Evaluating Uncertainty and Modes of Variability for Antarctic Atmospheric Rivers

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Key Points:

- Antarctic-specific AR detection tools better capture continental interior footprint
- Modes of variability (MOVs) generally hold greater influence over West Antarctica than East Antarctica and are consistent across most AR detection tools
- IOD teleconnections in phase with ENSO produce a stronger AR precipitation response compared to other MOVs

Abstract

Antarctic atmospheric rivers (ARs) are driven by their synoptic environments and lead to profound and varying impacts along the coastlines and over the continent. The definition and detection of ARs specifically over Antarctica accounts for large uncertainty in AR metrics, and consequently, impacts quantification. We find that Antarctic-specific detection tools consistently capture the AR footprint inland over the ice sheets, whereas most global detection tools do not. Large-scale synoptic environments and associated ARs, however, are broadly consistent across detection tools. Using data from the Atmospheric River Tracking Method Intercomparison Project and global reanalyses, we quantify the uncertainty in Antarctic AR metrics as well as evaluate large-scale environments in the context of decadal and interannual modes of variability. The Antarctic western hemisphere has stronger connections to both decadal and interannual modes of variability compared to East Antarctica, and the Indian Ocean Dipole (IOD)'s influence on Antarctic ARs is stronger while in phase with ENSO.

Plain Language Summary

Atmospheric rivers (ARs) are large-scale weather features that transport significant amounts of moisture and are akin to "rivers in the sky". ARs traveling to Antarctica from the mid-latitudes can bring enough moisture to produce extreme snowfall, or if accompanied by warm air, can result in melt events, both of which affect ice sheets across the continent. How we define ARs in gridded datasets significantly impact what we say about them. If a definition uses Antarctic-specific constraints, it does a better job at describing the actual spatial footprint for ARs impacting inland locales on the continent. The large-scale environments that produce ARs, and how these environments naturally vary, however, are generally consistent regardless of how we define ARs. ARs impacting the western hemisphere of Antarctica are more deeply connected to specific atmospheric patterns that repeatedly occur compared to weaker connections with East Antarctic ARs.

1 Introduction

Atmospheric rivers (ARs) are long, narrow synoptic-scale weather phenomena that serve as meridional transport vehicles important for both large-scale and local hydrological climate across the globe. ARs transport both water and energy from lower to high latitudes and are often connected to extratropical cyclones where moisture laden bands of water vapor and clouds extend and travel across and along baroclinic zones (Ralph et al., 2018, AMS Glossary of Meteorology, 2017). Although the bulk of the current literature describe ARs in mid-latitude locations impacting western coasts of continents, such as western North America and western Europe, ARs are equally important in polar regions where the interaction of these moisture streams with land and sea ice, result in consequential precipitation events impacting the local cryosphere (Turner et al., 2019, Mattingly et al., 2018). Specific to Antarctica and depending on the thermal characteristics, ARs can produce significant snow accumulation over the ice sheet, (Gorodetskaya et al., 2014, Adusumilli et al., 2021, Terpstra et al., 2021, Wille et al., 2021), or melt events with consequences for ice shelf stability (Wille et al., 2019, Wille et al., 2022, Turner et al., 2022, Clem et al., 2022). Generally, ARs reaching Antarctica are relatively rare occurrences (Wille et al., 2021), fully extending into the continent only a few times per year but clearly tied to favorable synoptic conditions, such as blocking events in the Southern Ocean that funnel ARs into the continent (Wille et al., 2021, Pohl et al., 2021, Maclennan et al., 2021, Bozkurt et al., 2018, Terpstra et al., 2021). Despite their low frequency, they account for the largest percentage of total precipitation observed over Antarctica (Turner et al. 2019, Wille et al., 2021) and have important consequences for the continent's hydroclimate. ARs can also be tied to teleconnections and modes of natural variability (MOVs). AR occurrences for different regions around Antarctica have been attributed to various MOVs, such as the Southern Annular

Mode (SAM) (Wille et al., 2021, Clem et al., 2016, Raphael et al., 2016, Marshall et al., 2016), the Pacific South American Mode 2 (PSA2) (Maclennan et al., 2021, Marshall et al., 2016), the Pacific Decadal Oscillation (PDO) (Turner et al., 2019, Fogt et al., 2019), the Indian Ocean Dipole and El Nino Southern Oscillation (IOD, ENSO, respectively) (Nuncio and Yuan, 2015). Parts of the cold temperature anomalies in West Antarctica can also be explained by the influence of the Indian Ocean Basin mode and Atlantic Zonal and Meridional Modes (Li et al., 2015; Lee and Jin, 2021; Gutierrez et al., 2021, Table Atlas.1). In this study, we explicitly evaluate the relationship between these MOVs, ARs, and their associated precipitation and boundary layer temperature, to characterize the varied impacts across different regions and flavors of ARs. We do not evaluate surface impacts themselves, such as surface mass balance on glaciers, rather, we focus on understanding the large-scale variability that drives these impacts. Although we do not consider here an exhaustive list of MOVs of consequence for ARs, we limit this study to the decadal and interannual bimodal indices of variability introduced above. Additionally, because the very definition an AR is often debated (i.e., is the feature simply a moisture transport alone, or rather, connected to an extratropical cyclone) (Shields et al., 2019, Ralph et al., 2018, Gimeno et al., 2021) we quantify the uncertainties in AR metrics such as occurrence and climatology, as well as MOV impact, to provide context for our results.

