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Links between the Big Dry in Australia and hemispheric multi-decadal climate variability – implications for water resource management

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Abstract

Southeast Australia (SEA) experienced a protracted drought during the mid-1990s until early 2010 (known as the Big Dry or Millennium Drought) that resulted in serious environmental, social and economic effects. This paper analyses a range of historical climate data sets to place the recent drought into context in terms of Southern Hemisphere inter-annual to multi-decadal hydroclimatic variability. The findings indicate that the recent Big Dry in SEA is in fact linked to the widespread Southern Hemisphere climate shift towards drier conditions that began in the mid-1970s. However, it is shown that this link is masked because the large-scale climate drivers responsible for drying in other regions of the mid-latitudes since the mid-1970s, did not have the same effect on SEA during the mid to late-1980s and early-1990s. More specifically, smaller-scale synoptic processes resulted in elevated autumn and winter rainfall (a crucial period for SEA hydrology) during the mid to late-1980s and early-1990s, which punctuated the longer term drying. From the mid-1990s to 2010 the frequency of the synoptic processes associated with elevated autumn/winter rainfall decreased, resulting in a return to drier than average conditions and the onset of the Big Dry. The findings presented in this paper have marked implications for water management and climate attribution studies in SEA, in particular for understanding and dealing with “baseline” (i.e. current) hydroclimatic risks.

1 Introduction

1.1 The Big Dry and other protracted droughts in Australia’s history

Australia, with its naturally highly variable climate, is no stranger to drought conditions. For example, the Federation Drought (~ 1895–1902) was associated with drought conditions covering the majority of the eastern two thirds of Australia (Verdon-Kidd and Kiem, 2009a). From 1937–1945 Southeast Australia (SEA) was subjected to another

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multi-year drought, known as the World War II Drought, while more recently the Big Dry (or Millennium Drought) affected SEA during the mid-1990s through to early 2010 and resulted in a marked reduction in rainfall and runoff (NWC, 2006; Murphy and Timbal, 2008; Verdon-Kidd and Kiem, 2009a, b; Kiem and Verdon-Kidd, 2010; Gallant et al., 2012). In addition to the multi-year droughts mentioned, a number of shorter, equally intense droughts have also occurred during SEA's instrumental history (e.g. 1914–1915, 1965–1968 and 1982–1983).

In terms of annual rainfall deficits the Big Dry has been shown to be more severe in parts of SEA than the earlier multi-year droughts for durations 3–19 yr (CSIRO, 2012); however the Federation and World War II droughts were more widespread (Verdon-Kidd and Kiem, 2009a). The Big Dry was also characterised by a lack of high one-day rainfall totals (Murphy and Timbal, 2008; Verdon-Kidd and Kiem, 2009a) and wet months (CSIRO, 2012), which is consistent with a reduction in the amount of rainfall associated with cut-off low pressure systems over this period (Pook et al., 2006) and an absence of persistent pre-frontal troughs that aid the penetration of rain producing cold fronts into SEA (Verdon-Kidd and Kiem, 2009b; Alexander et al., 2010). There is considerable debate about the causes of the Big Dry. For example Verdon-Kidd and Kiem (2009a) attribute the rainfall deficits primarily to the El Niño/Southern Oscillation (ENSO) and the Southern Annular Mode (SAM), while van Dijk et al. (2013) estimate that the latter part of the drought (2001–2009) was driven by ENSO with a small contribution by the Inter-decadal Pacific Oscillation (IPO). Others (e.g. Timbal et al., 2010) attribute the drought to an intensification of the Subtropical Ridge.

In 2010/2011, a strong La Niña combined with warm sea surface temperatures (SSTs) off north-western Australia (i.e. a negative Indian Ocean Dipole – IOD – event) resulted in wet austral spring/summer conditions across much of SEA, providing relief from the extended drought. A second La Niña event followed in 2011/2012 which resulted in average to above average rainfall across much of SEA from mid-spring to early autumn and further replenished water storages.

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1.2 The Big Dry in the context of other Southern-Hemisphere droughts

It has been suggested that the Big Dry in SEA has similarities to the extended dry spell that began in the late-1960s/mid-1970s in south-west Western Australia (SWWA) (e.g. Hope et al., 2009; IOCI, 2002) and has continued to the present time, with a possible intensification occurring from the mid-1990s (Hope et al., 2006). Indeed, both regions exhibit a common winter-maximum rainfall regime, with peak rainfall occurring from May to October, and rainfall variability (on a synoptic to interannual scale) in the two regions is significantly related, with rainfall during May, June and July being significantly correlated (Hope et al., 2009). However, while both regions have experienced reduced cool season rainfall, the timing with respect to the start of the decreased rainfalls is not consistent. For example, in SWWA average winter (June–August) rainfall totals have decreased by approximately 20 % since the 1970s, while in Victoria the decreased rainfalls trend occurred mostly from the mid-1990s, predominantly during late autumn and early winter (a decrease of approximately 20 % during 1997–2010 relative to the historic average) (e.g. Murphy and Timbal, 2008; Hope et al., 2009; Verdon-Kidd and Kiem, 2009a; Gallant et al., 2012). The decreased rainfalls in SWWA have been linked to a reduction in winter storm formation, with the growth rate of the leading storm track modes affecting southern Australia being more than 30 % lower during the period 1975–1994 compared to the period 1949–1968 (Frederiksen et al., 2005, 2007). The differences in timing of the decreases between SWWA and SEA make it unclear as to whether the post mid-1970s SWWA climate shift is related to or independent of the mid-1990s to early-2010 SEA Big Dry.

