Article Title: The Southern Annular Mode: Variability, Trends, and Climate Impacts across the Southern Hemisphere

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Abstract

The Southern Annular Mode (SAM) is the leading mode of extratropical Southern Hemisphere climate variability, associated with changes in the strength and position of the polar jet around Antarctica. This variability in the polar jet drives large fluctuations in the Southern Hemisphere climate, from the lower stratosphere into the troposphere, and stretching from the midlatitudes across the Southern Ocean to Antarctica. Notably, the SAM index has displayed marked positive trends in the austral summer season (stronger and poleward shifted westerlies), associated with stratospheric ozone loss. Historical reconstructions demonstrate that these recent positive SAM index values are unprecedented in the last millennia, and fall outside the range of natural climate variability. Despite these advances in the understanding of the SAM behaviour, several areas of active research are identified that highlight gaps in our present knowledge.
Caption. The Southern Annular Mode has displayed an unprecedented positive polarity in the last several decades, with implications for climate across the entire extratropical Southern Hemisphere.
1. INTRODUCTION

The Southern Annular Mode (SAM) is the leading mode of climate variability across the extratropical Southern Hemisphere (SH) (Rogers & van Loon, 1982; Thompson & Wallace, 2000), and serves as a primary pathway through which Antarctic climate responds to changes in the SH mid-latitudes and tropical variability. Due to the major influence of the SAM on the climate in the SH mid- and high-latitudes, and its robust response to stratospheric ozone depletion over Antarctica, research on this important climate mode has increased dramatically over the last several decades.

This review summarizes key aspects of the scientific literature over the last several decades on drivers of SAM variability, its climate impacts across the SH, and changes in the SAM, with a particular focus on the atmosphere; only connections to sea ice will be discussed for the cryosphere, and we only briefly describe connections of the SAM with the Southern Ocean. Rather than focus on a single season (austral summer) as done in other reviews (Thompson et al., 2011), here we attempt to summarize the SAM signal associated with different temporal resolutions. Furthermore, as research has started to investigate the SAM variability prior to the IGY (International Geophysical Year), through reconstructions, the review also discusses possible historical aspects of SAM variability in the early 20th century and prior. Knowledge gaps and areas of future research are interwoven throughout, since although scientific understanding has increased over the last several decades, these discoveries often lead to other questions yet to be addressed, especially regarding the future behaviour of the SAM and its role in SH climate change.

2. SAM DEFINITIONS AND CHARACTERISTICS

The Southern Annular Mode (SAM), sometimes also referred to as the Antarctic Oscillation (AAO), is a large-scale mode of climate variability, spanning the entire extratropical Southern Hemisphere. Compared to many other modes of climate variability, research on the SAM is relatively new, with the earliest studies discussing the SAM dating back to the late 1970s and early 1980s (Rogers & van Loon, 1982; Trenberth, 1979, 1981). This is perhaps tied to SH observations: direct meteorological / climate observations in the SH extratropics are both sparse — due to the relatively poorly sampled Southern Ocean dominating the SH extratropics, together with the remoteness of Antarctica — and short in length. Most meteorological stations didn’t begin measurements until the IGY in 1957-1958 (J. M. Jones et al., 2016). Furthermore, one of the challenges in understanding SAM variability is the fact that reliable gridded climate datasets over southern high-latitudes only began at the same time as the ozone hole appeared so they are unable to portray natural SAM variability. In combination with the region’s especially large natural climate variability, this has posed an additional challenge in understanding how the SAM behaves across a variety of timescales.

Fundamentally, the SAM is an internal mode of climate variability (Thompson & Wallace, 2000), implying this pattern operates naturally, although, as will be shown later, its intensity or polarity can change in response to external forcing such as Antarctic stratospheric ozone depletion and greenhouse gas increases. As mentioned in the introduction, the SAM appears as the leading mode of extratropical climate variability in the Southern Hemisphere, represented here in Fig. 1 for monthly and annual mean data using the first empirical orthogonal function (EOF) of mid-tropospheric detrended, area weighted 500 hPa geopotential height (20°-90°S) during 1979-2018. Figure 2 provides seasonal EOFs calculated in the same fashion as Fig. 1. The word annular, meaning
‘ring-shaped’ or approximately circular, describes the overall structure of the SAM when viewed from above the South Pole. The SAM is approximately zonally symmetric, although its structure / shape changes on various timescales (Fogt & Bromwich, 2006; Rogers & van Loon, 1982), as evidenced when comparing the various panels in Figs. 1-2, yet it still remains the leading SH mode of variability outside the tropics on daily (Mark P. Baldwin, 2001) to decadal timescales (Kidson, 1999). The decorrelation time (persistence) of the SAM is approximately ten days (Robinson, 2000), which makes it challenging to predict its behaviour beyond two weeks, although seasonal to interannual predictions are potentially possible due to connections with the stratosphere (M. P. Baldwin et al., 2003; Byrne et al., 2019; E.-P. Lim et al., 2018), potential connections with tropical variability (L’Heureux & Thompson, 2006) and sensitivity to external forcing (Miller et al., 2006). Further, the overall structure of opposite geopotential height or pressure anomalies across Antarctica / poleward of 60°S and in the SH midlatitudes remains across various timescales (L’Heureux and Thompson 2006; Fogt and Bromwich 2006; Fogt et al. 2011; Clem and Fogt 2013).

Figure 1. Leading EOF of ERA5 (the fifth global reanalysis produced by the European Centre for Medium-Range Weather Forecasts, ECMWF) (Hersbach et al., 2019) 500 hPa geopotential height based on a) monthly and b) annual mean data during 1979-2018. The EOFs are based on detrended weighted (by cosine of latitude) 500 hPa geopotential height anomaly data from 20°-90°S and are shown here as regression maps of the leading PC time series on the time-varying height anomalies (contour interval 10m / std dev of PC timeseries). The percentage of explained variance and corresponding standardized PC timeseries / SAM index is also given in each panel.
From Figs. 1-2, the SAM explains between 22% - 34% of the variability in the extratropical Southern Hemisphere atmospheric circulation (Kidson, 1988, 1999; Rogers & van Loon, 1982). In terms of its spatial pattern, Figs. 1-2 indicate the SAM structure is much more zonally symmetric on monthly and annual mean data, as well as in the austral summer (December – February, DJF, Fig. 2a) (Fogt, Jones, et al., 2012; J. M. Jones et al., 2009; J. Kidston et al., 2009; Rogers & van Loon, 1982). In austral autumn and winter, the height anomalies over Antarctica extend the furthest equatorward in the eastern Pacific Ocean sector. These seasonal changes in the spatial structure of the SAM are strongly tied to the dynamics that modify the SH polar jet (Section 3.1) (Hall & Visbeck, 2002; Limpasuvan & Hartmann, 2000), including connections to tropical variability (L’Heureux & Thompson, 2006) (Section 3.3).