2 Data and Methods

2.1 Reanalysis Datasets

We employ both the Modern Era Retrospective Analysis for Research and Applications, version 2 (MERRA-2) (Gelaro et al., 2017) and European Centre for Medium-Range Weather Forecasts’

Reanalysis Version 5 (ERA5) (Hersbach et al., 2020) global reanalyses in this work. To represent large scale synoptics and analyze modes of variability, we primarily use MERRA-2, which explicitly represents the energy and hydrologic budgets over ice sheets in Antarctica (Gelaro et al., 2017). A more in-depth evaluation of the cryosphere in MERRA-2 is available in Section 9 of Bosilovich et al. (2015) as well as Gossart et al. (2019). Sea surface temperature and sea ice concentration in MERRA-2 are prescribed as indicated by Table 3 of Gelaro et al. (2017). At approximately 50 km resolution, MERRA-2 is sufficient to resolve weather features, such as atmospheric rivers, along with their associated precipitation, and is the baseline dataset for the Atmospheric River Tracking Method Intercomparison Project (ARTMIP) (Shields et al., 2018, Rutz et al., 2019). ARTMIP provides a collection of AR “catalogues” from a variety of ARDTs (Atmospheric River Detection Tools) that detail gridded and timeslice information on where and when ARs exist. Using MERRA-2 across the same years as included in ARTMIP (1980-2016) allows us to consistently apply all available ARTMIP ARDT catalogues to Antarctic AR uncertainty quantification. ERA5 datasets are also applied (1980-2020), where available, to further represent the spread in climatology metrics across both ARDT and reanalysis products and robustly quantify uncertainty by using as many catalogues as possible. Monthly MERRA-2 data is used to compute MOV indices (GMAO, 2015a; GMAO, 2015b), daily data to compute precipitation (GMAO, 2015c) and 850 hPa temperature (GMAO, 2015d) for AR days, and 3-hourly data is used for AR identification (GMAO, 2015d). Only ARDTs with polar constraints (those the incorporate a lower threshold designed for polar latitudes, here referred to as P-ARTMIP) are used for MOV analysis to minimize errors by only including appropriately designed ARDTs.

2.2. Atmospheric River Detection

Identification and tracking of ARs require decisions dependent on the AR definition. Because this definition varies wildly from one project to another (Ralph et al., 2018, Rutz et al., 2019), metrics such as AR frequency and seasonality differ depending on choice of ARDT. ARTMIP has shown that uncertainty based on ARDT far outweighs uncertainty based on model (O'Brien et al., 2021) as well as reanalysis (Collow et al., 2022). Thus, uncertainty quantification is an important component to any analysis where AR detection is required. It is also important to recognize that applying many different ARDTs for each science problem is not always practical for individual researchers, so a balance must be struck to address ARDT uncertainty, either by applying multiple ARDTs, such as this work and ARTMIP, or minimally, determining if the chosen ARDT is fit for purpose (Rutz et al., 2019). Traditional ARDTs designed for the mid-latitudes typically apply moisture thresholds using the quantity called integrated vapor transport (IVT). However, for ARs making landfall and extending poleward onto the continent, one option is to identify ARs by simply using the meridional component. Here, we primarily apply Antarctic-specific ARDTs to diagnose the relationship between MOVs and ARs across Antarctica but include all methods with polar constraints to represent uncertainty spread. For climatology metrics, we include all available global ARTMIP ARDTs to highlight the large differences in metrics. The Antarctic-specific algorithms, herein referred to as Wille_vIVT and Wille_IWV, focus on meridional geometry and filter for high (98% percentile) relative moisture flow into the continent to better capture ARs impacting polar latitudes, rather than zonally around the Southern Ocean. Further details on Wille the ARDTs (Wille et al., 2019, Wille et al., 2021), ARTMIP ARDTs, and IVT/IWV calculations are in Supplemental.

2.3 Modes of Variability

We calculate both decadal and interannual modes of variability consistent with the Climate Variability and Diagnostic Package (CVDP) developed by Phillips et al., 2014. Modes were chosen based on current literature, as described in the introduction, with an already established or potential connection to AR impacts in and around Antarctica. Decadal modes are represented here by the SAM and the PDO, and for interannual modes, PSA2 and IOD, both in and out of phase with ENSO. All of these indices have been found to influence both Antarctic precipitation and temperature (as summarized in Gutierrez et al., 2021, Table Atlas 1). Specific details on computation are found in supplemental material. One caveat to using the PDO is the relatively short timespan of available data of ~four decades. Tropical pacific decadal variability (TPDV) such as the PDO have timescales from 8 to 40 years (Power et al., 2021), making significance testing challenging. Because we are limited to the ARTMIP time period and thus only 37 years are used, PDO and AR correlations are shown for qualitative illustration, but significance inferences are limited and used with caution.

