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The Southern Annular Mode: a comparison of indices

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Abstract

The Southern Annular Mode (SAM) has been identified as a climate mechanism with potentially significant impacts on the Australian hydroclimate. However, despite the identification of some relationships between SAM and Australia's hydroclimate, the association has not been extensively explored or robustly quantified. Further complicating the situation is the existence of numerous indices (or methods) by which SAM has been approximated. In this paper, the various SAM definitions and indices are reviewed and the similarities and discrepancies are discussed, along with the strengths and weaknesses of each index development approach. Further, the sensitivity of the relationship between SAM and Australian rainfall on choice of SAM index is quantified and recommendations are given as to the most appropriate index to use when assessing the impacts of the SAM on Australia's hydroclimate.

1 Introduction

It is well known that Australia's hydroclimate exhibits significant spatial and temporal variability (e.g. Chiew et al., 1998; Franks and Kuczera, 2002; Nicholls, 2004; Verdon et al., 2004; Verdon-Kidd and Kiem, 2009a). Much of this variability has been linked to ocean-atmospheric processes occurring in the Pacific and Indian Ocean, specifically the El Niño/Southern Oscillation (ENSO) (McBride and Nicholls, 1983; Drosdowsky, 1993; Kiem and Franks, 2001; Meyers et al., 2007; Risbey et al., 2009), the Inter-decadal Pacific Oscillation (IPO) (Power et al., 1999; Kiem et al., 2003; Kiem and Franks, 2004) and the Indian Ocean Dipole (IOD) (Saji and Yamagata, 2003; Verdon and Franks, 2005; Meyers et al., 2007; Risbey et al., 2009; Ummenhofer et al., 2009). Other studies have also identified relationships between the Southern Annular Mode (SAM) and Australia's hydroclimate, with Gillett et al. (2006) and Meneghini et al. (2007) suggesting that the SAM's influence on Australian hydroclimatology may be equal or even greater than the influence of ENSO or IOD in certain regions during particular

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seasons and epochs. Recent papers (e.g. Murphy and Timbal, 2008; Gallant et al., 2011) provide a comprehensive summary of the key ocean-atmospheric processes driving Australian hydroclimatic variability and from these review papers it is clear that, in comparison with ENSO and IOD, very little is known about the SAM and its relationship with Australian hydroclimate. The literature that does exist on SAM and its teleconnections also reveals inconsistencies relating to (a) how SAM is defined, (b) the index used to represent SAM and (c) how the various phases of SAM should be classified. This confusion as to how to approximate (i.e. which SAM index to use) and classify SAM, combined with the lack of research focusing on climate drivers originating from the Southern Ocean, has led to a significant knowledge gap in our understanding of how much of Australia's hydroclimatic variability can be attributed to SAM. Furthermore, it is not yet clearly understood how SAM interacts with other large-scale climate drivers (e.g. ENSO, IOD, IPO) and local-scale synoptic weather patterns known to influence Australian hydroclimatology (Meneghini et al., 2007; Gallant et al., 2011; Kiem and Verdon-Kidd, 2011).

Importantly, the recent protracted droughts in south-west Western Australia (SWWA) and south-east Australia (SEA) have been linked to anomalous SAM behaviour (e.g. Cai and Cowan, 2006; Hendon et al., 2007; Murphy and Timbal, 2008; Gallant et al., 2011) that is projected to become more frequent under global warming (Cai et al., 2005; McGowan et al., 2010). Despite these studies, significant knowledge gaps still exist around how much of Australia's historical climate variability can be attributed to SAM and also the role SAM may play in determining Australia's future climate (Kiem and Verdon-Kidd, 2011). Improved characterisation of the role of SAM on Australia's hydroclimate will not only increase our understanding of historical hydroclimate variability, but will also provide valuable performance indicators for global and regional climate models. Realistic climate model representation of SAM and its impacts are crucial given the suggested links between SAM and Australian droughts and the possibility of enhanced SAM impacts in an anthropogenically warmed world. This paper aims to provide a fundamental first step in addressing the knowledge gaps identified above by

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reviewing the various SAM definitions and indices and analysing the similarities and discrepancies, along with the strengths and weaknesses of each index development approach. Further, the sensitivity of the relationship between SAM and Australian rainfall on choice of SAM index is quantified and recommendations are given as to the most appropriate index to use when assessing the impacts of SAM on Australia's hydroclimate.

2 The large-scale climate phenomena known as the Southern Annular Mode (SAM)

Past studies have identified a zonally symmetric or annular structure of circulation in both the Northern and Southern Hemispheres (Kidson, 1988; Thompson and Wallace, 1998). This Southern Hemisphere annular structure has been referred to as the Southern Hemisphere Annular Mode (Thompson and Wallace, 1998), the Southern Hemisphere Circulation (Karoly et al., 1996), the Antarctic Oscillation (Gong and Wang, 1998) and the Southern Annular Mode (Jones and Widmann, 2004; Gillett et al., 2006; Meneghini et al., 2007). For consistency, the term Southern Annular Mode (SAM) will be used in this paper. SAM is defined as the alternating pattern of strengthening and weakening westerly winds between the mid to high latitudes (i.e. polewards of 40° S) in the Southern Hemisphere (Rogers and van Loon, 1982). The alternating or wave-like structure is centred at approximately 50° S with zonal (west to east) winds weakening north of 40° S. SAM also varies seasonally with a strong zonally symmetric pattern in summer that deteriorates and becomes weaker in winter and spring (Jones et al., 2009).

The fundamental mechanism driving SAM circulation is the non-uniform heating of the Earth and the subsequent energy transport and atmospheric circulations that occur (King and Turner, 2007). The build up of heat and energy near the Equator results in surface convergence and rising air along the Inter-Tropical Convergence Zone (Sturman and Tapper, 2006). The rising air then moves polewards, loses heat and sinks. In the Southern Hemisphere, the subsiding air forms sub-tropical high pressure regions at the surface (around 30–35° S in summer and 20–25° S in winter).

The Earth's poles receive reduced insolation and a large amount of sunlight that is received is reflected due to the relatively high albedo of the ice sheets and snow at high latitudes. Antarctica therefore acts as a heat sink, drawing in warm air from the mid-latitudes (∼40–60° S) through the mid-troposphere (∼5000 m a.s.l.). The air cools over Antarctica, increases in density and sinks. The subsiding air over Antarctica generates anti-cyclonic (anti-clockwise in the Southern Hemisphere due to the Coriolis Effect) circulations at the surface and in the lower atmosphere as it moves north. The air moving north from the South Pole intersects with the air moving south from the subtropical high regions and rises. This results in a circumpolar trough, a region of low pressure surrounding Antarctica at approximately 60–70° S. The regions of longitudinally alternating bounds of high and low pressure may therefore be crudely explained by the non-uniform heating of the Earth and ensuing air and heat transports.

A positive SAM phase is characterised by anomalously high pressure in the mid-latitudes and anomalously low pressures in the latitudes closer to the South Pole. A positive SAM indicates the occurrence of a strengthening circumpolar vortex and zonal (westerly) winds that circle Antarctica which leads to a shift in the storm track towards the South Pole (Marshall, 2003). A negative SAM phase exhibits a reverse of the pressure conditions described above and weakening westerly winds leading to a northward shift in the storm track.

A positive SAM is associated with warming of mid-latitude areas such as Tasmania, south-east Australia, Chile, Argentina and the south island of New Zealand (Gillett et al., 2006). This warming effect is most pronounced during the austral summer where effects are enhanced by increased insolation (McGowan et al., 2010). The seasonal influences of the SAM on rainfall have been shown to be stronger than ENSO over specific regions of Australia, predominantly western Tasmania and southern regions of Australia (Meneghini et al., 2007). Kiem and Verdon-Kidd (2010) also suggested that during a positive SAM phase the rain bearing systems resulting from La Niña

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are prevented from moving into the SEA region. However, despite these preliminary insights there is a lack of agreement and understanding relating to the relationship between SAM and hydroclimatic variability in Australia, and other Southern Hemisphere regions. For example:

- Gillett et al. (2006) identified a decrease in summer rainfall in SWWA during positive SAM phases, however, Meneghini et al. (2007) found that positive SAM was associated with increased rainfall in SWWA, while Cai and Cowan (2006) found that the decrease in rainfall during a positive SAM phase only occurred during winter;
- Meneghini et al. (2007) deduced that the cause of long term reductions in winter rainfall in SWWA (from 1965 onwards) was unlikely to be due to trends in SAM, while Cai and Cowan (2006) concluded that the robust relationship between SAM and winter rainfall in SWWA explained 67 % of the long-term decline, despite this trend being statistically insignificant;
- In contrast to the findings of Gillett et al. (2006) that no SAM effects were observed north of latitude 40° S with the exception of Australia, the studies by Fan and Wang (2004) and Nan and Li (2003) attributed variations in precipitation and dust events within China to SAM.

