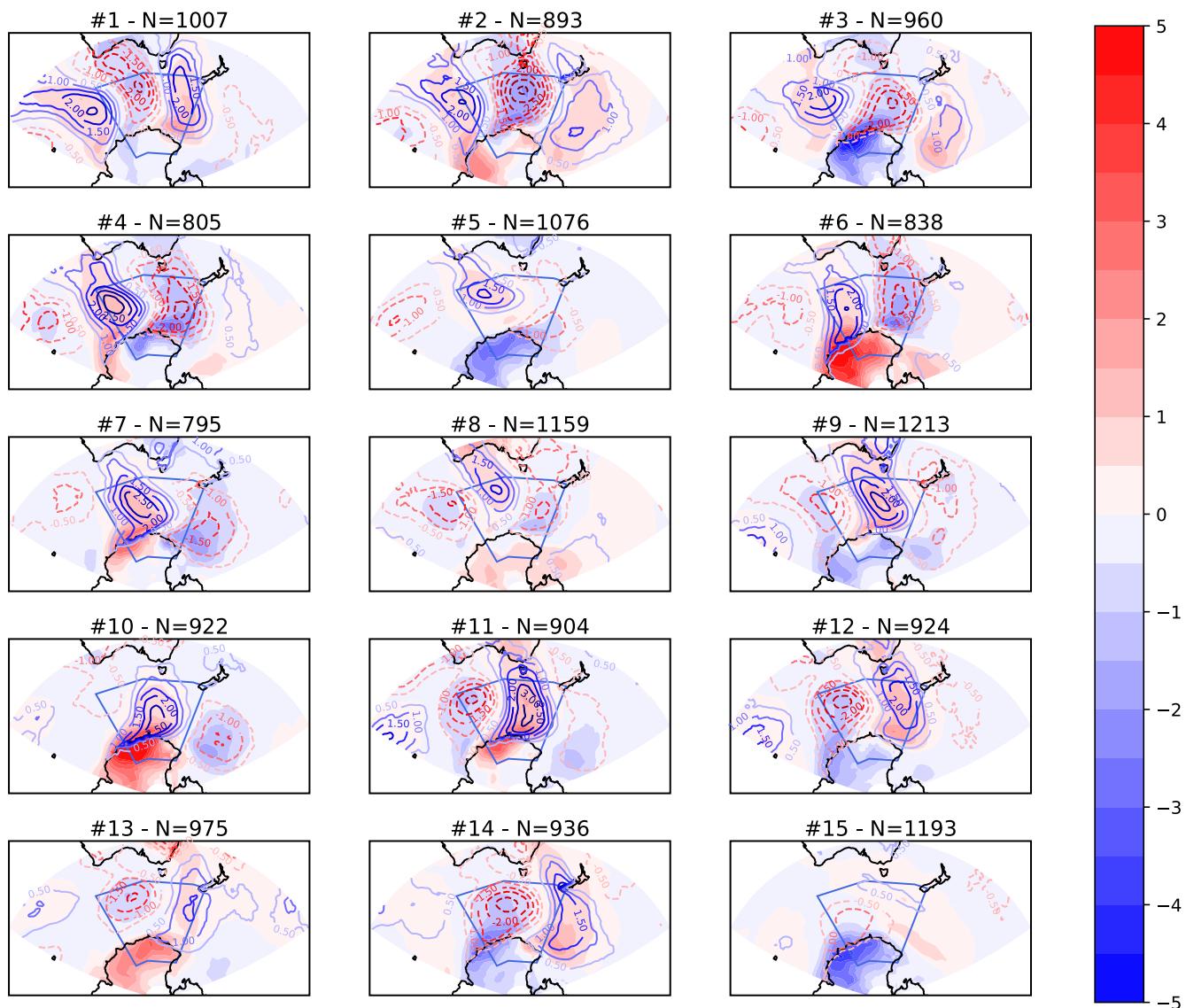


Figure 3. As Figure 2 for the 2-m air temperature anomalies (in colors: $^{\circ}\text{C}$, see color legend) and total column water (contours, $\text{kg} \cdot \text{m}^{-2}$). Contour interval is $0.5 \text{ kg} \cdot \text{m}^{-2}$, with solid blue (dashed red) contours corresponding to positive (negative) anomalies.

association with the SAM for 11 out of 15 regimes. Correlations generally tend to be stronger during the austral summer season (Figures S4 and S5 in Supporting Information S1), and they are of consistent sign throughout the year. This relationship with the seasonal mean state of the SAM is responsible for the strong and significant correlation between weather regimes and Southern Ocean SST (Figures S8 and S9 in Supporting Information S1). The positive phase of the SAM corresponds with a southward shift of the westerly wind circulation (e.g., Fogt & Marshall, 2020; Gillett et al., 2008; Thompson & Wallace, 2000), increases surface fluxes and northward Ekman transport and favoring anomalously cold SST (e.g., Lenton & Matear, 2007).

In spite of such statistical significance, the strength of the relationship between the SAM and the occurrence of the regimes should not be overestimated as the teleconnection with the southern hemispheric Z700 field corresponds quite rarely to the canonical signature of the SAM, especially in winter (Figures S4 and S5 in Supporting Information S1). Once the variability linearly related to the SAM is removed (Figures S6 and S7 in Supporting Information S1), only smaller-scale signals remain significant, especially in the east hemisphere close to the domain used to define the regimes. This suggests a predominant, yet moderate association with the SAM, superimposed to more regional mechanisms; the latter, statistically independent of the SAM (at least at

Table 1
Transition Between Regimes, 1979–2018

		Day _{d+1}														
		#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11	#12	#13	#14	#15
Day _d	#1	291	129	86	73	55	71	15	93	18	17	5	16	31	41	66
	#2	10	390	67	79	9	110	3	131	2	2	0	3	34	48	5
	#3	7	49	412	110	125	7	4	84	10	0	0	5	1	17	129
	#4	7	21	47	373	148	69	70	46	11	4	0	0	0	1	8
	#5	31	0	57	82	455	7	96	39	180	8	5	4	0	0	112
	#6	23	30	3	31	12	410	51	125	26	93	7	0	23	1	3
	#7	17	0	1	35	59	22	424	5	121	95	11	0	1	0	4
	#8	83	21	11	7	20	23	8	327	129	61	154	97	94	35	89
	#9	129	0	6	3	78	8	79	18	491	81	148	80	5	1	86
	#10	91	4	0	1	7	75	40	38	45	460	108	4	46	1	2
	#11	87	2	0	0	2	0	2	24	52	85	365	141	119	9	16
	#12	93	4	11	0	2	0	0	36	26	3	51	355	65	173	104
	#13	38	109	3	0	1	36	0	82	0	13	31	36	522	103	1
	#14	21	126	103	3	2	0	0	50	4	0	4	61	30	448	84
	#15	79	7	153	8	101	0	3	61	98	0	15	122	4	58	484

Note. The two largest (weakest) values for each regime are in dark red and red (dark blue and blue).

the seasonal scale), seem to relate to finer-scale perturbation in the circumpolar westerly circulation. In Supporting Information S1, we also refine these results at the daily timescale, by considering synchronous associations between regime occurrences and the daily SAM index (Figure S10 in Supporting Information S1). Results are broadly consistent with the seasonal timescale, that is, regime showing association with a given polarity of the SAM at the seasonal scale are preferentially associated with similar SAM polarities at the daily (intraseasonal and synoptic) scale. Strong variability and diversity are nonetheless found within each regime, thereby weakening the relationship with the SAM. The SAM being a mode of much larger-scale than our regimes and ARs, we also consider a more regional index, consisting in the normalized difference of SLP between Hobart and DDU (Figure S11 in Supporting Information S1). Results are very similar to those obtained with the daily SAM index, although smaller-scale atmospheric features like transient disturbances act to decorrelate both indices. Overall, these results at the seasonal and daily scale are strongly consistent (see Supporting Information S1 for details), and corroborate those of Udy et al. (2021).

