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Extreme Amundsen Sea Low (ASL) events and climate of West Antarctica

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Abstract. The Amundsen Sea Low (ASL) is a regional atmospheric circulation feature that significantly influences the climate of West Antarctica through its impact on the meridional wind field. An observed deepening of the ASL over the satellite era has raised concerns about the possibility of more extreme ASL conditions through the end of the twenty-first century. Here we use ERA5 reanalysis and passive microwave satellite observations to examine the impact of extreme ASL events on West Antarctica during the period 1979-2025. In total, we identify 13 extremely strong and 8 extremely weak events that vary geographically based on magnitude. Strong events tend to be concentrated poleward and centered in the vicinity of the Amundsen Sea while weak events are found farther north and display large zonal spatial heterogeneity. Composite maps of surface anomalies suggest that the location of extreme events serve to explain a regional dipole in surface temperatures and sea ice concentration, both of which are co-located with anomalous wind velocities modulated by ASL strength. Given the link between the regional ASL and additional large-scale modes of atmospheric variability in the Southern Hemisphere, we also investigate extreme ASL events in relation to the Southern Annular Mode, El Niño Southern Oscillation, and Zonal Wave 3. We find that nearly all extremely strong events occur when the three modes of variability are positively in-phase; there is less agreement during extremely weak ASL events. We assess future ASL variability and extremes using CESM2 model output under middle- and high-emission scenarios. Future projections indicate a higher proportion of extremely strong ASL events relative to weak events through the end of the 21st century, suggesting an increased likelihood of more extreme meridional conditions across West Antarctica in the near future.

1 Introduction

The ASL is a climatological area of low pressure located in the Pacific Sector of the Southern Ocean (SO) between the Antarctic Peninsula (AP) and the Ross Sea (62°W-170°E) (Fogt et al. 2012; Hosking et al. 2013; Raphael et al. 2016). It is the deepest of three low-pressure centers surrounding Antarctica and results from the interaction between the westerly winds and the continent's complex topography (Baines and Fraedrich 1989; Goyal et al. 2021; Raphael 2004; Raphael et al. 2016).

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Given the forcing of atmospheric circulation that results from this interaction, a large number of high-latitude synoptic systems are steered towards the region of the ASL, thereby contributing to its underlying variability at various timescales through their density and intensity (Fogt et al. 2012).

As a meridional circulation feature, the ASL controls north-south flow across West Antarctica and influences climate variables such as surface temperature and sea ice concentration (SIC). A thermodynamic response is observed when the feature's cyclonic rotation advects cold continental air equatorward over the Ross Sea and relatively warm marine air poleward toward the AP and Bellingshausen Sea (hereinafter referred to as AP/BS). Northerly (southerly) winds along the eastern (western) flank of the ASL can also dynamically compact (extend) sea ice toward (away from) the continental coastline (Dalaiden et al. 2021; Holland and Kwok 2012; Raphael et al. 2016). Indeed, previous work by Holland and Kwok (2012) has highlighted the prominent role of surface winds in driving sea ice trends in the ASL region. Stammerjohn et al. (2008) have also suggested a link between ASL-driven winds and regional asymmetries in sea ice, namely reductions in the Bellingshausen Sea and growth in the Ross Sea.

The geographic location of the ASL center is significant since variations in its position determine the placement of meridional winds, which facilitate the exchange of heat and momentum between middle and high southern latitudes (Fogt et al. 2012; Hosking et al. 2013). On a seasonal timescale, the ASL exhibits a zonal progression to the east in austral summer (December-January-February, DJF) and west in winter (June-July-August, JJA). Meridionally, the ASL is located farther north than average in DJF and farther south in JJA (Fogt et al. 2012; Hosking et al. 2013; Raphael et al. 2016; Turner et al. 2013). Previous research has also documented a poleward shift in austral spring (September-October-November, SON) when the ASL is at its greatest intensity, or magnitude (Hosking et al. 2013).

ASL magnitude is an additional factor contributing to the feature’s impact on West Antarctic climate variability. A stronger (i.e. deeper) ASL is generally associated with stronger cyclonic rotation, which enhance meridional wind anomalies and intensify the advection of temperate air over the region. When the ASL is weaker (i.e. shallower), anticyclonic wind anomalies can weaken meridional exchanges, thus producing less pronounced effects on the region’s surface climate.

In recent years, shifts in the magnitude of the ASL have been linked to large-scale modes of atmospheric variability (MOVs) such as the Southern Annular Mode (SAM), El Niño Southern Oscillation (ENSO), and Zonal Wave 3 (ZW3) (Clem et al. 2017; Raphael 2004, 2007; Turner et al. 2013). SAM is the principal mode of SH atmospheric variability and describes the zonally-symmetric pressure gradient between middle and high latitudes (Marshall 2003). During the positive (negative) phase of SAM, negative (positive) pressure anomalies set over Antarctica and the ASL deepens (weakens) in response. Although it is often described as an annular phenomenon, SAM consists of a non-annular component influenced by a ZW3 pattern, which consists of three opposite-sign pressure couplets that enhance meridional flow into Antarctica, specifically in the Amundsen Sea sector (Campitelli et al. 2021; Schroeter et al. 2023). A number of studies have emphasized the particularly strong sea ice response to ZW3 in the ASL region (Eabry et al. 2024; Goyal et al. 2022; Raphael 2007).

Tropical teleconnections have also been shown to play a role in ASL variability (Turner 2004; Wang et al. 2023; Yuan 2004). During ENSO’s cold (warm) phase, heating discrepancies across the tropical Pacific lead to convective

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anomalies that increase ascent and alter upper-level divergence. This induces Rossby waves that propagate poleward in the southeastern direction and promote negative (positive) pressure anomalies over the ASL region, effectively deepening (weakening) the ASL. Prior studies maintain that the ENSO influence on the ASL is only significant when it occurs in-phase with SAM, likely because of the convergence of transient eddy momentum fluxes which reinforce circulation anomalies of the same sign (Fogt et al. 2011; Stammerjohn et al. 2008; Wang et al. 2023). It is therefore possible that the operation of numerous in-phase MOVs can reinforce pressure anomalies and intensify the magnitude of the ASL on monthly timescales and longer.

A recent deepening of the ASL has raised concerns about the possibility of a transition to more meridional conditions across West Antarctica, which could potentially amplify baseline warming and significantly alter the surface climate of the region. This study therefore examines the large-scale atmospheric context of extreme ASL events as well as their influence on the surface conditions of West Antarctica for the period 1979-2025. Additionally, we conduct a preliminary analysis of projected extreme ASL events under middle- and high-emission scenarios using output from the Community Earth System Model version 2 (CESM2). The latter work, although limited, allows us to gauge potential changes in the frequency and persistence of extreme ASL events through the end of the 21st century. Data and methods are outlined in Sect. 2 and results are included in Sect. 3. A brief discussion and conclusion are presented in Sect. 4.