3 Climatological characteristics and uncertainty due to ARDT

ARs impacting high latitude locales such as Antarctica do not necessarily follow mid-latitude storm tracks. Rather, ARs often bend and flow around high-pressure blocks or follow baroclinic zones connected to low pressure regimes ultimately pushing moisture intrusions into the continent. ARs that make it onto the continent are dominated by the north-south meridional component of the wind (not shown). This can be demonstrated by computing heat maps of AR occurrence for each method and comparing the Antarctic specific occurrences to traditional methods developed for mid-latitudes. Figure 1a shows the spatial distribution differences between the mean Wille Antarctic-specific ARDTs and the ARTMIP mean. ARs that make landfall are generally rare (a few times per year, Wille et al., 2021), but even so, the Antarctic specific ARDTs consistently detect ARs in the interior of the continent where most traditional ARDTs detect more in the Southern Ocean. Even global ARDTs that allow for polar thresholds (P-ARTMIP) (Figure 1b) ultimately do not capture ARs on the interior ice sheets, especially over East Antarctica. This is likely because the Antarctic specific ARDTs applied here focus on the meridional component of the moisture transport that allows for AR detection deeper into the dry Antarctic interior.

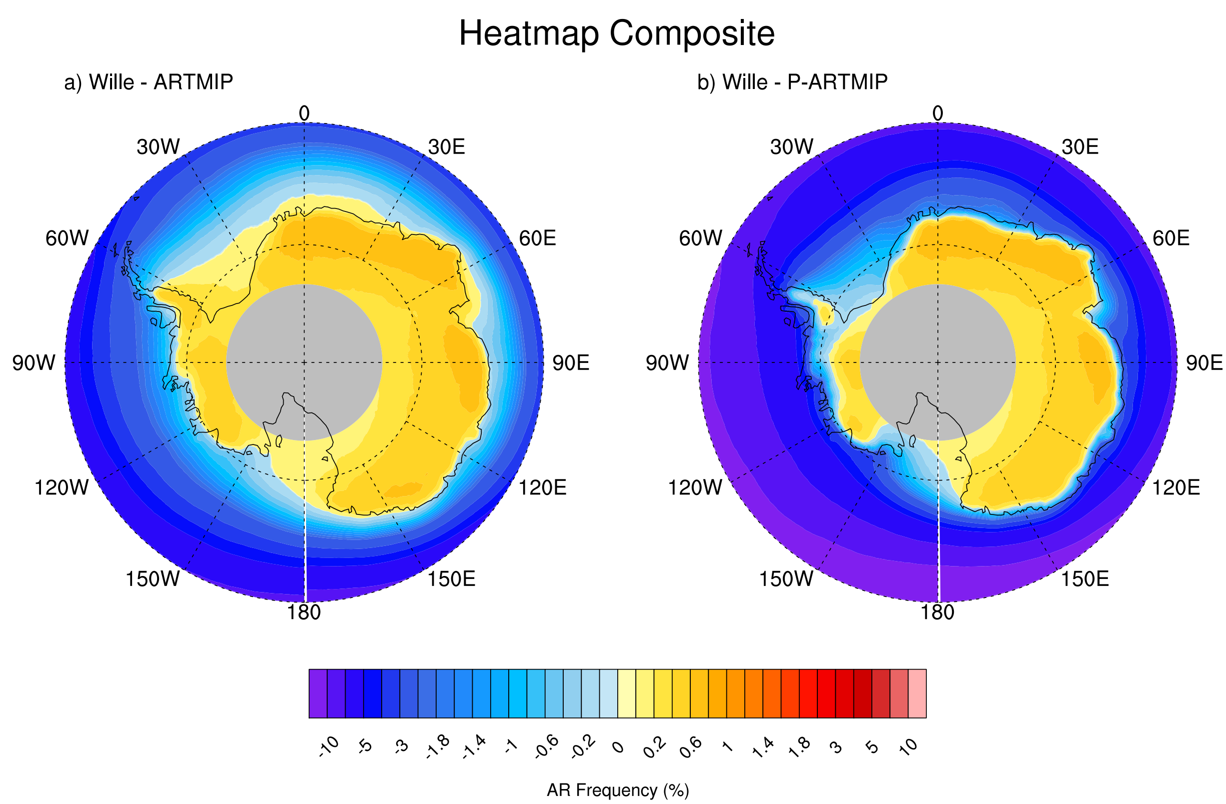

Figure 1. Composite difference heatmaps of AR frequency in % time (relative to the entire ARTMIP MERRA-2 timespan, 1980-2016). Wille ARDTs versus all applicable global ARDTs (a) and Wille ARDTs versus P-ARTMIP (b).

From a continent-wide, climatological perspective, (Figure 2), the Wille ARDTs detect ARs distributed throughout the year, with maximum occurrence in Austral fall and winter, consistent with instrumental observations and Regional Climate Model (RACMO2) that show high accumulation events with synoptic conditions for both West Antarctica over Thwaites Glacier (~108.5°W) (Maclennan et al., 2021, Lenaerts, et al., 2018) and East Antarctica over Dronning Maud Land (~20°W – 45°E) (Gorodetskaya et al., 2014). (See Figure S1 in supplemental for Antarctic geography). Distinctly different from Wille ARDTs, ARs detected from global and P-ARTMIP methods, peak in February and Austral Fall, and are likely due to the predominance of ARs impacting the Antarctic Peninsula, which in some cases, are the only location where ARs are identified (Supplemental Figures 3 and 4). Because of the geographic position of the Peninsula in the Southern Ocean, the global ARDTs, designed for mid-latitudes, capture more zonally-oriented ARs. Specific regional climatologies (Antarctic Peninsula, Dronning Maud Land, and Princess Elizabeth/Queen Mary Lands, ~73°E-100°E) can be found in Supplemental.