5. Association With Atmospheric Rivers

5.1. Co-Occurrence and Modulation of AR Properties

Here, the AR events identified by Wille et al. (2019, 2021) and reaching East Antarctica near DDU (between 138°E and 142°E; see Section 3.2) are extracted over the period 1979–2018, and their occurrences are intersected with those of the regimes discussed above. Results are displayed in Figure 4, for each month of the year. While AR events are well distributed over the year, with nearly equal occurrences every month, they mostly coincide with 3 weather regimes (# 9, 10, 11). Some AR occurrences are also found for other regimes (especially, #7, 12, 13). These regimes are all characterized by positive geopotential height anomalies that are located off the coast of East Antarctica and channel northerly wind anomalies on their western flank towards the higher latitudes (Figure 2). This results in anomalous warm and moist conditions along the western flank, an atmospheric signature that corresponds very well to the regional effects of AR events on the climate of Antarctica (Wille et al., 2021). Such a concentration of ARs in a limited number of regimes is less clear when considering the IWV detection scheme (Figure S12 in Supporting Information S1), even if the hierarchy of the most favorable regimes for AR events is almost unchanged. In each case, the rela-

Table 2

Interannual Correlations Between the Seasonal Regime Occurrences, the SAM Index and the Niño3.4 Index, for the Austral Summer (DJF) and Winter (JJA) Seasons, 1979–2018

	SAM		ENSO	
	DJF	JJA	DJF	JJA
#1	-0.02	0.36	-0.17	-0.04
#2	-0.66	-0.14	0.15	0.14
#3	0.64	0.44	-0.07	0.00
#4	0.24	-0.06	-0.03	-0.03
#5	0.65	0.37	-0.18	-0.13
#6	-0.57	-0.71	0.38	-0.12
#7	-0.20	-0.30	0.01	0.02
#8	-0.41	-0.12	0.21	-0.04
#9	0.58	0.34	-0.22	-0.03
#10	-0.45	-0.50	0.02	-0.09
#11	-0.14	-0.23	-0.02	-0.17
#12	0.42	0.37	-0.12	-0.04
#13	-0.69	-0.51	0.25	0.14
#14	-0.05	0.16	-0.15	0.44
#15	0.72	0.72	-0.08	0.03

Note. Bold red (blue) cells indicate positive (negative) correlations that are statistically significant at the 95% level according to a Bravais-Pearson test.

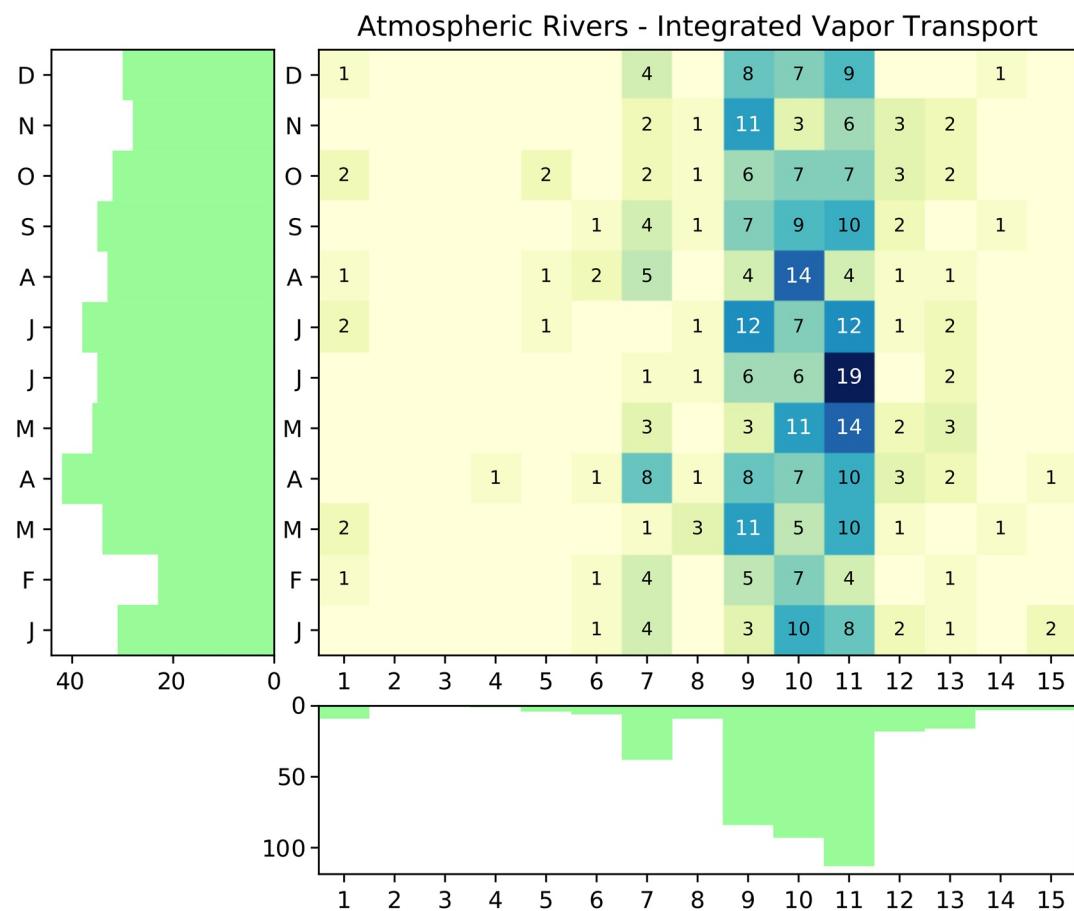


Figure 4. Time distribution of atmospheric rivers (vIIVT scheme: see text for details) depending on their regime (x-axis) and year (y-axis) of occurrence. The main panel indicates the average number of occurrences over the period 1979–2018. Lateral panels show the total number of occurrences per month and per regime.

tionships between AR events and weather regimes remain stationary over the year, that is, they are not modulated by the annual cycle. These results clearly point out that the synoptic context has a strong influence on the occurrence and probability of AR events over the Southern Ocean region (a result that holds for the nodes obtained by Udy et al., 2021; Supporting Information S1).

Are the intrinsic characteristics of ARs (intensity, location and mean orientation) modified by the synoptic context, that is, are their attributes different from one regime to another? Figure 5 addresses this issue, and presents the statistical distributions of associated water vapor transport, the average longitude of AR patterns, and the average orientation of each AR, for the 5 most favorable regimes. Analyses are also duplicated for the 12 months of the year, in order to explore the seasonality of such AR properties. The orientation is computed here as $\Delta\text{lon}/\Delta\text{lat}$, with Δlat the difference in latitude between the northernmost point where the AR is detected and the latitude of DDU, and Δlon the longitudinal difference between these two same points. This simple metric approximates the angle of the AR over the oceanic part of the domain, that is, before it reaches land and become more diffuse. Results for the IWV detection scheme are shown by Figure S13 in Supporting Information S1. For both AR detection schemes, water vapor transport and AR mean longitude and orientation are all quite stable across the year (right-hand column), except for a weak tendency for austral spring events (occurring from September to November) to be associated with slightly weaker vapor transport. There is a large spread in the monthly distributions of AR attributes, which denotes strong diversity from one event to another. This indicates that ARs can occur (Figure 4) and have roughly similar mean characteristics (Figure 5) throughout the year. Water vapor transport associated with the AR events is also similar across regimes: the larger transport values found for regimes #7 and #13 should be considered with caution, since associated sample size is much smaller than for regimes #9-10-11 (Figures 4 and 5).