There are three primary methods of creating an index to monitor temporal SAM variability: (i) the first principal component of mean sea level pressure (MSLP) or lower-tropospheric SH extratropical geopotential height from gridded datasets like atmospheric reanalyses (as represented by the EOFs in Fig. 1) (Fogt & Bromwich, 2006; Mo, 2000; Rogers & van Loon, 1982; Thompson & Wallace, 2000); (ii) the difference of standardized zonal mean pressure between 40°S and 65°S, also from gridded data (D. Gong & Wang, 1999); or (iii) like the latter, but based on pressure observations that are approximately located at 40°S and 65°S (G. J. Marshall, 2003). The latitudes 40°S and 65°S were suggested by Gong and Wang (1999) as they show the strongest anticorrelation in pressure, therefore best representing the opposite-signed anomalies between the SH middle and high latitudes characteristic of the SAM pattern (Fig. 1). A particular benefit of the observational-based index of Marshall (2003) is that it avoids concerns about changes in the quality of gridded reanalyses products across the SH and especially near Antarctica, both within the early 20th century (Schneider & Fogt, 2018) and around 1979 due to the vast quantity of data assimilated over the Southern Ocean from satellites after this time (Bracegirdle & Marshall, 2012; Bromwich et al., 2007; Bromwich & Fogt, 2004; Fogt et al., 2018; Hines et al., 2000). However, since it is based on the location of observations which are not geographically evenly distributed across both 40°S and 65°S, the Marshall (2003) SAM index may not fully capture the extent of its spatial variability or connections to the eddy-driven polar front jet. All indices are constructed to be consistent with the spatial pattern implied in Fig. 1; the positive SAM polarity (or phase) is therefore characterized with lower pressures / geopotential heights over Antarctica (65°S) and higher pressures / geopotential heights in the SH midlatitudes (40°S) (D. Gong & Wang, 1999; G. J. Marshall, 2003; Thompson & Wallace, 2000).

Figure 2 displays the seasonal means of the three main types of SAM indices, with the principal component and Gong and Wang (1999) indices based on 500 hPa geopotential height anomalies and MSLP data from ERA5, respectively. The correlations with the Marshall (2003) index are given in each panel. Several studies have examined the relationship between the various SAM indices, and the correlations presented in Fig. 2 are generally consistent with these studies, demonstrating a high similarity between the indices after 1979, with correlations near 0.85 or higher in all seasons (Barrucand et al., 2018; M. Ho et al., 2012; J. M. Jones et al., 2009). Further, Figs. 2a-b indicate that significant (p<0.05) positive SAM trends since 1979 are observed in austral summer and autumn in most, if not all, indices (discussed further in Section 5). The degree of similarity prior to 1979 is lower between various SAM indices (and reconstructions), partly due to different types and locations of data used in the longer-term estimates of the SAM (M. Ho et al., 2012; J. M. Jones et al., 2009). The stronger correlations in summer reflect the higher zonal symmetry in the SAM spatial structure in this season (Fogt, Jones, et al., 2012), while the lower correlations between the PC1 and Marshall
(2003) in spring reflect the more zonally asymmetric structure of EOF1 in this season (Fogt & Bromwich, 2006), which is not fully captured by the station locations used in the Marshall (2003) index (Figs. 1, 2). There is not a consensus on which SAM index is the ‘best’, as this depends on how the SAM index is to be used, but M. Ho et al. (2012) noted that prior to 1979 different SAM indices can give opposite-signed climate relationships in some regions.

Recently, other specific estimates of SAM behavior have also been analyzed. In particular, the varying degrees of symmetry in the SAM structure, related to changes in the seasonal cycle of the polar jet and underlying eddy activity in the SH, were discussed using a SAM index that highlights the asymmetrical behavior of the SAM (Fogt, Jones, et al., 2012). Importantly, the asymmetric nature is also strongly related to tropical variability and the zonal wavenumber 3 pattern across the extratropical SH (Fogt, Jones, et al., 2012).

Figure 2. Seasonal mean EOFs calculated as in Fig. 1 and the corresponding standardized seasonal mean PC and other SAM index timeseries. The percentage of variance explained for each EOF is given in the upper right of each EOF spatial plot. Each timeseries was standardized over its full length (1957-2018 for Marshall (2003) index, 1979-2018 for all others, and regression lines over the full period are also shown (thin lines). The correlation between the Marshall (2003) SAM index with the other indices is provided at the top of each panel as well as the trends and 95% confidence intervals during 1979-2018 (units of standardized SAM index per decade) at the bottom of each panel.
3. CAUSES OF SAM VARIABILITY

The opposing pressure and height anomalies between the mid and high latitudes of the SH in the SAM structure (Figs. 1,2) implies the SAM fundamentally represents changes in the meridional pressure gradient across the middle latitudes of the Southern Hemisphere, and the associated meridional location and intensity changes in the polar front jet encircling Antarctica (Gallego et al., 2005; Neil C. Swart et al., 2015; Thompson & Wallace, 2000). As such, variability in the SAM, represented by the timeseries in Figs. 1 and 2, stems from changes in the extratropical atmospheric circulation from the surface up through the stratosphere. Furthermore, since the intensity and location of the polar jet is also influenced by tropical sea surface temperature (SST) variability, the SAM shares connections with the El Niño-Southern Oscillation (ENSO) and other patterns of tropical variability (Clem & Fogt, 2013; Ding et al., 2011, 2012; Fogt et al., 2011; Fogt & Bromwich, 2006; L’Heureux & Thompson, 2006; Wilson et al., 2016).

