

# 1 Curved atmospheric rivers and their moisture remnants: a new 2 detection tool for Antarctica

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7 **Abstract.** Atmospheric rivers (ARs) represent the main intrusions of moisture and heat into Antarctica, exerting a major  
8 influence on the continent's surface mass balance. Yet, due to geometric and directional constraints, existing detection  
9 algorithms often fail to track their evolution inland after landfall or in regions where abrupt directional changes occur. We  
10 introduce DARK (Detecting ARs using their Kurvature), a new Antarctic AR detection framework designed to overcome these  
11 limitations. DARK applies a strict 98th-percentile threshold to total integrated vapor transport and computes AR length along  
12 the curved axis to evaluate the 2000-km AR criterion. This enables the continuous detection of ARs with complex geometries,  
13 including those that curve, overturn, or extend across the South Pole. An additional AR-children module identifies smaller but  
14 still intense moisture remnants that detach from parent ARs after landfall yet continue to transport vapor and heat inland. The  
15 resulting climatology shows that DARK ARs account for about 18 % of total Antarctic precipitation and are linked to roughly  
16 half of top 1 % daily precipitation anomalies, 60 % of top 1 % daily maximum temperature anomalies, and 80 % of compound  
17 warm-and-wet events. DARK provides a more detailed assessment of AR-related precipitation and temperature impacts in the  
18 South Pole region. Despite slightly higher occurrence, risk ratio analysis shows that DARK ARs more effectively capture the  
19 most intense events than earlier Antarctic schemes. Including AR-children further strengthens these associations, especially  
20 over Victoria Land, where they contribute to about one third of AR-related precipitation.

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30 **Plain Language Summary.** Atmospheric rivers (ARs) are long, narrow bands of air that carry large amounts of moisture and  
31 heat from the lower latitudes into Antarctica, where they trigger snowfall, surface melt, and extreme temperature events.  
32 Existing tools to detect these features often miss them when they arrive at the coast in unusual directions or continue moving  
33 inland after landfall. We developed a new detection method, called DARK, that can identify atmospheric rivers regardless of  
34 their shape or direction, including those that curve or cross the South Pole. DARK also tracks smaller moisture remnants,  
35 called AR-children, that split off from the main system after it reaches the continent but continue to bring moisture inland. Our  
36 results show that atmospheric rivers detected by DARK are responsible for about 18 % of Antarctic snowfall and are associated  
37 with half of the top 1 % precipitation anomaly days, 60 % of the top 1 % warm anomaly days, and 80 % of days with  
38 simultaneous top 1 % warm and precipitation anomalies. AR-children make additional contributions, particularly in Victoria  
39 Land. This new framework provides a more complete picture of how atmospheric rivers shape the weather and mass balance  
40 of the Antarctic Ice Sheet.

41

42 **Keywords :** Atmospheric rivers – Antarctica – Precipitation – Detection tool – Methodology

## 43 **1 Introduction**

44 Atmospheric rivers (ARs) are long, narrow filaments of enhanced horizontal water vapor transport that are an essential  
45 component of the global hydrological cycle and particularly play a central role in the Antarctic surface mass balance (e.g. Zhu  
46 and Newell, 1998; Wille et al., 2025). ARs contribute positively to the Antarctic Ice Sheet (AIS) mass balance through  
47 enhanced snowfall (Turner et al., 2019; Wille et al., 2021; MacLennan et al., 2022), but they can also induce surface melt and  
48 promote ice-shelf instability when transporting warm, moist air masses inland (Gorodetskaya et al., 2014; Adusumilli et al.,  
49 2021; Wille et al., 2019; Wille et al., 2022). Given their dual role, robust detection of ARs is essential for quantifying their  
50 frequency and impacts.

51

52 Many AR detection tools (ARDTs) have been developed for different purposes and regions (Collow et al., 2022), but only a  
53 few are tailored to polar environments (Wille et al., 2021; Gorodetskaya et al., 2014; Mattingly et al., 2018; Wille et al., 2025).  
54 At the global scale, the most widely used scheme remains that of Guan and Waliser (2015), recently updated in Guan and  
55 Waliser (2024). It employs seasonally and spatially varying vertically integrated water vapor transport (IVT) thresholds (85th  
56 percentile), which provide broad applicability and robust intercomparison across reanalyses (Collow et al., 2022). The method  
57 also applies a set of geometric and directional filters, including a minimum feature length of about 2000 km, a length-to-width  
58 ratio requirement to ensure narrow filamentary structures, and directional coherence criteria that retain only elongated,  
59 dynamically consistent moisture transport features. In its latest version (Guan and Waliser, 2024; hereafter G&W v4), several  
60 refinements were introduced, including a revised treatment of directional coherence, improved handling of zonally oriented  
61 ARs in the extratropics, and a polar refinement based on a hemispheric IVT threshold, defined from the area-weighted spatial

62 5th percentile of local IVT thresholds. This replaces the previously fixed  $100 \text{ kg m}^{-1}\text{s}^{-1}$  minimum and allows ARs to extend  
63 farther inland in polar regions. Despite these advances, limitations remain over Antarctica. Because the threshold is based on  
64 hemispheric IVT climatology, its effective local percentile varies strongly across the continent. It corresponds to relatively low  
65 local percentiles in West Antarctica and coastal regions, favoring numerous AR detections, but to very high percentiles over  
66 the cold, dry East Antarctic interior, sometimes exceeding the 99th percentile, which prevents inland detections. Consequently,  
67 AR occurrence remains spatially heterogeneous, with frequent detections along the coast and in West Antarctica but few over  
68 much of the East Antarctic Ice Sheet.

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70 For Antarctica, the most widely used polar-specific ARDT is that of Wille et al. (2021), which includes two variants of the  
71 same method applied to different input variables: the meridional component of IVT (vIVT, hereafter Wille vIVT) and vertically  
72 integrated water vapor (IWV, hereafter Wille IWV). Among these, the vIVT-based version is the most commonly used. It  
73 applies a monthly, locally defined 98th-percentile threshold on vIVT, combined with a  $20^\circ$  meridional extent criterion, to  
74 identify the strongest southward moisture intrusions linking the lower latitudes to the Antarctic continent. This design is  
75 physically consistent with the dynamics of extreme Antarctic precipitation, as intense snowfall events are generally associated  
76 with above-average IVT directed southward and approximately perpendicular to the coast (Wille et al., 2021). Consequently,  
77 the Wille vIVT scheme effectively isolates the ARs that have been linked to intense precipitation (Wille et al., 2021; Maclennan  
78 et al., 2022), surface melt (Wille et al., 2019, Gorodetskaya et al., 2023), firn depletion, large iceberg calving events, and ice-  
79 shelf destabilization (Wille et al., 2022). Thus, this ARDT has become the reference framework for polar AR studies (Wille et  
80 al., 2025).

81  
82 However, the Wille et al. (2021) framework, while robust, does not capture the full range of intense moisture transport features  
83 relevant to Antarctica. While weaker or more diffuse intrusions are rightly excluded by design, some long, narrow, and intense  
84 filaments of water vapor transport, dynamically consistent with the physical definition of ARs (American Meteorological  
85 Society, 2022), remain undetected. This underdetection arises from methodological constraints related to the orientation,  
86 coherence, and geometric requirements of the detection scheme.

87  
88 First, the use of vIVT in the Wille vIVT scheme introduces a discontinuity at the South Pole. When an AR crosses the pole,  
89 the sign of vIVT reverses from poleward to equatorward, preventing its identification. This discontinuity also breaks the  
90 continuity of the feature's axis, preventing it from satisfying the minimum length criterion ( $20^\circ$  meridional extent) at the  
91 highest latitudes. This issue does not affect the Wille IWV scheme, which does not consider the meridional wind; however,  
92 Wille et al. (2021) restricted their detection domain to  $85^\circ \text{ S}$  (Fig. 1b) to avoid this singularity, in both vIVT and IWV schemes,  
93 to maintain consistency of AR climatologies between both algorithms. While this boundary had little impact on coastal AR  
94 landfalls and when tracking their progression inland, it introduces a progressive detection bias toward lower latitudes, up to  
95 around  $65^\circ \text{ S}$ , as a result of the  $20^\circ$  meridional-extent requirement.

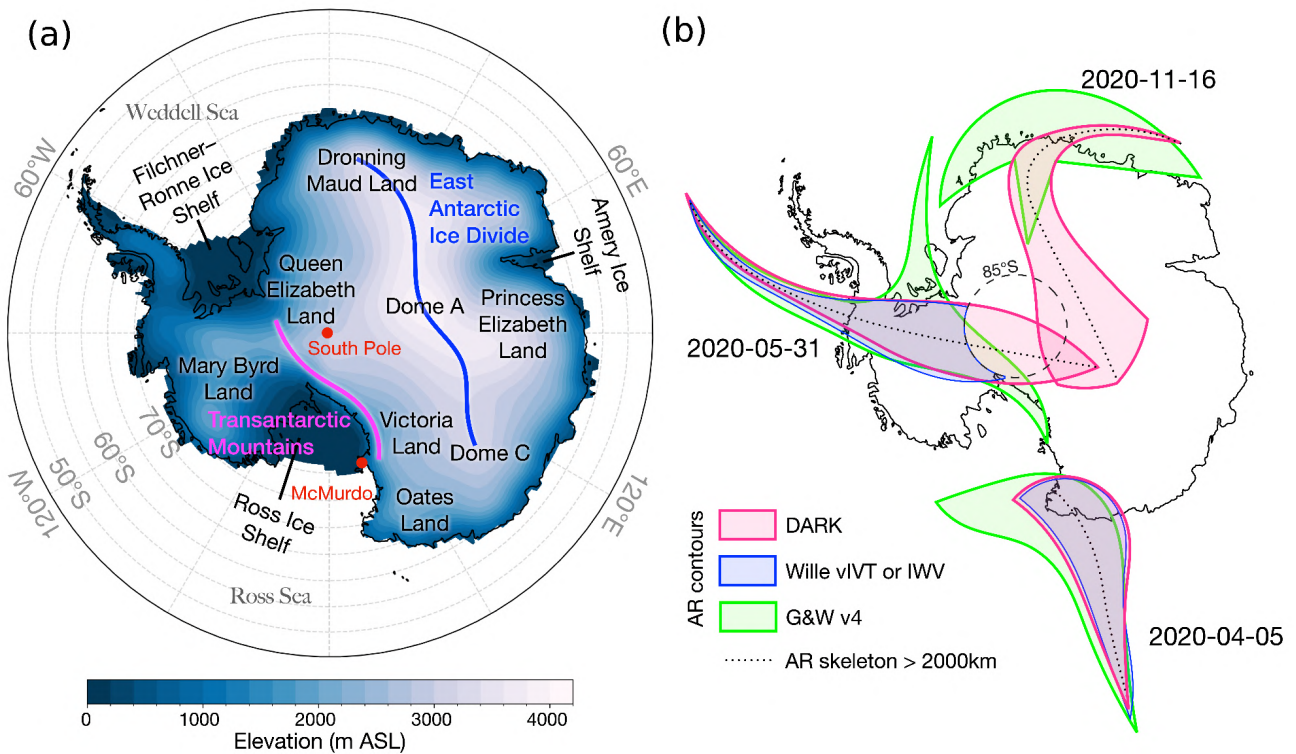
97 Second, focusing on “moisture transport axes”, a term introduced to unify ARs, tropical moisture exports, and warm moist  
98 intrusions; Spensberger et al. (2025) note that one third of those axes exhibit an equatorward component. This behavior likely  
99 reflects synoptic-scale processes such as frontal occlusion and the curvature of moisture pathways within mature cyclones, as  
100 well as the modulation of moisture transport by quasi-stationary large-scale circulation features and topographic forcing. As  
101 these systems move poleward and their associated ARs approach the Antarctic coast, they interact with the prevailing near-  
102 surface easterlies and the steep topography of the ice sheet margin. These interactions often cause the moisture plumes to curve  
103 or tilt at landfall, deviating from a purely meridional orientation. Approximately 20% of “moisture transport axes” south of  
104 70° S display such equatorward curvature (Spensberger et al., 2025). This behavior is particularly common in the Ross Sea  
105 and Weddell Sea regions (see Fig. 1a for geographic regions referenced in this study), where synoptic and orographic effects  
106 jointly steer moisture fluxes away from the meridional direction. In these cases, vIVT decreases and reverses sign as the AR  
107 curves equatorward, leading to a loss of detection at and beyond the inflection point. Although this specific limitation does not  
108 affect the Wille IWV scheme, it remains constrained by the 20° meridional-extent criterion, which also excludes long, curved,  
109 or overturning ARs that are dynamically consistent with AR characteristics but have limited meridional span due to their  
110 complex geometry. This limitation is not unique to the Wille vIVT and IWV frameworks. Global AR detection schemes such  
111 as G&W v4 also apply directional-coherence constraints that may limit the detection of ARs with strongly curved or reversing  
112 geometries, though their primary limitation over Antarctica relates to the effective IVT threshold rather than directionality, as  
113 further discussed in Sect. 3.

114  
115 Another limitation of existing detection approaches concerns the evolution of ARs after they reach the Antarctic continent.  
116 As they make landfall, they often diverge and lose their narrow filamentary geometry due to condensation, latent heat release,  
117 and the spreading of moisture fluxes within occluding or decaying frontal systems (Dacre and Clark, 2025). Although this  
118 morphological transition causes them to fall outside the geometric criteria of standard AR detection methods, these features  
119 frequently remain highly moisture-laden and continue to drive precipitation, cloud formation, and surface melt inland. To  
120 capture the continuation of AR influence, identifying and tracking such post-landfall remnants would be relevant but has not  
121 yet been proposed. This would allow the monitoring of structures representing the inland evolution of decaying but still active  
122 AR-provided moisture remnants. Accounting for these structures would be essential for quantifying the sustained hydrological  
123 and thermodynamic effects of ARs on the Antarctic surface mass balance, while extending the study of the Antarctic AR life  
124 cycle to its terminus (Wille et al., 2024).