2 Data and Methods

2.1 Identifying extreme ASL events

We use Hosking's ASL climate index (Hosking et al. 2016) to obtain the date, location, and magnitude of monthly ASLs from January 1979 to December 2025. Indices are calculated from a minima-finding algorithm, which uses monthly data from the European Center for Medium-Range Weather Forecast (ECMWF) Reanalysis version 5 (ERA5) (Hersbach et al. 2020) to find the geographic location of the local pressure minima across the ASL region (60°-80°S, 62°W-170°E). ASL magnitude can be evaluated using two index parameters: actual central pressure (ACP) and relative central pressure (RCP). ACP is defined as the pressure at the location of the ASL while RCP is the regional anomaly that results by subtracting ACP from the area-averaged pressure over the ASL region. In this study, the magnitude of the ASL is measured using ACP to acknowledge and further analyze the influence of additional SH modes of atmospheric variability on the climatological ASL.

We identify instances in which the ASL is extremely strong or weak by first standardizing monthly ACP values to z-scores. Extreme ASL events are then defined as those months with ACP values two standard deviations (SDs) above (i.e. extremely weak) or below (i.e. extremely strong) a climatological, or fixed, mean. A fixed mean for the period 1979-2010 is implemented to account for the observed deepening of the ASL over the satellite era, which reflects a non-stationary polar climate.

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2.2 Parameterizing West Antarctic climate

Mean sea-level pressure (MSLP), 2-meter air temperature (T2M), and 10-meter zonal (U) and meridional (V) winds are retrieved from ERA5 reanalysis. Reanalyses combine observational data with forecasting models to provide a more complete picture of the global climate. Such datasets are useful when conducting analyses of remote locations like Antarctica, where in-situ observations are limited and unevenly distributed.

SIC data are utilized to detect changes in sea ice related to the dynamic and thermodynamic forcing of surface winds associated with the circulation around the center of the ASL. Monthly SIC values represent the fraction of sea ice present at each 25 km x 25 km grid cell and are obtained from the National Snow and Ice Data Center (NSIDC) Climate Data Record of Passive Microwave Sea Ice Concentration, version 5. Continuous sea ice records over the study period are available at https://nsidc.org/data/g02202/versions/5.

We produce monthly climatologies to represent average climatic conditions in West Antarctica and calculate anomalies during individual extreme ASL events using the climatology corresponding to the month in which the event occurs. Anomalies are then composited to broadly illustrate the impact of extreme ASL events on the study region. Since our work uses a single anomaly composite map to represent changes to the surface climate of West Antarctica, composite maps show averaged - and not the full range of - anomalies calculated during individual extreme ASL events. Our results and discussion sections therefore highlight averaged anomalies across all extreme ASL events; anomalies for individual events may at times be included for context but will be explicitly described as such. Additional details on individual extreme ASL events can be found in the section containing supplemental material.

Composite maps also include a contour indicating the position of the sea ice edge. The ice edge here is defined as the area where climatological SIC values are at least 15%. Sea ice climatologies are based on the three months in which extreme ASL events occur most frequently (e.g. extremely strong ASL events tend to develop in austral spring, so the ice edge for strong events is calculated based on the averaged SIC climatology for SON).

2.3 Interactions with additional SH MOVs

SAM values are obtained from a station-based index that uses integers to represent the zonal pressure gradient between SH middle (40°S) and high (65°S) latitudes (Marshall 2003). A positive value is associated with the positive polarity of SAM (SAM+), which suggests a strengthening and poleward shift of the westerlies. Negative values represent SAM's negative phase (SAM-), in which a general weakening of the westerly winds is observed. Indices date back to 1957 and are available at https://legacy.bas.ac.uk/met/gjma/sam.html.

ENSO phase is determined using values from the Southern Oscillation Index (SOI), which considers the pressure gradient between the eastern (i.e. Tahiti) and western sides of the tropical Pacific (Darwin, Australia). Positive values represent ENSO's cold phase (i.e. La Niña conditions) while negative values indicate the warm phase (i.e. El Niño

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conditions). SOI values are available through NOAA's National Centers for Environmental Information (NCEI): https://www.cpc.ncep.noaa.gov/data/indices/soi.

ZW3 is a zonally-asymmetric feature of the SH atmospheric circulation that contributes to the meridional transport of heat and momentum to high southern latitudes (Goyal et al. 2021, 2022; Raphael 2004, 2007). It originates due to zonal asymmetries in deep convection across the tropics, which promote the propagation of a Rossby wave train into the Pacific sector of the SO, and manifests as a structure with three pairs of alternating troughs and ridges (Goyal et al. 2021, 2022). Past research has demonstrated the significant impact of ZW3 on the Pacific sector of the SO (Raphael and Hobbs 2014). In this study, ZW3 values are calculated by extending the work of Raphael (2004) through the end of the study period. Indices are an average of the normalized 500-geopotential height anomaly at three fixed spatial locations that represent the three ridges comprising the ZW3 pattern. Positive ZW3 (ZW3+) values indicate stronger, more meridional conditions over the study region with greater poleward energy/heat transport towards West Antarctica. Negative ZW3 (ZW3-) values represent weakened meridional flow.

All climate indices are scaled between -1 and 1 to ensure comparability across MOVs. Using this range allows us to represent each MOV using a simple positive or negative integer that indicates the MOV's phase (i.e. integer sign) and magnitude (i.e. numerical value). A normalized SAM value of 0.9, for example, suggests strong SAM+ conditions.

2.4 Future projections of extreme ASL events throughout the 21st century

In addition to our historical analysis, we conduct a preliminary forecast of future ASL extremes using the Community Earth System Model version 2 (CESM2), a state-of-the-art global model that provides future simulations based on various socioeconomic development strategies, or Shared Socioeconomic Pathways (SSPs). Each SSP yields different radiative forcing by the end of the 21st century. In this study, we employ CESM2 given its fidelity in reproducing the basic structure of certain SH MOVs, specifically SAM, the leading MOV in the SH known to strongly modulate ASL variability (Simpson et al. 2020).

Surface atmospheric pressure conditions for the ASL region during the years 2015-2100 are calculated from a three-member ensemble average of output for both middle- (SSP245) and high-emission (SSP585) climate scenarios. Each scenario corresponds to a radiative forcing of 4.5 and 8.5 W m^{-2}, respectively. The position and magnitude of the ASL are obtained by using the minima-finding algorithm developed by Hosking et al. (2016). Future ASL extremes are then identified using the same process discussed in section 2.1 but with a fixed mean (1979-2010) calculated from the model's historical output.