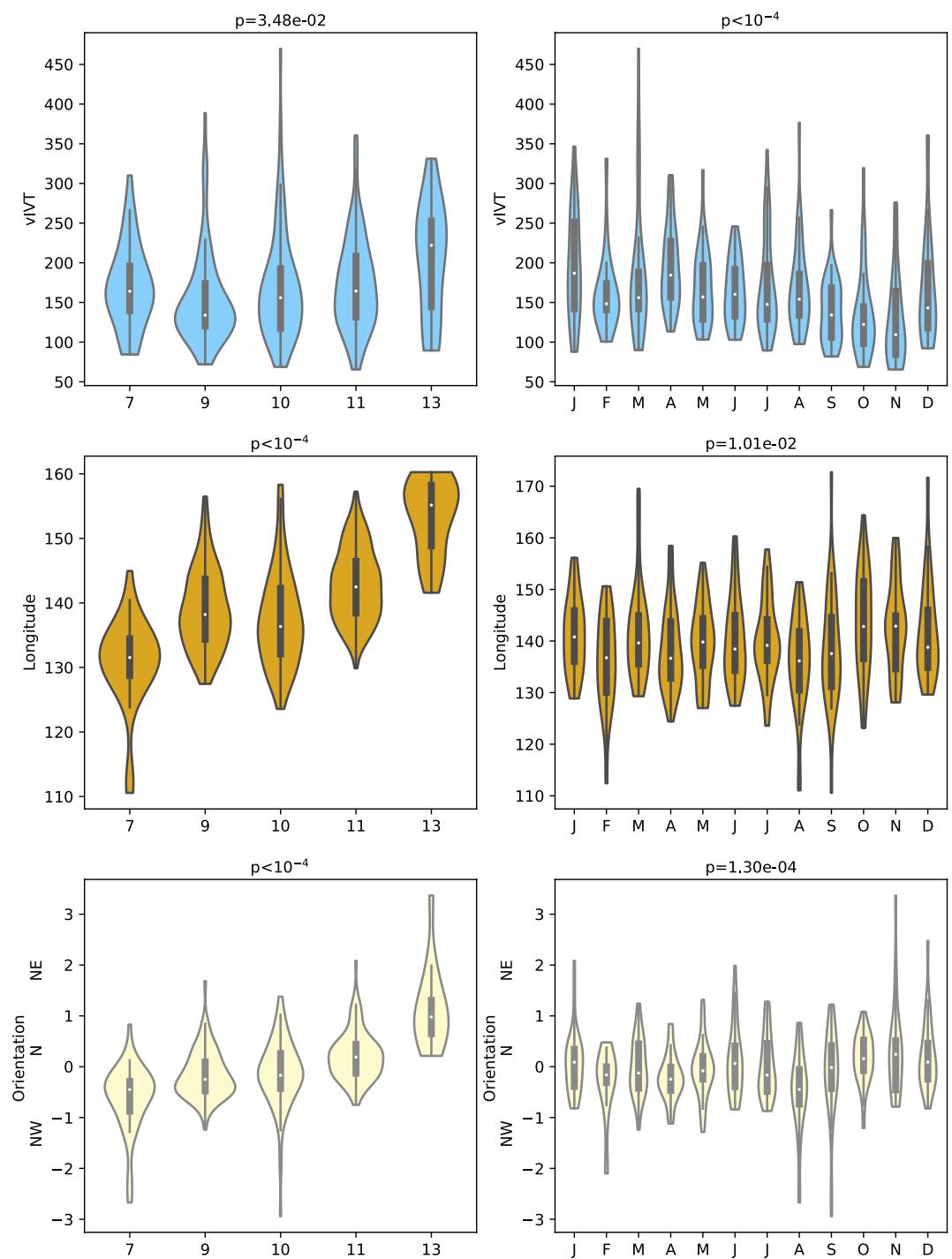


Figure 5. Violin plot of the vertically integrated water vapor transport (first line), mean longitude (second line) and mean orientation (third line) of atmospheric rivers during occurrences of the most favorable regimes (left-hand column) and over the annual cycle (right-hand column). The violin plots show the whole statistical distribution. The boxes extend from the first to the third quartile, and the white dot represents the median value. The whiskers extend to the extreme values. The significance (p-value) of an analysis of variance as estimated by a Fisher test is labeled in the figure.

As expected, weather regimes have a major influence on the location of ARs, with the mean longitude of the AR events coherent with the regime classification. The latter (increasing from one regime to another, as a consequence of the regime reordering by increasing longitudes of associated patterns: Figures 2 and 3) corresponds well to the longitude of the southward advections found west of the anticyclonic ridge/blocks in the composite mean anomaly patterns associated with the regimes. Regimes also modify the orientation of ARs reaching DDU: regimes #7 and #9 are mostly associated with AR events oriented northwest to southeast, while the north-south direction prevails for regime #10 and #11. ARs display a marked northeast to southwest angle when co-occurring with regime #13; however, this contains fewer events (this regime being likely associated with ARs often reaching Antarctica further east). Results are consistent for both AR detection schemes. These results suggest that (a) the synoptic configurations with marked northerly wind anomalies (likely to span from northwesterly to northeasterly from one AR to another) embedded in and located west of atmospheric ridges/blocks are the most favorable conditions for AR occurrence; (b) that these ARs reaching the DDU sector could advect southwards moisture coming from a vast region, from the southern part of the Indian Ocean to the southwest Pacific sector near New Zealand. Further analysis is ongoing to assess the moisture sources of these ARs in detail.

5.2. Combined Effects on the Climate of East Antarctica

Figure 6 presents the anomalies of atmospheric variables measured at the synoptic weather station of DDU synchronous with the 15 regimes (corresponding climatologies are shown in Figure S14 in Supporting Information S1). The weather regimes being based on geopotential height, strong regime-dependency is logically found in SLP. Regime effects are similar between the two opposite seasons of austral winter and summer (Figures S15 and S16 in Supporting Information S1).

While diurnal thermal range is quite stable across regimes, the latter have a larger influence on air temperature, modulating daily minimum and maximum temperature in an almost similar way. Here, the sign of meridional wind anomalies is the key parameter that controls the sign of temperature anomalies along the coast: regimes favoring southerly anomalies from the hinterland, enhancing katabatic winds, lead to anomalously cold conditions at DDU (this is for instance the case for regimes # 3, 4, 5 and 15). Symmetrically, northerly advections clearly favor warm anomalies reaching DDU (e.g., regimes # 6, 10, 11), associated with larger local wind speeds. The role of synoptic regimes for modulating local-scale temperature may also be damped by more local effects: this is the case for regime #9, which advects warmer air from the mid-latitudes west of the station, but circulation anomalies associated with anticyclonic conditions further east deflect the winds, with a marked westerly component over coastal Antarctica that enhances their residency time over land. This acts to weaken the temperature anomalies associated with this regime. The amplitude of temperature anomaly changes from one regime to another (typically $\pm 5^{\circ}\text{C}$) should be compared (a) to the total spread internal to each regime (typically, 5°C according to the inter-quartile range regrouping 50% of the days: see boxplots in Figure 6) and (b) the annual thermal range (roughly 15°C : Figure S14 in Supporting Information S1). The effects of the regimes on air temperature anomalies are very similar in winter and in summer (Figures S15 and S16 in Supporting Information S1), albeit a much larger amplitude of the anomalies in winter. These results show that, while weather regimes significantly influence temperature variability according to analyses of variance (labels in Figure 6), they only account for a limited fraction of the total variability. Residual variance internal to the regimes needs therefore to be considered for more detailed analyses (see Section 5.3).

Quite logically, the regimes associated with warm anomalies caused by advections from the Southern Ocean also transport moisture towards the DDU sector. This leads to stronger modulation of Q anomalies and weaker modulation of RH anomalies by the synoptic configurations, and hence the regimes. Q also shows much stronger seasonality than RH (Figure S14 in Supporting Information S1). Yet, regime influence on air humidity is similar throughout the year (Figures S15 and S16 in Supporting Information S1), the opposite seasons differing mostly in the larger amplitude of Q anomalies in summer. As expected for polar latitudes, surface solar radiation (RAD) is the variable showing the largest modulation by the annual cycle, with values close to zero in winter. Regimes appear to have a weak influence on RAD on average (Figure 6), which logically increases in summer (Figure S16 in Supporting Information S1). At that time, regimes associated with positive anomalies of Q clearly correspond to the most negative anomalies of RAD, presumably due to increased cloud cover. Counter-intuitively, these regimes are not associated with low-pressure anomalies in the DDU region, but tend to correspond to the regimes associ-