125 To address these limitations, we develop a new Antarctic ARDT called DARK (Detecting ARs using their Kurvature), that  
126 builds upon the intensity-based framework of Wille et al. (2021) while removing directional constraints that limit the  
127 identification of curved or equatorward-turning ARs (like the AR making landfall on 2020-11-16, in Dronning Maud Land,  
128 Fig. 1b). The method applies a 98th-percentile threshold on total integrated vapor transport (IVT), computed using a 15-day  
129 rolling window to capture temporal variability and regional seasonality. Features smaller than 200,000 km<sup>2</sup> are removed prior

130 to classification. ARs are then defined as contiguous structures exceeding the IVT threshold with a total length of at least 2000  
 131 km, approximately equivalent to the 20° meridional extent criterion of Wille et al. (2021) (Fig. 1b), but regardless of their  
 132 orientation or directional coherence. In addition, we introduce an add-on to identify and track post-landfall moisture remnants  
 133 with IVT above the local 98th-percentile, with an area exceeding 20,000 km<sup>2</sup>, which evolve from previously detected ARs but  
 134 no longer meet the geometric length criterion, hereafter referred to as AR-children. This study aims to illustrate that our  
 135 framework provides a more complete and physically consistent view of AR-driven moisture transport and its influence on  
 136 Antarctic precipitation and near-surface temperature variability, with implications for surface melt and ice-shelf stability.

137 We apply this framework to a multi-decadal ERA5 reanalysis (1979–2023) to produce the first comprehensive assessment of  
 138 Antarctic ARs detected by DARK (hereafter DARK ARs) and their post-landfall AR-children. The analysis quantifies their  
 139 contribution to Antarctic precipitation, as well as to precipitation, temperature, and compound extreme anomalies. It further  
 140 characterizes the magnitude and orientation of IVT and presents representative case studies illustrating their synoptic evolution.  
 141 Throughout, DARK is compared against the Wille vIVT, Wille IWV, and G&W v4 catalogues to contextualize its added value.  
 142 This framework aims to fill key observational and methodological gaps left by existing ARDTs, providing a more  
 143 comprehensive representation of Antarctic ARs and their impacts on the AIS.



144

145 Figure 1. (a) Map of the Antarctic Ice Sheet showing surface elevation (m a.s.l.) and key geographic regions discussed in the  
146 text. (b) Conceptual schematic illustrating detection differences between the DARK, Wille AR and G&W v4 frameworks  
147 during three arbitrary yet representative landfall events.

## 148 **2 Data and methodology**

### 149 **2.1 Data**

150 We use the ERA5 reanalysis produced by the European Centre for Medium-Range Weather Forecasts (ECMWF; Hersbach et  
151 al., 2020) for the period 1979–2023, at a horizontal resolution of  $0.25^\circ \times 0.25^\circ$ . Atmospheric rivers are detected at 6-hourly  
152 intervals using the eastward ( $uIVT$ ) and northward ( $vIVT$ ) components of integrated vapor transport (IVT). Diagnostic  
153 variables, including wind and geopotential height at 500 hPa, are analyzed at the same 6-hourly timestep.  
154 Surface diagnostics are evaluated at daily resolution: total precipitation is aggregated to daily sums, and 2 m air temperature  
155 is used to derive daily maximum values.

156 For intercomparison, the Wille et al. (2021) Antarctic AR detection schemes based on integrated water vapor (IWV) and  
157 meridional IVT ( $vIVT$ ) were recomputed at 6-hourly intervals. To ensure spatial consistency with the new DARK framework,  
158 both Wille schemes were extended northward to  $15^\circ$  S while retaining their original southern boundary at  $85^\circ$  S. This  
159 adjustment provides uniform temporal and spatial coverage across methods, enabling a direct comparison of AR frequency,  
160 geometry, and associated surface impacts over the 1979–2023 period.

161 We additionally use the tARget version 4 AR catalog (Guan and Waliser, 2024; hereafter referred to as G&W v4), generated  
162 from ERA5 for 1940–2023. Only the 1979–2023 period is retained to match the analysis window used throughout this study.

### 163 **2.2 DARK AR Detection Algorithm**

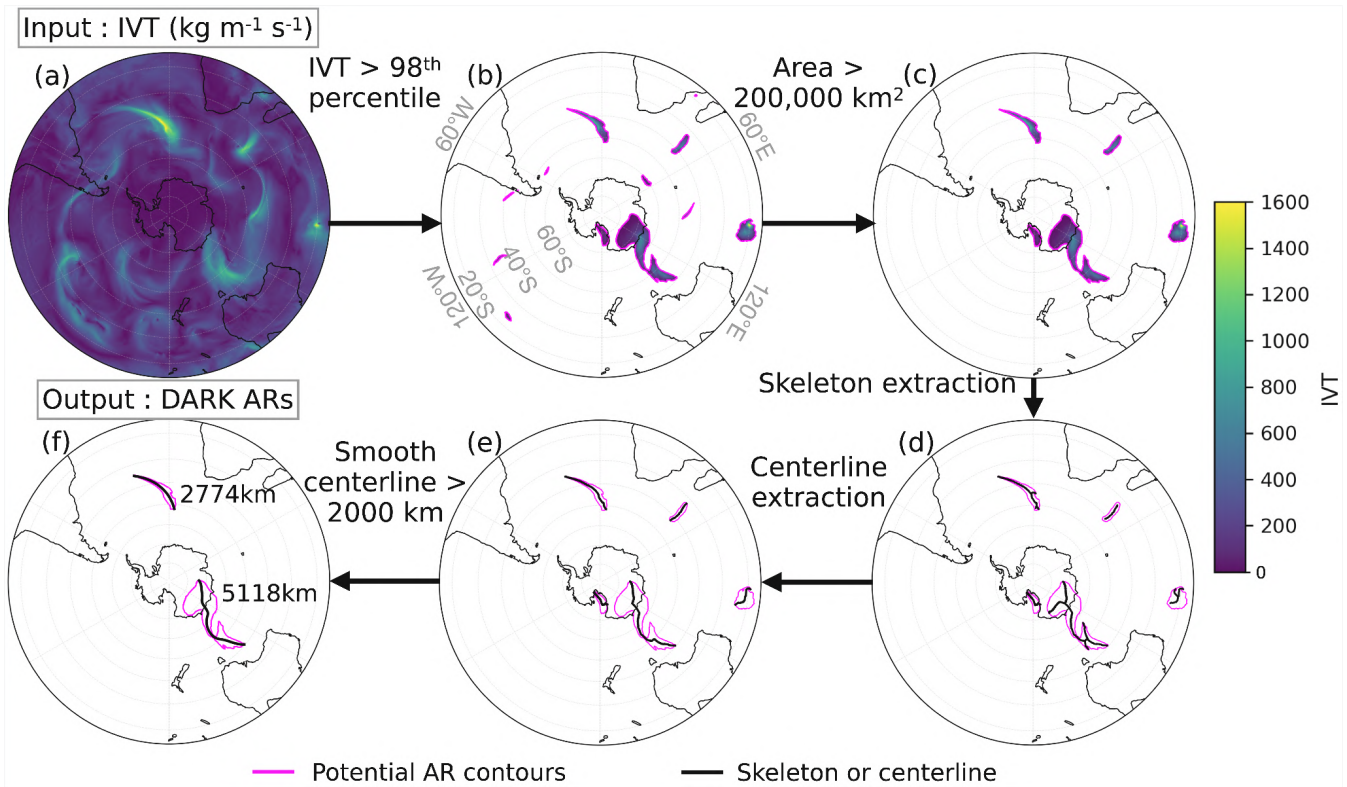
164  
165 At each 6-hourly time step, the DARK framework is applied over the  $15^\circ$  S– $90^\circ$  S domain. The magnitude of IVT is computed  
166 from its zonal and meridional components as

$$167 \quad IVT = \sqrt{uIVT^2 + vIVT^2} \quad (1)$$

168 where  $uIVT$  and  $vIVT$  are the zonal and meridional components of IVT from ERA5.

169 A rolling 15-day 98th-percentile threshold of IVT is calculated for each grid point and day of year using all available years  
170 (1979–2023). Grid cells exceeding this threshold are identified at each 6-hourly time step and grouped into contiguous features  
171 using a connectivity criterion that links all directly adjacent or diagonally touching cells (Fig. 2a). Objects smaller than 200,000  
172  $\text{km}^2$  are removed (consistent with the typical spatial scale of ARs, which are generally hundreds of kilometres wide and at least

173 2,000 km long) before centerline computation to avoid processing small, isolated exceedances that are not representative of  
 174 large-scale moisture transport and for which centerline estimation is computationally expensive and prone to numerical error  
 175 (Fig. 2b). The remaining features are processed to extract a smoothed centerline (Fig. 2d,e). An object is classified as an AR if  
 176 the geodesic length of this centerline equals or exceeds 2000 km, consistent with the typical length scale used in established  
 177 AR detection frameworks (Fig. 2f; e.g., Guan and Waliser, 2015; Guan and Waliser, 2024; Wille et al., 2021; Skinner et al.,  
 178 2020; Gorodetskaya et al., 2014). This procedure yields a binary AR mask indicating the presence or absence of an AR at each  
 179 grid point and time step.  
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181  
 182 Figure 2. Schematic overview of the DARK detection workflow applied to a single 6-hourly ERA5 time step. (a) Total IVT  
 183 field used as input. (b) Grid cells exceeding the local 98th-percentile threshold. (c) Objects with an area exceeding 200,000  
 184  $\text{km}^2$  retained. (d) Skeleton extracted from each remaining object. (e) Smoothed centerline derived from the skeleton. (f) Final  
 185 DANK AR classification: objects whose centerline geodesic length equals or exceeds 2000 km are retained, with their  
 186 centerline length indicated in km. Magenta contours show the potential (b–e) or final (f) AR object boundaries and black  
 187 lines show the skeleton (d), centerline (e) or smoothed centerline (f).  
 188

### 2.3 Optional AR-children add-on

The AR-children add-on is an optional extension of the main detection algorithm. It builds upon the AR catalog described above to identify post-landfall moisture structures that remain intense after the parent AR loses spatial coherence. Accordingly, two catalogs are provided: one including only DARK ARs and another combining DARK ARs with their AR-children, with accompanying binary and classification variables (see Data Availability). At each time step, regions where IVT exceeds the 98th-percentile threshold are labeled as contiguous features using a connectivity criterion that links all directly adjacent or diagonally touching grid cells. Temporal continuity is established through spatial overlap between consecutive time steps, ensuring consistent tracking of moisture structures while maintaining computational efficiency. A feature is classified as an AR-child when it previously overlaps with a detected parent AR and subsequently detaches from it while being in contact with, or located over, the Antarctic continent. A minimum area of 20,000 km<sup>2</sup> is imposed to exclude small structures. This approach ensures both physical and temporal consistency while remaining computationally efficient for multi-decadal, hemispheric reanalysis datasets.

The AR-children module requires approximately 9h of CPU time and ~17 GB of memory for the full 1979–2023 climatology, compared to 1h and ~8 GB for the core DARK algorithm (see Code and Data Availability section).

### 2.4 Attribution of events to ARs

To attribute surface impacts to ARs (or AR-children), we identify precipitation and temperature events associated with AR occurrence at each grid cell. Because AR-related precipitation and temperature anomalies can persist beyond the period when a given grid cell is directly affected by an AR, the attribution window is extended to include adjacent days, depending on the variable.

For precipitation, AR-related events are defined as those occurring on the day of AR landfall ( $D_0$ ) and the following day ( $D_{+1}$ ), following Wille et al. (2021) and Maclennan et al. (2022). We use here a daily timescale for computing efficiency and to avoid multiple detections of single extreme events due to serial correlation at sub-daily timescales. This extension accounts for residual precipitation that continues after the main AR plume loses coherence or moves inland.

For temperature, AR-related events are considered on the day before ( $D_{-1}$ ), the day of ( $D_0$ ), and the day after ( $D_{+1}$ ) AR landfall. This accounts for both preconditioning (e.g., warm advection ahead of the AR) and lagged warming due to persistent cloud cover, latent heat release, or surface melt following AR passage.

220 For precipitation, daily totals are compared to the mean daily climatology for each calendar day (1979–2023), while for 2 m  
221 air temperature, daily maxima are compared with the corresponding daily-maximum climatology. In both cases, the anomaly  
222 represents the deviation from the daily mean climatological value at each grid point.

223 Extreme events are defined as days when these anomalies exceed the 99th percentile of their respective daily anomaly  
224 distributions, computed independently at each grid point. Compound events, defined as the co-occurrence of extreme  
225 precipitation and temperature anomalies, are identified when an extreme precipitation day coincides with or occurs within  $\pm 1$   
226 day of an extreme temperature anomaly. This temporal window ensures that temporally overlapping or closely spaced extremes  
227 are captured within a single compound-event framework. This approach allows both direct and short-lagged compound  
228 extremes associated with ARs to be included in the analysis.

## 229 **2.5 Characterisation of AR moisture transport directionality**

230 To characterise the directionality of moisture transport during AR events, we analyse the ERA5 IVT components ( $uIVT$  and  
231  $vIVT$ ; eastward and northward respectively) at each grid cell and 6-hourly time step flagged as an AR over the 1979–2023  
232 period. Three metrics are computed for each grid cell. First, the fraction of AR time steps where meridional flow dominates  
233 (i.e.  $|vIVT| > |uIVT|$ ) is computed as a percentage of all AR time steps at that grid cell; the complementary fraction corresponds  
234 to zonal-dominant flow ( $|uIVT| > |vIVT|$ ). Second and third, the fraction of AR time steps with eastward ( $uIVT > 0$ ) and  
235 northward ( $vIVT > 0$ ) IVT are computed likewise.

## 236 **2.6 Risk Ratio**

237 Because extending the attribution window naturally increases the number of AR-associated events, we quantify their statistical  
238 relevance using risk ratios (RR; Katz et al., 1978; Scholz and Lora, 2024). This ensures that higher counts reflect genuine  
239 physical associations rather than the effect of broader temporal inclusion. RR are computed as the ratio between the probability  
240 of an extreme event during AR conditions (Eq. 2) and the probability during non-AR conditions (Eq. 3).