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3 Results

3.1 Monthly ASL variability (1979-2025)

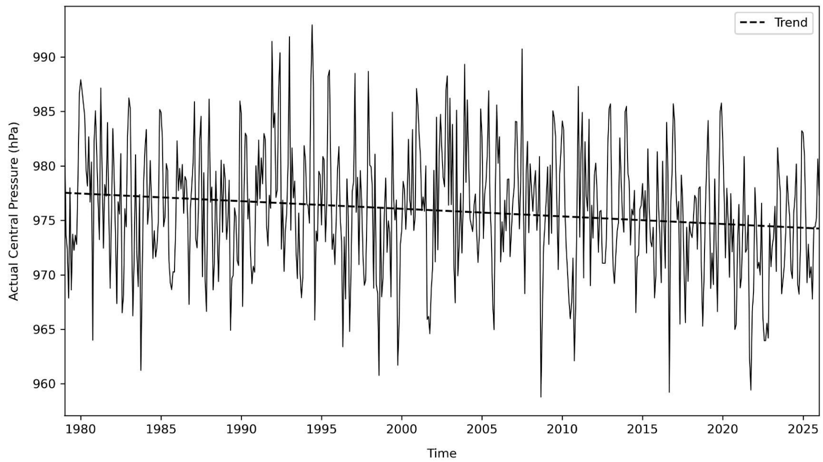

Figure 1: Timeseries of ASL ACP from January 1979 to December 2025. A statistically significant negative trend (dashed black line) is observed over the satellite period.

ASL magnitude demonstrates high interannual variability during the period 1979-2025 (Fig. 1). Monthly ACP values range from 958.79 - 992.94 hPa and exhibit a statistically significant negative trend ($r=-0.16$, $p<0.05$, black dashed line), suggesting a deepening of the ASL over the satellite era. These results are consistent with previous findings that have used both observations and reconstructions to show a strengthening of the ASL in the latter half of the twentieth century (Dalaiden et al. 2021; Raphael et al. 2016; Turner et al. 2013). A deeper ASL is believed to be the product of a stronger SAM+ since SAM+ conditions promote lower pressure over Antarctica (Clem and Fogt. 2013). In the near future, the deepening ASL trend confirmed here is projected to continue as both the regional ASL and large-scale SH MOVs respond to changes in stratospheric ozone and greenhouse gas (GHG) concentrations (Arblaster and Meehl 2006; Raphael et al. 2016).

3.2 Extreme ASL events

Among 564 monthly ASLs, we identify 13 extremely strong (blue) and 8 extremely weak (red) ASL events that exceed the fixed mean (976.5 hPa) by two SDs (Fig. 2). The dates and ACP values of extremely strong and weak ASL events can be found in Tables 1 and 2, respectively.

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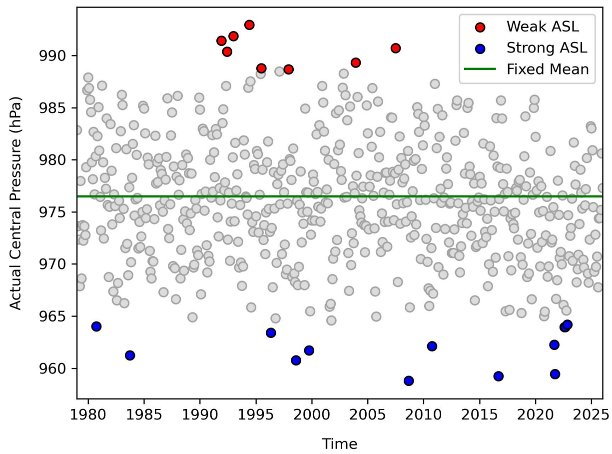

Figure 2: Scatterplot of monthly ASLs between 1979-2025. Thirteen extremely strong (blue) and eight extremely weak (red) ASL events were identified based on ACP, or the pressure value at the central location of the ASL.

Extremely Strong ASL Events

Date	*ACP (hPa)*
01 October 1980	964.01
01 October 1983	961.24
01 May 1996	963.39
01 August 1998	960.77
01 October 1999	961.71
01 September 2008	958.79
01 October 2010	962.11
01 September 2016	959.23
01 September 2021	962.24
01 October 2021	959.43
01 August 2022	963.97
01 September 2022	963.97
01 November 2022	964.19

Table 1: The date and magnitude of 13 extremely strong ASL events identified during the period 1979-2025.

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Extremely Weak ASL Events

Date	*ACP (hPa)*
01 December 1991	991.42
01 June 1992	990.38
01 January 1993	991.85
01 June 1994	992.94
01 July 1995	988.79
01 December 1997	988.68
01 December 2003	989.32
01 July 2007	990.73

Table 2: The date and magnitude of 8 extremely weak ASL events identified during the period 1979-2025.

Table 1 shows that a majority of extremely strong events (9 of 13) occur in September and October. Our results align with previous research that has found the ASL to be deepest in austral spring (Fogt et al. 2012). Specifically, the prevalence of extremely strong ASL events in the month of October (5/13) is in close agreement with the findings of Turner et al. (2013), whose investigation of the ASL during the years 1979-2008 found monthly ASL pressure values to be lowest in October. Across all extremely strong ASL events, the event with the deepest central pressure (958.79 hPa) is recorded in September 2008. Remaining strong events occur in May (1), August (2), and November (1).

In contrast to strong events, extremely weak ASL events are identified in the months of December (3), January (1), June (2), and July (2) (Table 2). This aligns with prior work, which found ASL pressure maxima in summer and winter (Fogt et al. 2012; Turner et al. 2013). Across all weak ASL events, ACP values above 988.68 hPa indicate shallow centers.

3.3 Temporal variability of extreme ASL events

Extremely strong ASL events are well distributed from a temporal perspective. They occur between October 1980 and November 2022. Particularly strong ASL events like the series of three recorded in late 2022 have previously been associated with SAM+ conditions (Lin et al. 2023). This link will be addressed at length in the following section that explores ASL variability in relation to additional SH MOVs such as SAM, ENSO, and ZW3 (Sect. 3.4).

Extremely weak ASL events, on the other hand, are temporally limited and occur strictly between the years 1991-2007. The weakest ASL event (992.94 hPa) was recorded in June 1994. Research by Holland et al. (2022) points to a period of significant anticyclonic wind anomalies across the West Antarctic Ice sheet (WAIS) during the 1990s, which aligns with the presence of extremely weak ASL conditions over the study region identified by our work. Since then, however,

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observed decreases in pressure over high southern latitudes have strengthened the ASL, and there has been no weak ASL event detected by this study in nearly twenty (20) years.