3.1 Connections with the polar jet

The generalized picture of the relationship between SAM and the zonal jets (both polar and subtropical) is provided in Fig. 3. Climatologically, in austral winter, a strong tropospheric subtropical jet near 30°S is observed in the SH zonal mean zonal winds, as well as a stratospheric vortex above 100 hPa at 60°S (Fig. 3a, right), which is in contrast to a broader and weaker polar jet near 50°S in summer (Fig. 3a, left) (Bals-Elsholz et al., 2001). During the positive polarity of the SAM, positive zonal wind anomalies occur on the poleward side of the tropospheric jet near 60°S, indicating a strengthening and poleward shifting of the polar jet (Fig. 3b, left) (Kidson & Sinclair, 1995). Across all months, the greatest anomalies appear near in the upper troposphere (400 hPa – 100 hPa), but can extend upwards through the lower stratosphere, as discussed in the following section. The anomalies are opposite in the negative SAM polarity (Fig. 3b, right), representing a weakening of the zonal westerly flow (or potentially, a more meridional structure to the jet), with an equatorward shift (Hartmann & Lo, 1998; Kidson & Sinclair, 1995). Associated with these changes in the strength and intensity of the polar jet are changes in the atmospheric zonal mean temperature (shading in Fig. 3b), which are partly due to adiabatic responses in the mean meridional circulation (Thompson & Wallace, 2000). In the positive SAM polarity, upward vertical motion and adiabatic cooling in the troposphere occur on the poleward side of the polar jet, and subsidence and adiabatic warming occur in the troposphere on the equatorward side of the polar jet (these temperature anomalies are opposite in the negative SAM polarity, Fig. 3b, right).
Figure 3. a) ERA5 Zonal mean zonal wind seasonal climatology for austral summer (left column) and winter (right column), contour interval is 5 m/s, with approximate locations of the polar front jet (PFJ) and the subtropical jet (STJ) indicated. b) ERA5 Zonal mean monthly anomaly composites for SAM + (left column) and SAM – (right column) for zonal wind (contoured) and temperature (shaded). The stippling indicates zonal wind anomalies statistically different from zero at $p<0.05$ while only temperature anomalies significantly different from zero at $p<0.05$ are shown. Composites are based on months that are outside of 0.75 standard deviations from the 1979-2018 mean, and the distribution of the months for each composite is given in the histograms in c). The pronounced zonal wind anomalies at 60°S show the stronger SAM impacts on the PFJ than on the STJ.

Fundamentally, the changes in the polar jet characterized by the SAM represent differences in the eddy momentum flux convergence (Hartmann & Lo, 1998; Limpasuvan & Hartmann, 1999, 2000; Robinson, 2000), and the strength of the mean meridional circulation, including the Ferrel and Hadley Cells (Hartmann & Lo, 1998; L’Heureux & Thompson, 2006; Polvani, Waugh, et al., 2011; Thompson & Wallace, 2000). Because eddy activity is generally unconfined by large continental barriers in the high southern latitudes, the role of transient eddy momentum flux convergence, typically from traveling cyclones, dominates in the SH polar jet (Karoly, 1990; Oort & Peixóto, 1983; Peixoto & Oort, 1992) rather than the more spatially persistent stationary eddies that are associated with atmospheric standing waves in the Northern Hemisphere. In terms of the polar jet, this implies that the poleward eddy momentum flux contributions to the jet are approximately the same across
all longitudes (Gerber & Thompson, 2017; Hall & Visbeck, 2002; Hartmann & Lo, 1998; Karoly, 1990),
giving rise to the nearly zonally symmetric structure present in the SAM, especially in summer (Fig.
2a). Even in the summer, negative planetary wave momentum flux feedbacks can be associated with
zonal asymmetries (Isla R. Simpson, Shepherd, et al., 2013), while contributions from other patterns
of atmospheric variability (Fogt, Jones, et al., 2012) may give rise to the more asymmetric structure
seen outside of austral summer (Figs. 2b-d). A positive feedback exists between the mean flow (the
polar jet) and the strength of these transient momentum fluxes into the polar jet, in such a way that
stronger eddies (and their convergence) result in a stronger westerly flow (Barnes & Hartmann,
2010; Gerber & Thompson, 2017; Hall & Visbeck, 2002; Lorenz & Hartmann, 2001; Isla R. Simpson,
Shepherd, et al., 2013; Trenberth, 1986, 1991) and therefore a more positive SAM. However, it is
noted that at least one study questions the role of this positive eddy feedback mechanism (Byrne et
al., 2016).

3.2 Connections with the stratosphere

While the SAM exists year-round in the troposphere, Fig. 3b shows that significant zonal wind
anomalies can also exist in the stratosphere. However the connection to the stratospheric circulation
is most pronounced in seasons when there are favorable conditions for stratosphere – troposphere
interactions. The absence of solar radiation throughout the winter over Antarctica enhances the
pole-to-equator meridional temperature gradient, which strengthens the stratospheric vortex.
Nonetheless, the interactions from the troposphere on the stratospheric vortex are only possible
when the flow is westerly, and below a certain threshold (Charney & Drazin, 1961). During the peak
of the winter in the SH, the circumpolar stratospheric westerly winds are too strong (Hurrell et al.
1998), and as such, troposphere-stratosphere interactions only occur during the weakening of the
stratospheric winds (the polar vortex breakdown) during austral spring (September-November). The
planetary wave fluxes from the troposphere into the stratosphere during austral spring can be
associated with sudden stratospheric warming events such as seen in 2002 (Hio & Yoden, 2005),
although these are less common in the SH compared to the Northern Hemisphere (Kuroda & Kodera,
1998; E.-P. Lim et al., 2019; Shiotani & Hirota, 2007). Thus, in contrast to other times of the year
when the SAM has the most marked impact on the troposphere (discussed further in the next
section, see Fig. 5.1), zonal wind anomalies during austral spring often extend into the stratosphere,
strengthen with height (not seen in Fig. 3 since this is based on all months), and temperature
anomalies in the stratosphere are most marked (Thompson & Wallace, 2000).