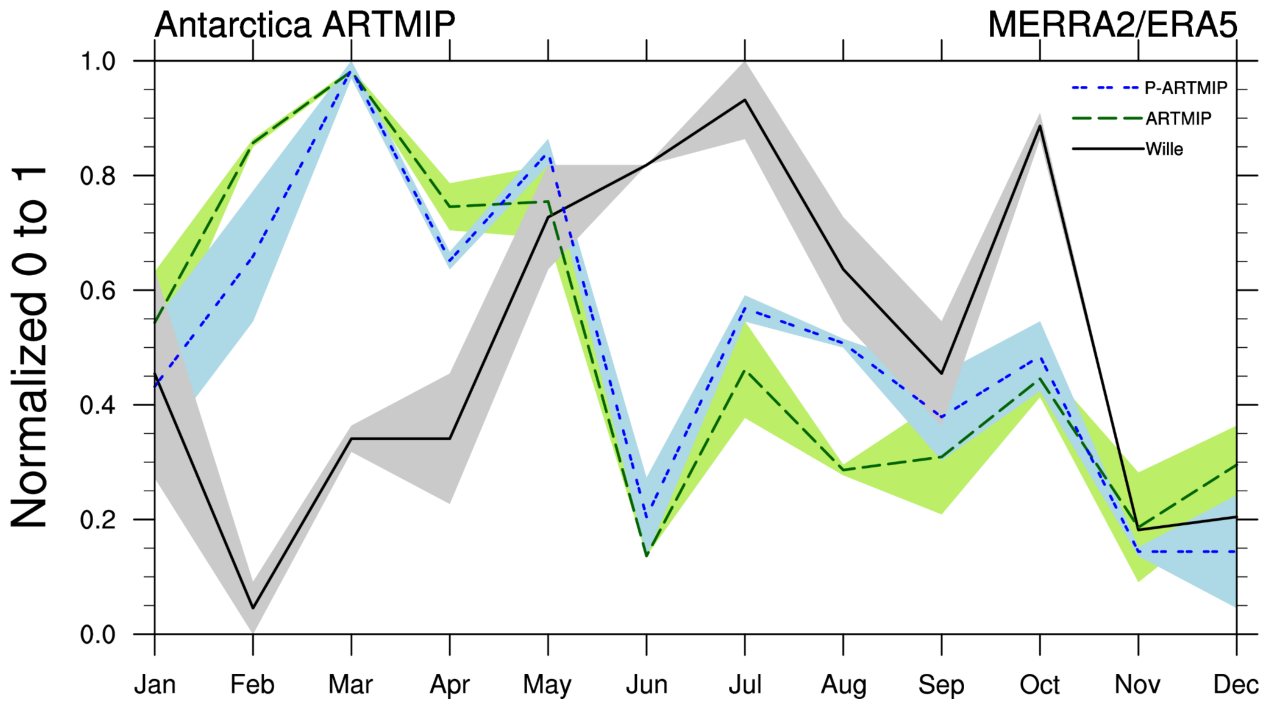

Figure 2. Antarctic seasonal cycle of ARs for ARTMIP mean (lines) and spread (shading) which includes applicable available ARDTs (Supplemental Table S1, Figure S3) and both reanalysis datasets ARTMIP Tier 1 MERRA-2 and Tier 2 ERA5. All available global ARDTS (ARTMIP) versus ARTMIP with polar constraints (P-ARTMIP) versus Antarctic specific (Wille ARDTs).