The large degree of inconsistency in the findings of existing studies may be due to the limited availability of reliable data in and around the Southern Ocean with which to develop a robust SAM index, resulting in SAM being approximated by numerous indices (discussed in Sect. 3.1). Compounding this is the fact that numerous methods also exist by which to classify SAM into its positive, negative and neutral phases. Kiem and Franks (2001) have previously demonstrated the implications of the subjectivity associated with selecting an index and classification method to characterise impacts associated with large-scale climate drivers. This study builds on that work by investigating the sensitivities associated with the index chosen to represent SAM.

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3 Data

3.1 SAM indices

Recent studies aimed at investigating the impacts of the SAM (e.g. Nan and Li, 2003; Reason and Rouault, 2005; Gillett et al., 2006) have resulted in numerous indices being developed to approximate the SAM. These indices differ in either the climate variables used, the data sources used or the method used to define the index. The two most common methods by which SAM indices are formulated are:

- Principal Component (PC) analysis: The first PC of a Southern Hemisphere extra-tropical climate variable (e.g. geopotential height (GpH), mean sea level pressure (MSLP), temperature) (e.g. Thompson and Wallace, 2000; Nan and Li, 2003);

- Gong and Wang (1999) method: The difference between normalised zonal mean pressure between 40° S and 65° S as shown in Eq. (1).

$$\text{Gong \& Wang} = P^{*}_{40^\circ\,\text{S}} - P^{*}_{65^\circ\,\text{S}} \tag{1}$$

Where: P^* is the normalized zonal MSLP (at 40° S and 65° S) for every month.

Several existing SAM indices that are readily available, commonly used and compared in this study are reviewed below and summarised in Table 1, which shows the method used to construct the index, the data used (source and variable), period of availability and the temporal resolution.

3.1.1 National Oceanic and Atmospheric Administration (NOAA) index

Thompson and Wallace (2000) used seven different gridded data sets for variables such as monthly temperature, MSLP, GpH, wind and total column ozone to spatially analyse month to month variability of atmospheric circulations in the polar regions. It was shown that the spatial structure of what is now known as SAM could be identified through the analysis of GpH anomalies regressed upon their leading principal

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component time series. Based on the study by Thompson and Wallace (2000), the National Oceanic and Atmospheric Administration (NOAA) calculated (using the PC method) the NOAA index of SAM (referred to by NOAA as Antarctic Oscillation) which is defined as the monthly anomalies of 700hPa GpH south of 20° S projected onto the first empirical orthogonal function mode of monthly 700hPa GpH during 1979–2000. The NOAA SAM index is based on a mixture of station observations and widespread satellite data. Satellite data has been shown to be the most reliable data source for analysing Antarctic meteorology (King and Turner, 2007, p. 63) and hence SAM behaviour. Therefore gridded data based on satellite data is less influenced by spurious errors encountered with earlier reanalysis data (Marshall, 2003). Hence the NOAA index, which covers the period post 1979 where satellite data is available, will be used as the baseline, or reference index, for the remainder of this study. The NOAA index data is updated in real time and can be accessed at: http://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/aao/aao.shtml.

3.1.2 jisaoAAO index and jisaoSLP index

Fan and Wang (2004) calculated a SAM index, referred to here as the Joint Institute for the Study of Atmosphere and Ocean (jisao) Antarctic Oscillation Index (AAO). The definition of jisaoAAO is based on the first PC of 850 hPa GpH anomalies south of 20° S. This SAM index is calculated using National Centres for Environmental Prediction-National Centre for Atmospheric Research (NCEP-NCAR) data from 1954 to 2002. Since release of the Fan and Wang (2004) study, the jisaoAAO record has been extended to 1948 (still ending in 2002) and is available on: http://jisao.washington.edu/data/aao/.

Fan and Wang (2004) compiled another index, referred to in this paper as jisaoSLP, in order to assess the occurrences of dust in storms in northern China, which are particularly prevalent during the boreal spring (consisting of the months March, April and May (MAM)). The jisaoSLP is calculated using the first PC of MSLP anomalies south of 20° S averaged over the boreal winter (or austral summer consisting of the

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months of December, January and February (DJF)) and spring months (MAM) with the data set beginning in 1954. This data set has now been extended back to 1948 and is regularly updated and available at: http://jisao.washington.edu/data/aao/slp.

3.1.3 Regional Antarctic Oscillation Index (AOIR)

Meneghini et al. (2007) used the Gong and Wang (1999) definition of the SAM, however, their analysis concerned seasonal rainfall and as such, the index was redefined to provide a seasonal SAM index:

$$\mathrm{AOIR}_t = \frac{\mathrm{MSLP}_{40^\circ\,\mathrm{S}}(t) - \overline{\mathrm{MSLP}_{40^\circ\,\mathrm{S}}(\mathrm{season})}}{\sigma_{\mathrm{MSLP}\,40^\circ\,\mathrm{S}}(\mathrm{season})} - \frac{\mathrm{MSLP}_{65^\circ\,\mathrm{S}}(t) - \overline{\mathrm{MSLP}_{65^\circ\,\mathrm{S}}(\mathrm{season})}}{\sigma_{\mathrm{MSLP}\,65^\circ\,\mathrm{S}}(\mathrm{season})}$$

Where: MSLP (t) is the seasonal MSLP; $\overline{\mathrm{MSLP(season)}}$ is the mean of the seasonal MSLP for the season of interest; and σ (season) is the standard deviation of the seasonal MSLP for the season of interest.

This seasonal SAM index was calculated using the European Centre for Medium Range Weather Forecasts' Re-analysis (ERA) ERA-40 gridded monthly MSLP data set and resulted in one AOI value per season per year. The AOIR used only data between 90° E to 180° E to encompass all of Australia and make it region specific. Although this data set is no longer available, and therefore is not assessed in this study, the methodology used to develop a region specific index for quantifying SAM proved to be useful in identifying SAM effects on Australian rainfall.

3.1.4 Marshall index

Marshall (2003) also used the Gong and Wang (1999) definition to develop an index of SAM. However, the Marshall (2003) index was based on station data (as opposed to reanalysis data), which measured the monthly mean difference between the MSLP at six stations close to 40° S and six stations close to 65° S. The index was then normalised and used to regress temperature and precipitation in the Southern

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Hemisphere. The index is available from 1957 to the present and is available at: http://www.antarctica.ac.uk/met/gjma/sam.html.

3.1.5 Southern Annular Mode Index (SAMI)

Nan and Li (2003) created the Southern Annular Mode Index (SAMI) for the period of 1948-2001 based on the Gong and Wang (1999) method but with the difference being that SAMI is defined as the difference between the normalized monthly zonal MSLP between 40° S and 70° S (as opposed to 40° S and 65° S). Nan and Li (2003) believed that the negative correlation in the zonal MSLP anomalies between 40° S and 70° S was stronger than between 40° S and 65° S. Although Thompson and Wallace (2000) show that this is not the case, the SAMI was formulated to be region specific as spring SAMI showed stronger correlations with summer rainfall in the Yangtze River valley. SAMI has since been updated to the present and is available on: http://web.lasg.ac.cn/staff/ljp/data-NAM-SAM-NAO/SAM-AAO.htm.