Interestingly, changes in the stratospheric circulation, particularly from ozone depletion, as
discussed in Section 5.2, can also influence the state of the SAM in the troposphere (Nathan P. Gillett
& Thompson, 2003; Polvani, Waugh, et al., 2011; Thompson et al., 2011; Thompson & Solomon,
2002). Unlike the upward fluxes of heat and momentum from the troposphere to the stratosphere
described in the previous section, the dynamics governing the connection from the stratosphere
downward to the troposphere are relatively recently discovered, and generally much less well
understood (Gerber et al., 2012; Joseph Kidston et al., 2015; Thompson et al., 2011). The consensus
in the literature is that the eddy-mean flow dynamics and their control on the polar jet in the upper-
troposphere and lower stratosphere are of key importance. One potential mechanism, often called
‘downward control’ (Byrne et al., 2019; Haynes et al., 1991; Song & Robinson, 2004; Thompson et
al., 2006), is where changes in the planetary waves (and their breaking into the stratosphere) drive
vertical motion, which leads to temperature and circulation anomalies extending down from the
stratosphere into the troposphere, as evidenced in the Northern Hemisphere (M. P. Baldwin & Dunkerton, 2001). There is a delay in these anomalies extending down to the troposphere: typically a stratospheric anomaly is first prevalent in austral spring during the vortex breakdown, which later manifests itself near the Antarctic surface in austral summer (Nathan P. Gillett & Thompson, 2003; Thompson et al., 2005; Thompson & Solomon, 2002). Importantly, the timing of the stratospheric vortex breakdown also has important influence on the tropospheric SAM (M. P. Baldwin et al., 2003; I. R. Simpson et al., 2011). As the vortex begins to breakdown in austral spring, it is more frequently subjected to planetary wave influence from the troposphere; the influence from the troposphere enhances the variability in the stratospheric vortex and has subsequent implications for downward propagation of the vortex anomalies into the troposphere, which can additionally be traced by measures of variability in the zonal winds and SAM index (M. P. Baldwin et al., 2003).

In comparison, other studies demonstrate the coherent response from the Antarctic stratosphere down to the surface can be related to changes in refraction of synoptic scale waves (Limpasuvan & Hartmann, 2000; Isla R. Simpson et al., 2009), planetary waves (Fletcher & Kushner, 2011; Song & Robinson, 2004), or baroclinic instability (Riviére, 2011). Part of the challenge in isolating an exact mechanism is the interaction (lack of independence) between these eddy-driven processes and the poorer stratospheric resolution in dynamical and chemistry-climate models used to analyze them, although the latter has been improving (Gerber et al., 2012).

### 3.3 Connections with ENSO

A further complication in understanding the causes of SAM variability is that multiple studies demonstrate that the SAM can also be influenced by tropical SST variability, particularly in the tropical Pacific associated with the phase of the El Niño-Southern Oscillation (ENSO) (Clem & Fogt, 2013; Ding et al., 2011, 2012; Fogt et al., 2011; Fogt & Bromwich, 2006; L’Heureux & Thompson, 2006; Wilson et al., 2016). Through variations in the Hadley cell and SH mean meridional circulation, the location of Rossby wave breaking in the Pacific sector changes markedly during ENSO events, which influence the polarity of the SAM (T. Gong et al., 2010, 2013). Potentially connected to the variations in Rossby wave breaking, ENSO variability also modifies the magnitude of the poleward eddy momentum flux (and its convergence), which in turn alters the strength and position of the SH polar jet, especially in the Pacific sector (Fogt et al., 2011; L’Heureux & Thompson, 2006). Due to the seasonality of both ENSO (Trenberth, 1997; Trenberth & Caron, 2000) and the general SH polar jet behaviour (Bals-Elsholz et al., 2001), the relationship between SAM and ENSO also shows a seasonal cycle, with stronger correlations between ENSO and SAM indices in austral summer than winter (Clem & Fogt, 2013; Fogt et al., 2011; Fogt & Bromwich, 2006); however, the ENSO-related teleconnection to the Amundsen Sea often appears as stronger circulation anomalies in the mid-troposphere in austral winter than summer due to the stronger source for tropically-driven Rossby waves in winter (tied to the strength of the winter STJ, Fig. 3a) and the favourable conditions for Rossby wave propagation into the high latitude South Pacific (Yiu & Maycock, 2019). Nonetheless, the relationship between ENSO and SAM tends to more frequently favour positive SAM polarity during La Niña, and negative SAM polarity during El Niño, although other combinations tied to internal variability can (less frequently) occur (Fogt et al., 2011; Wilson et al., 2016). From reconstructions and models, this negative correlation appears to persist until around 1400 CE (Dätwyler et al., 2019), but with variations driven by internal variability throughout much of the past
millennium; however another study suggests variations are due to solar forcing throughout the Holocene (Gomez et al., 2012).

4. CLIMATE IMPACTS OF THE SAM

While Section 3 and Fig. 3 depict the SAM influence throughout the troposphere and stratosphere, the SAM impacts on the surface climate are robust as well. Figure 4 represents a few of the larger-scale impacts, with anomaly composites of SAM positive (left column) and SAM negative (right column) on monthly MSLP (Fig. 4a) and 2-m temperature (Fig. 4b), and seasonal precipitation (Figs. 4c-d); climate anomalies statistically different from zero associated with the SAM polarities are stippled in each panel, and discussed in more detail below.

Figure 4. As in Fig. 3, but for ERA5 monthly composites for a) MSLP and b) 2m temperature. Composites of ERA5 seasonal mean total precipitation anomalies for c) JJA and d) DJF. Contour interval is 1 hPa in a), 0.3°C in b), and 0.3mm in c)-d). In all composites, anomalies statistically different from zero at $p<0.05$ are stippled.

4.1 Southern Hemisphere middle latitudes and into the Northern Hemisphere

Simple regression analysis reveals that the impact of SAM variability is seen well north of Antarctica and the Southern Ocean (N. P. Gillett et al., 2006), affecting both pressure and temperature (Figs.
4a-b), with generally warmer conditions and higher pressure during periods of positive SAM polarity across the SH midlatitudes (M. E. Jones et al., 2019). Precipitation anomalies across the SH midlatitudes are also strongly modulated by the SAM (Fig. 4c-d). The positive trend in the SAM in recent decades suggested in Fig. 2 has been linked to observed zonal changes in precipitation across the extratropical SH (Fyfe et al., 2012; Gonzalez et al., 2014; Kang et al., 2011; Thompson et al., 2011). Within these broad-scale changes are large regional impacts. In Australia, a positive SAM is associated with significant precipitation and temperature anomalies, with opposing relationships between different seasons and across different parts of the country (Fig. 4c-d) (Hendon et al., 2007; Meneghini et al., 2007). In particular, the southward shifting winter storm-track has led to reduced winter rainfall across much of southern Australia, but especially in the southwest (Raut et al., 2014) and western Tasmania, where SAM variability has been linked to wildfire activity (Mariani & Fletcher, 2016). The impact of the SAM on precipitation is also observed in southeastern South America, where its interplay with ENSO drives precipitation variability (G. E. Silvestri & Vera, 2003; Vera & Osman, 2018) and, similar to Tasmania, fire activity (Holz et al., 2017). The latter alter the moisture transport pathways into the East China Sea, including changes in regional tropical cyclone activity (C.-H. Ho, 2005). Further west, the June SAM has a correspondingly significant impact on the Indian Monsoon with opposing sign in different areas of India (Pal et al., 2017). In addition to the summer monsoon, East Asian winter precipitation is also influenced by SAM behaviour, through modulating the Inter-tropical Convergence Zone (ITCZ) in late autumn/early winter via changes in SSTs (Wu et al., 2015).