4 Relationship between Antarctic ARs and MOVs

4. 1 MOV Synoptics for AR days

Around and across Antarctica, there are a variety of different climate regimes, but coastal climates depend on geometry and orientation of the coast relative to the zonal and meridional flow. However, for the purposes of evaluating broad synoptic influences, we divide our study into West and East Antarctica. To isolate and amplify unique west and east hemispheric patterns, we apply the split hemisphere technique, commonly used for peak (seasonal) tropical cyclone track density analysis (Korty et al., 2012, Yan et al., 2016), except here, we composite synoptic conditions for landfalling ARs for each, respective hemisphere. That is, for days where ARs impact West Antarctica, synoptic conditions are composited for the western hemisphere, and for days where ARs impact East Antarctica, synoptic conditions are composited for the eastern hemisphere. All spatial figures presented here contain a solid thick line dividing as a reminder that the hemispheres are treated separately but plotted together for illustration. We highlight the Wille_vIVT ARDT because this algorithm better represents AR dynamics (Wille et al., 2021). Figure 3 plots annual anomalies for low-level (850 hPa) moisture flux (vectors) and temperature (contours) for AR days occurring during the different phases of SAM and PSA, a decadal and interannual mode of variability, respectively, that represents variations in the dynamics. Across polar ARDTS (Fig. 3 e-h), clearly show the fluxes in (SAM positive Antarctic Peninsula, PSA2 negative for the West Antarctic Ice Sheet, Amundsen and Ross Seas (Figure S1) and out of the continent for the western hemisphere, consistent with Antarctic MOV patterns in Marshall and Thompson (2016) and Marshall et al. (2017). For East Antarctica, the fluxes are varied but generally the opposite, with, for example, Dronning Maud Land showing fluxes into the continent during SAM negative. Overall PSA2 holds greater influence for the western hemisphere, and results are consistent across all global ARDTs, regardless of polar constraints or not (not shown). Across ARDTs for AR days, although there are variations in boundary layer temperature, moisture, and winds, synoptic conditions are robust across methods, unlike frequency metrics and seasonal climatology although some regional differences exist from Wille_vIVT (Fig 3 i-l), our primary method. For example, SAM-, the Wille_vIVT ARDT detects more ARs with onshore flow (~180-150^{o}E) to Terre Adelie Land (~140 E) (Fig 3j).

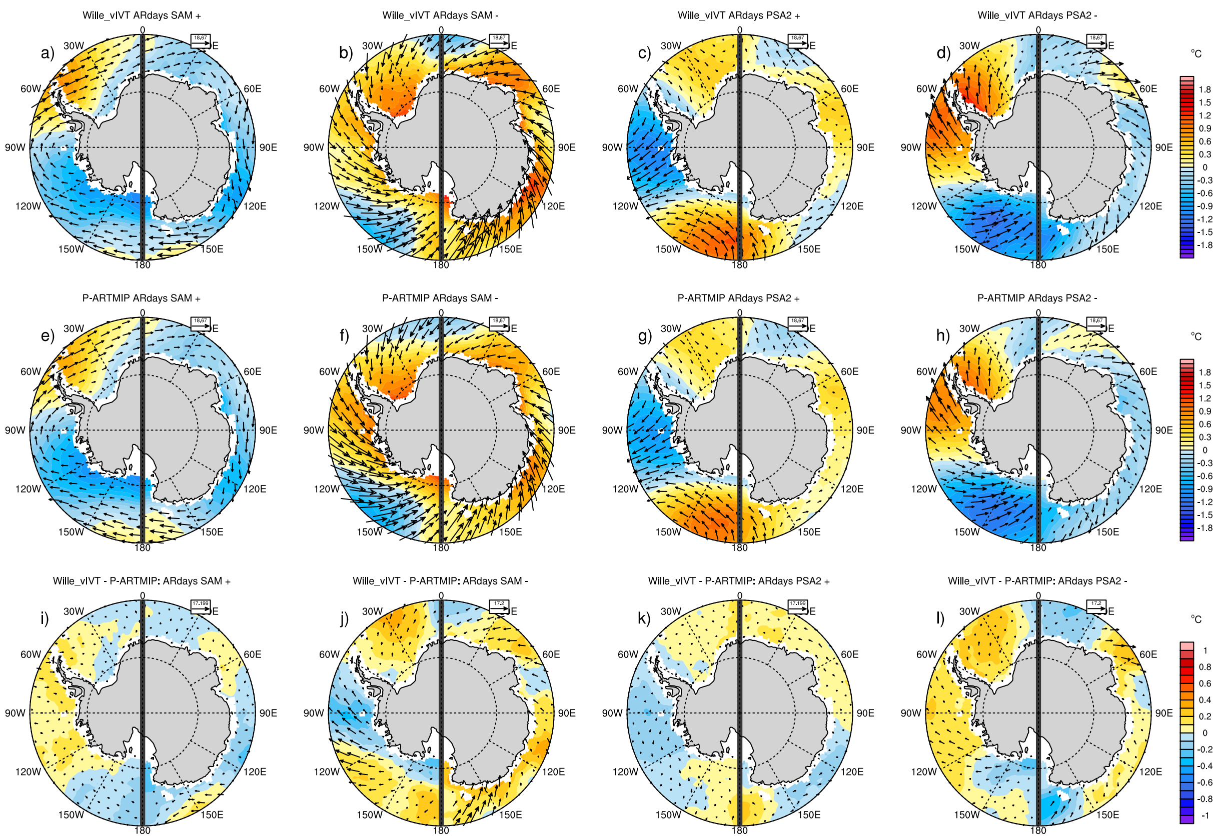

Figure 3. Anomalies of 850 hPa Air temperature for AR day composites (color contours, ^{o}C) and 850 hPa moisture flux (kg m^{-1}s^{-1})(arrows) during SAM phases (a-b,e-f,i-j), PSA2 phases (c-d,g-h,k-l) in split hemisphere format. West Antarctic ARs are composited separately from East Antarctic ARs to maintain unique hemispheric synoptic signatures and combined for illustration, separated by thick gray line. Wille_vIVT (a-d), ARTMIP mean for ARDTs with polar constraints (P-ARTMIP) (e-h) and differences (i-l) are shown. Reference vector is shown in the box at the upper right of each panel.