3.1.6 Visbeck index

Visbeck (2009) developed an index of SAM using a similar method to Marshall (2003). However, the Visbeck index used different selection criteria for stations, resulting in the inclusion of 43 stations to develop the index. This index begins in 1958, as this is when improved data coverage for Antarctic stations became available. The Visbeck index was then extended through a method of reconstructing the Antarctic MSLP time series (Visbeck, 2009) based on the concept of atmospheric mass conservation between Antarctica and sub-tropical latitudes. The reconstructed Visbeck SAM index was originally extended to 1884, however, since publication, a stricter revision of the station selection criteria resulted in the reconstruction being shortened and data only being available from 1887 (Martin Visbeck, personal communication, 22 June, 2010). The Visbeck index is formulated in three monthly periods from the start of the calendar year (JFM, AMJ, JAS, OND) and is available through: http://www.ifm-geomar.de/fileadmin/ifm-geomar/fuer_alle/PO/SAM/sam_ann. A monthly data set is also available and was

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obtained through personal communication with Martin Visbeck (personal communication, 6 January 2011).

3.1.7 Fogt index and the Jones and Widmann index

Relationships developed from the ERA-40 reanalysis MSLP data from 1958–2001 and station MSLP data were used to produce the SAM index prior to 1958 for both the Fogt reconstructed index and the Jones and Widmann (JW) reconstructed indices. PC analysis, as described in Sect. 2.1, was used to calculate both indices (Jones et al., 2009). The key difference in the reconstructions was that the Fogt reconstructions were fitted to the Marshall index, whilst the JW reconstructions were fitted to a SAM index using ERA-40 data (1958–2001) and the PC method of developing a SAM index. The Fogt reconstructions are available through: http://polarmet.osu.edu/acd/sam/sam_recon.html. The JW reconstructions were obtained through personal communication from 1866 to 2005. Several JW reconstructions were developed with different starting dates of 1866, 1905, 1951 and 1958. Of the JW reconstructions, only the index with the start date of 1958 (JW58 index) is used in this study, as this JW reconstruction uses the most stations in reconstructing the SAM index for the post 1979 analysis period and has also been shown to be a better indicator of SAM than the longer JW reconstructions (Jones et al., 2009).

According to Jones et al. (2009) both the Fogt and JW58 reconstructions are most robust during the austral summer (DJF) due to the nature of the SAM being most zonally symmetric during this season. As the SAM's zonal symmetry begins to break down after summer, spring proved to be the most problematic season for SAM reconstructions, followed by winter and autumn, where a reduced number of stations could be utilised to reconstruct the index (Jones et al., 2009). Fogt reconstructions proved to be more reliable than the JW reconstructions during JJA and SON while both Fogt and JW reconstructions were deemed to be equally reliable in DJF and MAM (Jones et al., 2009).

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3.2 Rainfall data

The Australian Monthly Gridded Rainfall Dataset (1900–2008) from the Australian Bureau of Meteorology is used to compare the relationship between Australian surface rainfall and the various SAM indices. The gridded data has been generated from observed data using an optimized Barnes successive correction technique (Barnes, 1973) that applies a weighted averaging process to the station data.

4 Method

This analysis compares SAM indices and the sensitivity associated with choice of SAM index when seeking to quantify the relationship between Australian rainfall and SAM. SAM indices were compared on seasonal and, where possible, monthly resolutions. As the NOAA index is only available from 1979 onwards and the jisaoAAO is only complete to 2002, all indices were compared over the same period (1979 to 2002) via correlations and scatter plots. The scatter plots were all developed using the NOAA index as the point of reference. All indices were normalised on a seasonal, and where available a monthly, scale by subtracting the seasonal/monthly mean (calculated over the 1979 to 2002 period) and dividing by the seasonal/monthly standard deviation to enable all scatter plots to be easily comparable.

To quantify the sensitivity associated with choice of SAM index when seeking to quantify relationships between Australian rainfall and SAM two investigations were conducted:

1. On a seasonal resolution, correlation between the different SAM indices and Australian rainfall for the entire period that the relevant SAM index is available. As indicated in Table 1 some SAM indices exist prior to 1900, however, the analysis here is restricted to beginning in 1900 and ending in 2008 as that is when the gridded rainfall data is available;

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2. On a seasonal resolution, correlation between the different SAM indices and Australian rainfall for the period over which all of the SAM indices being investigated are available (i.e. 1979–2002), to enable equitable comparisons to be made. The NOAA index-rainfall correlations are used as the baseline index and the difference between the seasonal index-rainfall correlations and the NOAA index-rainfall correlations are determined.

5 Results

5.1 Comparison of seasonal and monthly SAM index values

Table 2 shows the correlations between the NOAA index and the remaining indices on a seasonal scale. All correlations are statistically significant at the 99th percentile.

Both jisao indices and the NOAA index are highly correlated. This result was somewhat expected given that the NOAA, jisaoSLP and jisaoAAO indices are all developed using the PC analysis method and NCEP-NCAR reanalysis pressure data. SAMI is also highly correlated to the NOAA and jisao indices, despite being based on the Gong and Wang (1999) method and this is perhaps because the SAMI also utilises NCEP-NCAR reanalysis pressure data. There is a clear difference between the indices based on gridded reanalysis data and the indices based on station observations (i.e. the Marshall and Visbeck indices). Marshall (2003) has previously shown that the use of NCEP-NCAR data exaggerates trends in the SAM signal by a factor of two or three, especially in winter, due to the nature of the NCEP-NCAR reconstructions, whose errors increase at higher latitudes when compared with station data. Of the indices available prior to 1950 (i.e. Fogt, JW58, Visbeck), Visbeck is the most highly correlated with the NOAA index (used as the reference point in this study as it utilises gridded data that is based on a mixture of satellite data and observed surface data). The notable difference between the Visbeck index and both the Fogt and JW58 indices is that the Visbeck index uses a method of reconstructing sea level pressures in the

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mid-latitudes in order to gain insights into SAM behaviour and hence create a physically based extended SAM index record prior to the availability of continuous station records. In contrast to the physically based Visbeck method, the Fogt and JW reconstructions (note that as previously discussed in Sect. 3.1.7, JW58 is the only JW index assessed in this paper) were based on statistical regression models developed using long-term station data (starting as far back as 1865) as predictors and relationships between the Marshall index (for Fogt) and ERA-40 MSLP PC (for JW).

To further investigate the similarities and differences between the various SAM indices in comparison to the NOAA index, scatter plots of the normalised SAM index values against the normalised NOAA index were developed. Figure 1 shows the seasonal index values plotted against the corresponding seasonal NOAA index value for the same time period (1979–2002). Many hydroclimatic studies are however focused on sub-seasonal timescales, where monthly and weekly information on climate states are required for historical investigations as well as for forecasts. Therefore it is also necessary to compare monthly SAM indices and, for the SAM indices that are available at a monthly resolution (see Table 1), this is shown in Fig. 2.

For both Figs. 1 and 2 consistency between indices (i.e. the NOAA index and the SAM index being compared) is depicted by a clustering of data points around the 1:1 gradient and, importantly, no data points in the second and fourth quadrants. Data points in the second and fourth quadrants indicate a complete disagreement from the indices as to what the SAM phase is for a given season (i.e. one index is suggesting positive SAM conditions while the other is indicating negative SAM). This is of concern as it indicates the choice of index may result in the phase of SAM being incorrectly identified which could lead to misrepresentation of SAM's influence and incorrect attribution of hydroclimatic variability to SAM behaviour.

Figure 1 shows similar patterns to Table 2, in that all indices correlate well with NOAA except Fogt and JW58 and, to a lesser degree, Visbeck. In particular, the jisaoAAO and jisaoSLP show little variation in comparison to the NOAA index, however, there is an increasing degree of scatter for the Marshall, SAMI and Visbeck indices. It also

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appears that the NOAA index is often greater in magnitude than either the Marshall or Visbeck indices. Figure 1f (Fogt against NOAA) and 1g (JW58 against NOAA) show an increased number of data points recorded in the second and fourth quadrants, indicating a high degree of inconsistency with the NOAA index. The results are replicated at the monthly resolution (Fig. 2) suggesting that a SAM index that is acceptable at the seasonal scale will also work in a similar fashion at the monthly scale.