4.2 Antarctica and the Southern Ocean

4.2.1 Pressure and the Amundsen Sea Low

From its structure in Figs. 1-2, the SAM has strong connections to the pressure across Antarctica (Fig. 4a). In its positive polarity, negative pressure anomalies are relatively uniform over the continent, and statistically significant (N. P. Gillett et al., 2006; Thompson & Wallace, 2000). One particular area where the SAM displays a more pronounced pressure response is in the high-latitude South Pacific, off the coast of West Antarctica. This area, called the pole of variability, displays the highest interannual pressure / geopotential height variability in the SH (Connolley, 1997). A semi-permanent region of low pressure, the Amundsen Sea Low (ASL) (Fogt, Wovrosh, et al., 2012; Raphael et al., 2016; John Turner et al., 2013), is located in this region, and is significantly deeper (strong negative pressure anomalies) during the positive polarity of the SAM (Clem et al., 2016, 2017). However, since the ASL is also modulated by ENSO (Karoly, 1989; John Turner, 2004), the SAM-related
pressure anomalies are also dependent on the ENSO phase. Collectively, research suggests that when La Niña occurs with the positive SAM polarity, or El Niño occurs with the negative SAM polarity, the pressure anomalies in the ASL are strengthened (negative anomalies in positive SAM, positive anomalies in negative SAM), but they are significantly reduced or altogether absent in other SAM / ENSO combinations (Clem et al., 2016; Clem & Fogt, 2013; Fogt et al., 2011; Fogt & Bromwich, 2006; Stammerjohn et al., 2008; Wilson et al., 2016). The widespread association of SAM with latitudinal pressure anomalies also implies that it influences cyclonic activity around Antarctica, with more cyclones in the circumpolar trough during positive SAM (Grieger et al., 2018) together with a poleward shift in the mean storm track (Yin, 2005).

4.2.2 Temperature

In contrast to pressure, there are more regional patterns in the SAM relationship with temperature across Antarctica (Fig. 4b). The differences between the Antarctic continent, which is commonly colder during positive SAM, and the Antarctic Peninsula, which is commonly warmer, are a combination of geography and regional circulation patterns (N. P. Gillett et al., 2006; Gareth J. Marshall, 2007; Gareth J. Marshall & Bracegirdle, 2015; Nicolas & Bromwich, 2014; Thompson & Solomon, 2002). First, the northward extension of the Antarctic Peninsula into the circumpolar westerly winds: air masses can cross the Peninsula and warm adiabatically as they descend on the lee side, explaining the connection with warming on the eastern Antarctic Peninsula when the SAM is positive (Clem et al., 2016; Gareth J. Marshall, 2007; Orr et al., 2008; van Lipzig et al., 2008). On the western Antarctic Peninsula, the northerly meridional winds along the eastern flank of the ASL drive warm conditions on the western Antarctic Peninsula associated with the positive SAM (Clem et al., 2016; Lefebvre, 2004; Gareth J. Marshall, 2007; Sen Gupta & England, 2006). Across the Antarctic interior, the positive SAM, characterized by stronger zonal flow, reduces the meridional exchange of warm midlatitude air poleward, keeping the continent marked with negative temperature anomalies (Gareth J. Marshall, 2007; Gareth J. Marshall & Thompson, 2016; Nicolas & Bromwich, 2014; Thompson & Solomon, 2002; van den Broeke & van Lipzig, 2004). Furthermore, adiabatic cooling over the continent in the ascending air in the polar cell during positive SAM (Thompson & Wallace, 2000) also aids in promoting negative surface temperature anomalies, although these tend to be more marked in the troposphere (Fig. 3b).

Unlike pressure, whose relationships with the SAM are persistent across seasons and through time (Fogt et al., 2019), there are both seasonal variations in the strength of the SAM – Antarctic temperature relationships (Gareth J. Marshall, 2007; Gareth J. Marshall & Thompson, 2016), and reversals in the sign of the relationship through time, particularly along strong temperature anomaly gradients near the Antarctic Peninsula and portions of East Antarctica (Fig. 4b) (Gareth J. Marshall et al., 2006, 2011, 2013). These seasonal and temporal changes occur due to variations in the phase of the climatological wavenumber 3 pattern around Antarctica, which alter the longitudinal patterns of northward and southward advection of temperature and sea ice, ultimately presenting challenges in interpreting the influence of the SAM on Antarctic surface temperature (Gareth J. Marshall et al., 2011, 2013). Along the western Antarctic Peninsula, the connection is further complicated by influences from ENSO; the western Antarctic Peninsula often shows stronger temperature anomalies during ENSO events compared to independent SAM events (Clem et al., 2016), however the anomalies during individual ENSO events can significantly change in time (Clem & Fogt, 2013; Gareth J. Marshall et al., 2006).
4.2.3 Precipitation

Since few direct measurements exist, SAM impacts on precipitation across Antarctica are often inferred from reanalyses, models, or ice cores (Gareth J. Marshall et al., 2017; Medley & Thomas, 2019; John Turner, Phillips, et al., 2019; van den Broeke & van Lipzig, 2004). Generally, these studies reveal that precipitation decreases over the Antarctic interior during the positive SAM polarity, with small regional increases in areas influenced by more meridional flow in positive SAM, especially areas of West Antarctica influenced by the ASL (Figs. 4c-d) (Hosking et al., 2013). Across the Antarctic Peninsula, the western side receives significant positive orographic precipitation anomalies when the SAM is positive (Figs. 4c, d, left) due to the preferred flow from the ocean (Gareth J. Marshall et al., 2017), while a rain shadow effect (decreased precipitation) occurs on the eastern Antarctic Peninsula due to the high mountain range along the Peninsula that impedes moisture advection. Ice core evidence suggests that there has been a doubling of precipitation on the western side of the southern Antarctic Peninsula over the 20th century (Thomas et al., 2008), partly tied to recent positive SAM trends (Fig. 2), which will be discussed in Section 5.