241 For each grid point, the conditional probabilities are defined as:

$$242 \quad P(E | AR) = \frac{N_{E,AR}}{N_{AR}} \quad (2)$$

$$243 \quad P(E | \neg AR) = \frac{N_{E,\neg AR}}{N_{\neg AR}} \quad (3)$$

244 where  $N_{E,AR}$  is the number of days with both an AR and an extreme event (considering the temporal extension defined in Sect.  
245 2.6),  $N_{AR}$  is the total number of AR days (including the temporal extensions defined in Sect. 2.6),  $N_{E,\neg AR}$  is the number of  
246 extreme events without an AR, and  $N_{\neg AR}$  the number of non-AR days.  
247 RR is then expressed as:

$$RR = \frac{P(E|AR)}{P(E|\neg AR)} \quad (4)$$

Values of  $RR > 1$  indicate that extreme events are more likely under AR conditions. For example, a value of  $RR = 2$  implies that extreme events are twice as likely to occur during AR conditions compared to non-AR conditions. This metric accounts for the frequency of AR occurrence, ensuring that results reflect the relative enhancement of extremes rather than the prevalence of ARs themselves.

## 2.7 Statistical significance

Differences in AR occurrence between schemes were evaluated using a two sample test of equality of proportions at each grid point. For the share of precipitation attributable to ARs, as well as for extreme precipitation, temperature, and compound events, significance was assessed using the same bootstrap framework: AR dates (including their variable-dependent temporal extensions) were kept fixed, while entire precipitation or temperature years were permuted without replacement, preserving their autocorrelation and seasonality but breaking their co-occurrence with ARs. The observed AR-associated fraction (or the difference between detection schemes) was compared against 1000 bootstrap realizations, and values were considered significant when they lay outside the corresponding 95 % bootstrap confidence interval.

The statistical significance of the RRs was assessed following the log-normal approximation method of Katz et al. (1978), because the distribution of the risk ratio is asymmetric while its logarithm is approximately normally distributed, allowing reliable confidence intervals to be derived using standard normal theory. To handle zero count cases, we applied the Haldane–Anscombe correction (Haldane, 1940; Anscombe, 1956) by adding 0.5 to both co-occurrence counts and 1 to the total-event denominators. A 95 % confidence interval was computed on the log-transformed RR and then exponentiated back to the RR scale. Grid cells were considered significant when the confidence interval excluded 1; otherwise, they were masked as non-significant.

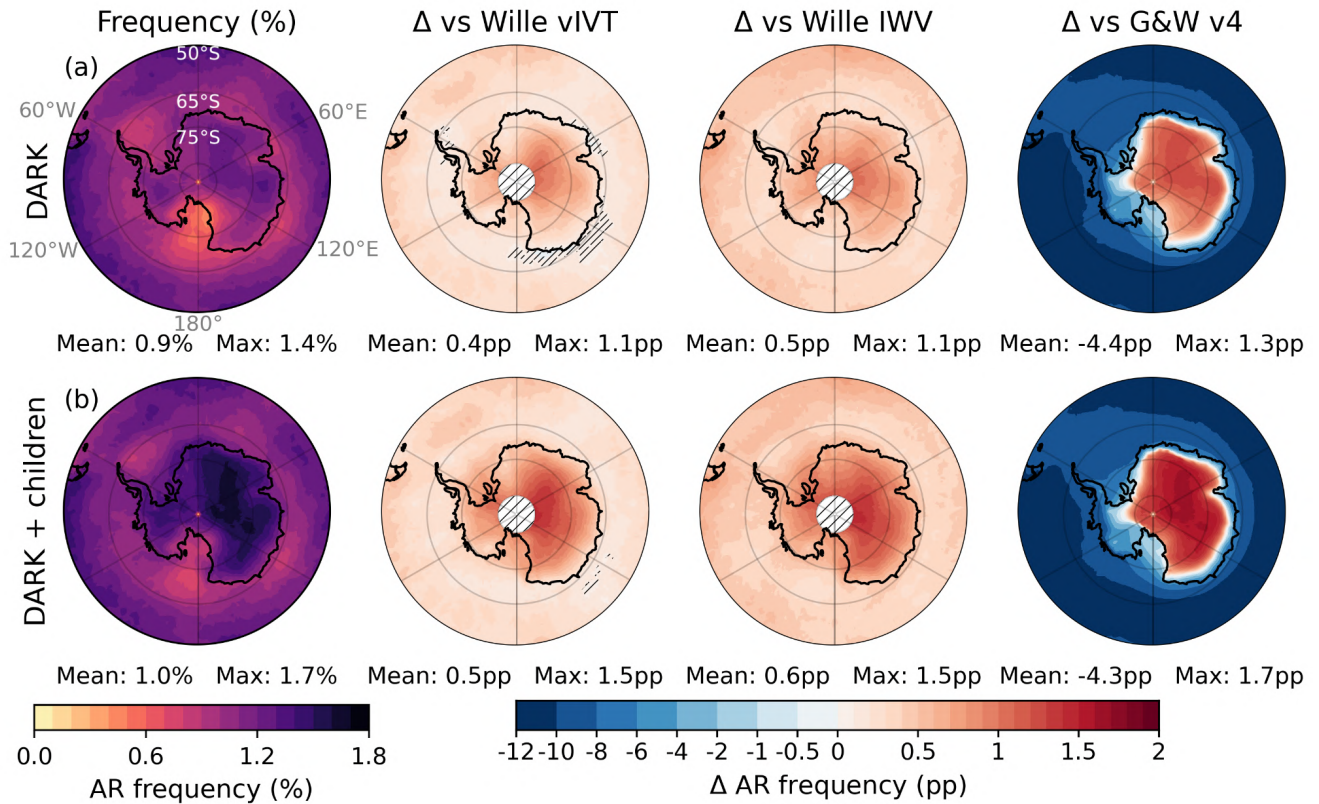
## 3 Results

### 3.1 Frequency of DARK ARs and AR-children

DARK ARs exhibit their highest occurrence within the midlatitude storm-track regions ( $\sim 50^\circ\text{S}$ , Fig. 3a; Chemke et al., 2022) (Chang et al., 2002; Wirth et al., 2018), with maxima during austral winter (see Fig. S1). The lowest frequencies occur over the Ross Sea sector, where the minimum is most pronounced in winter. The spatial distribution closely matches that of Wille vIVT and Wille IWV schemes, although DARK ARs yields higher overall frequencies, particularly over the AIS. Over South of the East Antarctic Ice Divide (EAID, Fig. 1a), occurrence is up to 1.2 percentage points (pp) higher than in Wille vIVT and IWV, while along the East Antarctic coast the difference remains small ( $\approx 0.3$  pp), indicating that the total frequency of AR

279 landfalls along the Antarctic coastline remains roughly unchanged between the Wille and DARK schemes. By construction,  
280 AR-children occur exclusively over the continent and its coastal margins, with mean frequencies up to 0.3 % along the coast  
281 and local maxima of 0.6 % near McMurdo and farther inland over the plateau (Fig. S2a), bringing the total frequency of DARK  
282 ARs and their AR-children at 1.5 % across most of the AIS (Fig. 3b).

283 The G&W v4 scheme exhibits a strikingly different spatial distribution of AR occurrence from both DARK and the Wille  
284 schemes. On average, G&W v4 detects 4.4 pp more AR occurrence than DARK across the Antarctic continent, but this average  
285 conceals an extreme spatial heterogeneity. Along the coast of West Antarctica, the Antarctic Peninsula, and the broader AIS  
286 coastline, G&W v4 exceeds DARK by up to 10 pp, while inland, south of the East Antarctic Ice Divide, DARK detects up to  
287 1.3 pp more than G&W v4 (Fig. 3a). This sharp gradient is further illustrated in Fig. S2: G&W v4 detects more than 2000 AR  
288 days at the coastline but fewer than 10 South of the EAID over the full 1979–2023 period, compared to around 400 for DARK  
289 and around 300 for the Wille schemes. This sharp coastal-to-inland gradient reflects a fundamental limitation of the G&W v4  
290 hemispheric threshold for capturing the full lifecycle of Antarctic ARs, and results in detection frequencies that are either far  
291 in excess of or far below those of DARK and the Wille schemes across most of the continent, with only a narrow transitional  
292 zone where they are broadly comparable. While G&W v4 effectively detects the most intense moisture intrusions at the coast,  
293 where IVT is highest, its effective threshold of  $46.8 \text{ kg m}^{-1}\text{s}^{-1}$  in January and  $39.4 \text{ kg m}^{-1}\text{s}^{-1}$  in July (Guan and Waliser, 2024)  
294 prevents detection of ARs as they penetrate inland and progressively lose intensity. As shown in Fig. S2, mean AR IVT values  
295 for DARK and the Wille schemes decrease to  $10 \text{ kg m}^{-1} \text{ s}^{-1}$  or below south of the EAID, well below the G&W v4 effective  
296 threshold, and G&W v4 records no detections (Fig. S2) at all over some interior regions such as Dome A and the area  
297 surrounding the South Pole. This suggests that G&W v4 captures the arrival of the most intense ARs at the Antarctic margin,  
298 but is not designed to monitor their inland penetration and associated surface impacts on the ice sheet.



299

300 Figure 3. Frequency of DARK atmospheric rivers (ARs) (a) and DARK ARs and their children (b) from 60° S to 90° S. From  
 301 left to right: AR occurrence (%), differences from the Wille vIVT, the Wille IWV and the G&W v4 schemes (percentage  
 302 points, pp). Hatched white areas south of 85° S mark regions without data in the Wille schemes, hatches elsewhere cover non-  
 303 non-significant regions (Sect. 2.7). Land-area weighted mean and maximum values are indicated below each panel.

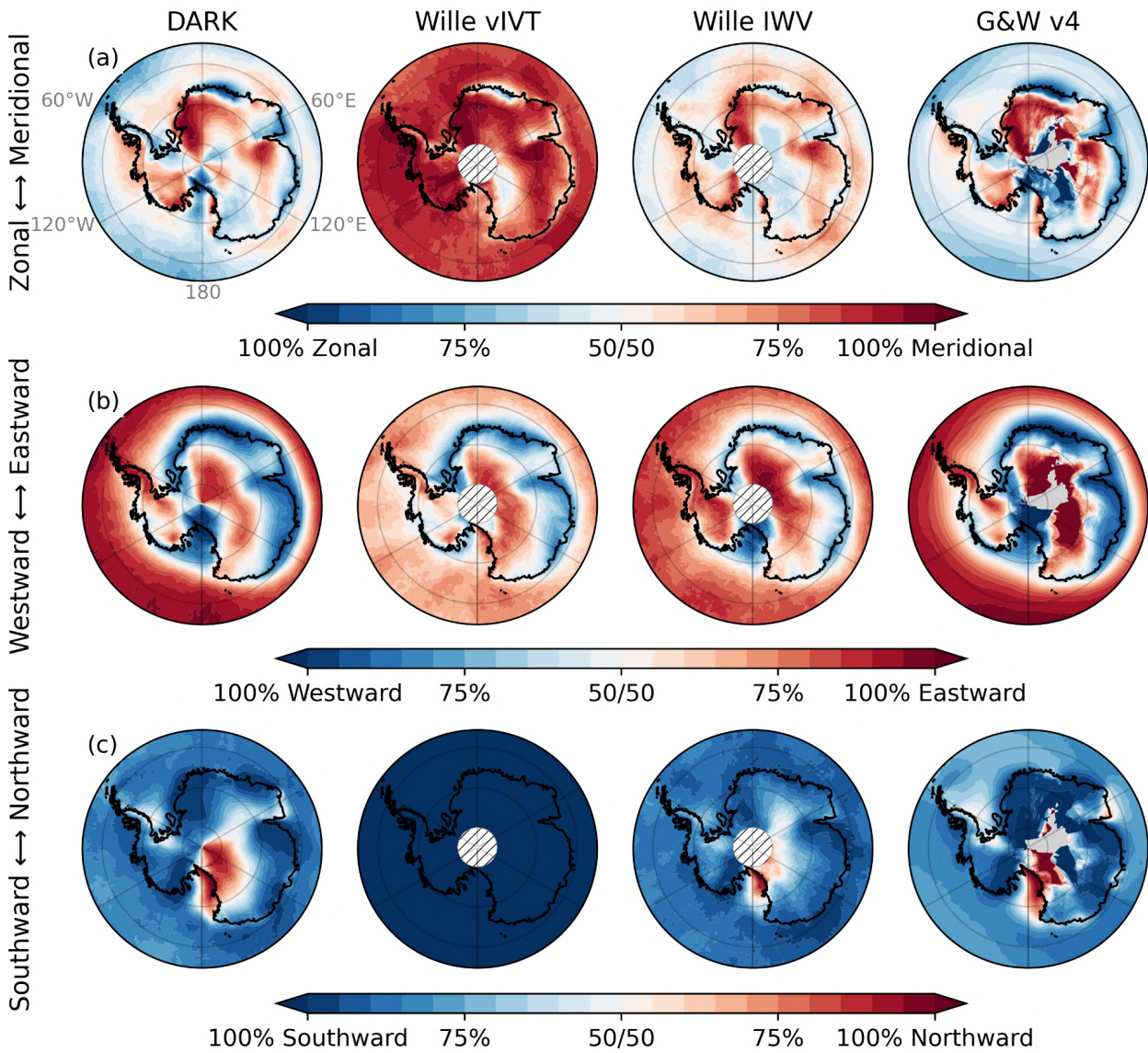
304

### 3.2 Direction and orientation of DARK ARs

305 DARK ARs exhibit a much wider range of orientations than either Wille schemes while still reproducing well the dominant  
 306 large-scale IVT orientation patterns (zonal versus meridional, and eastward versus westward) captured by Wille IWV (Fig. 4a,  
 307 c; Sect. 2.5). A majority of Wille vIVT ARs are also detected by DARK, with 64 % agreement over the Southern Ocean and  
 308 about 61 % on average across the AIS (Fig. S5a). The co-detection is strongest where DARK ARs exhibit predominantly  
 309 meridional, southward orientations, such as over southern Dronning Maud Land, Coats Land, and along the northern flank of  
 310 the East Antarctic Ice Divide. However, a substantial fraction of ARs detected by DARK are not captured by Wille vIVT:  
 311 across the Antarctic Ice Sheet, roughly 67 % of DARK ARs are exclusive to the new detection framework (Fig. S5b). These  
 312 additional detections are particularly frequent from the Ross Ice Shelf to Dome A along the southern flank of the East Antarctic