The results from Figs. 1 and 2 indicate that if you were to characterise the relationship between SAM and hydroclimatic variability at a given location then you could expect similar results if you used the NOAA, jisaoAAO, jisaoSLP SAM indices, slightly different results if you used Marshall, SAMI or Visbeck, and extremely different results if you used Fogt or JW58 (indeed in some cases the results obtained using Fogt and JW58 would be the direct opposite to those obtained using any of the other indices). This highlights the importance of acknowledging the subjectivity, and quantifying the uncertainty, associated with choice of climate index (e.g. Kiem and Franks, 2001; Verdon and Franks, 2005).

5.2 Seasonal relationships between various SAM indices and Australian rainfall

In order to assess the inconsistencies resulting from the subjectivity associated with choice of SAM index, an investigation into the differences in the relationship between Australian rainfall and SAM, as represented by the various SAM indices, was undertaken. It is important to note that correlations are only used in this study to identify the differences between the SAM indices (i.e. in a comparative study), not to establish relationships between SAM and Australian rainfall. The limitations associated with using correlations in establishing hydroclimatic relationships are discussed in Sect. 6.

SAM is a climate mechanism that has varying seasonal impacts. It is therefore necessary to consider the correlations between seasonal SAM indices and seasonal rainfall and the results for this are presented in the following sections. Note that for each season and SAM index the period of analysis corresponds with the period of SAM index availability (i.e. different periods of analysis for each SAM index). As such the results from index to index are not directly comparable but again illustrate the different results obtained based purely on choice of SAM index. Section 5.3 repeats the analysis over a consistent period, 1979–2002 where all SAM indices are available, to enable comparison of the relationship of various SAM indices and Australian rainfall with the uncertainties associated with length of SAM index availability removed.

5.2.1 Summer (DJF)

Figure 3 shows the correlation between summer SAM indices and summer rainfall over the period where both SAM and rainfall data are available. Broadly speaking, similar patterns are observed for the NOAA, jisaoAAO and jisaoSLP indices (consistent with Sect. 5.1) and these relationships (which are consistent with the results of Risbey et al., 2009) are totally different to those obtained using Fogt and JW58 indices. Also important to note is the fact that despite the SAM indices being very similar, the correlations between the NOAA, jisaoAAO and jisaoSLP indices and Australian rainfall are different, especially in central to eastern Australia. This is most likely due to the differences in the periods being analysed and strongly suggests SAM relationships vary over time and are possibly subject to multidecadal modulation via other climatic drivers. This could be similar to the way the IPO modulates the frequency and magnitude of ENSO impacts in Australia (e.g. Power et al., 1999; Kiem et al., 2003; Kiem and Franks, 2004; Verdon et al., 2004).

5.2.2 Autumn (MAM)

As with summer, there are significant similarities and differences observed in the relationship between autumn rainfall and SAM depending on the choice of SAM index (Fig. 4). Autumn rainfall correlations with SAM indices all show negative correlations in south-east Australia (consistent with the finding of Kiem and Verdon-Kidd (2010), who showed the positive phase of SAM was strongly related to a decrease in SEA autumn rainfall). A negative correlation in SWWA is seen in all of the gridded and station data based indices (Fig. 4a–e) as well as Tasmanian rainfall with the exception of the NOAA index in the latter case. Positive correlations between autumn rainfall and SAM are also found for northern Australia (to varying degrees depending on choice/length of SAM index). This is consistent with Meneghini et al. (2007) who found significant correlations in autumn were located in northern and north-west central Australia. However, as with summer, the Fogt and JW58, and also Visbeck, (Fig. 4f–h) show a markedly different pattern with positive correlations in SWWA and also clear differences in central Australia and SEA.

5.2.3 Winter (JJA)

Figure 5 shows the correlation between winter SAM indices and winter rainfall over the period where both SAM and rainfall data are available. Negative correlations between winter rainfall and winter SAM indices are a consistent feature for SWWA and SEA, including Tasmania, which supports the work of Risbey (2009). However, the magnitude and spatial extent of relationship varies markedly dependent on SAM index and the patterns for the remainder of Australia are noticeably inconsistent. Interestingly, Meneghini et al. (2007) found significant positive correlations between SAM and eastern Australia rainfall during winter, however similar results are only indicated here when the Marshall, Visbeck or JW58 index is used (Fig. 5d, f, h) whereas the jisaoAAO, jisaoSLP and SAMI indices show the complete opposite. This again highlights the fact that completely different insights can be obtained dependent on (a) which index you choose and (b) the period of time over which you investigate the relationship.

5.2.4 Spring (SON)

Figure 6 shows the correlation between spring SAM indices and spring rainfall over the period where both SAM and rainfall data are available. All of the SAM indices are negatively correlated to spring rainfall in western Tasmania, the southern coast of Victoria, and SWWA. The dominance of positive correlations between spring SAM and

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spring Australian rainfall is consistent with previous work by Hendon et al. (2007) and Risbey et al. (2009) but inconsistent with the study by Meneghini et al. (2007). Although the correlation patterns between spring rainfall and spring SAM indices appear to be similar for all the indices, there is still variability between the indices with respect to the strength and spatial extent of positive or negative correlations.

The results displayed in Fig. 3 through to Fig. 6 are based on data over the longest period of rainfall and SAM index data availability. As a result, some correlations are based on up to 106 yr of data, while others are based on as little as 30 yr of data. This analysis was carried out simply to illustrate that different relationships are obtained when various SAM indices when are correlated with Australian rainfall over various time periods. This is a fairly obvious result but one that is often overlooked as SAM indices are used interchangeably or teleconnections obtained using one SAM index over a certain time period are assumed to represent the relationship between SAM and Australian rainfall in the past, now and in the future. As mentioned in Sect. 5.2.1, and as demonstrated by these results, the potential multi-decadal modulation of the frequency and magnitude of SAM impacts is an area that requires further investigation, however this is beyond the scope of this paper. The focus here is to quantify the sensitivity of SAM-rainfall relationships to SAM index choice and to do that it is necessary to perform the analysis over a consistent baseline period (see Sect. 5.3).

5.3 Differences between SAM indices and rainfall relationship (1979–2002)

In order to make equitable comparisons between the relationships of each SAM index with Australian rainfall, each SAM index (seasonal resolution) was correlated with Australian rainfall from 1979–2002 (i.e. the period for which all SAM indices exist). To enable distinctions between the indices to be made, the NOAA index (correlated with rainfall) was used as the baseline. Figure 7 through to Fig. 10 show the difference between each SAM index correlated with rainfall and the correlation of the NOAA index with rainfall for each season. Figure a) in the difference maps in Sect. 5.4 is comparing NOAA with NOAA and therefore always results in zero difference. The NOAA index

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correlation (i.e. the reference point) for each season can be seen in Figs. 3a, 4a, 5a, and 6a.

Consistent with results presented in Sect. 5.1, jisaoAAO, jisaoSLP and the SAMI correlations with rainfall are similar to the NOAA correlations (as indicated by the pale colours on the correlation maps) for summer (DJF), autumn (MAM) and spring (SON) but large discrepancies are observed in winter (JJA). The Marshall and Visbeck correlations with rainfall are similar to each other, but both are different to the NOAA correlations. Also consistent with previous results, the Fogt and JW58 reconstructed indices result in totally different relationships to what is obtained if NOAA is used – this is consistent across all seasons.

6 Discussion and conclusions

The results presented here demonstrate that, despite supposedly representing the same physical process, there are differences in the various indices used to represent SAM which are dependent on the method, variable, or source of data used to develop the index. In some cases (e.g. Fogt and JW58) these differences are marked and lead to large uncertainty as to whether the SAM is in its positive or negative phase. Sections 5.2 and 5.3 demonstrate the implications of this uncertainty when trying to determine the seasonal relationship between SAM and Australian rainfall. Indeed, the magnitude and spatial pattern of the relationships vary drastically depending on the SAM index chosen. Therefore, given the numerous studies that have suggested that SAM is responsible for at least some of Australia's hydroclimatic variability, and the fact that the results and conclusions in these previous studies are not always consistent, the following questions emerge: (a) which SAM index most satisfactorily represents what we know as the SAM process?; (b) what is the true relationship between SAM and Australia's temporal and spatial hydroclimatic variability?; and (c) how is SAM related to, or how does SAM interact with, other large-scale (e.g. ENSO, IOD, IPO) climate drivers and local-scale weather patterns known to influence Australian hydroclimatology?