4.2 Precipitation and temperature impacts

4.2.1 Decadal modes of variability: SAM and PDO

Decadal modes of variability, their relationship with AR precipitation and 850 hPa temperature, and ARTMIP uncertainty, is shown in Figure 4. Again, we highlight the Wille_vIVT ARDT for spatial plots that regress PC timeseries for SAM (Fig. 4b, e) and PDO (Fig. 4c, f) onto precipitation and temperature anomalies for AR days. For the PDO, we show western hemisphere only due to the lack of any significance elsewhere. Both precipitation and temperature follow the composite plots for AR days (Fig. 3) in that where moisture fluxes flow into the continent, enhanced precipitation occurs, along with corresponding temperature anomalies. For example, SAM in the positive phase typically indicates a deeper Amundsen Sea Low (and vice-versa), and generally less mass transport between Antarctica and the southern mid-latitudes (Turner et al., 2013, Spensberger et al., 2020). Figure 4b shows the precipitation is positively and significantly correlated with SAM over Antarctic Peninsula (label A) and negatively correlated over the Amundsen sea region (label B), resulting from a deeper Amundsen Sea Low that brings cyclonic, clockwise flow into the Peninsula and out of the Amundsen sea region during SAM positive. SAM negative, oppositely correlated with precipitation between Amundsen and Ross Seas near Marie Byrd Land (~120^{o}W), supports onshore flow during the negative phase. The eastern hemisphere shows less significance in precipitation although SAM's influence is hinted at in regions such as Dronning Maud Land, Kemp Land and the Amery Ice Shelf, and Wilkes Land (labels C, D, E, respectively; supplemental Figure S1 for Antarctic locations). The PDO shows a negative correlation with the Antarctic Peninsula in both temperature and precipitation (labels K, F), and a positive one between the Amundsen and Ross Seas (labels L, G), although significance is weak and overall shows less influence than SAM. Each region that shows significance is tested across all P-ARTMIP algorithms (Fig. 4a, d) to quantify uncertainty in these calculations. Across most regions and methods, the sign of the correlation is robust for both temperature and precipitation, except for Dronning Maud Land (DML) for precipitation (label C), where the strength of the correlation is generally tied to frequency climatology.