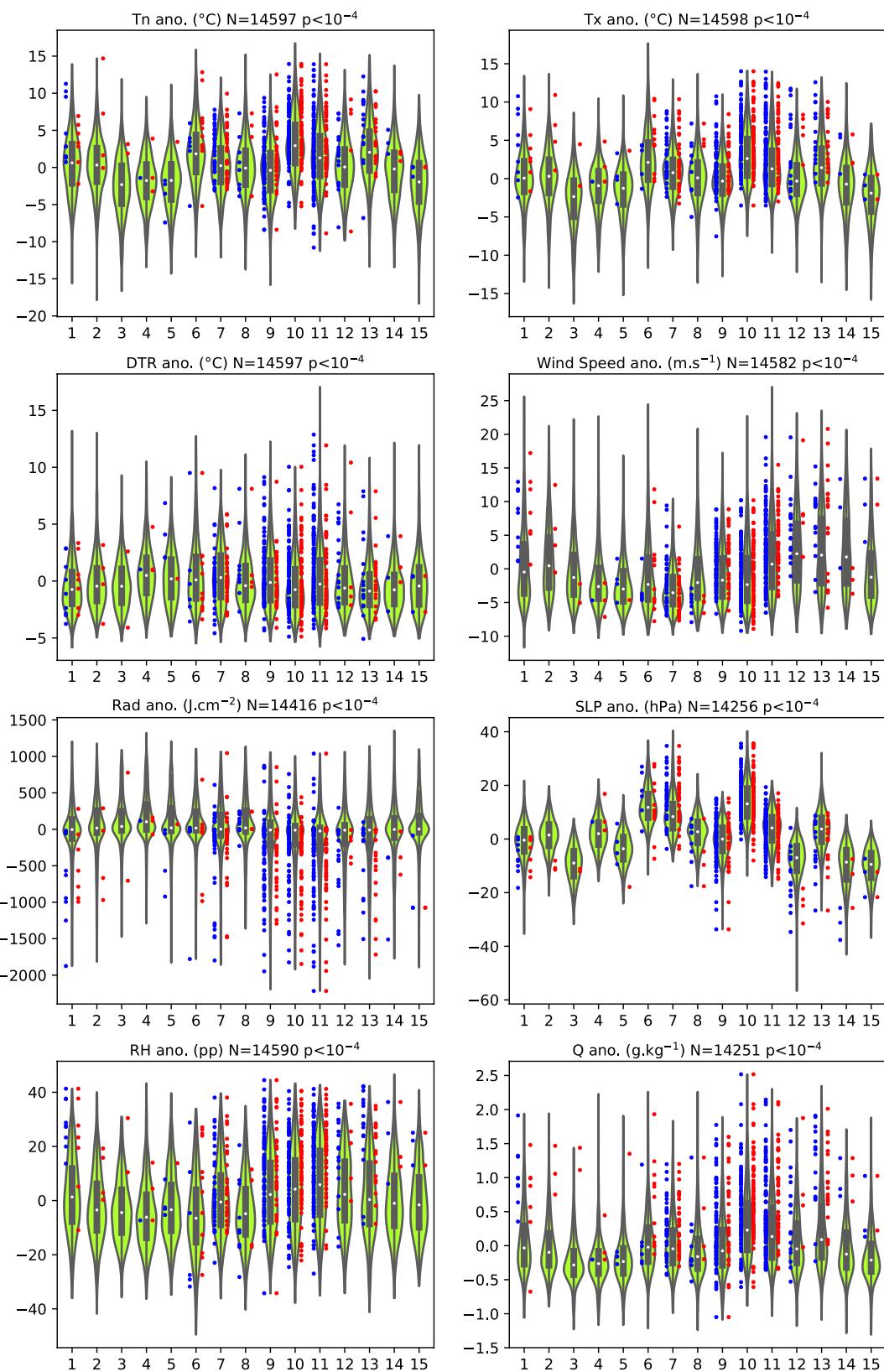


Figure 6.

ated with the largest occurrence of AR events, such days contributing to the most negative RAD anomalies (even in winter: Figure 6 and Figures S15 and S16 in Supporting Information S1). AR days tend also to be anomalously windy and humid (especially for Q), and anomalously warm (during all seasons, and more particularly for Tx). While the concept of daily extrema is less meaningful in winter, the strong influence of ARs on Tx denotes abrupt warming events, mostly driven by strong and sudden advects of moisture and heat from the lower latitudes.

In order to disentangle the mean influence of synoptic conditions (materialized here by the regimes) on the local climate in DDU, from the specific effect of AR events, Figure 6 is accompanied by Table S1 in Supporting Information S1, that tests the significance of (a) local anomalies against the climatology during all regime occurrences, and (b) local differences between AR and non-AR days within each regime. Results reveal that overall regime anomalies and differences between AR and non-AR days are not directly related. This implies that the specific effects of ARs on the local weather are largely independent of the mean conditions that prevail at DDU during similar synoptic contexts. They also strongly depend on the considered meteorological variable. As far as the main AR-favorable regimes (#9-10-11) are concerned, most anomalies (against the climatology) and most differences (between AR and non-AR days) tend to be significant, except for AR influence on the diurnal thermal range and sea-level pressure.

Figure 7 presents similar analyses for meteorological variables (2-m air temperature, surface pressure and wind speed) measured at the D10 skiway station (5 km away from the DDU synoptic station, on the mainland) and at Dome C, at about 1100 km from the coastline. This interior site is also more elevated (3250 m asl on an ice dome over the Antarctic plateau: Section 2.2). Corresponding seasonalities are shown in Figure S17 in Supporting Information S1. D10 displays strong similarities with nearby DDU station, both in terms of seasonality and composite anomalies during regime and AR occurrences. By contrast, in Dome C, the annual cycle of temperature is much stronger, especially due to very cold conditions during the polar night. Surface pressure also shows some seasonal dependency (which is not the case for coastal stations), and wind speeds are much reduced compared to the katabatic wind regime recorded along the coast (Figure S17 in Supporting Information S1). Weather regimes have limited influence on wind speed at Dome C, but AR days at DDU tend to coincide with the windiest days there (especially during the most favorable regimes, #9-10-11). They modulate surface pressure in a coherent and consistent way compared to D10 and DDU, indicative of large-scale signals with strong spatial coherence. Similar results hold for air temperature in Dome C, also responding to both regimes and coastal AR events consistently with DDU. In particular, regimes associated with northerly anomalies favor anomalously warm (that is, less cold) conditions in Dome C, a result further enhanced during AR events. This is consistent with the relatively larger wind speed during these days, which corresponds to strong advects of temperature and moisture from lower latitudes. These observations are consistent with reanalyses (Figure 3), an issue further explored in Section 5.3.

5.3. Interactions Between Regimes and ARs at Regional Scale

Here, we complement the local analyses presented in Section 5.2 at the regional scale, using reanalyses and regional climate simulations. Our goal is to identify the differences between AR and non-AR days within the same regime. This question leads us to analyze more in detail the residual variability occurring within weather regimes, and to determine if AR events can contribute to explain part of it.

Figure 8 presents normalized snowfall anomalies during the 5 regimes most favorable for ARs at DDU (namely, #7, 9, 10, 11, 13: Figure 4; Figure S12 in Supporting Information S1). The normalization is used to consider the strongly decreasing snowfall amounts from the coastal regions to the inland plateau (e.g., Turner et al., 2019). Figure S18 in Supporting Information S1 complements these analyses by presenting the raw (non-normalized) anomalies during the occurrence of all 15 weather regimes. The regimes most frequently associated with ARs are among those that bring the largest snowfall amounts, especially along the coast (Figure S18 in Supporting Information S1). The location of the largest amounts coincides well with the longitude of the northerly anomalies advecting moisture from the lower latitudes towards Antarctica (Figures 2 and 3; Servettaz

Figure 6. Composite anomalies of meteorological variables measured at the weather station of Dumont d'Urville during the regime occurrences with respect to their respective 40-year mean climatology, period 1979–2018. Variables considered: daily minimum (Tn) and maximum (Tx) air temperature at 2m (°C); diurnal thermal range (DTR, °C); wind speed (m.s⁻¹); global surface radiation (J.cm⁻²); sea-level pressure (hPa); relative (percentage points) and specific humidity (g.kg⁻¹). The number of data included in each analysis is labeled in each panel title. Violin plot representation, sample construction and statistical significance are as in Figure 5. The blue (red) dots represent days associated with atmospheric rivers as detected by the vIWT (IWV) scheme.