3.4 Spatial variability of extreme ASL events

The spatial distribution of extreme ASL events is shown in Fig. 3. Most prominent is the concentration of extremely strong ASL events (blue) in the vicinity of the Amundsen Sea. Here, strong ASL centers are found between 90.75-156.5°W. Meridionally, extremely strong ASL events tend to have centers located farther south and closer to the continental coastline. Our results are in close agreement with past work that noted a southward displacement of the ASL when the feature was at its greatest intensity (Fogt et al. 2012). Although strong events reach as far north as 69.5°S, their average latitude of occurrence is 71.05°S and reflects the inclusion of an anomalously strong ASL center along the coast of Marie Byrd Land (at 74.5°S). Results presented here therefore suggest that strong ASL events tend to concentrate across just five degrees (5°) of the ASL region in the meridional direction.

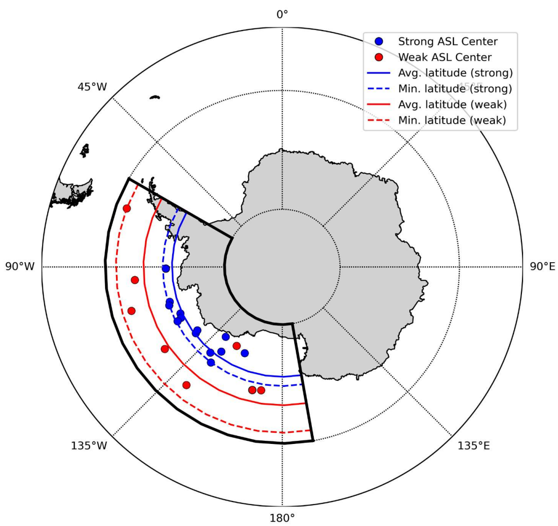

Figure 3: A map showing the spatial variability of extreme ASL events identified between 1979-2025. Extremely strong events (blue) tend to concentrate to the south while extremely weak events (red) are found farther north.

In contrast, extremely weak ASL events exhibit large spatial heterogeneity. In most cases, weak ASL centers (red) are located farther north across the study region, with one event positioned as far north as 61.75°S. Their average latitude of occurrence is 66.3°S, more than 4.7° north of the average latitude of extremely strong events. Our findings validate previous

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work that suggests a northward displacement of the ASL when positive pressure anomalies are present in the region (Fogt et al. 2012). However, we note the presence of an outlier, whose center is displaced far south near the coast of the Amundsen Sea (74.25°S).

We also investigate temporal shifts in the zonal position of extreme ASL centers (Fig. 4). Despite a small sample size (n=13), Fig. 4 shows a strong positive correlation (r=0.66, p<0.05, blue dashed line) between the central longitude and timing of extremely strong ASL events (blue). Such a correlation suggests that the central position of strong ASL events has shifted east in time, moving closer toward the AP. The zonal shift detected here is in line with reconstruction-based studies pointing to a broader eastward migration of the ASL since the 1950s (Dalaiden et al. 2021). Additional research suggests that the climatological location of the ASL will continue moving east in the near future, specifically in austral autumn (March-April-May, MAM) and winter (Hosking et al. 2016).

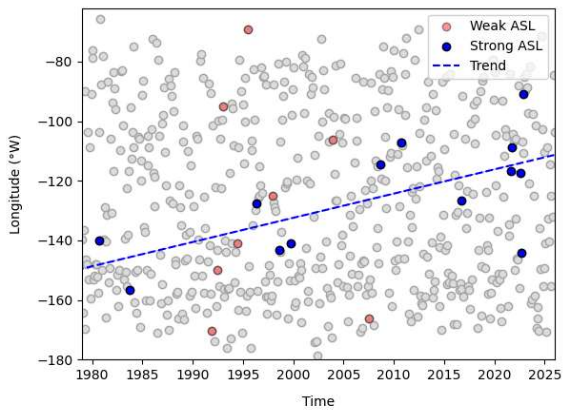

Figure 4: The relationship between the timing and zonal position (i.e. longitude) of extreme ASL events. An eastward shift is observed across extremely strong ASL events (blue) identified between 1979-2025. No shift is detected for weak events (transparent red).

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3.5 West Antarctic surface anomalies driven by extreme ASL events

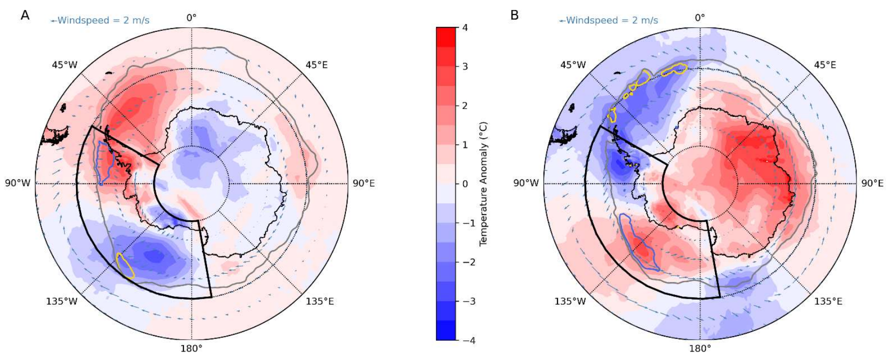

Figure 5: Anomaly composites of surface conditions during extremely strong (a) and weak (b) ASL events between 1979-2025. Anomalous winds are represented by vectors while ST and SIC anomalies are denoted using coloured shading and contours, respectively. A gray solid line indicates the climatological sea ice edge. A dipole of ST and SIC is found across the study region in both instances.

Anomaly composites illustrate the impact of extreme ASL events on the surface climate of West Antarctica between 1979-2025 (Fig. 5). During extremely strong ASL conditions, negative pressure anomalies (~12.75hPa lower than average) extend across the study region (not shown) and serve to enhance cyclonic rotation in the ASL region (Fig. 5a). The eastern flank of the ASL is characterized by north-northwesterly wind vectors that approach the AP/BS and even extend into the western edge of the Weddell Sea. Along its western flank, ASL-driven winds move offshore in a south-southwesterly direction and cover large swaths of the Ross and Amundsen Seas (hereinafter referred to as RS/AM) region. In general, anomalous winds associated with extremely strong ASL events depart from the climatological average by 3.06 m s^{-1}, although wind anomalies for individual events can reach up to 11.57 m s^{-1} (May 1996, Fig. S1c).