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To answer the first question, numerous studies have shown that the SAM annular structure is best characterised by MSLP, 700 hPa or 850 hPa GpH measurements, with readings at latitudes 40° S and 65° S being the most suitable for identifying the nature of SAM (Gong and Wang, 1999). Given this physical basis, it then follows that the NOAA and jisaoAAO could be considered good indicators of SAM behaviour, since they are based on the physical understanding outlined above. As discussed in Sect. 5.1, the jisaoSLP and SAMI are also very similar (Table 2, Fig. 1, 2) to NOAA and jisaoAAO implying that NOAA, jisaoAAO, jisaoSLP or SAMI could be used with equal confidence to represent SAM – noting that NOAA is only available from 1979 (whereas the other three are available from 1948) and jisaoAAO is not available after 2002. A common factor between NOAA, jisaoSLP, jisaoAAO and SAMI is the use of NCEP-NCAR reanalysis data. The advantage of reanalysis data is the availability of information with a broader spatial coverage (as opposed to station based data which is somewhat limited in the Southern Hemisphere). However, Marshall (2003) warns that spurious trends exist in the reanalysis data and that the strengthening SAM signal observed over past decades is magnified by a factor of two to three in the NCEP-NCAR reanalysis data. Also, seasonal analysis using NCEP-NCAR data incorrectly identifies the greatest increasing SAM trends as occurring in winter instead of summer due to winter reanalysis data being particularly poor. While this does not necessarily mean that SAM indices based on reanalysis data are flawed, it does highlight the fact that reanalysis data is effectively modelled data and relationships obtained using reanalysis based SAM indices should be verified with observational (i.e. station based) data.

SAM indices based on station records of pressure at 40° S and 65° S (Gong and Wang, 1999) are most likely to have the most accurate representation of SAM, but are limited to periods when good quality stations are available. The Visbeck and Marshall indices are both developed using station based data as opposed to reanalysis data. In the case of the Visbeck index, the issue of limited data is partially resolved through the use of reconstructed pressure readings, which introduces another source of uncertainty (Visbeck, 2009). The results in Sect. 5.1 (Table 2, Figs. 1, 2) indicate that the

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Visbeck and Marshall indices are not dissimilar to each other or to the reanalysis-based representations of SAM (correlations of about 0.9 in all cases) that were previously mentioned as being realistic (i.e. NOAA, jisaoSLP, jisaoAAO and SAMI). However, the results in Sect. 5.2 and 5.3 clearly illustrate that these minor differences in station-based and reanalysis-based indices result in marked inconsistencies in the magnitude and spatial pattern of the SAM relationship with Australian rainfall. Therefore, this raises the question – which is the most reflective of the true relationship? In our opinion, and especially considering the issues associated with SAM representation in the reanalysis data (Marshall, 2003), the station-based SAM indices are most reliable (i.e. Marshall or Visbeck). Given the uncertainties associated with the reconstructed pressure readings in the Visbeck index our recommendation is to use the Marshall index when it exists (1957–2011) and the Visbeck index if analyses are required prior to that.

Following on from that, and with respect to the question as to the true relationship between SAM and Australian rainfall (i.e. question (b)), it should be noted that the majority of correlations between SAM and Australian rainfall are between −0.3 and 0.3 (Sects. 5.2 and 5.3), and therefore not statistically significant. However, it should also be recognised that the lack of a significant correlation does not neccessarily mean that there is no relationship between SAM and Australian rainfall. It just may be that the relationship is non-linear, non-stationary or modulated by other factors (Hendon et al., 2007; Verdon-Kidd and Kiem, 2009b; Gallant et al., 2011). Therefore, further investigation is required into the non-linear, and potentially non-stationary, nature of SAM impacts and novel methods need to be developed to gain insights into how SAM is related to, or interacts with, other large-scale (e.g. ENSO, IOD, IPO) climate drivers and local-scale weather patterns known to influence Australian hydroclimatology (i.e. question (c) posed above).

Climate indices are a practical way of approximating large-scale climate phenomena. The climate indices can then be used in empirical studies aimed at improving our understanding into the causal processes behind observed hydroclimatic variability. However, this only works if (a) the index is a realistic approximation of the climate

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process and (b) the empirical relationships developed using the index are physically real. It is important to realise that all indices are approximations and the "best" index, if there is such a thing, will depend on what you are using the index for. Importantly, this study has highlighted that it is crucial to be aware of the differences in the various SAM indices and to consider the fact that insights gained using climate index based analysis could be just an artefact of the index chosen (this applies equally to indices of climate modes other than SAM). It is critical to consider and account for this uncertainty in any climate impact attribution study and also in climate model verification and performance assessments if misunderstandings are to be avoided. It is also questioned whether it is sensible to assume that an index based on a single variable can ever be truly representative of the SAM process or whether more comprehensive multivariate monitors of the SAM state are required. Perhaps something similar to the Multivariate ENSO Index (MEI; Wolter and Timlin, 1993; 1998), which has been shown to more realistically and more consistently capture the entire ENSO phenomenon and its related impacts in Australia (e.g. Kiem and Franks, 2001), could be explored.

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Table 1. Summary of SAM index development methods and periods of availability.

		NOAA	jisaoAAO	jisaoSLP	Marshall	SAMI	Visbeck	Fogt	JW58
Method	PC reanalysis	x	x	x				x	x
	Gong and Wang				x	x	x		
Source	Station readings				x		x	x	
	Gridded data[a]	x	x	x		x			x
Variable	Sea level pressure			x	x	x	x	x	x
	700 hPa GpH	x							
	850 hPa GpH		x						
Period	Start Year	1979	1948	1948	1957	1948	1887	1865[b]	1958
	End Year	2011[c]	2002	2011[c]	2011[c]	2011[c]	2005	2005	2005
Time scale	Monthly	x	x	x	x	x	x		
	Seasonal							x	x

[a] NCEP-NCAR gridded data except for JW58, where ERA-40 data is used.
[b] 1865 for summer and autumn; 1905 for winter and spring.
[c] Updated monthly.

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Table 2. Correlation between various SAM indices at a seasonal resolution (normalised for 1979–2002).

	NOAA	jisaoAAO	jisaoSLP	Marshall	SAMI	Visbeck	Fogt	JW58
NOAA	1	0.981	0.968	0.903	0.945	0.890	0.670	0.712
jisaoAAO		1	0.989	0.893	0.955	0.897	0.650	0.704
jisaoSLP			1	0.895	0.961	0.911	0.643	0.695
Marshall				1	0.880	0.880	0.700	0.695
SAMI					1	0.874	0.686	0.677
Visbeck						1	0.642	0.670
Fogt							1	0.784
JW58								1

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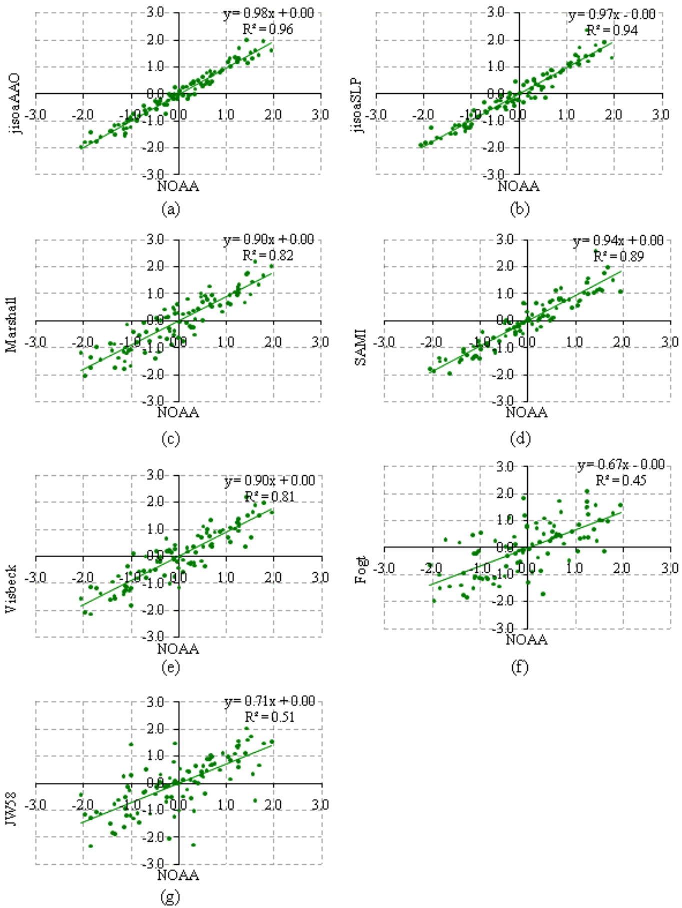

Fig. 1. Seasonal SAM index values plotted against seasonal NOAA index (normalised 1979–2002) for **(a)** jisaoAAO; **(b)** jisaoSLP; **(c)** Marshall; **(d)** SAMI; **(e)** Visbeck; **(f)** Fogt; **(g)** JW58.