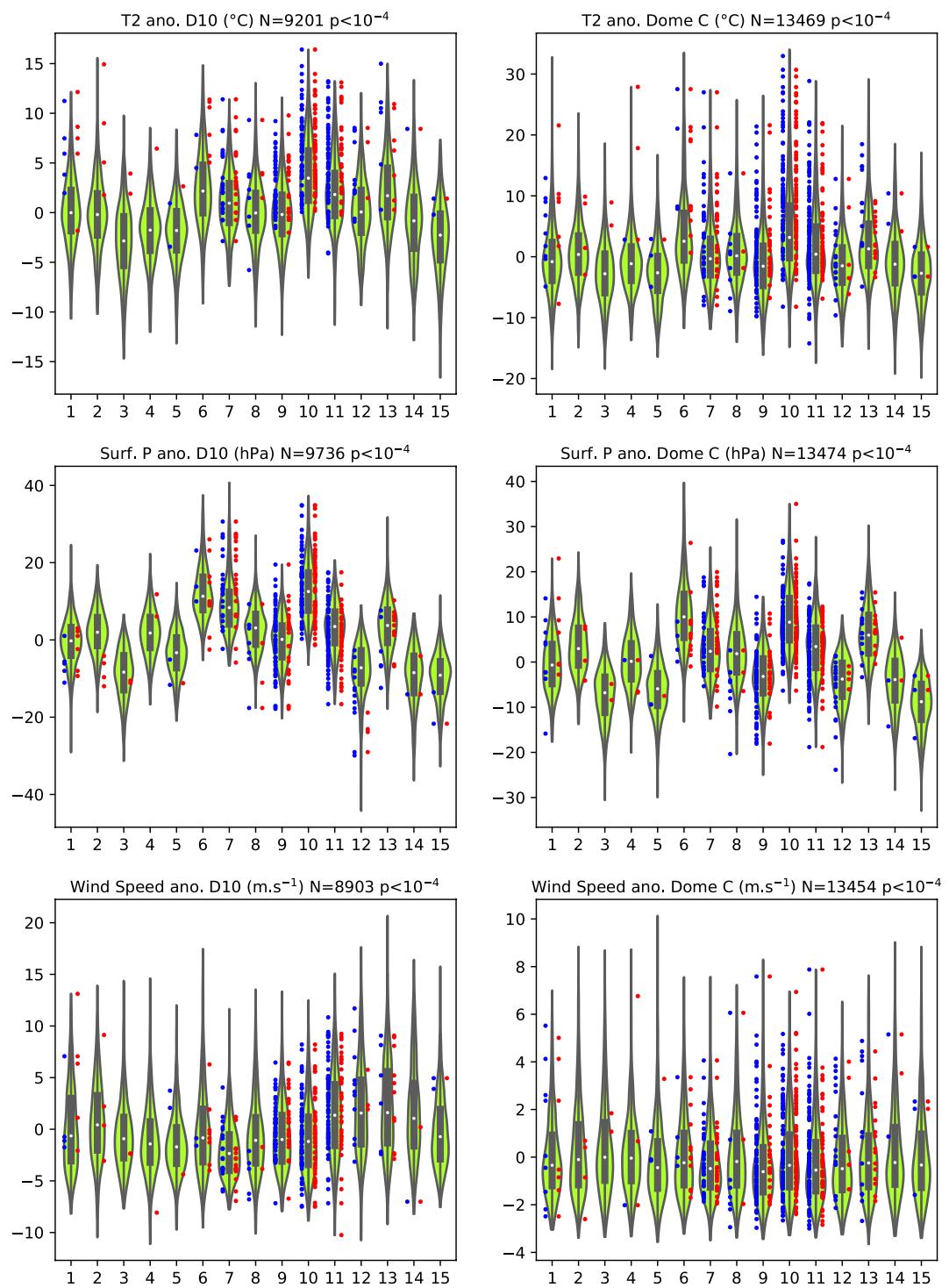


Figure 7. As Figure 6 but for a comparison between the automatic weather stations of Antarctica coastline (D10, left-hand column) and hinterland (Dome C, right-hand column). Location of stations is shown in Figure 8.

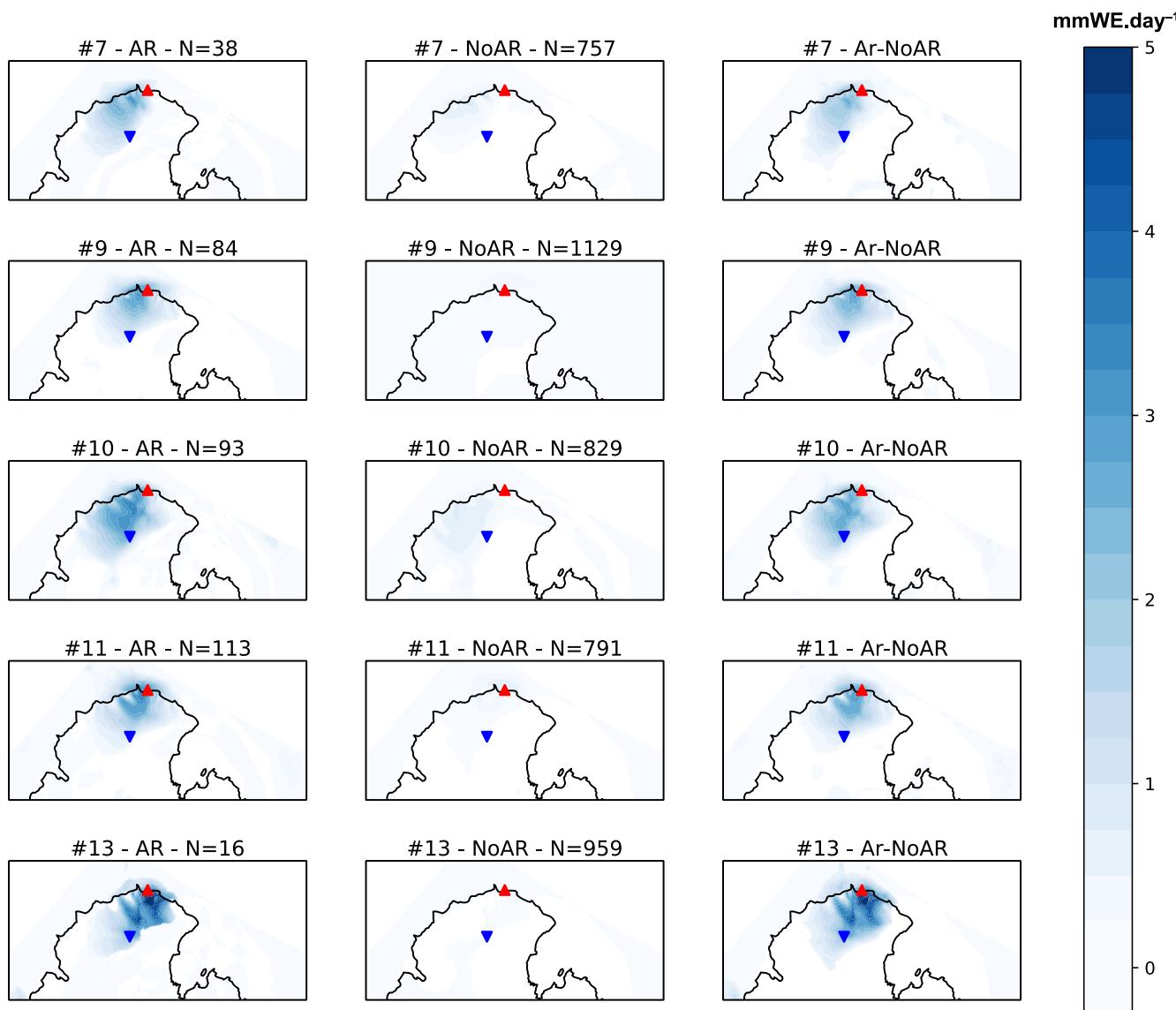


Figure 8. Simulated anomalies of daily mean snowfall accumulation ($\text{mmWE} \cdot \text{day}^{-1}$, see color legend) for selected regimes associated with largest atmospheric river (AR) occurrences (Figure 3), during AR occurrences (left-hand column), without AR occurrences (central column), and differences between both samples (right-hand column). Significance of anomalies for the first two columns is tested as for Figure 2, while the differences between samples is tested using a two-tailed t-test (right-hand column). The red (blue) triangle shows the location of the Dumont d'Urville (Dome C) station. Anomalies that are not significantly different from the mean climatology according to a t-test at the 95% confidence level are shaded white. N = number of days in each regime.