313 Ice Divide. In these regions, DARK ARs are mainly northward (Fig. 4c; and eastward, due to the influence of the East Antarctic  
314 topography and the Coriolis deflection of the pressure-driven circulation) oriented, which is incompatible with Wille's strict  
315 requirement of southward vIVT. Elsewhere across the continent, all three schemes, DARK, Wille vIVT, and Wille IWV, show  
316 predominantly southward-oriented ARs, confirming that most intense moisture transport toward Antarctica occurs in a  
317 poleward direction. Wille vIVT ARs that do occur there generally correspond to relatively strong meridional, but weak total  
318 IVT, since the percentile-based threshold can be met even under low IVT. In contrast, DARK detects ARs in these sectors  
319 because they exceed the 98th-percentile threshold in total IVT, capturing dynamically stronger but more geometrically  
320 complex structures. Compared with Wille IWV, DARK shows a more homogeneous agreement across the AIS, with up to 90  
321 % co-detection in Dronning Maud Land (Fig. S5a). This higher overlap reflects the greater directional flexibility of Wille  
322 IWV, which can capture zonal or northward ARs (Fig. 4a,c), including those turning over the Ross and Amery Ice Shelves  
323 and along the East Antarctic coastline. However, Wille IWV remains limited by its 20° meridional-extent criterion, which  
324 disfavors fully zonal filaments. Moreover, because IWV represents static moisture rather than dynamic transport, it detects  
325 only about 50 % of DARK ARs in localized regions such as the Dronning Maud Land coast (Fig. S5b). These undetected cases  
326 typically contain high humidity but insufficient wind to produce large IVT values, preventing them from meeting the DARK  
327 threshold. Overall, Wille vIVT and IWV ARs only partially overlap with DARK detections. A majority of Wille (vIVT or  
328 IWV) ARs are identified by DARK, but many DARK ARs are not detected by Wille ARDTs. This asymmetry highlights that  
329 while the methods share a common physical basis, DARK extends beyond Wille's directional and geometric constraints,  
330 capturing a more dynamically coherent and diverse range of AR geometries, including curved, zonal, and poleward-turning  
331 filaments that were missed by previous frameworks.

332 Compared with G&W v4, DARK shows broadly consistent large-scale IVT orientation patterns across both the Southern  
333 Ocean and the Antarctic continent, although the G&W v4 fields appear noisier over the interior due to the very low number of  
334 detections in these regions.



335

336 Figure 4. Fraction of AR time characterized by (a) zonal vs. meridional dominant IVT components ( $|u_{IVT}|$  vs.  $|v_{IVT}|$ ), (b)  
 337 westward vs. eastward uIVT, and (c) southward vs. northward vIVT, for each AR catalogue (from left to right: DARK, Wille  
 338 vIVT, Wille IWV and G&W v4). Hatched white areas south of 85° S mark regions without data in the Wille schemes. Grey  
 339 shading in the G&W v4 column indicates grid cells where no AR was detected over the full period.

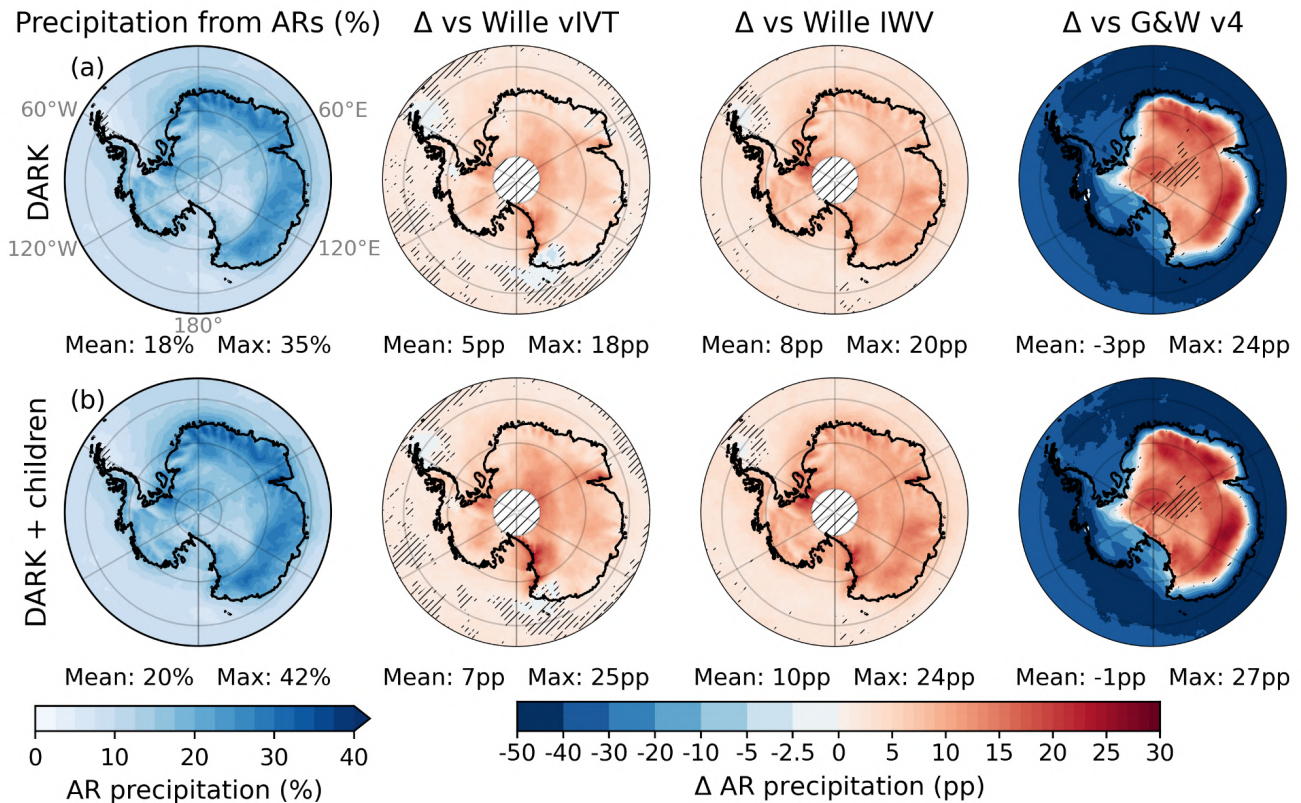
340

### 3.2 Contribution of ARs to Antarctic precipitation

DARK ARs account for an average of 18 % of total AIS precipitation, reaching up to 35 % in some regions (Fig. 5a). Only along the relatively straight, zonally oriented sectors of the East Antarctic coastline, their contribution is comparable to that of Wille vIVT ARs. In contrast, in areas where the coastline geometry departs from this alignment, particularly within the major embayments such as the Ross, Ronne–Filchner, and Amery Ice Shelves, DARK ARs contribute to substantially more precipitation, with enhanced signals extending inland over the catchments located south of the EAID. The only region where DARK ARs contribute to less precipitation than Wille vIVT ARs is Oates Land.

On average, DARK ARs deliver 5 (8) pp more precipitation than Wille vIVT (Wille IWV), with local increases up to 18 (20) pp in the interior, notably near the South Pole and the Transantarctic Mountains. Even when both Wille schemes are combined, DARK ARs still produce 2 pp more precipitation on average, with local differences reaching up to 15 pp (Fig. S6). The comparison with G&W v4 reveals spatially contrasting differences that cannot be summarized by the AIS-averaged difference alone, as the two schemes have fundamentally different detection footprints over Antarctica. Along the coast and over the WAIS, the very high AR occurrence in G&W v4 translates into substantially more attributed precipitation, locally exceeding DARK by up to 50 pp. Moving inland, this signal reverses sharply: DARK explains up to 24 pp more precipitation north of the EAID, where G&W v4 detections drop off rapidly due to its effective hemispheric IVT threshold. This coastal dominance outweighs the inland gains, yielding a slightly negative AIS-averaged difference of -3 pp (Fig. 5a, right column). This sign reversal reflects the different purposes of the two approaches: G&W v4 was designed for global applicability and captures intense coastal moisture intrusions, while DARK was specifically designed to monitor AR activity across the full Antarctic continent, including its interior. Within the DARK framework itself, AR-children contribute little on average (Fig. 5b) but represent a significant additional source within these embayments, most notably over the Amery Ice Shelf and Victoria Land, where they account for more than 8 % of total AIS precipitation (Fig. S2b).

In this analysis, precipitation occurring on the day of AR landfall ( $D_0$ ) and the following day ( $D_{+1}$ ) is attributed to ARs throughout this study (Sect. 2.4), and to ARs and their children when using the DARK+children framework, consistent with common practice (Wille et al., 2021; Maclennan et al., 2022). When AR-children are included, however, a comparable AIS-averaged share of precipitation is obtained (Fig. S7) even when considering precipitation associated with DARK ARs and their children on the day of landfall alone ( $D_0$ ), compared to attributing precipitation to DARK ARs without including AR-children over both the day of landfall ( $D_0$ ) and the following day ( $D_{+1}$ ). This reflects not a temporal substitution, but a spatial refinement: AR-children explicitly capture the inland propagation and dissipation of moisture that, in previous approaches, was only approximated by extending the temporal attribution window beyond landfall. Their inclusion therefore provides a more physically consistent representation of post-landfall hydrological impacts.



371

372

Figure 5. Share of total precipitation attributed (Sect. 2.4) to (a) DARK ARs and (b) DARK ARs and their children. From left to right: percentage of precipitation from ARs, differences from the Wille vIVT, the Wille IWV, and the G&W v4 schemes (pp). Antarctic land-only (inside-coastline) mean and maximum values are reported below each panel. Hatched white areas south of 85° S mark regions without data in the Wille schemes, hatches elsewhere cover non-significant regions (Sect. 2.7).

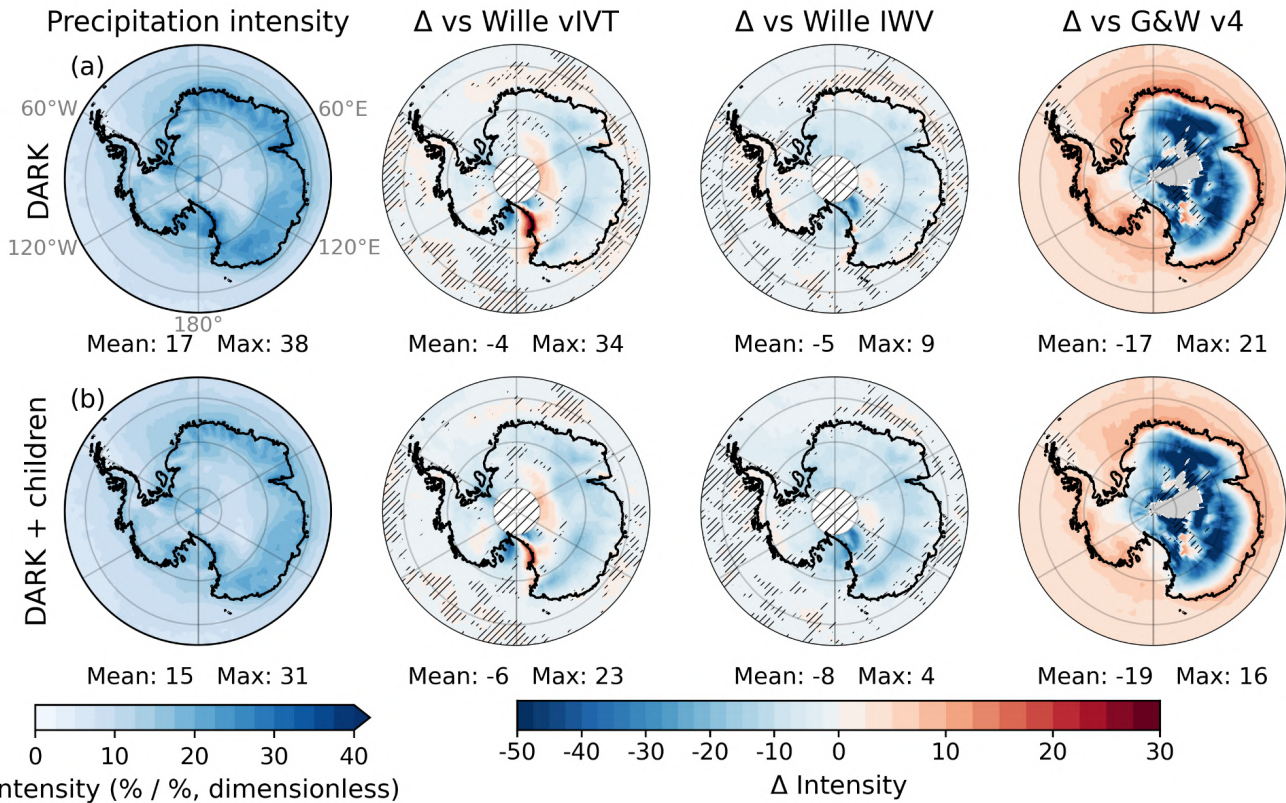
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377

While DARK ARs contribute more to precipitation than either Wille scheme across most of the AIS, this increase primarily reflects their higher occurrence frequency rather than higher precipitation per event (Fig. 6a). When normalized by AR occurrence, that is, expressed as the ratio of AR-related precipitation (%) to AR occurrence (%), the mean precipitation intensity (pp pp<sup>-1</sup>, dimensionless) associated with DARK ARs is slightly lower overall than in both Wille schemes (around -5). Relative to Wille IWV, precipitation intensity is lower across the AIS in a broadly uniform pattern. However, relative to Wille vIVT, differences are more heterogeneous: intensity is reduced over most of the AIS but locally enhanced over the Amery Ice Shelf and south of the EAID, peaking along the Ross sector of the Transantarctic Mountains (up to 34). When DARK ARs and their associated children are considered together, the overall AR intensity further decreases, although they remain more intense than Wille ARs in the latter regions (Fig. 6b).