4.2.4 Sea Ice

Changes in Antarctic sea ice have been linked to near-surface wind changes associated with the SAM (Doddridge & Marshall, 2017; Hall & Visbeck, 2002; William R. Hobbs et al., 2016; Holland & Kwok, 2012; Lefebvre, 2004; Pezza et al., 2008; Stammerjohn et al., 2008). The relationship of the SAM to Antarctic sea ice variability is perhaps more complicated than temperature, pressure, or precipitation due to the complex regional nature of sea ice variability and near-surface wind patterns around Antarctica (William R. Hobbs et al., 2016), together with the influence from both the ocean and atmosphere. While zonal winds tend to favour the equatorward expansion of the Antarctic-wide (total) sea ice through the oceanic Ekman effect (Hall & Visbeck, 2002), meridional winds, especially those associated with the regional circulation of the ASL, play an even stronger role in regional sea ice extent variability through wind-driven ice drift (expansion for southerly flow, and compaction for northerly flow) (Coggins & McDonald, 2015; W.R. Hobbs & Raphael, 2010; Holland & Kwok, 2012; Hosking et al., 2013).

4.2.5 The Southern Ocean

The circumpolar westerly winds associated with the SAM play a significant role in the upwelling in the Southern Ocean, including potential changes in the sink of global carbon into the ocean (Hall & Visbeck, 2002; Lovenduski et al., 2007, 2008). Indeed, the role of the SAM in modulating the Southern Ocean carbon sink is an area of active research (Keppler & Landschützer, 2019). With the general consensus that the Southern Ocean carbon sink has weakened over the last several decades and this is at least in part in response to the positive trend in the SAM (Le Quere et al., 2007), although this may not hold true into the future (Russell et al., 2006). On much longer timescales, the SAM has been proposed as a control on the marked glacial-interglacial changes in atmospheric carbon through altering the physical and biological processes that govern carbon uptake and storage in the Southern Ocean (d’Orefeville et al., 2010; Tschumi et al., 2008). Further, the impact of the SAM on the Southern Ocean carbon sink appears to be sensitive to the model(s) employed, due to latitudinal biases in the associated zonal wind changes (Isla R. Simpson, Hitchcock, et al., 2013; N. C. Swart & Fyfe, 2012) and whether or not the ocean model is eddy-resolving (Ito et al., 2010).
The SAM has been associated with a warming of SSTs prior to 1980, and a cooling thereafter (Fan et al., 2014; J. M. Jones et al., 2016; Sen Gupta & England, 2006). Below the surface through the mixed layer, a general warming of the Southern Ocean has also been suggested to be linked to the changes in the SAM, through driving a poleward movement of the eastward moving Antarctic Circumpolar Current (Ferreira et al., 2015; Gille, 2008; Spence et al., 2014). Additionally, modelling studies have also shown that the stronger zonal winds associated with the positive SAM can decrease sea ice extent by upwelling warm circumpolar deep water close to the Antarctic coast through enhanced surface easterly flow (Ferreira et al., 2015; M. Sigmond & Fyfe, 2010; Michael Sigmond & Fyfe, 2014). The increased warming of coastal Antarctic waters through changes in upwelling of circumpolar deep water has been linked to the melting of outlet glaciers in the Amundsen Sea Embayment (Dutrieux et al., 2014; Holland et al., 2019; Schmidtke et al., 2014; Stewart & Thompson, 2012), with implications for global sea level rise.

5. SAM TRENDS AND FORCING

5.1 Seasonal and time-varying trends

Figure 5. a) Annual mean Marshall (2003) SAM index (red line, right axis) and 30-year running trend and 95% confidence interval (black line with shading, left axis). The running trend is plotted on the x-axis by the middle year of the trend. b) Seasonal time-varying trends, with the start of the time interval for the trend indicated by the y-axis and the ending year by the x-axis. The trends on the x=y line are exactly 30 years (trends are only shown if longer than 30 years). Cross-hatching and stippling in b) indicate trends statistically different from zero at $p<0.10$ and $p<0.05$, respectively.
As evident in the SAM index time series in Fig. 2, the SAM has displayed positive trends, which are further detailed in Fig. 5. The 30-year annual mean SAM index trend has been persistently positive throughout the period of the Marshall (2003) index, beginning in 1957, with many 30-year periods displaying positive trends that are significantly different from zero at $p<0.05$ (J. M. Jones et al., 2016; G. J. Marshall, 2003; Gareth J. Marshall, 2007; Thompson et al., 2000). The trends in the annual mean SAM index were stronger in the late 20th century, and have slightly weakened when including the early 21st century. The seasonal trends of the Marshall (2003) SAM index, which are similar to those of other indices (Fig. 2), are summarized in Fig. 5b. Notably, as indicated in Fig. 2a, since 1957 the strongest positive trends occur in austral summer, DJF (Fogt et al., 2009; G. J. Marshall, 2003; Gareth J. Marshall, 2007; Thompson & Solomon, 2002). The summer trends were strongest in the later part of the 20th century and were weaker in the last 30 years (and no longer significant at $p<0.10$), as reflected in the annual mean. There are also significant positive trends in austral autumn (Figs. 2b, 5b) (G. J. Marshall, 2003; Gareth J. Marshall, 2007), which peaked at the same time as the summer trends in the late 20th century, but still remain significantly positive for trends ending after 1995. In contrast, there are generally statistically insignificant positive and negative trends observed in various time periods in austral winter and spring (Clem & Fogt, 2015). However, Fig. 5b does suggest that in winter many positive SAM index trends ending after 2010 are significant at $p<0.10$, due to the high positive value in 2019 JJA and persistently positive values from 2014-2017 (Fig. 2c).