et al., 2020). In detail, however, these “snowy” regimes appear strongly driven by high accumulations recorded during a few AR events, while the large majority of days not associated with ARs exhibit much weaker snowfall (Figure 8). This means that the “snowy” regimes are mostly snowy during ARs, and that a few AR days strongly influence the average amounts recorded during all regime occurrences agreeing with the analysis of AR-influence on high precipitation events on this region (e.g., Wille et al., 2021). The same conclusions hold for all 5 regimes, and for the coastal regions near DDU but also for Plateau regions like Dome C. There, snowfall amounts are lower, and working with non-normalized anomalies would suggest strongly decreasing AR influence towards the south. Moreover, a study at Dome C should consider the role of “diamond dust” and hoar frost in net accumulation (e.g., Schlosser et al., 2016, 2017; Stenni et al., 2016). However, there are far fewer occurrences with relatively large daily totals, with significantly higher magnitude than what is expected for diamond dust precipitation (e.g., Schlosser et al., 2017). Nonetheless, our results confirm that even far from the coast, ARs are responsible for a sizeable fraction of total snowfall amounts, despite their infrequent occurrence (Wille et al., 2021).

Such intra-regime diversity leads us to reinvestigate the composite mean anomaly patterns discussed above (Figures 2 and 3) as the typical spatial signature of the regimes. Figure 9 duplicates the analyses of Figure 8 but for the geopotential height, horizontal wind and specific humidity at 700 hPa derived from ERA5 reanalyses (thus giving results directly comparable to Figure 2 but breaking down by AR and non-AR days at DDU). The AR detection scheme used here is vIVT: the results obtained using the IWV criterion are similar (Figure S19 in Supporting Information S1). Figure 10 (complemented by Figure S20 in Supporting Information S1 for the IWV detection scheme) shows similar analyses applied to anomalies of 2-m temperature and total water in the air column, as an equivalent of Figure 3 including specific AR effects.

Whatever the regime considered, days associated with AR events significantly differ from other days. AR days generally correspond to synoptic configurations that are much stronger than other (non-AR) days. This is particularly true for the anticyclonic ridge/blocking (materialized in the figure by positive geopotential height anomalies) located northeast of the DDU region, and acting to deviate atmospheric fluxes, and thus in promoting meridional transport of heat and moisture towards that region (e.g., Irving & Simmonds, 2015; Massom et al., 2004). Through geostrophy, such enhanced blockings favor stronger moisture and heat transport, forming a favorable regional-scale configuration in which AR events can be embedded (and to which they can contribute). The southward transport of heat and atmospheric moisture associated with ARs is channeled by strong ridges/blocks located further east (Figure 9). This explains the paradox of heavy precipitation occurring during high pressure and high wind conditions in coastal regions like DDU and D10 (Figures 6 and 7). These amplified atmospheric fluxes yield strong extended warm anomalies over Antarctica that reach the plateau (Figure 10). They also convey precipitable water in the air column, but humidity barely penetrates over the landmass due to orographic lifting along and near the coastline, bringing abundant snowfall there (Figure 8; Servettaz et al., 2020). This explains why AR events at the coastline may affect Dome C (at about 1100 km from the coast), as proposed by Schlosser et al. (2017) for the strongest blocking anticyclones, where they are associated with strong wind speeds and warm anomalies (Figure 8; Figure S18 in Supporting Information S1).

From the frequency labels of Figures 9 and 10, it is clear that AR days only represent a very small proportion of all days ascribed to each of these AR favorable regimes. Such marked difference in the number of days considered to perform the analyses of Figures 9 and 10 raise two questions. (a) From a statistical point of view, could the significance of the differences between AR and non-AR days be altered by dissimilar sample sizes, or in other words, what is the statistical robustness of the differences identified in these figures? (b) From a physical point of view, do all strong anticyclonic ridges/blocks lead to AR events, or are these anomaly patterns a necessary but not a sufficient condition for AR development? Table 3 attempts to address these issues, by analyzing how often positive geopotential height anomalies differ between AR and non-AR samples of days within each weather regime. The systematic or occasional significance of the differences is assessed by choosing randomly 100,000 samples of non-AR days within each regime, that have the same size as corresponding AR samples. Table 3 then presents the proportion of significance differences among these 100,000 samples, according to two-tailed t-tests at contrasted significance bounds. Here, these tests are applied to the regional maximum of positive geopotential height anomalies, identified as a robust descriptor of atmospheric centers of action associated with extra-tropical weather regimes by Pohl, Lorrey, et al. (2021). Results (Table 3) reveal that, for rather low significance levels (95%, i.e., $p = 5 \times 10^{-2}$), geopotential height anomalies are almost systematically larger during AR days, confirming the importance of strong ridges/blockings for poleward AR transport. Results are less clear at higher significance level (99.99%, i.e., $p = 10^{-4}$). Here, the proportion of non-AR days that differ from AR days, while virtually unchanged for regime #10, drops to roughly 63%–69% for regime #7 (depending on the AR detection scheme). For regime #9 the detection scheme has a dramatic influence (84% of statistically significant Max_Z differences for vIVT against only 17% for IWV). Regime #11 shows similar behavior. Regime #13 forms a noticeable exception, with much weaker proportion of significance differences between AR and non-AR days, whatever the detection scheme used. Caution is needed with this regime, because AR days are very rare (only 16 days over the 40-year long period: Figure 9). This is probably because this regime yields AR events that reach Antarctica further east (through northwesterly or northerly anomalies), the case of northeasterly ARs remaining rather rare (Figure 5).

Overall, these results suggest that some strong anticyclonic ridges/blocks may exist, even in the absence of ARs. From one regime to another, the fraction of strong geopotential maxima co-occurring with ARs is very dissimilar, which leads us to conclude that strong ridges/blocking are a necessary, but not a sufficient condition for AR development. These results help identify the most favorable conditions leading to ARs. They also point out that