Across West Antarctica, anomalous winds are collocated with a dipole of T2M anomalies (shaded contours) that confirm the thermodynamic impact of extremely strong ASL events on the region. Temperature anomalies essentially separate the AP/BS and Weddell Sea from the RS/AM. In Fig. 5a, the eastern half of the study region is marked by positive T2M anomalies, which vary from the climatological average by as much as 3.25°C and are most pronounced over the coastal AP. Warmer temperatures are also observed across much of the Weddell Sea. Over the Ross Sea, however, we observe negative T2M anomalies associated with the equatorward advection of cold continental air. Relative to the warmer temperatures to the east, here we note cooler temperatures of -3.04°C. An eastern extension of cool air into the Amundsen Sea is also apparent and may reflect the interaction between the more regional southerly flow of the ASL and the broader westerly winds.

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In general, SIC anomalies align well with T2M anomalies observed during extremely strong ASL events (Fig. 5a). Decreases in SIC (blue contour) are found in the ASL region's warm sector while increases (yellow contour) are noted across areas that experience cooling. Though individual events suggest large SIC anomalies that deviate from monthly climatologies by as much as -91% and 76% (not shown), averaged SIC anomalies across all extremely strong ASL events range between -34% and 29%. Most apparent in our anomaly composite are SIC increases along the northern edge of the Ross Sea just west of 135°W (Figure 5a). It is possible that SIC increases are the product of a dynamic extension of sea ice northward along the seasonal ice edge (solid grey line). Note that increases along the ice edge can occur simultaneously with reductions across the interior associated with sea ice advection away from the continental coastline. To the west of the AP (east of 90°W), however, where surface warming is most prominent, we observe a reduced concentration of sea ice likely associated with the transport of relatively warm northerly air. Northerly flow can inhibit the expansion of Antarctic sea ice away and even induce early retreat, especially when the timing of retreat coincides with strengthened northerly winds. Past research has also linked ASL dynamics in spring to minimum sea ice area in the following summer (Wang et al. 2023). As is indicated by our analysis, a majority of extremely strong ASL events occur between September and October - months that mark the onset of the retreat season.

Surface anomalies observed during extremely weak ASL events are shown in Fig. 5b. Anticyclonic (i.e. counterclockwise) wind anomalies signal a weakening of the regional circulation associated with the climatological ASL. Weaker cyclonic winds are directly related to higher pressure conditions that on average surpass the monthly climatology by 13.87 hPa (not shown).

Figure 5b shows a dipole in surface temperature anomalies that closely follow the direction of anomalous winds during weak ASL events. However, the sign of the anomalies found on this composite is reversed, indicating warming over the RS/AM while the AP/BS experiences a general cooling. Temperatures in the warm sector increase by as much as 2.39°C while decreases of -3.52 °C are observed over parts of the AP/BS. Cooling is also noted in the Weddell Sea.

SIC anomalies are often spatially co-located with anomalous temperatures. Expansive reductions in sea ice SIC (yellow contour) are identified over the northernmost edge of the Amundsen Sea, with decreases of 44% centered around 135°W. In this part of the study region, negative SIC anomalies extend in the zonal direction and appear to reflect the dynamic forcing of zonal wind anomalies, which can redistribute ice from west to east. Positive SIC anomalies (30%) are found outside of the ASL region in the northern Weddell Sea, where yellow contours indicate a slight extension of sea ice to the north of the ice edge (east of 45°W). Minor increases in SIC are also identified along the AP's western coast in connection with southeasterly wind vectors moving away from the continent.

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3.6 Extreme ASL events in relation to additional SH MOVs

Extremely Strong ASL Events in relation to additional MOVs

Date	*ACP (hPa)*	*SAM*	*SOI*	*ZW3*
01 October 1980	964.01	0.18	0.11	0.2
01 October 1983	961.24	0.48	0.23	0.35
01 May 1996	963.39	0.45	0.2	0.30
01 August 1998	960.77	0.59	0.48	0.13
01 October 1999	961.69	0.71	0.42	0.55
01 September 2008	958.79	0.19	0.48	0.48
01 October 2010	962.11	0.68	0.63	0.17
01 September 2016	959.0	0.55	0.48	0.45
01 September 2021	962.24	0.41	0.35	-0.36
01 October 2021	959.43	0.25	0.32	0.29
01 August 2022	963.97	0.22	0.42	0.12
01 September 2022	963.97	0.51	0.6	0.16
01 November 2022	964.2	0.78	0.2	0.26

Table 3: Thirteen (13) extremely strong ASL events in relation to SAM, ENSO, and ZW3 indices.

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Extremely Weak ASL Events in relation to additional MOVs

Date	*ACP (hPa)*	*SAM*	*SOI*	*ZW3*
01 December 1991	991.42	-0.12	-0.45	0.1
01 June 1992	990.38	-0.47	-0.08	-0.12
01 January 1993	991.85	-0.29	-0.17	0.004
01 June 1994	992.94	-0.32	-0.02	0.2
01 July 1995	988.79	-0.68	0.23	-0.86
01 December 1997	988.68	-0.06	-0.2	0.08
01 December 2003	989.32	-0.02	0.45	0.09
01 July 2007	990.73	-0.39	0.02	0.34

Table 4: Eight (8) extremely weak ASL events in relation to SAM, ENSO, and ZW3 indices.

As a regional circulation feature, the ASL can develop independently or in conjunction with additional modes of atmospheric variability. Given this, our work considers the atmospheric background conditions that contribute to the development of ASL extremes. Figure 6 shows the central pressure value of extremely strong ASL events in relation to standardized indices representing the various phases of SAM, ENSO, and ZW3. Positive (negative) index values represent the positive (negative) polarity of each MOV.

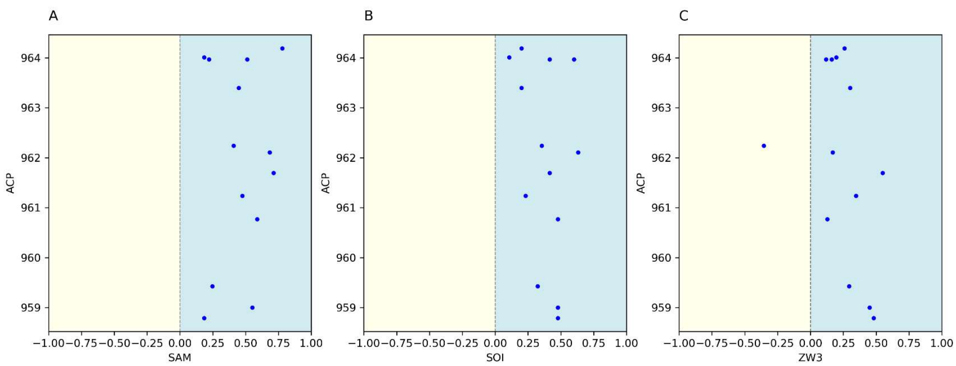

Figure 6: The ACP value of extremely strong ASL events in relation to SAM (a), ENSO (b), and ZW3 (c). In nearly all cases, extremely strong events coincide with an MOV’s positive phase.