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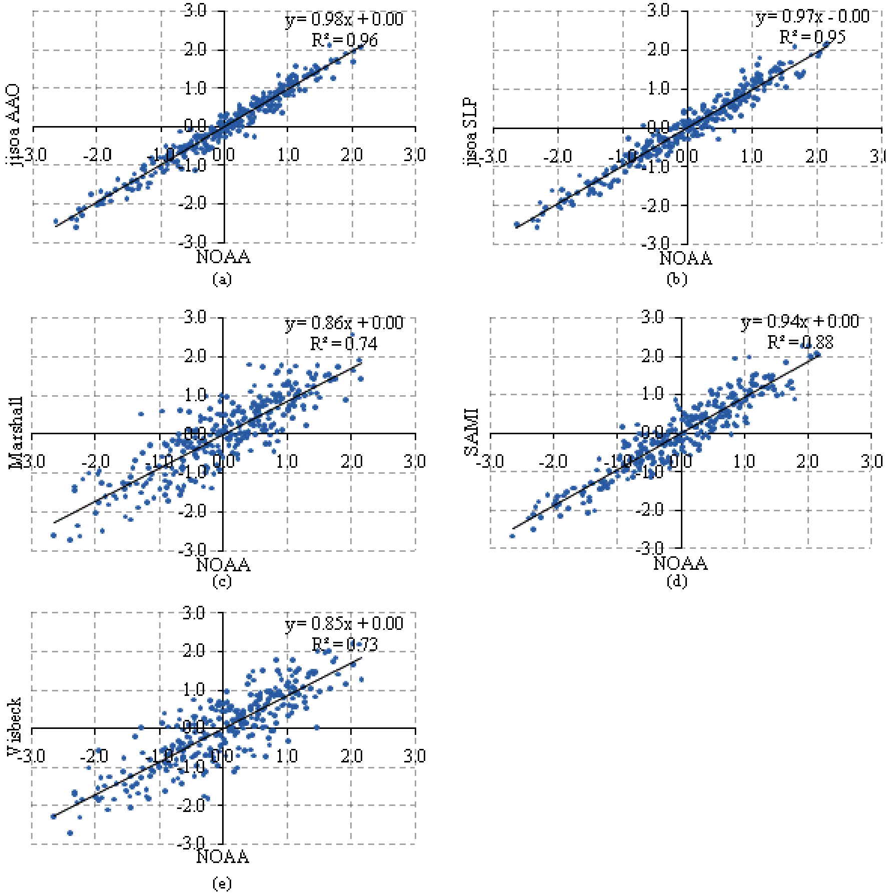

Fig. 2. Monthly SAM index values plotted against monthly NOAA index (normalised 1979–2002) for **(a)** jisaoAAO; **(b)** jisaoSLP; **(c)** Marshall; **(d)** SAMI; **(e)** Visbeck; **(f)** Fogt; **(g)** JW58.

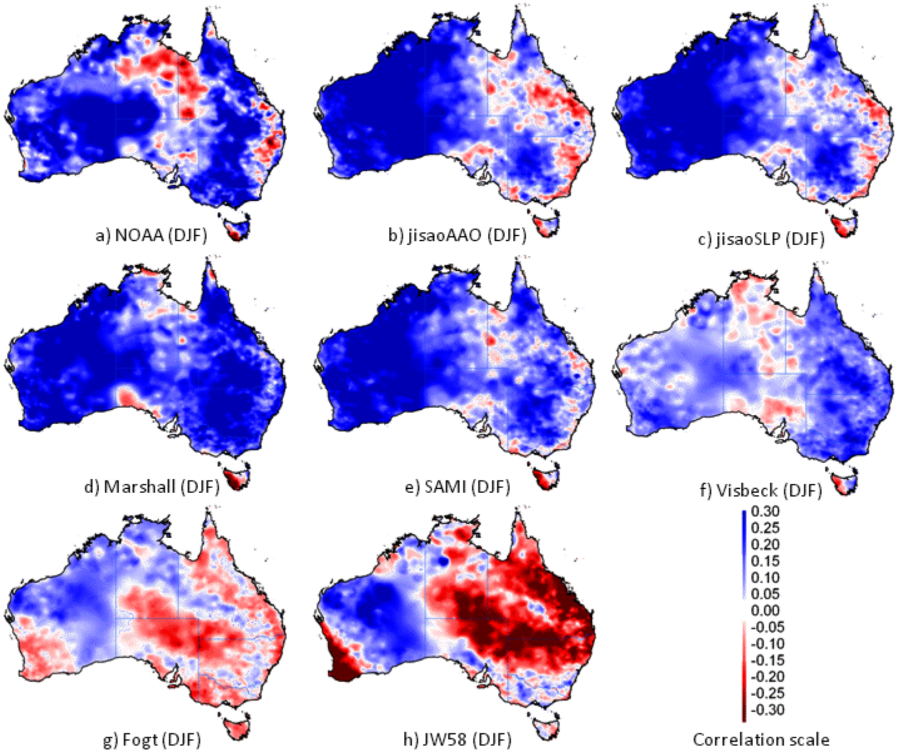

Fig. 3. Correlations between total summer (DJF) rainfall and summer SAM indices **(a)** NOAA (1979–2008); **(b)** jisaoAAO (1948–2002); **(c)** jisaoSLP (1948–2008); **(d)** Marshall (1957–2008); **(e)** SAMI (1948–2008); **(f)** Visbeck (1900–2005); **(g)** Fogt (1900–2004); **(h)** JW58 (1958–2004).

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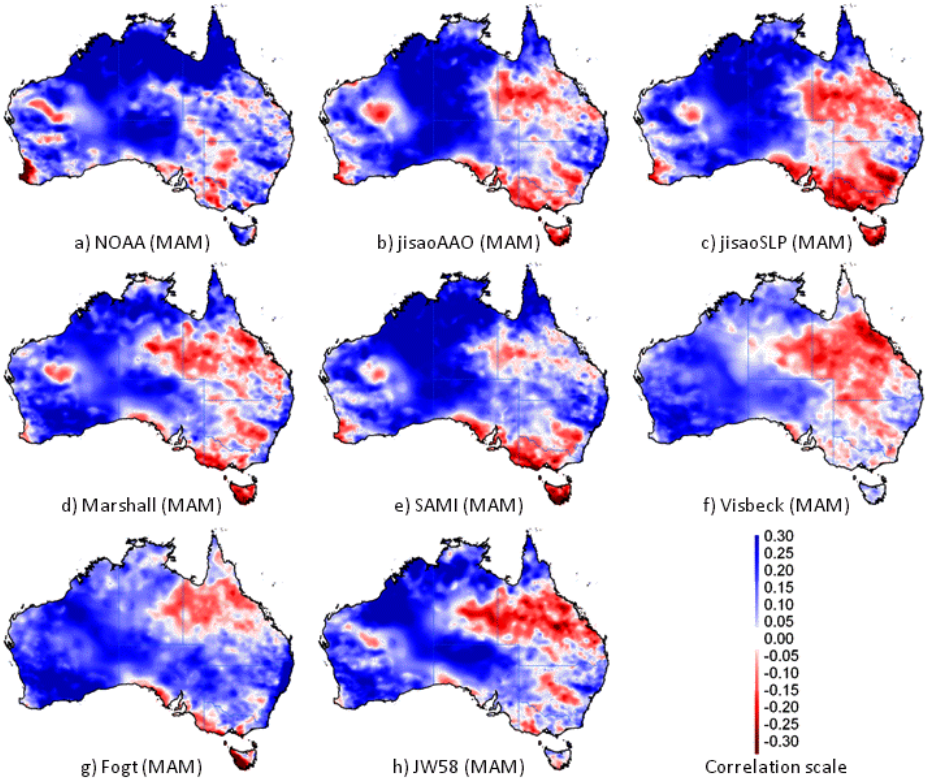