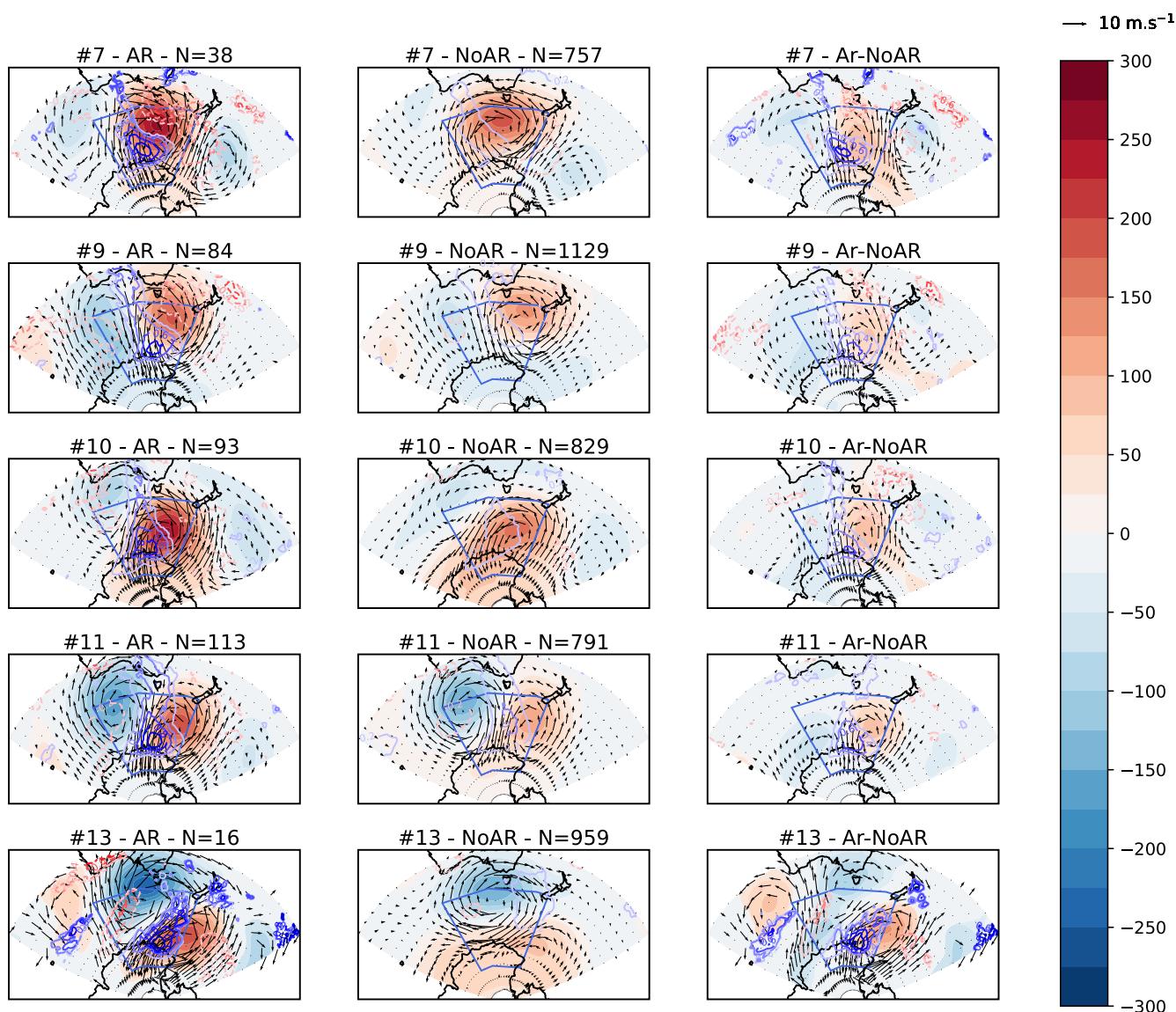


Figure 9. As Figure 2 but for selected regimes associated with largest atmospheric river (AR) occurrences (Figure 4), during AR occurrences (left-hand column), without AR occurrences (central column), and differences between both samples (right-hand column). Significance of anomalies and differences between samples tested as in Figure 8.

weather regimes conceal strong internal variability, but their usefulness to identify the atmospheric configurations leading to climate extremes in Antarctica has been confirmed in this work, although other influences are also at play.

6. Discussion and Conclusion

Weather regimes obtained through k-means clustering have been defined over the East Antarctica/Southern Ocean sector based on daily maps of 700 hPa geopotential height anomalies. These regimes depict the eastward propagation of transient perturbations embedded in the mid-latitude westerlies. Regime sequences are short, suggesting a strong association with the synoptic-scale variability. Nonetheless, interannual variability in regime occurrences is quite strong, and appears primarily driven by the phase of the SAM. These results tend to be stronger in austral summer.

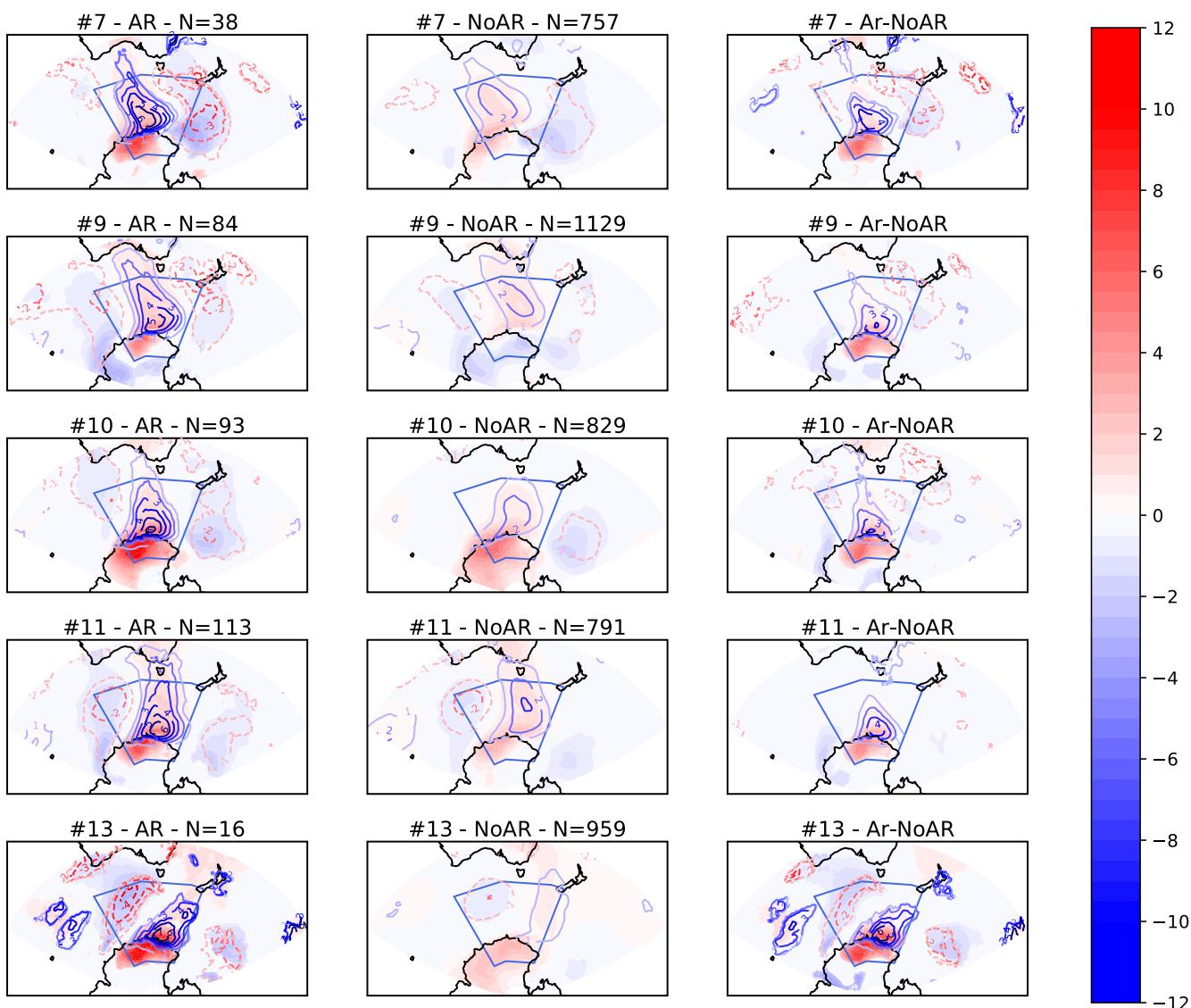


Figure 10. As Figure 3 but for selected regimes associated with largest atmospheric river (AR) occurrences (Figure 4), during AR occurrences (left-hand column), without AR occurrences (central column), and differences between both samples (right-hand column). Significance of anomalies and differences between samples tested as for Figure 8.

Regime occurrences were then compared to ARs detected over the same domain and period by two complementary schemes based on contiguous patterns of anomalously strong IVT or IWV in the air column between southern mid-latitudes and Antarctica. ARs show uniform distribution over the year but show strong preferential co-occurrence with regimes characterized by an atmospheric ridge/blocking located off the Antarctica coastline, and acting to favor meridional transport of heat and moisture from the lower latitudes to the polar regions. Such regimes are then associated, on average, with increased temperature and snowfall over Antarctica, but more detailed analysis reveals that such anomalies tend to be enhanced during AR events and much weaker (though still significant) the rest of the time. This is especially true for snowfall amounts and 2-m air temperature anomalies, dramatically amplified during AR days, as a consequence of southward transport from the middle to the high latitudes. Finally, we show that, within all regimes, days associated with ARs significantly differ from the composite mean. Generally, they correspond to stronger synoptic configurations, and especially, to stronger atmospheric ridges/blockings that are located to the northeast of the region most influenced by the corresponding ARs. One explanation for these enhanced downstream ridges is the moisture export from the lower latitudes at the beginning of the AR life cycle condenses as the flow travels poleward over cooler sea surface temperatures.