386

387 The comparison with G&W v4 mirrors the spatial heterogeneity seen in total precipitation. Along the coast and over the WAIS,  
 388 DARK ARs are more intense than G&W v4 ARs (positive differences), consistent with DARK having fewer but still highly  
 389 impactful detections in these regions. Inland, the picture reverses: intensity differences become negative over large parts of the  
 390 East Antarctic interior, reaching below  $-50$  in some areas. These strongly negative values, however, must be interpreted with  
 391 caution, as they correspond to regions where G&W v4 detects very few AR days over the full period (fewer than 35 where  
 392 differences exceed  $-50$ , fewer than 100 where they exceed  $-30$ ; Fig. S4). In these areas, the small sample of G&W v4  
 393 detections consists almost exclusively of the most intense inland moisture intrusions, inflating their mean intensity relative to  
 394 DARK. Overall, this confirms that G&W v4 selectively captures the most intense moisture intrusions at the coast and in the  
 395 rare inland locations where IVT remains sufficiently high, while missing the broader population of intrusions that DARK and  
 396 the Wille schemes track from the coast into the interior.



397  
 398 Figure 6. Normalized AR precipitation intensity, defined as the ratio between the percentage of precipitation from ARs (Fig.  
 399 3) and AR frequency (Fig. 3, unitless), for (a) DARK ARs and (b) DARK ARs and their children. From left to right: differences  
 400 from the Wille vIVT, the Wille IWV, and the G&W v4 schemes (pp). Antarctic land-only mean and maximum values are

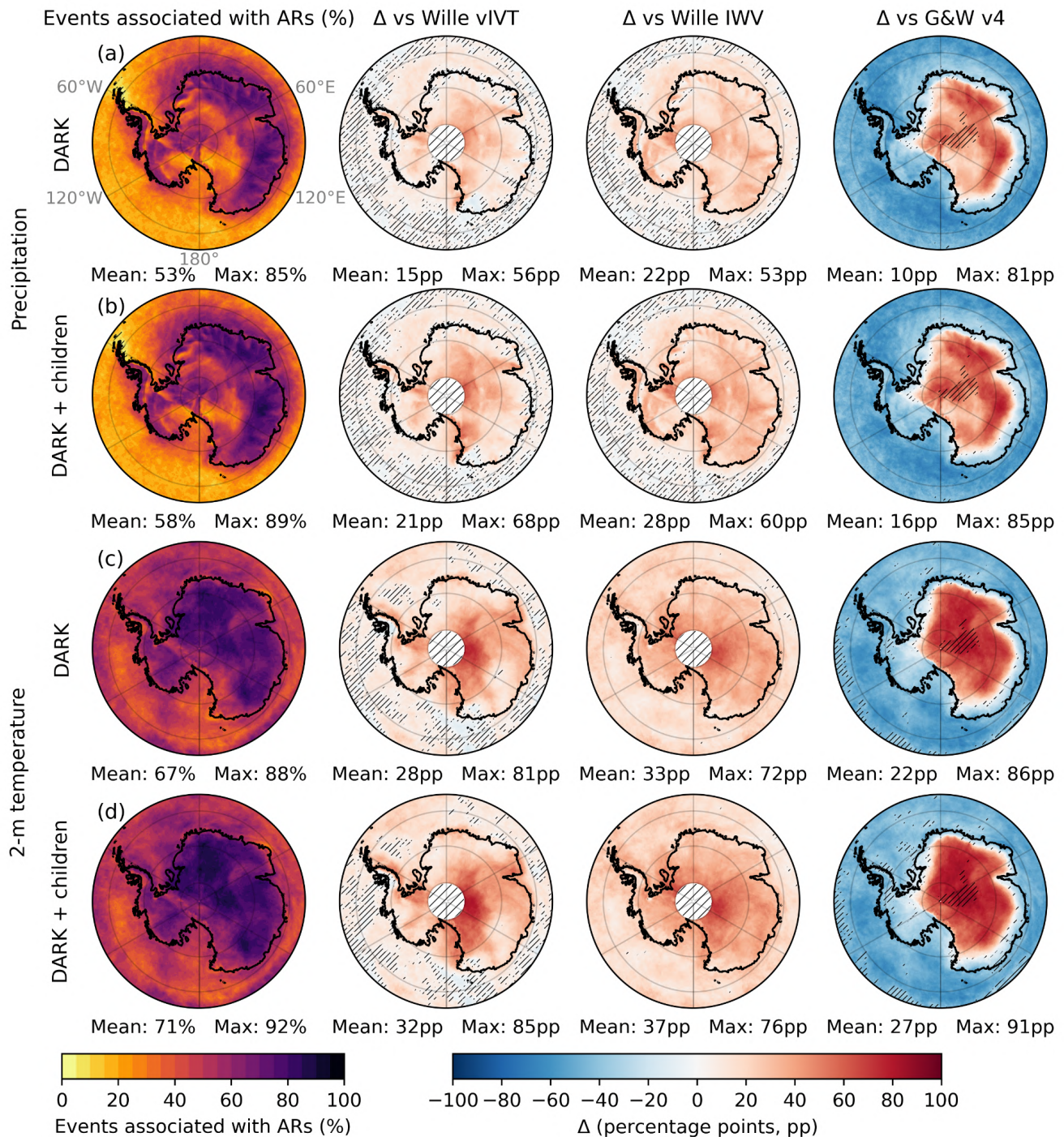
401 reported below each panel. Hatched white areas south of 85° S mark regions without data in the Wille schemes, hatches  
402 elsewhere cover non-significant regions (Sect. 2.7)

### 403 **3.3 Contribution to extreme events**

404 DARK ARs are associated with 53 % of extreme (Sect. 2.4) precipitation days on average (Fig. 7a), with local values reaching  
405 up to 85 % inland of the East Antarctic coast and decreasing toward Dome C. Although the mean precipitation per AR event  
406 is lower (Sect. 3.2), the DARK scheme captures a substantially larger proportion of the most intense precipitation anomalies  
407 than either Wille scheme. Compared to Wille vIVT, the association fraction is higher by 15 pp on average and locally by up  
408 to 56 pp south of the EAID, with only a few small areas showing slightly weaker associations, the largest being Oates Land.  
409 Relative to Wille IWV, the increase is more spatially homogeneous, with the largest differences following topography,  
410 particularly over Queen Elizabeth Land. This pattern indicates that DARK, like Wille vIVT, better represents topographically  
411 induced precipitation linked to moisture transport rather than static humidity. Compared with G&W v4, DARK explains on  
412 average 10 pp more extreme precipitation days across the AIS, with gains up to 81 pp inland. Along the coast and over the  
413 WAIS, G&W v4 associates more extreme days with ARs, consistent with its very high detection frequency in these regions.  
414 However, unlike for total precipitation, the AIS-averaged difference remains positive, reflecting the fact that many of the  
415 numerous G&W v4 coastal detections are associated with non-extreme precipitation events that do not reach the top 1%  
416 threshold. Including AR-children increases the mean association by only about 5 pp (Fig. 7a,b), but they remain locally  
417 significant, forming broad hotspots over the Amery Ice Shelf and across Victoria Land, where they account for more than 15  
418 %, and locally up to 20 %, of extreme precipitation days (Fig. S8). These regions represent the strongest and most spatially  
419 extensive contributions of AR-children, while more localized contributions also occur south of the EAID, where post-landfall  
420 moisture remnants sustain intense precipitation after the parent AR dissipates.

421 DARK ARs are associated with 67 % of extreme daily maximum temperature events on average (Sect. 2.4; Fig. 7c), with local  
422 values exceeding 80 % near Dome C and over Dronning Maud Land. Compared to the Wille schemes, DARK increases the  
423 association fraction by more than 28 pp on average. The gain is spatially uniform relative to Wille IWV and more spatially  
424 contrasted compared to Wille vIVT, with the largest improvements south of the EAID. Compared with G&W v4, DARK  
425 explains on average 22 pp more extreme temperature days, with a spatially uniform inland advantage reflecting DARK's more  
426 consistent continental coverage. As with precipitation extremes, G&W v4 explains more along the coast, but the AIS-averaged  
427 difference remains strongly positive, consistent with DARK's broader and more homogeneous detection across the interior.  
428 Including AR-children further raises the mean association to approximately 71 % (Fig. 7d), primarily through a uniform  
429 increase of about 4 pp across most of the AIS. In several regions, this leads to association fractions exceeding 90 % locally,  
430 while the largest increases occur over Victoria Land and the Ross Ice Shelf–McMurdo area, where AR-children contribute up  
431 to 20 pp of additional extreme temperature events. This reflects the persistence of warm, moist air masses following AR  
432 landfall (Fig. S8).

433 Compound (precipitation and 2 m air temperature) extremes (Sect. 2.4) occur widely across Antarctica but are absent leeward  
434 of the Antarctic Peninsula, where strong foehn winds produce warm but dry conditions (Fig. S9). DARK ARs are associated  
435 with approximately 78 % of compound extremes on average (Fig. 8a) and with nearly 100 % across broad sectors of East  
436 Antarctica. DARK identifies substantially more inland events than Wille vIVT, which captures many compound events along  
437 the coast but misses large interior regions south of the EAID, from southern Dronning Maud Land to Victoria Land and around  
438 the Amery Ice Shelf. Compared with G&W v4, DARK explains on average 30 pp more compound extremes across the AIS,  
439 with the same coastal-to-inland polarity as for precipitation and temperature extremes. Including AR-children increases the  
440 mean association modestly (by about 3 pp) but introduces a distinct new hotspot over Victoria Land (Fig. 8b), where AR-  
441 children contribute to more than 20 pp of additional compound extremes (Fig. S8). Notably, Victoria Land is also one of the  
442 two main regions of frequent compound events across the continent, although such events remain rare overall (fewer than 0.5  
443 % of days: Fig. S9).



444

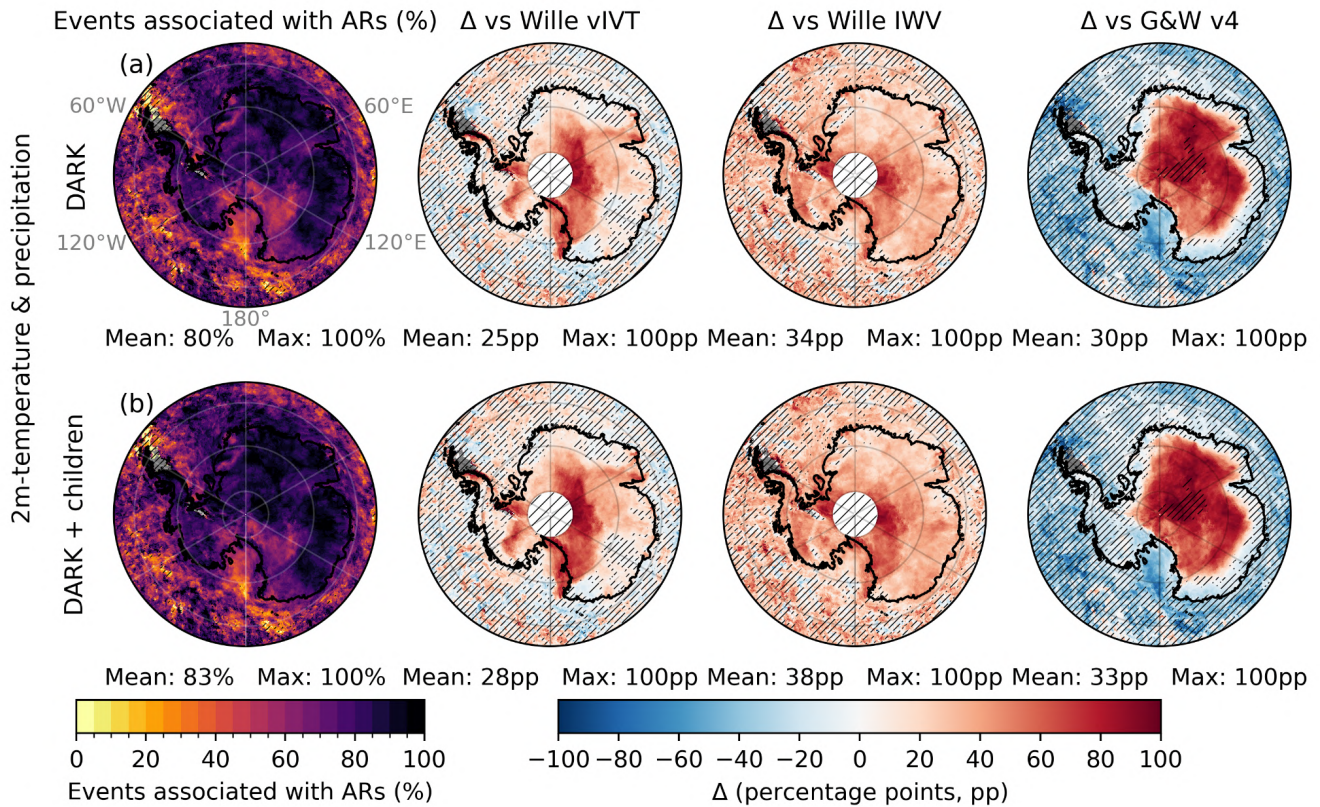
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Figure 7. Fraction of 99th-percentile anomaly days associated with DARK ARs for precipitation (rows a–b) and 2 m temperature (rows c–d). Within each variable, the first row shows DARK ARs and the second row shows DARK ARs + children. Columns show (left to right) the absolute fraction of extremes and the differences relative to the Wille vIVT, the Wille

448 IWV, and the G&W v4 schemes (percentage points, pp). Antarctic land-only mean and maximum values are reported below  
 449 each panel. Hatched white areas south of 85° S mark regions without data in the Wille schemes; hatched overlays indicate  
 450 non-significant values (Sect. 2.7); grey shading indicates grid cells with no detected extremes.  
 451