Fig. 4. Correlations between total autumn (MAM) rainfall and autumn SAM indices **(a)** NOAA (1979–2008); **(b)** jisaoAAO (1948–2002); **(c)** jisaoSLP (1948–2008); **(d)** Marshall (1957–2008); **(e)** SAMI (1948–2008); **(f)** Fogt (1900–2005); **(g)** Visbeck (1900–2005); **(h)** JW58 (1958–2005).

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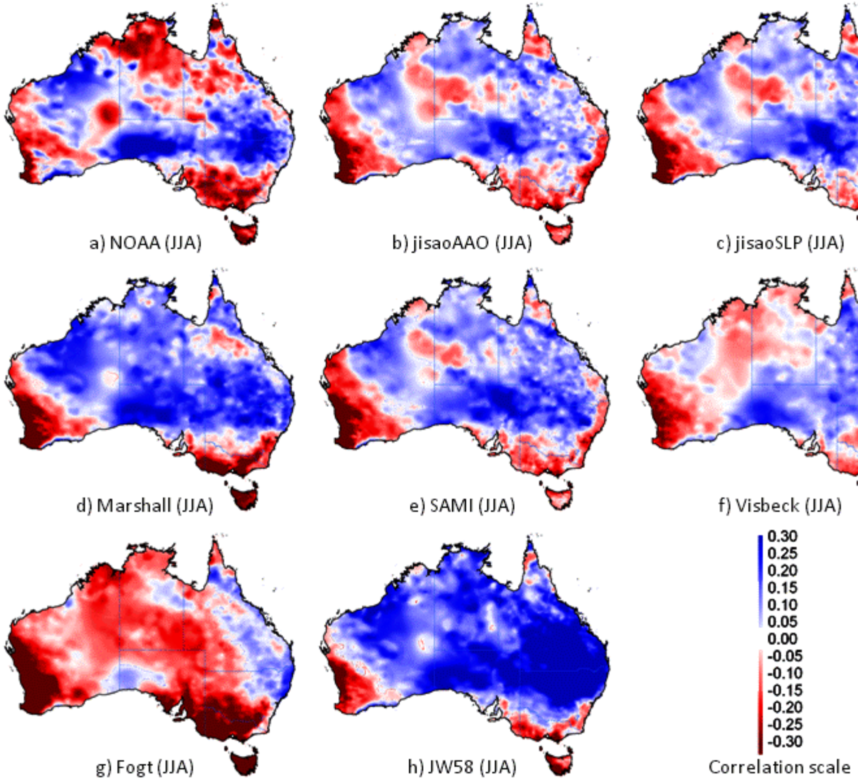

Fig. 5. Correlations between winter (JJA) rainfall and winter SAM indices **(a)** NOAA (1979–2008); **(b)** jisaoAAO (1948–2002); **(c)** jisaoSLP (1948–2008); **(d)** Marshall (1957–2008); **(e)** SAMI (1948–2008); **(f)** Visbeck (1900–2005); **(g)** Fogt (1905–2005); **(h)** JW58 (1958–2005).

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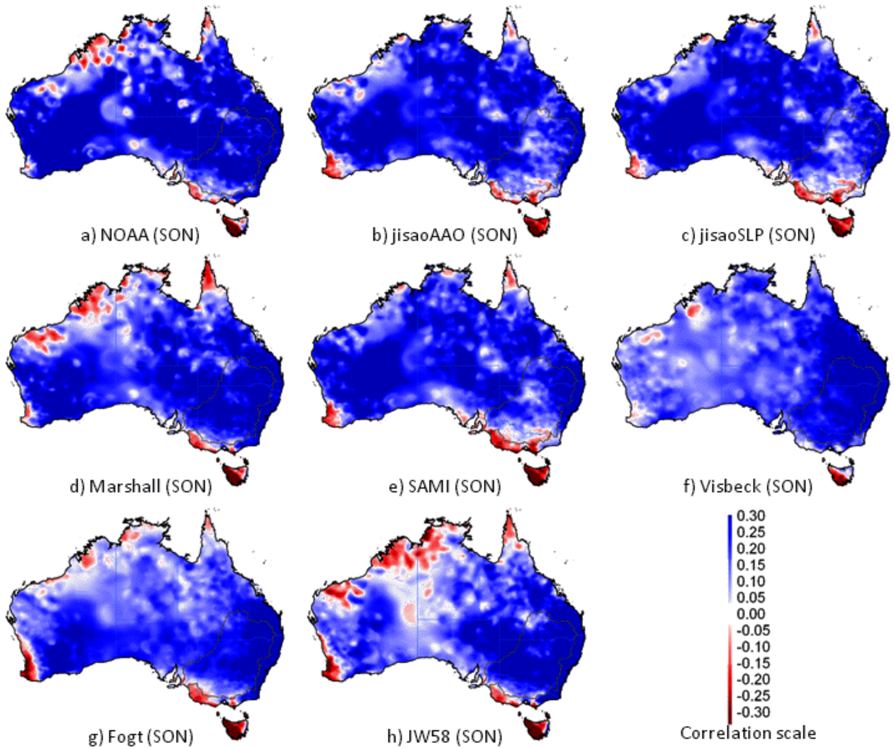

Fig. 6. Correlations between total spring (SON) rainfall and spring SAM indices **(a)** NOAA (1979–2008); **(b)** jisaoAAO (1948-2002); **(d)** jisaoSLP (1948–2008); **(d)** Marshall (1957–2008); **(e)** SAMI (1948-2008); **(f)** Visbeck (1900–2005); **(g)** Fogt (1905–2005); **(h)** JW58 (1958–2005).

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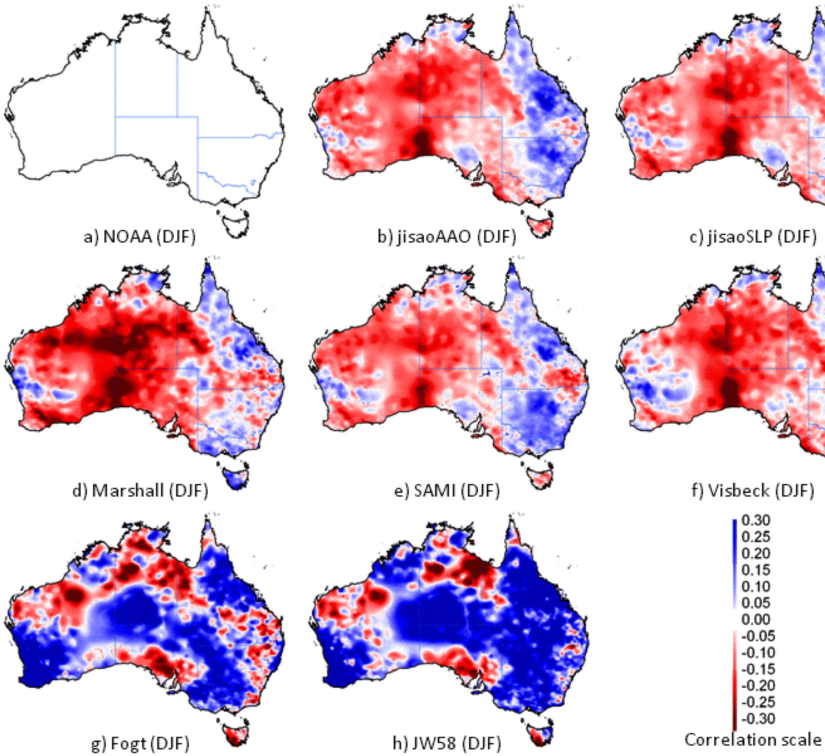

Fig. 7. Difference between summer NOAA index-rainfall correlation and summer SAM index-rainfall correlations for the period 1979–2002 for **(b)** jisaoAAO; **(c)** jisaoSLP; **(d)** Marshall; **(e)** SAMI; **(f)** Visbeck; **(g)** Fogt; **(h)** JW58.