Table 3

For the Five Regimes Most Favorable to AR Events, Proportion (%) of Samples Not Associated With Atmospheric Rivers (ARs) That Significantly Differ, at the Significance Level Indicated in the Table (p -Value), From the Sample of the Same Regime Associated With ARs, in Terms of Maximum Amplitude of Geopotential Height Anomalies (Max_z)

Max _z		vIWT	IWV
#7	$p < 10^{-4}$	63.59	69.11
	$p < 5 \times 10^{-2}$	99.97	99.99
#9	$p < 10^{-4}$	83.76	16.98
	$p < 5 \times 10^{-2}$	99.99	95.72
#10	$p < 10^{-4}$	99.97	98.85
	$p < 5 \times 10^{-2}$	100.00	100.00
#11	$p < 10^{-4}$	97.31	44.76
	$p < 5 \times 10^{-2}$	100.00	99.82
#13	$p < 10^{-4}$	0.30	0.50
	$p < 5 \times 10^{-2}$	44.71	46.88

Note. Analyses are duplicated for the vIWT and IWV AR detection schemes. Samples without ARs have the same size as those with ARs and are randomly chosen among the days ascribed to the same regime. The proportion is calculated based on the corresponding 100,000 random selections of non-AR days within each regime.

The condensation releases latent heat fueling cyclogenesis via differential diabatic heat and acts to decrease the potential vorticity of the downstream ridge (Madonna et al., 2014; Terpstra et al., 2021; Woollings et al., 2018). Although moisture sources still remain to be assessed, the large diversity in AR orientation, location and shape, suggests that moisture could mainly originate from a vast region spanning from the Indian Ocean to New Zealand, including thus the Great Australian Bight, Southwest Pacific Ocean and Tasman Sea. Anomalously strong ridge/blocking direct such moisture through northerly anomalies towards Antarctica. Along the coast, this leads to large snowfall accumulation, and the transport of heat from the lower latitudes can penetrate inland and yield warm anomalies more than 1000 km from the coast. In these interior regions, snowfall rates are much lower, but still above average, during coastal AR events. However, moisture amounts released in the cold atmosphere of Dome C could partly contribute to clear-sky precipitation occurring later (e.g., Schlosser et al., 2017), but such effect has not been analyzed here, as the processes associated with diamond dust occurrences are largely missed in most models (e.g., Genthon et al., 2009; Souverijns et al., 2019; van De Berg et al., 2005).

These results help identify the regional-scale conditions favoring AR events, particularly strong synoptic configurations of the regimes associated with an atmospheric ridge/block located off the Adélie Land (East Antarctica) coastline. In order to differentiate between ridging/blocking, blocking indices like those developed by Pook and Gibson (1999) could be used as a complement to the analysis of the positive Z700 anomalies. However, strong ridge/blocks are likely to be a necessary but not a sufficient condition. This is probably

true for the entire Antarctic coastline as an overall high zonal pressure difference between the upstream trough and downstream ridge coincides, but does not alone assure an AR landfall on the continent (Wille et al., 2021). The small number of ARs over the period should be compared to the size of their most favorable regimes (e.g., Figure 8): within regimes #9, #10 and #11 (i.e., those associated with the largest occurrence of ARs), only 6.9%, 10.1% and 12.5% of the days correspond to AR events according to the vIWT detection scheme, respectively. For the IWV detection scheme, these values even drop to 2.8%, 8.7% and 6.0%. Hence, all strong blocks are not associated with AR events (as confirmed by analyses of random selection of non-AR samples, that reveal that strongly variable proportions of strong ridges/blocks co-occur with AR events). There is therefore a strong need to better understand all mechanisms and processes that differentiate favorable conditions that are, and those that are not, associated with ARs.

Future work should be devoted to this issue. A better understanding and seamless forecasting of major AR events implies a more precise knowledge of their causes and intrinsic properties. Although this study clearly identified synoptic contexts/weather regimes favorable for AR occurrences, confirming the key role of intense anticyclonic ridging/blocking in the generation of intense warm and moist intrusions of marine air over the ice sheet (Scott et al., 2019), there is now a need to better differentiate the strong, quasi-stationary subpolar blocks, from other anticyclones and transient atmospheric ridges embedded in synoptic-scale disturbances and wave activity that cause precipitation variability and extreme events in southern hemispheric territories such as Australia and New Zealand (Pook et al., 2012; Udy et al., 2021). Large-scale wind shear in the middle latitudes upstream of the ridges/blocks could contribute to control the origin of the air particle, and therefore their heat and moisture content. Back-trajectories could be an efficient tool to explore this and identify sources of moisture export (e.g., Scarchilli et al., 2011; Sodemann & Stohl, 2013). At higher latitudes, the ventilation of the Antarctic air mass by northerly advections is likely to depend on the strength of the southerly katabatic winds. Horizontal pressure gradients between the landmass and the Southern Ocean could modulate the spatial extension of AR influence on the inland plateau: part of these gradients could be influenced by the state of the SAM, but many other factors could also be at play.

The results obtained here over Adélie and Victoria land point out a strong control of anticyclones on the location and orientation of AR events. Future work could attempt to analyze to which extent these results are zonally sym-

metric, that is, hold for other longitudes along the Antarctica coastline. Our results suggest that the mechanisms discussed here could be largely valid over most parts of East Antarctica (including remote regions of Wilkes, End-erby and Queen Maud lands) where the coastline and inland topography also show similarities with the region considered in this work, and strong zonal symmetry with relatively consistent annual AR frequencies along the coastline (Wille et al., 2021). Generalizing these results for other longitudes is among the remaining open issues to be addressed. Last but not least, long-term changes in AR (e.g., Espinoza et al., 2018), weather regimes, and their interdependence, are among the major aspects of climate change that need to be explored for these regions. Here, long-term evolutions mostly involve the latitudinal dimension. Changes in the general circulation and especially the expected meridional shifts of the storm tracks (either driven by increasing greenhouse effect or ozone recovery: e.g., Thompson et al., 2011), low-frequency evolutions in the state of the SAM, and ongoing warming trends, could all modify the intrinsic properties of both regimes and AR events, that is, their recurrence, location (Ma et al., 2020), extension and intensity. Potentially, they could also change their effects on the ice sheet, for example, through stronger extreme precipitation due to Clausius-Clapeyron scaling (Betts & Harshvardhan, 1987; Kharin et al., 2007; Muller et al., 2011; O’Gorman & Schneider, 2009; Pall et al., 2007; Trenberth et al., 2003; Westra et al., 2014), or through enhanced melt occurring under warmer surface air temperatures, especially near the coast (Wille et al., 2019). Because of their major influence for the climate of Antarctica, these issues certainly deserve further work from the scientific community.

Data Availability Statement

ERA5 data can be retrieved from <https://cds.climate.copernicus.eu/cdsapp#!/search?type=dataset&text=era5>. ERSST data is available at <https://psl.noaa.gov/data/gridded/data.noaa.ersst.v5.html>. Météo-France performs the meteorological data from Dumont d’Urville, partly available at <https://www.infoclimat.fr/observations-meteo/temps-reel/terre-adelie-dumont-d-urville/89642.html>. Meteorological data recorded at other sites in Adelie land are accessible at <http://pp.ige-grenoble.fr/pageperso/favier/observatory.php> and <http://amrc.ssec.wisc.edu/data/view-data.php?action=list&product=surface>. Weather data at Hobart was provided by the Australian Bureau of Meteorology (<http://www.bom.gov.au/climate/dwo/index.shtml>). The SAM index was retrieved from https://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/ao/ao.shtml. The Niño3.4 index was retrieved from <https://climatedataguide.ucar.edu/climate-data/nino-sst-indices-nino-12-3-34-4-oni-and-tni>. The MAR source code and outputs as used in this study can be found at <https://zenodo.org/record/4314872>. The MAR source code is tagged as v3.11.2 on <https://gitlab.com/Mar-Group/MARv3.7>: see <http://www.mar.cnrs.fr> for more information.

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