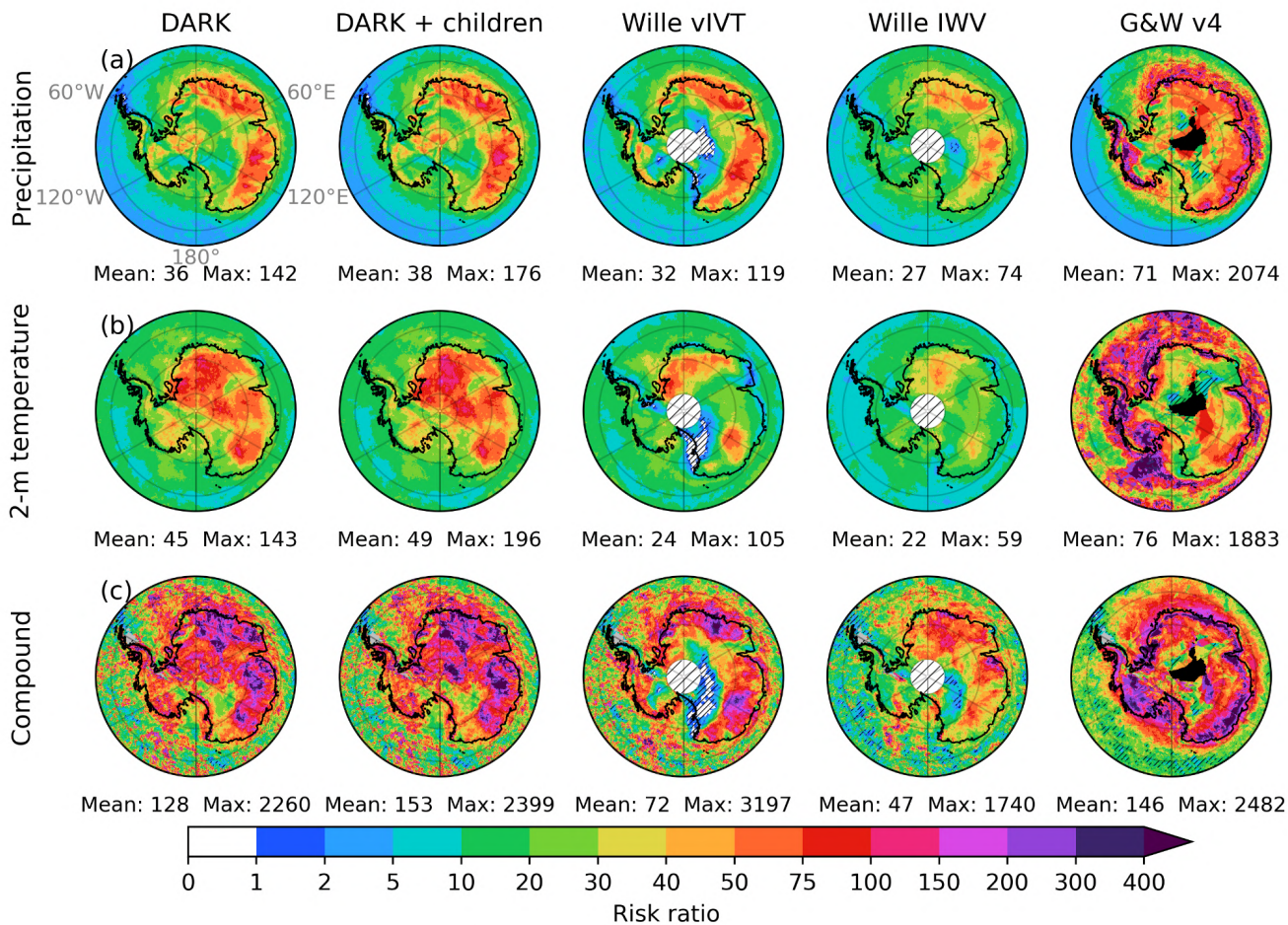
452  
 453 Figure 8. Fraction of compound extreme days combining 99th-percentile precipitation and 2 m air temperature anomalies  
 454 associated with DARK ARs. Row (a) shows DARK ARs and row (b) shows DARK ARs and their children. From left to right:  
 455 the absolute fraction of compound extremes and the differences relative to the Wille vIVT, the Wille IWV, and the G&W v4  
 456 schemes (percentage points, pp). Antarctic land-only mean and maximum values are reported below each panel. Hatched white  
 457 areas south of 85° S mark regions without data in the Wille schemes; hatched overlays indicate non-significant values (Sect.  
 458 2.7); grey shading indicates grid cells with no detected compound extremes.

459 Risk ratios (RR) are next used to account for differences in AR occurrence frequency (Sect. 2.6). For precipitation, DARK  
 460 yields RR values comparable to or higher than those of the Wille schemes across most of the AIS (Fig. 9a), indicating that  
 461 extreme precipitation is about 30 times more likely during an AR, independently from the selected ARDT. The spatial pattern  
 462 closely resembles that of Wille vIVT, with the highest values north of the EAID and local peaks reaching 142. However, for  
 463 2 m air temperature (Fig. 9b), the similarity with Wille's ARDTs is weaker. While DARK reproduces the main hotspots seen

464 in Wille's ARDTs, RRs are considerably larger over a much wider area. The Antarctic-wide mean RR reaches 45 (roughly  
465 twice the Wille means), with local maxima up to 143, demonstrating that DARK not only amplifies the temperature hotspots  
466 detected by Wille vIVT and IWV but also identifies additional regions of strong AR influence beyond those captured by the  
467 original scheme. For compound extremes (Fig. 9c), DARK produces a markedly higher RR than Wille's ARDTs, with an  
468 Antarctic-wide mean of 128, almost double that of Wille's 's ARDTs, and local maxima exceeding  $10^3$ , highlighting the  
469 dominant influence of ARs on concurrent warm and wet extremes. Including AR-children further increases both mean and  
470 peak RR for precipitation, temperature, and compound events, illustrating that post-landfall moisture remnants can cause  
471 extremes after the parent AR loses coherence.

472 The G&W v4 ARDT yields substantially larger RR values across the AIS for all variables (Fig. 9). For precipitation (Fig. 9a),  
473 the Antarctic-wide mean RR reaches 71, more than twice the values obtained with DARK and the Wille schemes. A similar  
474 difference is found for 2 m air temperature (Fig. 9b), where the mean RR rises to 76. For compound extremes (Fig. 9c), the  
475 Antarctic-wide mean RR reaches 146. These large ratios reflect a very strong statistical association between G&W v4 ARs  
476 and extreme events. However, their magnitude is strongly shaped by the particular spatial structure of G&W v4 detection  
477 frequency over Antarctica, with far more AR days than DARK or the Wille schemes at the coast and far fewer inland, which  
478 creates strongly contrasted AR and non-AR pools that mechanically amplify RR in both regimes. The spatial coincidence  
479 between the largest RR values and the regions of highest G&W v4 detection frequency is a direct consequence of these  
480 contrasts, rather than evidence of a stronger physical association. Consequently, the RR values from G&W v4 are less directly  
481 comparable to those obtained with DARK and Wille's ARDTs.

482



483

484 Figure 9. Risk ratio (RR; see Sect. 2.6) of 99th-percentile anomalies during AR conditions for (a) 2 m air temperature, (b)  
 485 precipitation, and (c) compound events (precipitation + temperature; see Sect. 2.4). Columns correspond to DARK ARs,  
 486 DARK ARs and their children, Wille vIVT, Wille IWV, and G&W v4 ARs. Values of  $RR > 1$  indicate an increased likelihood  
 487 of extremes under AR conditions. Grey areas indicate grid cells without detected compound extremes, hatches indicate non-  
 488 significant RR (Sect. 2.7), black shading in the G&W v4 column indicates grid cells where no AR was detected over the full  
 489 period.

490

491

### 3.4 Regional case studies

492

493 To illustrate the performance of the DARK framework during intense to extreme weather events, we analyze representative  
 494 cases. The first case study focuses on the McMurdo region, a well-known area situated between the Ross Ice Shelf and Victoria

495 Land, both of which show strong enhancement in DARK relative to Wille’s ARDTs. The second case study examines ARs  
496 detected south of the EAID, including those crossing the South Pole.

497

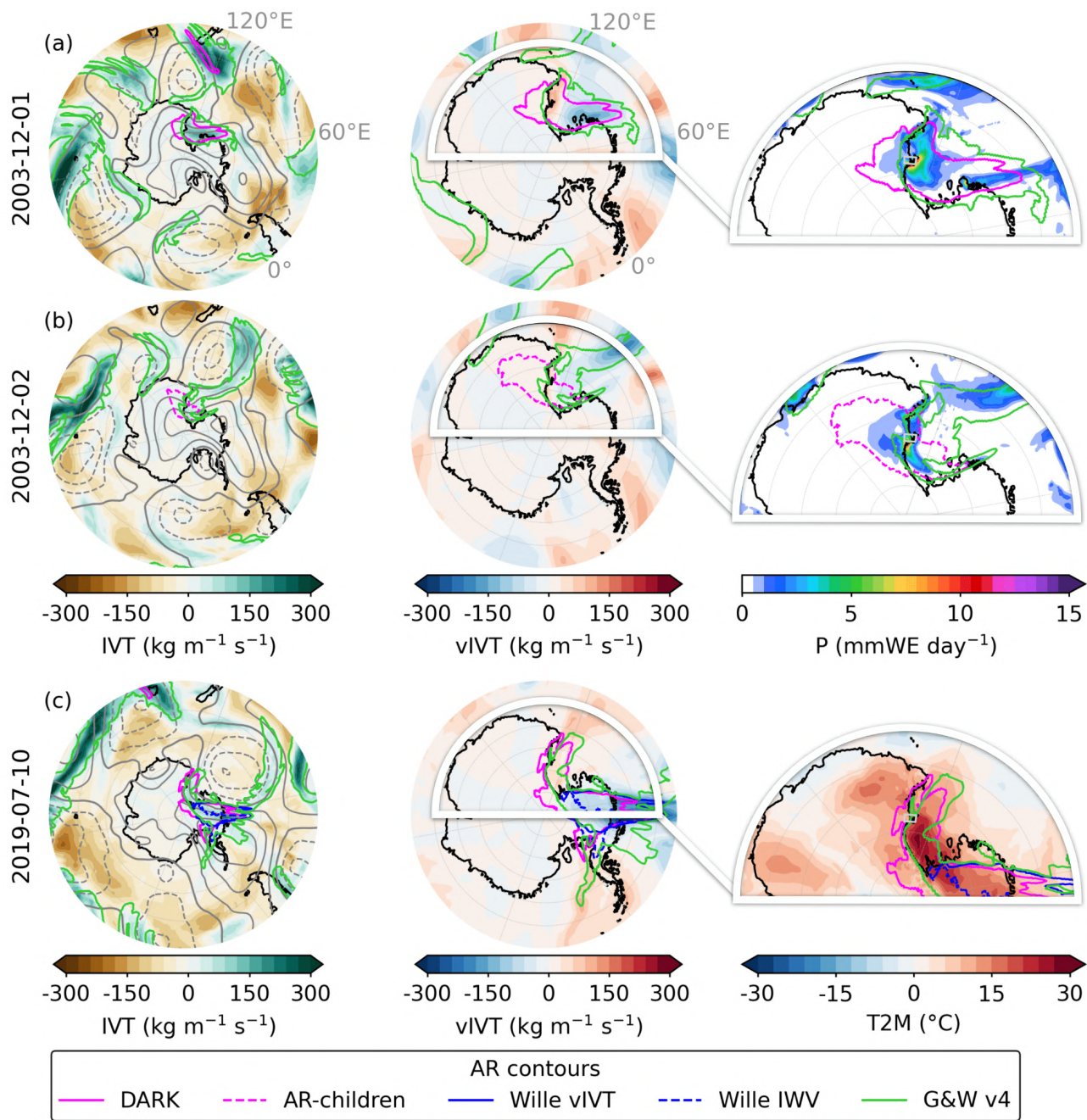
### 498 **3.4.1 Extreme events in the McMurdo–Dry Valleys region**

499 The first case study focuses on the McMurdo–Dry Valleys domain (160–168° E, 78.5–77.5° S), where two exceptional events  
500 exemplify the synoptic conditions driving major precipitation and temperature extremes.

501 On 1 December 2003 (Fig. 10a), the McMurdo–Dry Valleys region recorded more than 16 mm of precipitation, exceptionally  
502 high for this arid environment, representing the largest daily precipitation total in the 1979–2024 ERA5 dataset. Including the  
503 following day (2 December 2003, with more than 12 mm, corresponding to the 99.9th percentile), the two day total accounts  
504 for over 14 % of the annual precipitation in 2003. The 500-hPa geopotential height anomalies reveal a broad anticyclonic  
505 circulation spanning the Antarctic interior from the Bellingshausen Sea to Dome C, with a maximum over Marie Byrd Land.  
506 The western flank of this ridge directed a zonal moisture flux into the western Ross Sea sector. Upon encountering the  
507 Transantarctic Mountains, this flux curved equatorward and westward, producing intense coastal precipitation. The DARK  
508 scheme captures the full curvature of this moisture filament as it arcs inland over Victoria Land, while neither Wille vIVT nor  
509 Wille IWV detect the equatorward-turning portion (Fig. 10a). G&W v4 detects a broader moisture feature over the Ross Sea  
510 and Victoria Land, capturing part of the zonal flux but not the full inland portion of what DARK classifies as an AR. Notably,  
511 G&W v4 flags numerous AR objects across the Southern Hemisphere on this date, considerably more than DARK or the Wille  
512 schemes, reflecting its lower effective IVT threshold in high-IVT coastal regions. The precipitation maximum coincides with  
513 the AR’s interaction with the Transantarctic Mountains, followed by a sharp inland decline in IVT consistent with strong  
514 orographic precipitation. By 2 December, a deep trough northwest of the Ross Sea had aligned and channeled moisture from  
515 the South Pacific toward the Ross Ice Shelf, sustaining the precipitation event. The main AR filament had dissipated, leaving  
516 behind a remnant classified as an AR-child, while G&W v4 captures this day as a full AR extending from the South Pacific,  
517 detecting the entire moisture import corridor where DARK identifies only the inland tip. Despite its smaller spatial extent, this  
518 remnant produced more than 12 mm of precipitation, still within the top 0.1 % of daily values. This demonstrates that post-  
519 landfall AR fragments can sustain extreme precipitation even after the parent AR loses coherence. This event highlights the  
520 importance of explicitly identifying and tracking AR-children, which can prolong the hydrological impacts of ARs well beyond  
521 their formal duration.