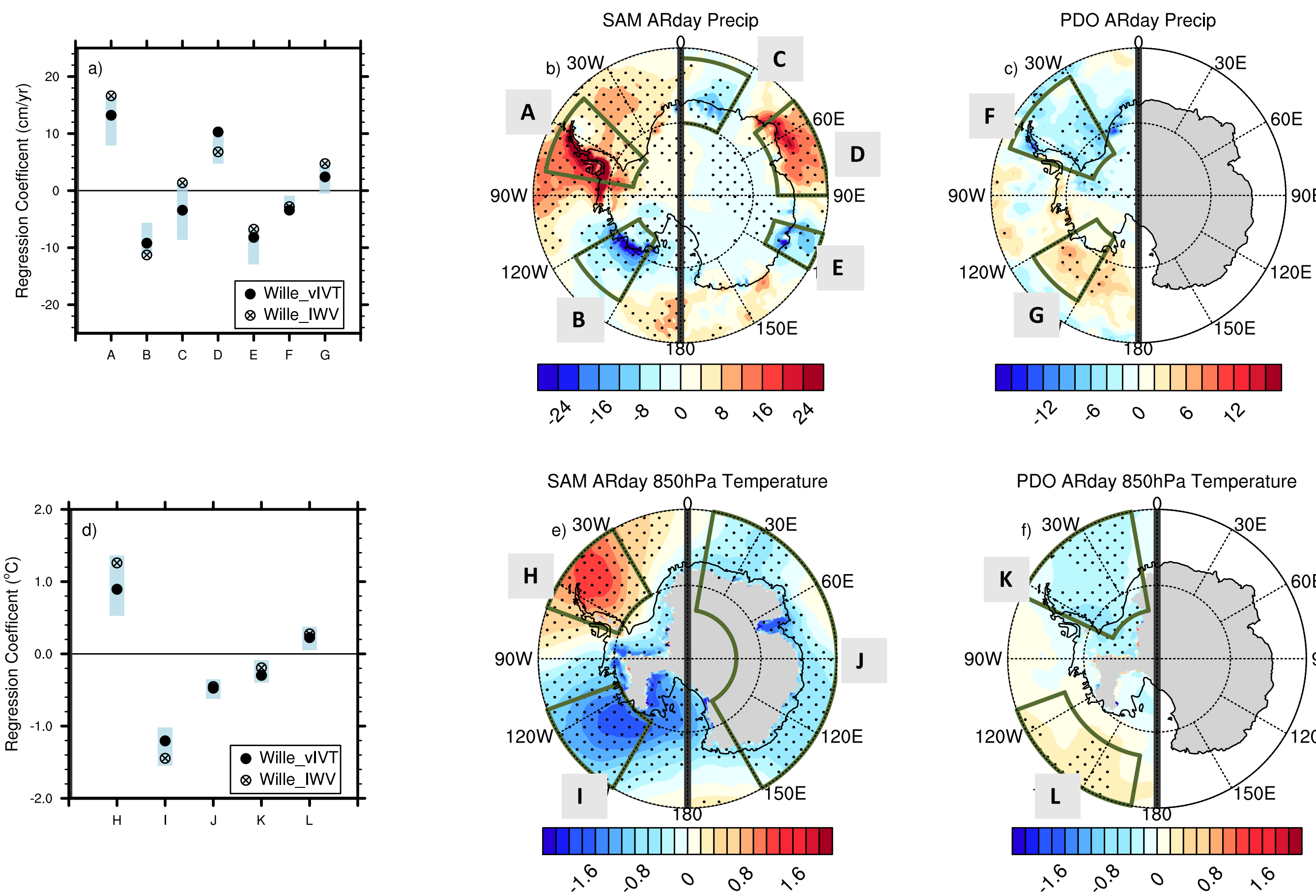

Figure 4. Regression patterns and spread for AR days and decadal modes of variability (SAM and PDO). Precipitation (cm yr^{-1}) (b-c) and 850 hPa temperature (^{o}C) (e-f) patterns are plotted for Wille_vIVT ARDT. Uncertainty is shown for area-averaged regression values across all P-ARTMIP ARDTs (a,d). Dark green boxes indicate areas used in the uncertainty calculation and are labeled alphabetically. Split hemisphere format, as Figure 3, is used. The PDO is shown for western hemisphere only. Significance was tested at 90% level using a student T-test. Where

shown, 850 hPa temperatures are plotted for topographical regions under 850 hPa highlighting coastal and escarpment zones and eliminating errors on pressure surfaces due to elevation.

4.2.2 Interannual modes of variability: PSA2, IOD and ENSO

Interannual modes of variability, their relationship with AR precipitation and 850 hPa temperature, and ARTMIP uncertainty, is shown in Figure 5. We evaluate PSA2 and IOD independently to illustrate their dominant, spatial impacts. However, it is important to note that no MOV, and especially interannual modes, operate in isolation. The PSA2 mode has been shown to excite sea surface temperature (SST) patterns tied to the evolution of ENSO (Lou et al., 2021), and the IOD is often paired with ENSO, in addition to decadal modes such as PDO. For simplicity, we evaluate the dynamical mode of PSA2 separately from modes defined by SST anomalies (IOD, ENSO). The PSA2 has already been shown to have significant implications for the Amundsen Sea Embayment and Thwaites Glacier (Maclennen et al., 2021), and we confirm this with our regression analysis that shows negative correlation with PSA2 and precipitation in this area (label B), consistent with flux composites in Figure 3 and a potential amplification of wavenumber 3 (Cai et al., 1999). Temperature anomalies for AR days also align with regressions where poleward flow from mid-latitudes brings warmth into the Ross Sea region and is positively correlated with PSA2 (label N) compared to equatorward flow, negative correlations, and colder temperature over Amundsen Sea (label M). The IOD (Fig 5c-d, g-h) is much more potent while in phase with ENSO with negative correlations over West Antarctic regions such as Ellsworth Land (labels GG, PP) and positive correlations with Eastern Dronning Maud Land (label II) and Ross Sea (labels HH, QQ). Temperature significance is stronger than precipitation significance, however, likely tied to the broad extratropical SST influences during these modes. Although significance with Wille_vIVT is strong for temperatures, the differences with Wille_IWV and the P-ARTMIP spread

(Fig5 a, e) suggest this result is not necessarily robust across ARDTs, and even potentially changes the sign of the correlation. Precipitation uncertainty is smaller, with most of the methods agreeing on correlation signs except for the IOD responses near Wilkes Land (label KK). Finally, the amplitude of IOD-ENSO response is much higher than any other MOV, interannual or decadal, suggesting that the IOD in phase with ENSO produces more anomalous precipitation than any other mode studied here. Nuncio and Yuan (2015) describe Antarctic sea ice correlations during IOD with ENSO in the Pacific sector and Ross Seas, and note the decrease is sea ice corresponding to warm meridional flow. Additionally, the wave train schematic in Nuncio and Yuan (2015) is consistent with our results that show for AR days, precipitation and warm low-level temperatures are positively correlated due to enhanced poleward flow at the Ross Sea and equatorward flow off the West Antarctic Ice Sheet.