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Our results indicate a clear relationship between lower ACP values and the positive phase of all three MOVs, thus suggesting that extremely strong ASL events tend to develop when SAM, ENSO, and ZW3 are in their positive phase (Figure 6). With the exception of one event (c. September 2021), all extremely strong ASL events occur in the context of SAM+, La Niña, and ZW3+ conditions.

The close alignment between extremely strong ASL events and the three MOVs may be associated with negative pressure anomalies that set over the ASL region when the MOVs experience positive polarity. Indeed, SAM+ and La Niña conditions have previously been shown to produce a deeper ASL via negative pressure anomalies, which deepen the climatological feature (Fogt et al. 2011; Hosking et al. 2013). Here we include ZW3 as an additional mode of variability with the potential to modulate ASL magnitude. Through our analysis, we find 12 of 13 extremely strong ASL events to coincide with ZW3+. It is possible that both the magnitude and position (i.e. phase) of ZW3 contribute to a regional intensification of the ASL. More specifically, we surmise that the ASL may interact with one of the three low-pressure troughs that comprise ZW3 to produce extremely strong ASL conditions. However, our results are preliminary, and further research is required to confirm this.

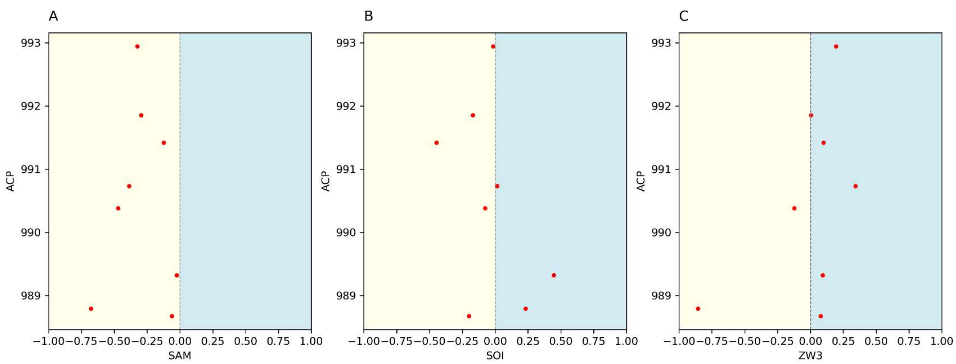

Figure 7: The ACP value of extremely weak ASL events in relation to SAM (a), ENSO (b), and ZW3 (c). All weak events occur under SAM- conditions, but their relationship to ENSO and ZW3 is less clear.

In general, there is less agreement between extremely weak ASL events and MOV phase. As seen in Fig. 7a, all extremely weak events develop in relation to SAM- conditions, which is expected since SAM- establishes positive pressure anomalies over the Antarctic that can ultimately weaken ASL depth. In relation to ENSO, extremely weak ASL events span a range of positive and negative SOI values of weak to moderate strength (Fig. 7b). This implies that weak ASL events have historically developed irrespective of ENSO phase, contrary to their apparent relationship with the polarity of the SAM.

Figure 7c shows 6 of 8 extremely weak events that coincide with slight to moderately positive ZW3 conditions. It is plausible for an extremely weak ASL event to develop under such conditions since both features are asymmetric, and since the phase of the former does not cancel out the meridional structure of the latter. Indeed, we have shown in our results that a weakening of the climatological ASL does not lead to a complete cessation of meridional exchanges.

Eabry et al. (2024) recently examined the interaction between SAM and ZW3 and found that a particular SAM state does not prefer a particular ENSO state. However, they maintain that during the negative phase of SAM, meridional wind anomalies associated with ZW3 have a stronger and more poleward impact on Antarctic sea ice, specifically along the ice edge. Our results for weak ASL events in Sect. 3.3 are consistent with these findings and show strong meridional heat transport to higher latitudes with a negative sea-ice response concentrated over the Amundsen Sea (~135°W). A reduction in sea ice aligns with those areas over the SO where increases in surface temperature are greatest (Fig. 5b). It is therefore possible that ZW3 plays an important albeit secondary role in ASL-driven anomalies across West Antarctica.

3.7 Future ASL variability and extreme events through 2100

Given the observed ASL deepening over the historical period, our study also includes an assessment of future changes to ASL variability using model output based on "middle-of-the-road" (SSP245) and "fossil-fueled development" (SSP585) climate scenarios. In this section, we explore possible trends in ASL extremes through the end of the 21st century under global warming.

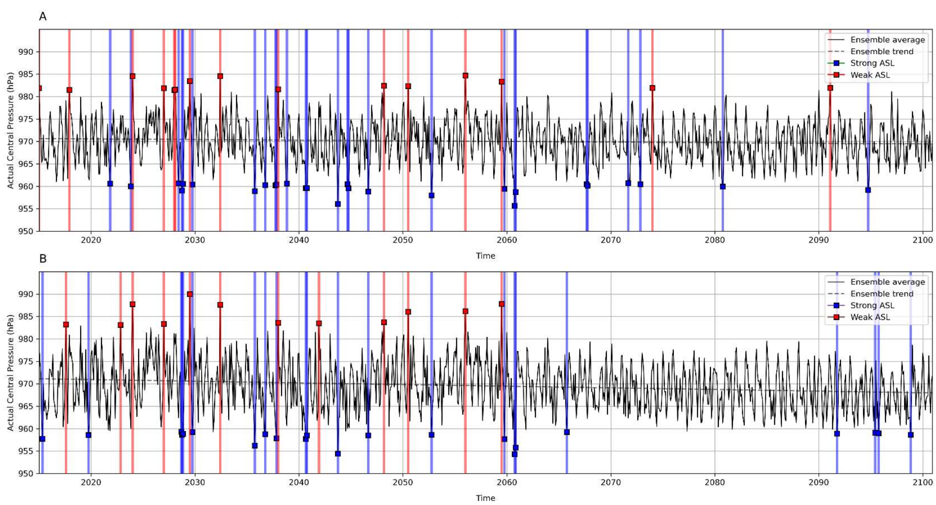

Figure 8: Timeseries of projected extreme ASL events through 2100 under "middle-of-the-road" (a) and "fossil-fueled development" (b). Both climate scenarios indicate a disproportionate number of strong ASL events (blue) when compared to weak ASL events (red).