522 On 9 July 2019 (Fig. 10b), an exceptional temperature extreme affected the Ross Ice Shelf region, including the McMurdo  
523 area, with 2 m air temperature daily anomalies peaking at +27.9 °C in the McMurdo–Dry Valleys. This event represents the  
524 largest daily-mean temperature anomaly in the 1979–2024 ERA5 record, and exceeded +31 °C over parts of the shelf. The  
525 500-hPa geopotential height anomalies show an extensive anticyclonic structure extending from the southern tip of South  
526 America across the Antarctic continent and into the southern Indian Ocean, centered over the Antarctic interior. A deep trough

527 north of the Ross Sea directed moist air from the South Pacific toward the Ross Ice Shelf, where the flow was deflected by the  
528 topography of the eastern Ross sector. As the IVT cyclonically curved along the Transantarctic Mountains, leading to  
529 equatorward fluxes off the coasts of Victoria Land, the strongest temperature anomalies occurred and peaked over the Ross  
530 Ice Shelf. DARK ARs capture the complete curved moisture transport pathway responsible for this event, whereas the Wille  
531 schemes detect only the initial southward intrusion and miss the equatorward-turning segment beneath which the peak  
532 temperature anomalies occurred. G&W v4 detects the initial southward intrusion from the mid-latitudes and, like DARK,  
533 captures the moisture transport toward the Ross Ice Shelf where the peak temperature anomalies occurred, but its detection  
534 stops at the coastline. As on 1 December 2003, G&W v4 flags numerous AR objects across the hemisphere on this date, in  
535 contrast to the more sparse detections of DARK and the Wille schemes.



536

537 Figure 10. Daily composites of the most intense (a–b) precipitation and (c) temperature events in the McMurdo–Dry Valleys  
 538 region (160–168° E, 78.5–77.5° S, grey window in the third column panels). Panels (a) and (b) correspond to 1 and 2 December  
 539 2003, respectively, showing the evolution of the same precipitation event, while panel (c) shows the temperature event on 9  
 540 July 2019. Each column displays, from left to right: integrated vapor transport (IVT) anomaly ( $\text{kg m}^{-1} \text{s}^{-1}$ ), meridional IVT

541 (vIVT) anomaly ( $\text{kg m}^{-1} \text{s}^{-1}$ ), and (a–b) daily precipitation ( $\text{mm w.e. day}^{-1}$ ) or (c) 2 m air temperature anomaly ( $^{\circ}\text{C}$ ). Grey  
542 contours in the first column indicate 500-hPa geopotential-height anomalies (m; solid = positive, dashed = negative) at 100-m  
543 intervals. DARK ARs (solid magenta) and their children (dashed magenta) are shown together with Wille ARs (solid blue =  
544 vIVT; dashed blue = IWV) and G&W v4 ARs (limegreen). For each day, AR contours represent the maximum spatial extent  
545 of each AR type across all 6-hourly time steps (i.e., the union of all detected positions within the day). White-shaded contours  
546 in the middle panels outline the domain shown in the rightmost panels.

### 548 **3.4.2 ARs reaching the South Pole**

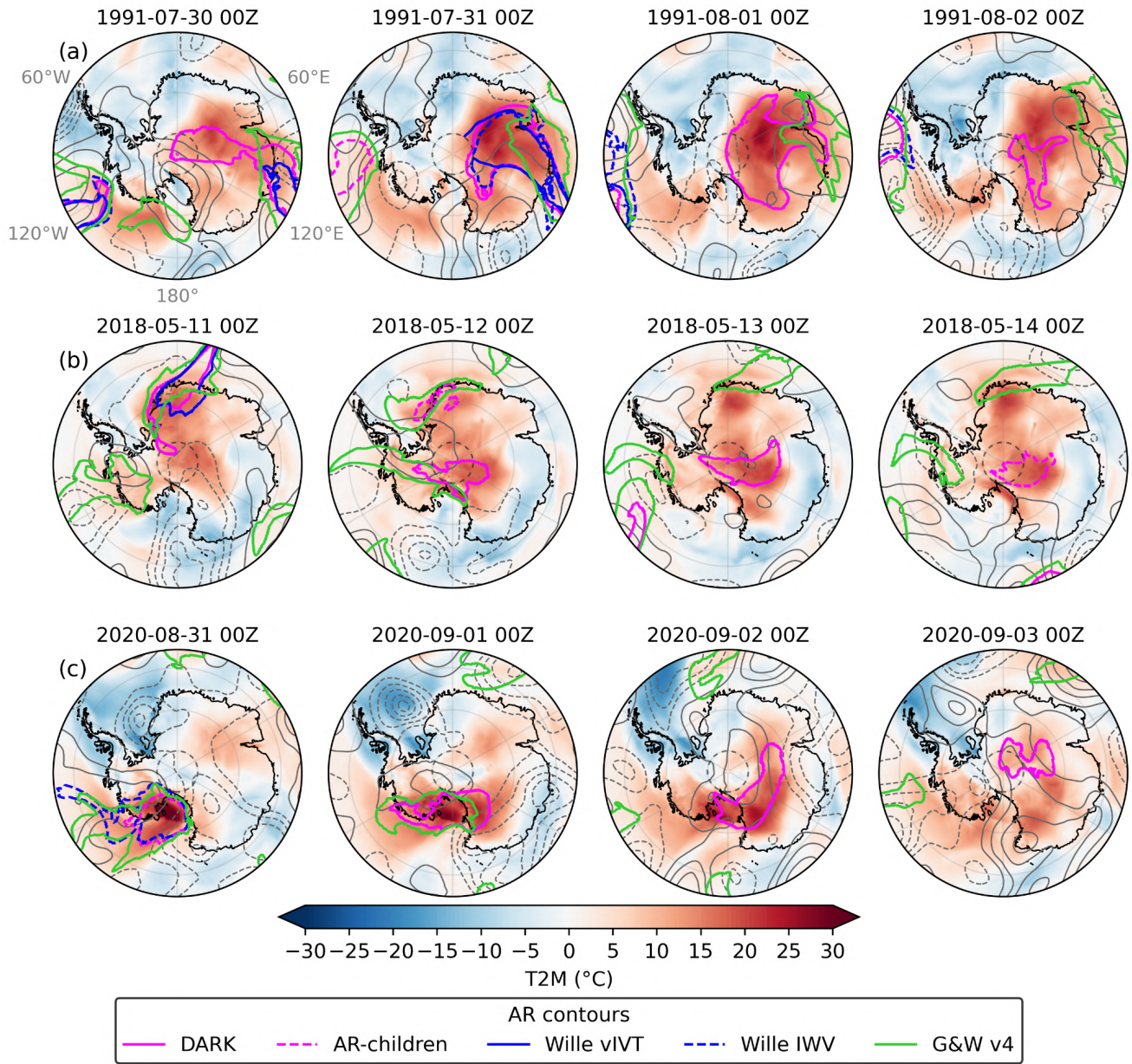
549  
550 One of the major advancements of the DARK framework is its ability to detect ARs reaching the South Pole, whereas previous  
551 schemes such as Wille vIVT and IWV ceased detection at  $85^{\circ}$  S. In ERA5, IVT vectors become ill-defined exactly at  $90^{\circ}$  S  
552 because of the coordinate singularity, which causes an artificial drop in detections at the pole. Nevertheless, DARK captures  
553 continuous poleward moisture transport all the way to the South Pole, enabling for the first time a physically consistent  
554 identification of ARs in this region. To illustrate this, we examine three events detected by DARK near the pole.

555 On 30 July 1991 (Fig. 11a), a DARK AR was detected extending from the Princess Elizabeth Land coast across the Antarctic  
556 interior to the South Pole. The synoptic configuration featured two centers of action, with a low-pressure system east of  
557 Princess Elizabeth Land and a high-pressure system farther east, jointly channeling the moisture plume poleward in a roller-  
558 like pattern. Both Wille vIVT and DARK identified ARs along this corridor on that day. However, the Wille vIVT AR stopped  
559 at the coast as the meridional IVT component weakened below the 98th percentile and the flow turned more zonal toward  
560 Dome A and the South Pole. Yet, the total IVT remained strong, allowing DARK to maintain continuous detection inland.  
561 G&W v4 detects multiple ARs around the continent on this date, including the AR of interest, but its detection stops shortly  
562 after the coastline. Under the AR footprint, 2 m air temperature anomalies already reached around  $+20^{\circ}\text{C}$ , reflecting the strong  
563 advection of warm, moist air from lower latitudes. On the following day, the IVT flow advanced farther across the East  
564 Antarctic Plateau. Both Wille and DARK detected ARs from the Princess Elizabeth Land coast over Dome A, with their extent  
565 broadening to cover areas from Dronning Maud Land to Victoria Land, reaching latitudes as far south as  $85^{\circ}$  S. G&W v4  
566 follows the moisture plume slightly further inland than on the previous day. Temperature anomalies intensified in step with  
567 the AR progression, spreading across the southern flank of the EAID. By the third day, the Wille ARs were no longer detected,  
568 while the DARK AR spanned a broad region south of the EAID, reaching the South Pole with a tail still visible along the East  
569 Antarctic coast. G&W v4 had already regressed to the coastline, failing to track the moisture transport over the interior where  
570 the strongest temperature anomalies, approaching  $+27^{\circ}\text{C}$ , were now concentrated beneath and slightly downstream of the  
571 DARK AR core. The strongest temperature anomalies, approaching  $+27^{\circ}\text{C}$ , were recorded at this stage beneath and slightly  
572 downstream of the AR core. By the fourth day, the feature had contracted into a thinner filament along the southern flank of  
573 the EAID, while the residual warm anomalies persisted in the area previously impacted by the main AR.

574 On 11 May 2018 (Fig. 11b), intense moisture transport was directed toward Dronning Maud Land, similarly driven by a marked  
575 pressure dipole, with a high-pressure system to the east and a low to the west. Both Wille vIVT and DARK detect ARs in this  
576 configuration, but the DARK AR extends farther inland, reaching Queen Elizabeth Land and up to 87° S. G&W v4 follows  
577 the moisture transport more closely than the Wille schemes, detecting the AR along the Queen Elizabeth Land coastline and  
578 the Ronne–Filchner Ice Shelf. It also captures an additional AR approaching from the WAIS that is not detected by DARK or  
579 the Wille schemes, which may represent the precursor moisture flux that evolves into the DARK AR over the South Pole on  
580 the following day. This event coincides with widespread positive 2 m air temperature anomalies across most of the Antarctic  
581 Ice Sheet, except along the East Antarctic coast from Victoria Land to the Amery Ice Shelf. On the following day, no Wille  
582 AR was detected, while the DARK AR had evolved and split into two structures: an AR over the South Pole, just north of the  
583 Ross Ice Shelf where surface temperatures continued to rise, and an AR-child along the original AR path over Dronning Maud  
584 Land. G&W v4 no longer detects the interior feature, consistent with its inland detection limitations. By the third day, only the  
585 main DARK AR remained, now centered over and slightly beyond the South Pole, having crossed the EAID before being  
586 deflected westward by the topography. Beneath this AR, 2 m air temperature anomalies intensified further, locally reaching  
587 +20 °C. By the fourth day, the AR had decayed into a smaller AR-child, yet the warm anomalies remained strong, particularly  
588 within these moisture remnants. Notably, after the AR had moved away from Dronning Maud Land, temperature anomalies  
589 there continued to increase through days 3 and 4, suggesting that the warm air mass and its heat content persisted well after  
590 the main AR passage.

591 On 31 August 2020 (Fig. 11c), a moisture-laden plume reached the Ross Ice Shelf, similarly guided by a high-pressure system  
592 centered over West Antarctica and a low-pressure system over Victoria Land. The disorganized structure of both systems, with  
593 wavy rather than well-defined closed centers of action, reflects relatively weak wind speeds, which likely explains why this  
594 event is not detected by either vIVT or DARK. The event was detected as a Wille IWV AR and as a G&W v4 AR, extending  
595 from the South Pacific across Marie Byrd Land to the Ross Ice Shelf. At its southern tip, a portion of this AR was also classified  
596 as an AR-child, indicating sustained, concentrated moisture transport embedded within the broader IWV and IVT structure.  
597 This episode produced exceptionally strong surface temperature anomalies over the Ross Ice Shelf, locally exceeding +30 °C.  
598 On the following day, the anticyclonic anomaly shifted southward toward the South Pole, while the low-pressure system  
599 elongated eastward, forming a double-centered trough. Together, these systems established a broad zonal corridor that directed  
600 the DARK AR across the Antarctic interior. By the third day, the AR extended along the southern flank of the EAID,  
601 maintaining a coherent filament structure. G&W v4 still detects the feature on this day but its detection stops shortly after the  
602 coastline, failing to follow the moisture plume as it propagates inland with DARK. The warm anomalies migrated with the AR  
603 core, indicating active advection of heat and moisture along its path. By the fourth day, the AR weakened and contracted into  
604 a diminished AR structure centered near the South Pole and extending over southern Dronning Maud Land and southern  
605 Princess Elizabeth Land. Despite this decay, pronounced 2 m air temperature anomalies persisted over the region previously

606 covered by the main AR on day 3, rather than beneath the contracted AR-child itself, reflecting the lingering thermal influence  
 607 of the moist and warm air mass advected during peak AR activity rather than active transport at this stage.



608

609 Figure 11. Synoptic evolution of three DARK AR events penetrating south of 85° S. Rows (a–c) correspond to the events from  
 610 30 July–2 August 1991, 11–14 May 2018, and 31 August–3 September 2020, respectively. Columns show sequential days at  
 611 00 UTC. Filled colors depict 2 m air temperature anomalies (° C), and grey contours show 500-hPa geopotential-height

612 anomalies (m; solid = positive, dashed = negative) at 50-m intervals. DARK ARs (solid magenta) and their children (dashed  
613 magenta) are shown together with Wille ARs (solid blue = vIVT; dashed blue = IWV) and G&W v4 ARs (limegreen). The  
614 dashed circle marks 85° S, and regions north of 60° S are masked.