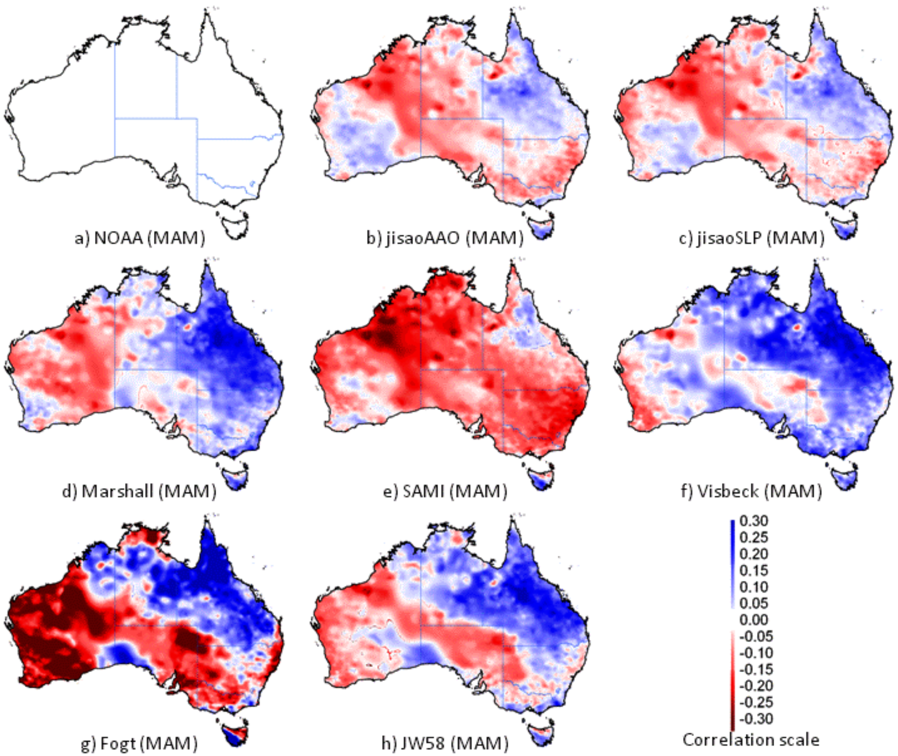

Fig. 8. Difference between autumn NOAA index-rainfall correlation and autumn SAM index-rainfall correlations for the period 1979–2002 for **(b)** jisaoAAO; **(c)** jisaoSLP; **(d)** Marshall; **(e)** SAMI; **(f)** Visbeck; **(g)** Fogt; **(h)** JW58.

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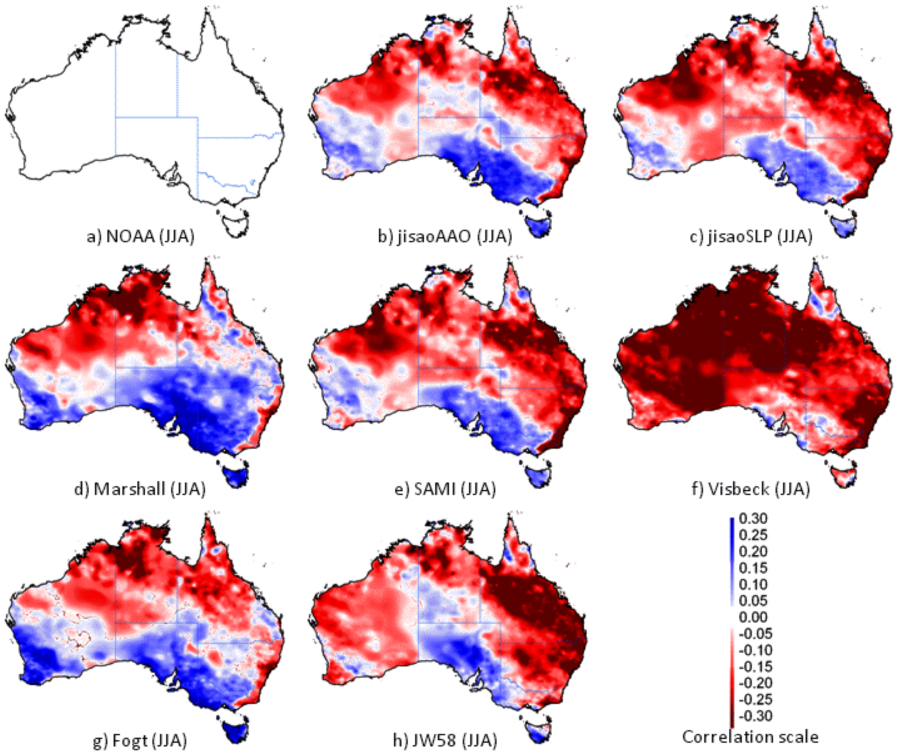

Fig. 9. Difference between winter NOAA index-rainfall correlation and winter SAM index-rainfall correlations for the period 1979–2002 for **(b)** jisaoAAO; **(c)** jisaoSLP; **(d)** Marshall; **(e)** SAMI; **(f)** Visbeck; **(g)** Fogt; **(h)** JW58.

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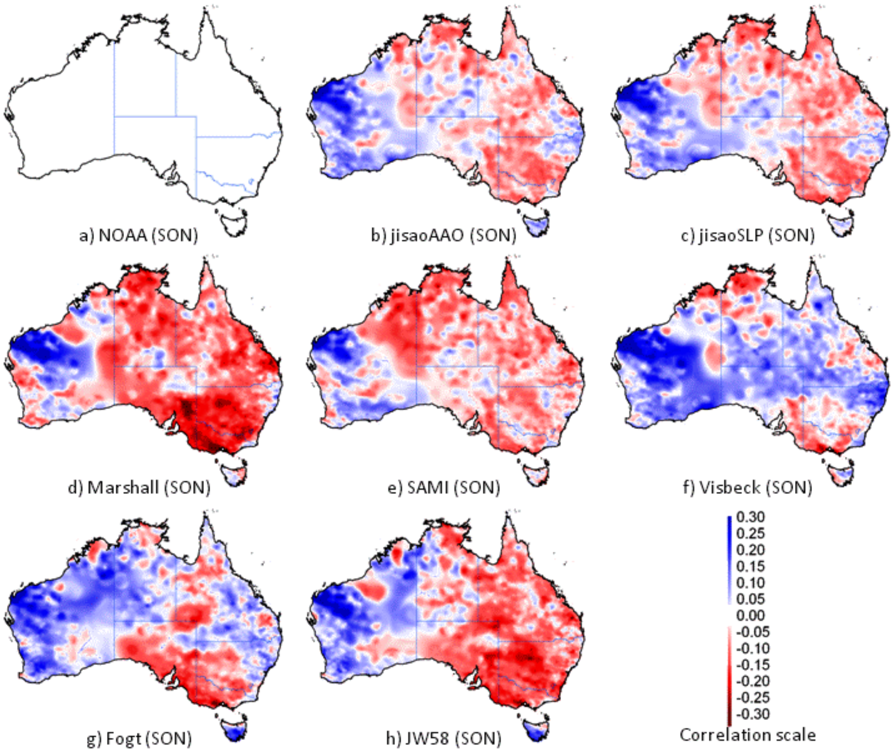

Fig. 10. Difference between spring NOAA index-rainfall correlation and spring SAM index-rainfall correlations for the period 1979–2002 for **(b)** jisaoAAO; **(c)** jisaoSLP; **(d)** Marshall; **(e)** SAMI; **(f)** Visbeck; **(g)** Fogt; **(h)** JW58.

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