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Output from both climate scenarios indicate a large proportion of extremely strong ASL events relative to weak events. This suggests a continuation of enhanced meridional heat exchanges and surface changes across West Antarctica in the near future (Fig. 8). The ensemble average under SSP245 shows twenty-seven (27) extremely strong and fifteen (15) extremely weak ASL events developing through 2100. Extreme events in this scenario occur in the context of a slight negative trend, which suggests a reduction in regional pressure (r=-0.07, p-value<0.05) (Fig. 8a). Under SSP585 conditions, we identify twenty-two (22) extremely strong and twelve (12) extremely weak ASL events (Fig. 8b). We note a negative pressure trend (r=-0.16) that is statistically significant (p-value<0.05) and more than two times stronger than the trend calculated for SSP245. ASL depth appears to be less variable in the second half of the future study period when compared to the first.

The temporal distribution of future ASL extremes differs considerably between the two climate scenarios. Under SSP245, extremely strong and weak ASL events are present through much of the study period. Although there are periods (~10-15 years) of paucity where extremely weak events cease to occur, extremely strong events persist and extend through 2094. After the early 2070s, the frequency of both extremes appears to drop considerably, with extremely strong and weak ASL events alternating in a sporadic manner.

The ensemble average for SSP585 displays a similar distribution of ASL extremes - one in which both extremely strong and weak ASL events are present - until ~2060 (Fig. 8b). Although we identify a few strong ASL events in the years that follow, after 2065, we identify an extended period of inactivity that extends for nearly twenty-five (25) years; pressure in the ASL region appears to deepen considerably during this time. Such a period is then brought to an end by four (4) extremely strong ASL events (between 2091-2098) that mark the final decade of the study period.

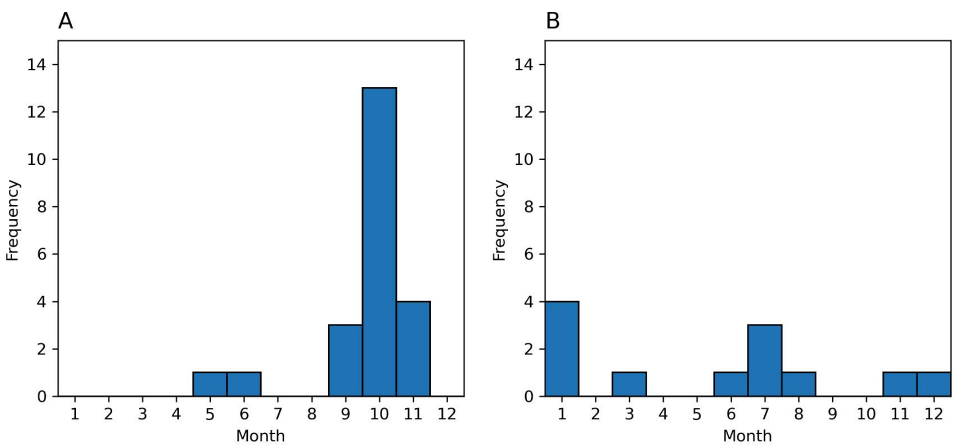

Figure 9: Histograms showing the monthly distribution of extremely strong (a) and weak (b) ASL events under future SSP585 conditions. Extremely strong events (left) show agreement with observation trends over the historical period

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1979-2025.

The seasonal distribution of projected ASL extremes aligns well with observed trends over the satellite period (Figs. 9, 10). Projections for the SSP585 future scenario suggest extremely strong ASL events are more likely to occur in SON, which coincides with the intensification of the ASL in spring (Fig. 9a). As with our results for the historical period 1979-2025, SSP585 output locates October as the month in which extremely strong ASL events are most likely to develop (13/22, or 59%). Placed in the context of previous research, our results are reason for concern since a negative correlation has been found between sea ice and ASL variations in October (Holland et al. 2018). In short, ASL-driven wind anomalies during this month can lead to earlier melting or thinning of regional sea ice, thus allowing for the oceanic absorption of heat that delays ice growth in the subsequent fall (Holland et al. 2017, 2018). However, we note that some strong ASL events are projected to develop earlier in the year (i.e. during the months of May and June) when the ice is still advancing. If strengthened northerly/southerly winds coincide with the timing of ice advance, strong ASL events occurring earlier in the year could potentially affect sea ice coverage in the ASL region, ultimately influencing total Antarctic sea ice area and extent. This is especially true if we consider the meridional location of strong ASL events, which tend to be located farther south, seeing as a more southerly ASL has previously been linked to larger ice concentrations during the advance season (Raphael et al. 2019). Extremely weak ASL events are less organized by month but show a seasonal preference in winter (5/12) and summer (5/12). Such results align with our observational findings presented in Sect. 3.2.

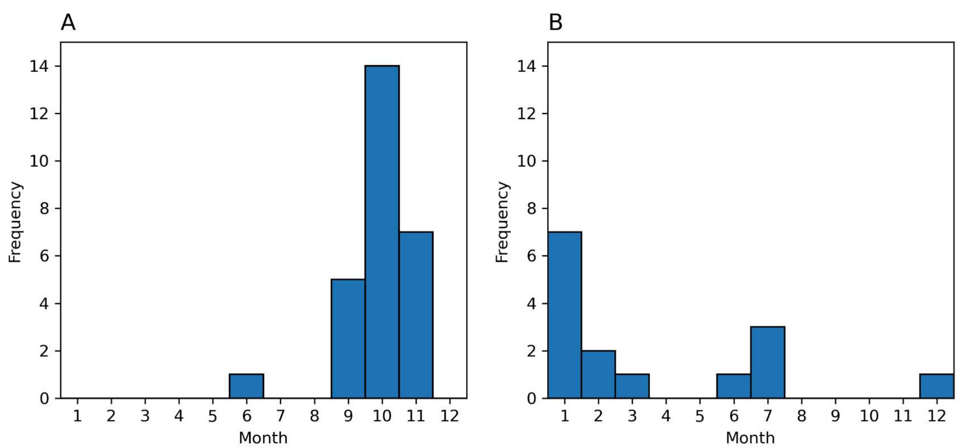

Figure 10: Histograms showing the monthly distribution of extremely strong (a) and weak (b) ASL events under future SSP245 conditions. Extremely strong events show strong agreement with observation trends that indicate a clear preference for spring months (left). Weak ASL events occur both in winter and summer (right).

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Extreme ASL events under SSP245 exhibit a much clearer seasonality relative to SSP585 in that a larger number of extremely strong ASL events develop during the spring months (Fig. 9a). These results are again consistent with the behavior of extremely strong ASL events over the historical period (1979-2025). Similar to SSP585, extremely weak events are present in the summer and winter seasons.