#### 615 **4 Discussion & Conclusion**

616 The DARK framework bridges the gap between the intensity-focused Antarctic schemes of Wille vIVT and IWV and the  
617 globally applied IVT-based approaches such as Guan and Waliser (2015, 2019), while extending the geometric flexibility  
618 recently introduced by Spensberger et al. (2025). Building on Wille's methods, DARK retains the strict 98th-percentile  
619 threshold to isolate the most intense moisture-transport events while introducing key advancements: it uses total IVT rather  
620 than only its meridional component and computes total filament length instead of meridional extent, thereby removing the  
621 directional and geometric constraints that previously limited the detection of curved or equatorward-turning ARs. Global IVT-  
622 based schemes such as Guan and Waliser (2015, 2019, 2024) also use IVT magnitude but impose a directional coherence  
623 constraint that may limit the detection of ARs with strongly curved or reversing geometries. By relaxing this requirement,  
624 DARK identifies dynamically coherent, non-meridional ARs that are common near the Antarctic coast, where synoptic  
625 steering, Coriolis deflection, and topographic deflection distort moisture pathways.

626 Unlike previous frameworks, DARK eliminates the artificial boundary effects that limited AR detection close to the poles. In  
627 Wille vIVT, the reversal of the meridional IVT component at the South Pole prevents continuous detection of pole-crossing  
628 features, while the 20° meridional extent criterion introduces a secondary edge effect up to about 65° S. The Wille IWV scheme  
629 avoids the vIVT singularity but remains affected by this geometric limitation, because it was developed and applied assuming  
630 a southward boundary at 85°S. G&W v4 avoids these specific boundary issues but introduces a different spatial limitation: its  
631 hemispheric IVT threshold is very permissive along the coast and over West Antarctica, generating far more AR detections  
632 than DARK or the Wille schemes in these regions, while being very restrictive over the cold, dry East Antarctic interior, where  
633 its effective threshold prevents detection of the weaker but climatologically relevant moisture intrusions that DARK and Wille  
634 capture. This results in a highly heterogeneous detection footprint, with overdetection at the coast and underdetection inland,  
635 and only a narrow transitional zone where detection frequencies are broadly comparable to those of DARK or the Wille  
636 schemes. This reflects the fundamental mismatch between a hemispheric IVT threshold and the strong spatial gradients in  
637 Antarctic IVT climatology, making G&W v4 better suited for characterizing coastal AR activity rather than tracking AR  
638 influence across the full Antarctic continent and into the interior. By using total IVT and defining the 2,000 km minimum  
639 extent along the full curved axis of the filament rather than its meridional projection, DARK, together with the AR-children  
640 add-on, enables continuous tracking of ARs throughout their lifecycle, from oceanic genesis across the Antarctic continent and  
641 occasionally the South Pole to their inland decay and fragmentation as AR-children. This provides a seamless representation  
642 of poleward moisture transport and its persistence over the ice sheet.

643 The climatology derived from DARK ARs is broadly consistent with that of Wille vIVT and IWV, confirming that it preserves  
644 the physical realism of established Antarctic AR frameworks. A majority of Wille ARs are detected by DARK, and overall  
645 AR frequency along the Antarctic coast remains similar to that obtained with Wille's schemes, indicating strong agreement to  
646 detect the initial moisture intrusions. This shows that the method extends rather than replaces previous approaches: Wille ARs  
647 represent some of the most intense events, accounting for much of the precipitation and extreme anomalies. DARK additionally  
648 identifies ARs systematically missed by Wille's directional and geometric constraints. These new detections occur mainly  
649 south of the EAID, but additional events are found across the continent wherever moisture plumes turn zonally or overturn  
650 under the combined influence of vorticity and topography. These ARs are dynamically coherent systems associated with strong  
651 precipitation, pronounced temperature anomalies, and compound extremes. Their frequency aligns with the 20 % of  
652 extratropical moisture-transport axes that turn equatorward beyond 70° S (Spensberger et al., 2025), although the proportion  
653 is smaller here (about 6 %), suggesting that the most intense filaments, such as those detected by Wille, are less likely to  
654 overturn than weaker or more diffuse transports. While Wille vIVT remains most effective at isolating direct, intense poleward  
655 intrusions, DARK complements it by capturing a broader spectrum of AR geometries that are still physically meaningful and  
656 climatically relevant.

657 DARK ARs account for an average of 18 % of total Antarctic precipitation, compared to about 13 % in Wille vIVT. The largest  
658 increases occur in coastal embayments and across catchments south of the EAID, where the inclusion of AR-children further  
659 amplifies local contributions, raising them from only a few percent in Wille vIVT to over 20 %. This rise does not result from  
660 more intense precipitation within individual events but from a higher occurrence and greater diversity of ARs detected by  
661 DARK. On average, individual DARK ARs are associated with slightly lower mean precipitation per event than Wille ARs,  
662 which remain the most precipitation-intense. However, DARK also identifies additional ARs that are moderately weaker while  
663 still belonging to the upper tail of the precipitation distribution. In particular, DARK captures a larger fraction of precipitation  
664 extremes, as defined above by the daily 99th-percentile anomaly, with the strongest signals in regions such as McMurdo,  
665 Victoria Land, and near the South Pole south of the EAID. A similar pattern emerges for 2 m air temperature and compound  
666 extremes, where DARK detects more events than Wille. Risk ratio analysis confirms that this stronger association with  
667 extremes is not simply a by-product of higher AR frequency: extreme events are statistically more likely to occur during DARK  
668 ARs than during Wille ARs, and even more so when AR-children are included. The comparison with G&W v4 reveals a  
669 contrasting picture for both precipitation attribution and risk ratios. While G&W v4 explains more total precipitation along the  
670 coast and over West Antarctica due to its high detection frequency in these regions, DARK explains substantially more inland,  
671 particularly north of the EAID where G&W v4 detections drop sharply. For extreme events, the same coastal-to-inland polarity  
672 applies, but the continent-wide mean difference remains positive in favor of DARK, as the abundance of G&W v4 coastal  
673 detections inevitably captures most extreme days by volume while attributing a large share of precipitation to non-extreme  
674 events. The very high RR values of G&W v4 along the coast reflect this detection structure. Conversely, inland where G&W  
675 v4 detections are sparse, the few detected ARs are almost exclusively associated with extreme events, while the vast non-AR

676 pool again drives the denominator toward zero. In both cases, the RR is not physically comparable to that of DARK or the  
677 Wille schemes, which maintain a spatially consistent detection range across the continent. This highlights a general limitation  
678 of the RR metric when comparing ARDTs with strongly contrasting detection frequencies: RR conflates physical association  
679 strength with detection selectivity, and should be interpreted alongside occurrence and fraction of extremes explained when  
680 assessing cross-ARDT performance.

681 Another key contribution of this work lies in the introduction of the AR-children module, which extends detection beyond  
682 landfall by identifying remnants with high moisture transport that remain dynamically connected to their parent ARs. As ARs  
683 encounter the Antarctic coast, condensation, latent heating, and orographic deflection often disrupt their filamentary structure,  
684 causing them to fall below the length or coherence thresholds of conventional algorithms. These fragments, although shorter,  
685 maintain IVT above the 98th percentile and continue to produce significant precipitation and temperature anomalies inland.  
686 The AR-children algorithm captures these post-landfall features, enabling the representation of the decaying yet dynamically  
687 active stages of the ARs (Wille et al., 2024). In Antarctica, AR-children are particularly important over Victoria Land and the  
688 Amery Ice Shelf, where they account for more than 8 % of total precipitation and contribute up to 20 % of all extreme events,  
689 including precipitation, temperature, and compound extremes. When AR-children are included in addition to DARK ARs, the  
690 mean association with precipitation extremes increases from 53 % to 58 %, with temperature extremes from 67 % to 71 %,  
691 and with compound extremes from 80 % to 83 %. These results demonstrate that AR-children are not marginal phenomena  
692 but intrinsic components of the Antarctic AR lifecycle, representing the decaying inland phase of ARs and accounting for their  
693 delayed effects on precipitation and temperature extremes. From a practical standpoint, users whose focus is limited to coastal  
694 AR landfalls and their immediate impacts may find the core DARK algorithm sufficient, given its substantially lower  
695 computational cost, while the AR-children module is recommended for studies focusing on inland moisture transport and  
696 surface impacts.

697 Despite these advances, DARK remains subject to methodological assumptions that introduce uncertainty. A minimum AR  
698 length of 2,000 km was imposed to match the typical scale of ARs described in the literature (e.g., Guan and Waliser, 2015;  
699 Wille et al., 2021; Skinner et al., 2020; Gorodetskaya et al., 2014), generally longer than 2,000 km and narrower than 1,000  
700 km. DARK does not explicitly constrain AR width, as the use of IVT naturally favors elongated structures, in contrast with  
701 IWV-based schemes that can produce broad, static moisture plumes. The AR-children module further applies a minimum  
702 feature area of 20,000 km<sup>2</sup> to remove small, short-lived moisture patches. This threshold is not physically based but chosen  
703 pragmatically to exclude spurious, localized post-landfall features. These thresholds are empirically motivated by case-study  
704 analyses, which show that post-AR moist structures typically extend over at least this spatial scale. While a comprehensive  
705 sensitivity analysis is beyond the scope of this study, future work could further explore how varying these thresholds affects  
706 detection frequency and precipitation attribution. Likewise, the 15-day rolling window used to compute the 98th-percentile  
707 IVT threshold improves upon monthly percentiles by avoiding discontinuities at month boundaries, but it adds complexity that

708 may affect reproducibility. These design choices illustrate the necessary balance between physical robustness and algorithmic  
709 simplicity inherent to percentile-based detection frameworks.

710 As with all threshold-based methods, DARK defines discrete events within a continuous moisture field. The 98th-percentile  
711 threshold represents both an empirical compromise between inclusiveness and selectivity and a deliberate choice to ensure  
712 methodological continuity with previous Antarctic AR frameworks, particularly Wille vIVT and IWV. Lowering the threshold  
713 would inflate detections but weaken dynamical coherence, while raising it would isolate too few, overly intense events.  
714 Retaining the 98th percentile thus preserves comparability with earlier studies while providing a pragmatic balance that isolates  
715 physically meaningful ARs and maintains statistical consistency. Future work could explore adaptive thresholds that evolve  
716 with temperature, such as those proposed by Barthélemy et al. (2025) and Macleannan et al. (2025), to better represent  
717 thermodynamic scaling under warming conditions and to extend the applicability of DARK and related tools across diverse  
718 climate states, from palaeoclimate to future projections.

719 Overall, DARK provides a coherent and physically consistent framework for characterizing Antarctic ARs and their climatic  
720 influence. By removing directional and geometric constraints, eliminating artificial boundaries at the pole, and, with the add-  
721 on incorporating post-landfall detection through AR-children, it allows continuous tracking of ARs from oceanic genesis to  
722 polar dissipation. In doing so, DARK better captures the full lifecycle of Antarctic ARs, from their formation in the lower  
723 latitudes, through landfall and inland decay, including a potential passage across the South Pole, thereby providing an  
724 unprecedentedly complete view of AR-driven moisture and energy transport over the Antarctic Ice Sheet. In addition to further  
725 highlighting the SMB impacts of ARs across the entire Antarctic Ice Sheet as seen here, DARK provides a tool for tracking  
726 the influence of residual AR moisture on Antarctic mesoscale-scale atmospheric dynamics like polar lows and barrier jets  
727 (Carrasco and Bromwich, 1993; Nigro et al., 2012). This framework bridges global and polar perspectives, linking large-scale  
728 moisture transport pathways to regional precipitation, temperature, and compound extremes over the Antarctic Ice Sheet, and  
729 highlighting that the influence of ARs extends well beyond their initial landfall.

### 730 **Code and data availability**

731 The DARK algorithm was developed in Python and is publicly available under an open-source license at  
732 [https://github.com/victoirebuffet/DARK\\_atmospheric\\_river\\_detection\\_tool](https://github.com/victoirebuffet/DARK_atmospheric_river_detection_tool). The detection and analysis scripts rely on  
733 standard Python libraries including xarray, numpy, scipy, matplotlib, and cartopy, and are designed to process ERA5 reanalysis  
734 data in NetCDF format, however codes were made for MERRA-2 and CESM-LE2, codes are available upon request. ERA5  
735 reanalysis data (Hersbach et al., 2023a; Hersbach et al., 2023b) are available from the Copernicus Climate Data Store (CDS)  
736 at <https://cds.climate.copernicus.eu/>. The DARK AR catalog is available at <https://doi.org/10.5281/zenodo.17963007>, while  
737 the DARK AR+children catalog is available at <https://doi.org/10.5281/zenodo.17962931>. The AR-children detection module  
738 requires substantially more computational resources than the core DARK algorithm. Processing the full 1979–2023 ERA5

739 climatology in a single run requires approximately 9h of CPU time and ~17 GB of memory on a single CPU core, compared  
740 to 1h and ~8 GB for the core DARK algorithm. Users requiring only AR detection without post-landfall remnant tracking can  
741 therefore run DARK at negligible computational cost, while the AR-children module is recommended for studies focusing on  
742 inland moisture transport or the full AR life cycle. AR catalogs for Wille vIVT and Wille IWV, re-run from the method of  
743 Wille et al. (2021), on the full period of study (1979–2023), are available at <https://doi.org/10.5281/zenodo.17968902>.

#### 744 **Author contributions**

745 VB developed the detection algorithms, curated and analyzed the data, and prepared the initial draft of the manuscript,  
746 including figures and visualizations. VF and BP guided the investigation, and contributed to refining the final version of the  
747 manuscript. JW contributed to the conceptual development of the study, provided scientific guidance throughout the research  
748 process, and contributed to revising the final manuscript.

#### 749 **Competing interests**

750 The authors declare that they have no conflict of interest.

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