5.2 External forcing: Polar stratospheric ozone depletion and greenhouse gas increases

The positive SAM trends in summer observed in the second half of the 20th century and the associated increase in tropospheric circumpolar westerly winds are primarily a response to external forcing, and are one of the few detectable forced responses in Antarctic climate (N. P. Gillett et al., 2005; Nathan P. Gillett et al., 2013; J. M. Jones et al., 2016). The majority of studies suggest positive summer SAM trends are due primarily to stratospheric ozone depletion (Englund et al., 2016; Fogt et al., 2017; Nathan P. Gillett & Thompson, 2003; J. M. Jones et al., 2016; Polvani, Waugh, et al., 2011; Thompson et al., 2011; Thompson & Solomon, 2002). The weakening of the summer trends in the last 30 years is also consistent with the role of ozone forcing, as the stratospheric ozone hole over Antarctica is beginning to show signs of recovery (Solomon et al., 2016). As discussed previously, the summer SAM trends first originate as temperature and height decreases in the stratosphere during austral spring, which propagate downward and reach the Antarctic surface / lower troposphere during summer (Nathan P. Gillett & Thompson, 2003; Thompson & Solomon, 2002, 2005). Compared to long-term SAM estimates (discussed in section 6) and model simulations, the recent summer SAM index trends fall outside the range of natural variability (Abram et al., 2014; Fogt et al., 2009; McLandress et al., 2011; Miller et al., 2006). In comparison, the overall weaker SAM trends in austral autumn appear within the (higher) estimates of natural variability (Fogt et al., 2009), although some studies suggest the ozone influence on Antarctic climate may persist into autumn and thereby be associated with the positive SAM trends in this season as well (Thompson & Solomon, 2002; John Turner et al., 2009).

While ozone depletion is thought to be the main mechanism for positive summer SAM trends, other studies have noted that greenhouse gas increases may also play a role throughout the year, as they work to cool the stratosphere and warm the tropical troposphere, thereby amplifying the mid-to-high latitude temperature gradient and hence increasing the circumpolar westerly winds (positive
SAM) in order to maintain the thermal wind balance (Julie M. Arblaster & Meehl, 2006; Cai et al., 2003; Fyfe et al., 1999; Shindell & Schmidt, 2004). These studies tend to note a secondary influence of greenhouse gases on the SAM (or don’t fully investigate the role of ozone depletion in their model configurations), or they suggest that the current positive trends are a combination of both increasing greenhouse gases and stratospheric ozone depletion (Julie M. Arblaster & Meehl, 2006; Shindell & Schmidt, 2004). Outside of austral summer, natural variability, particularly from ENSO and decadal tropical variability, tends to reduce the overall magnitude of SAM trends and their temporal persistence (Clem et al., 2016; Clem & Fogt, 2013, 2015). Even in austral summer, natural variability can play an important role on shorter timescales, such as the pre-ozone hole peaks in the SAM index around 1960 (Fig. 1) (J. M. Jones et al., 2009; J. M. Jones & Widmann, 2003, 2004), or the recent negative Antarctic-wide pressure anomalies since 2000 (Fogt et al., 2017), associated with tropical SSTs during a period of weaker ozone forcing. Volcanic activity may also drive short-term changes in the SAM index (Fogt et al., 2017; G. J. Marshall, 2003; Yang & Xiao, 2018) through modulations in the extratropical temperature gradient and wave-driving of the polar stratosphere, although the response varies between eruptions due to changes in tropical variability and other factors (Robock et al., 2007).

Sidebar title: Future projections of the SAM

The future state of the SAM is less certain in austral summer than other seasons, due to potentially offsetting roles of stratospheric ozone recovery and increases in GHGs (J. M. Arblaster et al., 2011; Karpechko et al., 2010; Polvani, Previdi, et al., 2011; Seok-Woo Son et al., 2009; Waugh et al., 2009). Summer SAM indices begin to diverge by the mid-21st century in response to differences in prescribed forcings (Simpkins & Karpechko, 2012). In simulations where ozone recovery is weaker (or not prescribed), the summer SAM remains in a positive polarity through the 21st century (Perlwitz et al., 2008; S.-W. Son et al., 2008). For simulations that include ozone recovery, the 21st century summer SAM ranges from insignificantly negative (J. M. Arblaster et al., 2011; Karpechko et al., 2010; Polvani, Previdi, et al., 2011; S.-W. Son et al., 2008) to positive (Miller et al., 2006), with the suggestion that GHG forcing and thus positive SAM trends will dominate by the late 21st century, depending on the rate of GHG increases (Simpkins & Karpechko, 2012). However, models that simulate the rate of ozone recovery through interactive stratospheric ozone chemistry (like chemistry-climate models) also give different SAM trends compared to models with prescribed ozone recovery (Perlwitz et al., 2008; Simpkins & Karpechko, 2012). Outside of austral summer, when the forcing from stratospheric ozone is weaker or absent, GHG forcing dominates the future SAM state. In these seasons, but especially in winter, the SAM displays a more consistent positive trend across models, which is similarly sensitive to the rate of GHG increases (Miller et al., 2006; Simpkins & Karpechko, 2012).

6. PAST CHARACTERISTICS OF THE SAM

Due to the short nature of Antarctic records (J. M. Jones et al., 2016; J. Turner et al., 2004; John Turner, Marshall, et al., 2019) and the higher uncertainty in 20th century reanalysis products in the high southern latitudes (Schneider & Fogt, 2018), long-term historical estimates of the SAM are
achieved through reconstructions. Currently, two main categories of SAM index reconstructions have been attempted, those based on historical pressure observations in the SH throughout the 20th century, and another set based on proxy data from the SH, including ice cores from Antarctica. Figure 6 displays two historical SAM reconstructions for reference.

6.1 Station-based SAM reconstructions

Station-based pressure records from the SH midlatitudes potentially serve as an important tool for historical SAM reconstructions due to the strong influence of the SAM on SH midlatitude pressures (Fig. 4) and the fact that many SH midlatitude surface pressure and MSLP observations extend back through the 20th century (J. M. Jones et al., 2009; J. M. Jones & Widmann, 2004). A group of these station-based SAM reconstructions employ seasonally-based statistical models following a principal component regression technique. In this method, relationships between subsets of SH midlatitude pressures (represented by principal components) were used as independent variables in multiple linear regression with a chosen SAM index in order to extend the SAM record back through time (Fogt et al., 2009; J. M. Jones et al., 2009; J. M. Jones & Widmann, 2004). Another approach (Visbeck, 2009) reconstructed the SAM using a conservation of mass assumption, such that changes in SH midlatitudes were opposite of those in Antarctica. It employed the relationship between geographically grouped subsets of mid-latitude stations and Antarctic observations to extend the SAM record back until the late 19th century using the former. Importantly, recent work from climate model simulations implies that the overall pressure relationships between Antarctica and the SH midlatitudes are stationary in the 20th century (Clark & Fogt, 2019), supporting all of these statistical approaches to reconstructing the SAM index based on such relationships.