4 Discussion and conclusion

Our study investigates the frequency of extreme ASL events over West Antarctica while also quantifying their impact on the surface climate during the period 1979-2025. In total, we identify 13 extremely strong and 8 extremely weak ASL events with anomalously deep/shallow central pressure values. A spatial analysis of their distribution finds the location of extreme ASL centers to vary based on the sign of the event. In general, extremely strong events tend to be located southward and closer to the Antarctic coastline while weak ASL events tend to have centers located farther north. The meridional position of extreme ASL events is important to note since the spatial variability of the ASL has been shown to influence the state of sea ice during retreat and advance seasons (Raphael et al. 2019). An additional characteristic considered here is ASL longitude, which modulates the relative position of northerly/southerly winds around the low. Our work demonstrates that extremely strong ASL centers tend to concentrate over the Amundsen Sea sector (90.75-156.5°W) while weak events are less uniform and more spatially spread across the ASL region.

Composite maps of surface anomalies suggest that changes in atmospheric circulation during extreme ASL months plays an important role in controlling West Antarctic climatic variables such as surface temperature and sea ice. We find enhanced cyclonic (anticyclonic) wind anomalies during particularly strong (weak) ASL events, which coincide with a dipole of temperature anomalies across the ASL region. During extremely strong (weak) ASL events, surface cooling is observed over the RS/AM region while warming (cooling) is noted over the AP/BS. Given the dynamic and thermodynamic response of sea ice to near-surface winds, increases (decreases) in SIC accompany negative (positive) temperature anomalies. In both composites, increases in SIC are noted near the seasonal ice edge, highlighting the dynamic impact of ASL-driven winds on seasonal sea ice. A future increase in the frequency of extremely strong ASL events would therefore lead to further warming of the AP/BS region and cooling over the RS/AM region.

Since the ASL is modulated by large-scale modes of atmospheric variability, we analyze the occurrence of extreme ASL events in relation to SAM, ENSO, and ZW3. In nearly all cases (12/13), extremely strong ASL events coincide with the positive phase of each MOV. In addition, extremely strong events occur when the three MOVs develop simultaneously, or when they are in-phase. Our work confirms previous findings connecting SAM+ and La Niña to the intensification of the ASL (Stammerjohn et al. 2008). However, our study is the first to consider a possible link between ASL magnitude and ZW3 phase. Results suggest a link between stronger-than-average ASL events and ZW3+ in the presence of SAM+ and La Niña conditions. Although we surmise that the three MOVs reinforce, or compound, negative pressure anomalies in the ASL region, therefore enhancing the depth of the ASL, additional research is required to explain the ASL and ZW3+ connection.

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Such efforts are particularly relevant given recent work by Trivedi et al. (2026), which highlights the dynamic impact of ZW3 on sea ice thickness and suggests a doubling of extreme ZW3 events under high-emission climate scenarios. This shift to more extreme ZW3 conditions will be accompanied by a projected strengthening of the positive polarity and variability of SAM (Goyal et al. 2021; Ma et al. 2026).

There is less agreement among MOVs during extremely weak ASL events. All weak events develop during the negative polarity of SAM, a result which reinforces the strong influence of SAM on the ASL, and a majority of weak events coincide with ZW3+ conditions. However, a clear link between the occurrence of extremely weak ASLs and ENSO is lacking.

Our investigation of ASL extremes through the end of the 21st century using CESM2 projections for middle- and high-emission climate scenarios shows statistically significant negative pressure trends and indicates a larger proportion of extremely strong ASL events relative to weak events. The frequency of occurrence of extremely weak ASLs is significantly reduced in the later part of the 21st century (post-2060) under SSP585 conditions, suggesting enhanced meridional exchanges of heat and momentum across West Antarctica if fossil-fueled development is pursued.

At sub-annual timescales, the seasonality of projected extreme ASL events is reminiscent of historical trends across both climate scenarios, with extremely strong events occurring most often in austral spring. Under the high-emission scenario, however, extremely strong ASL events are present earlier in the year at a time when sea ice is advancing equatorward. A shift to stronger and more frequent ASL events during the advance season could have significant implications for the state of regional and circumpolar sea ice across Antarctica, with northerly flow inhibiting the dynamic extension of sea ice to the north at zero lag. Previous work has also demonstrated that sea ice can exhibit a lagged response to ASL variations, suggesting that ASL-driven anomalies can persist and affect sea ice conditions for months (Holland et al. 2018). In terms of extremely weak ASL events, future projections suggest they will maintain current seasonal behaviors and develop in the winter/summer months.

Previous work has established the prominent role of the ASL in driving climate variability across West Antarctica. Our study adds to existing literature by quantifying the impact that extremes ASLs have on the region's temperature and sea ice. Through our work, we show that the ASL's historical trend since the 1950s - a deepening - has continued to the present day. Using model output for two possible future climate scenarios, we forecast a persistent strengthening of the ASL and an increased frequency in the occurrence of extremely strong ASL events. Our results suggest enhanced springtime warming across the eastern domain of the ASL region, including the Weddell Sea, and cooling across the western domain through the end of the century. Since air temperature and sea ice are closely related, temperature anomalies imply possible sea ice reductions (increases) across the AP/BS (RS/AM) region. At a time when the Antarctic region continues to exhibit rapid warming and the sea ice system dramatic variability - often attributed to changes in the state of the ocean - our work demonstrates how a regional atmospheric feature such as the ASL can continue to contribute to surface changes across West Antarctica.

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While the historical and projected deepening of the ASL may be associated with variations in circulation produced by anthropogenic activities, it is necessary to properly distill external forcing from internal variability to properly account for the role of each. The implications of such improvements would be significant for future global modeling efforts. Future studies should aim to build a more comprehensive understanding of this and other components of the climatological ASL, which we have shown here to significantly influence the surface climate of West Antarctica.

Code and data availability

The ASL Climate Index is available from Scott Hosking's GitHub repository: https://github.com/scotthosking/amundsen-sea-low-index (Hosking et al. 2016). ERA5 reanalysis data are available from the Copernicus Climate Data Store: https://doi.org/10.24381/cds.f17050d7 (Hersbach et al. 2018). To access CMIP6 output, including the CESM2 model runs used here to analyze future climate scenarios, you can visit: https://metagrid.esgf-west.org

Supplement link

The link to the supplement will be included by Copernicus, if applicable.

Author contributions

MDL led the data analysis and writing. MNR assisted in data analysis and writing. CN and FP contributed revisions to the written manuscript.

Competing interests

The authors declare no competing interests relevant to this study.

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The review statement will be added by Copernicus Publications listing the handling editor as well as all contributing referees according to their status anonymous or identified.

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