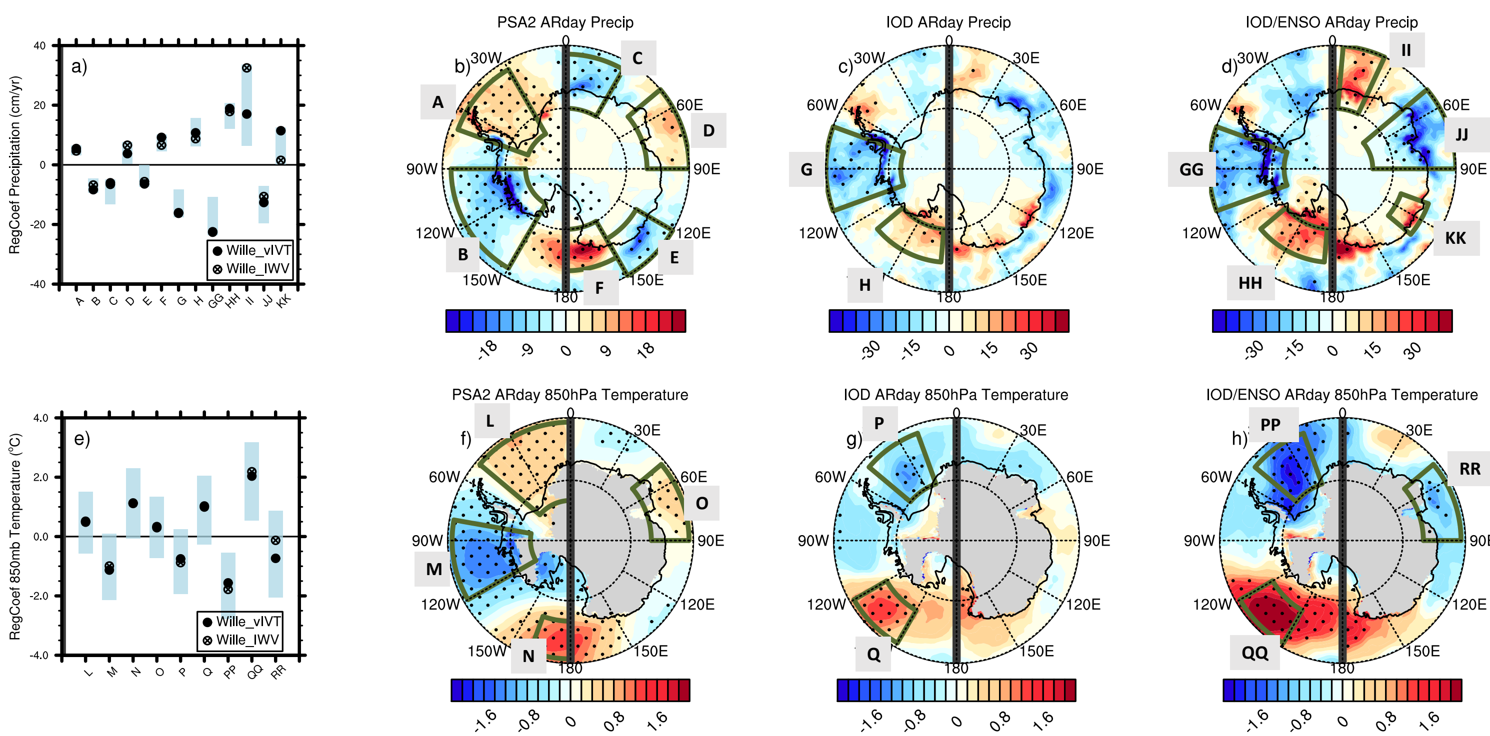

Figure 5. Same as Fig 4 except for interannual modes of variability PSA2 (b,f), IOD without (c,g) and IOD in phase with ENSO (d,h). Significance was tested at 90% level using a student T-test. Note precipitation contour scales are different for PSA2 versus IOD.

5 Conclusions

Studying Antarctic atmospheric rivers combines a unique set of disciplines incorporating both atmospheric science and the cryosphere, but also cross-disciplinary interests such as feature detection. To understand this phenomenon, we must both define it and put it into context with current research. Antarctic AR detection tools are generally robust across the synoptic meteorology, however large uncertainties exist for AR frequency climatology metrics such as seasonal cycle and location of landfall. Antarctic-specific tools that rely on the meridional characteristics of ARs capture the continental interior footprint of ARs more consistently compared to global ARDTs designed for the mid-latitudes. When evaluating ARs in the context of modes of natural variability (SAM, PSA2, PDO, IOD and ENSO), this study finds the MOVs studied here influence West Antarctic ARs more than East Antarctica. Spread among ARDTs is generally smaller for decadal modes of variability compared to interannual modes. This is likely due to the shorter period for interannual modes and the opportunity for compounding MOV events. Additionally, the Indian-ocean dipole teleconnections with ENSO produce a stronger AR response, mostly for West Antarctica and the Pacific sector, compared to other MOVs. Although we have chosen to diagnose MOVs that sample both decadal and interannual variability, it is not a complete list of potential influences on ARs onto the Antarctic glaciers and ice shelves. Future work includes understanding compound MOVs beyond IOD and ENSO. With our exploration of IOD and ENSO, compound MOVs clearly have the potential to amplify or suppress AR activity.

Understanding the interplay between MOVs and ARs improves predictability and the ability to manage consequences as we move into a warmer climate. A future increase in MOVs that favor AR landfalls and warmer conditions will likely increase snowfall in the impacted area, but also risk increased surface melt and ice shelf destabilization.

Acknowledgments

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Open Research

ARTMIP data is available from the Climate Data Gateway https://doi.org/10.5065/D6R78D1M and http://doi.org/10.5065/D62R3QFS. MERRA-2 is available from the Goddard Earth Sciences

Data and Information Services Center (GES DISC) at https://disc.gsfc.nasa.gov/, DOI numbers doi: 10.5067/9SC1VNTWGWV3 and doi: 10.5067/Q5GVUVUIVGO7. ERA5 data is available from the Copernicus Climate Change Service (C3S) Climate Data Store at https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels?tab=overview.

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