Figure 6. Annual mean SAM indices, smoothed with an 11-year Hamming filter. The Fogt reconstruction (J. M. Jones et al., 2009) is an example of a station-based SAM reconstruction, while the Abram reconstruction uses multiply paleo-proxies (Abram et al., 2014). Note that the annual mean Fogt reconstruction was calculated by averaging the four seasonal SAM reconstructions. The shading about each reconstruction represents the 95% confidence interval based on comparison with the Marshall (2003) index, and all data have been standardized over 1957-2005 prior to smoothing.
While these reconstructions share some similar patterns in historical SAM variability, they are also different due to differing stations used in the reconstructions (and the weight each station is given in the reconstruction model), and the various choices of SAM indices reconstructed (Barrucand et al., 2018), which may appear subtle after 1979 (Fig. 2), but can have larger impacts with a reduced station network that may not fully represent all aspects of the SAM structure (Fig.1). Indeed, when compared to measures of Australian precipitation, the various SAM indices can have quite different relationships prior to 1979 (M. Ho et al., 2012). Nonetheless, the reconstructions have helped to demonstrate that strong SAM trends in austral autumn observed since 1957 (Fig. 5) have likely occurred earlier in the 20th century (when external forcing was weaker), suggesting these recent trends are within the range of natural variability, as suggested by the annual mean SAM index in Fig. 6 (Fogt et al., 2009). The reconstructions also demonstrate the uniqueness of the recent summer and annual mean SAM index trends (Figs. 5 and 6), and their association to ozone depletion. In winter and spring, the SAM index is within the bounds of natural variability, with no significant trends during the 20th century (Fogt et al., 2009, 2019). Historical SAM indices show a more marked association with ENSO in the early 20th century (Barrucand et al., 2018), but no consistent periodicity throughout the 20th century. However, given the differences between SAM reconstructions (as partly suggested in Fig. 6), caution is warranted in interpreting specific (regional and / or short-duration) climate variability associated with the SAM in the early 20th century and prior from these reconstructions (Barrucand et al., 2018; M. Ho et al., 2012).

6.2 Proxy-based SAM reconstructions

Other SAM indices (or SH pressure / wind estimates) have been reconstructed over much longer time periods, many spanning back to AD 1000, using midlatitude proxy data such as tree rings and lake sediments (J. M. Jones & Widmann, 2003; Moreno et al., 2018; Villalba et al., 2012), ice core proxy data from Antarctica (Ian D. Goodwin et al., 2014; I.D. Goodwin et al., 2004; Yang & Xiao, 2018), or multi-proxy reconstructions based on a combination of midlatitude and Antarctic data (Abram et al., 2014; Zhang et al., 2010). Notably, as seen in South American (G. Silvestri & Vera, 2009) and Antarctic (Gareth J. Marshall et al., 2011, 2013) temperatures, recent work also suggests that many paleo-proxy relationships with the SAM are likely to be non-stationary, although this relationship varies regionally (Dätwyler et al., 2018). Therefore, similar to the station-based SAM reconstructions, care should be exercised when using these longer-term reconstructions to infer specific regional change across Antarctica or the SH midlatitudes.

Despite these challenges, a comparison of three main proxy SAM index reconstructions suggest they all show the unique nature of the recent positive SAM trends, and are more similar in the last two centuries than earlier in time (Hessl et al., 2017). Furthermore, the proxy-based SAM reconstructions demonstrate that the recent trends are unprecedented in at least the last 500 years, as suggested in Fig. 6 from the Abram reconstruction (Abram et al., 2014; Hessl et al., 2017). Many reconstructions also indicate a marked negative polarity during the 15th century prior to the recent increase that followed (Fig. 6) (Abram et al., 2014; Hessl et al., 2017; Villalba et al., 2012). Importantly, since these proxy-based SAM indices all show longer-term positive trends spanning the last several centuries (these trends are even more prominent when the smoothing window spans multiple decades, as in Abram et al. (2014)), it is apparent that other factors besides greenhouse gas
increases and ozone depletion play a role in determining long-term SAM behaviour, perhaps associated with changes in solar irradiance (Abram et al., 2014).

**Figures and Tables**

**Figures have all been embedded within the manuscript main body to expedite review.**

**Conclusion**

The SAM continues to be an important area of active climate research, as evidenced throughout this review. Since its initial discussion in the literature during the late 1970s and early 1980s, the principal breakthroughs relate to:

1. A more complete understanding of the connections of the role of eddy activity and positive feedbacks in maintaining the SH polar jet and its connection to SAM variability;
2. Important SAM-related connections to surface climate in Antarctica and the SH midlatitudes, and the non-stationarity of these impacts;
3. The relationship between SAM and ENSO, and the dynamics of these interactions throughout the Pacific sector;
4. The primary role of ozone depletion on the recent positive trends in the summer SAM, with greenhouse gas increases and tropical variability playing smaller secondary roles to date;
5. The unprecedented nature of these recent summer trends, as deduced from a wide variety of SAM reconstructions.

While these advances have improved our scientific understanding of the SAM, they have also led to new research areas focusing on different aspects of SAM behaviour. As such, current knowledge gaps provide the potential for future research opportunities, and include:

1. Further improvement in our understanding of how the dynamics of stratosphere-troposphere interactions, especially the mechanisms associated with ozone loss in spring, influence the polar lower troposphere around one season later (primarily in summer);
2. The relative magnitude of the competing roles of greenhouse gas increases and ozone recovery on the future state and evolution of the SAM;
3. A better representation of historical variability of the SAM prior to 1957 and throughout the last millennia to assess long-term behaviour of the SAM and its potential impacts, especially at larger scales where the relationships are likely to be more stationary.

As both modelling and historical data recovery continue to improve, it is expected future scientific breakthroughs on the SAM behaviour will be achieved over the next decade. These advances can prove timely in our understanding of the role of the large-scale SH atmospheric circulation on ongoing climate change, including Antarctic ice loss and carbon sequestration in the Southern Ocean, both of which have important global consequences.

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Research Resources

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ERA5 data are freely available from the ECMWF Copernicus Online Data Store (https://cds.climate.copernicus.eu/#!/search?text=ERA5&type=dataset). The Marshall SAM index can be accessed online at http://www.legacy.bas.ac.uk/met/gjma/sam.html. The Abram SAM reconstruction can be accessed online at https://www.ncdc.noaa.gov/paleo-search/study/16197 and the Fogt reconstruction can be obtained from http://polarmet.osu.edu/ACD/sam/sam_recon.html.

Notes

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