The mid-1970s corresponds to a period of change in ocean-atmospheric processes of the Pacific Ocean (i.e. ENSO and the Inter-decadal Pacific Oscillation (IPO)), which have resulted in more frequent droughts for much of eastern Australia (Power et al., 1999; Kiem and Franks, 2004; Verdon and Franks, 2006). There is also evidence that generalised warming across the Indian Ocean since the mid-1970s may be linked to the decreased rainfalls in SWWA (Verdon and Franks, 2005; Samuel et al., 2006).

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The mid-1940s and mid-1920s relate to periods of significant climatic shifts in the Pacific and Indian Ocean regions, highlighting the fact that the mid-1970s climate shift is not an isolated event (Mantua et al., 1997; Power et al., 1999; Kiem et al., 2003; Verdon and Franks, 2006). It has also been shown that inter-annual to multi-decadal variability not only affects Australia, with numerous studies identifying similar dry and wet epochs in other regions of the Southern Hemisphere. For example, a regime shift in New Zealand's climate around 1976 has also been identified (Salinger and Mullan, 1999), with the 1976–1994 period characterised by annual rainfall decreases in the north of the North Island, and increases in much of the South Island, except the east. An earlier shift in New Zealand's climate was also observed in the early-1950s, where the period 1951–1975 was characterised by increased rainfall in the north of the North Island, particularly in autumn, with rainfall decreases in the southeast of the South Island, especially in summer (Salinger and Mullan, 1999). In Southern Africa, overall moist conditions were reported between 1960 and 1970 and since then a switch to drier conditions has been noted (Ngongondo, 2006). Western Africa (in the Northern Hemisphere), which regularly experiences protracted drought conditions, has also experienced an extreme drought known "the Sahel Drought" beginning in the 1970s (Hulme, 1992), continuing to the present. Recent research by Van Ommen and Morgan (2010) reported a significant inverse correlation between the records of precipitation at Law Dome, East Antarctica and SWWA over the instrumental period. In particular, since the mid-1970s rainfall has increased at Law Dome, while rainfall has decreased in SWWA.

The apparent connection between rainfall in SWWA and East Antarctica, along with the similar timing of climate shifts in Southern Africa and New Zealand, provides evidence to suggest synchronicity in climate shifts occurs in the Southern Hemisphere. These observations also highlight the presence of climate phases/cycles that operate over multi-decadal timescales. Yet it is still unclear how/if the Big Dry in SEA is related to these hemispheric changes.

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1.3 Managing the Big Dry and future water availability of the SEA region

Resource managers in the water and agricultural sectors across SEA have a long history of dealing with climate variability. During the early-mid-1990s, at both the national and state level, significant effort went into ensuring drought preparedness and the development of effective drought response strategies. However, the unprecedented severity and duration of the Big Dry "stress-tested" these processes. In terms of the water entitlement, and water planning and management framework in Victoria, existing drought response processes served well during the early part of the drought. However, 2006 saw the lowest flows on record across most of the State and, from 2006–2009, additional contingency measures were required in some situations to ensure that essential water needs were met. These measures included water carting, groundwater bores, pumping from dead storage, qualification of rights to water, and changes to water sharing arrangements and water trading rules. In addition, the Victorian Government and water corporations invested in infrastructure and in water efficiency and conservation measures to augment supplies (DSE, 2012).

Recent research conducted under the South-eastern Australian Climate Initiative indicates that, while the Big Dry has broken, rainfall deficits during the cool season (April–October), which is the traditional filling season for water storages, have tended to persist (CSIRO, 2012). These changes have been shown to be associated with changes in the global atmospheric circulation via the expansion of the Hadley circulation (estimated at 50 km per decade) and associated increase in pressure in the sub-tropical ridge, resulting in mid-latitude storm tracks being "pushed" further south (CSIRO, 2012). The expansion of the Hadley Cell can only be reproduced by global climate models when human influences (in the form of greenhouse gases, aerosols and stratospheric ozone) are included, leading to the assertion that the expansion is at least partially attributed to anthropogenic climate change (CSIRO, 2012; Lucas et al., 2012). However, the exact cause of the expansion is highly debated. The width of the Hadley circulation is determined by the tropical tropopause height, pole-equator temperature

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difference and the global mean radiative equilibrium temperature (Hu and Fu, 2007). Each anthropogenic factor (i.e. greenhouse gases, aerosols and stratospheric ozone) impacts differently upon these dynamics – making it difficult to determine the relative importance of each. Model projections indicate that these trends are likely to continue, although the models tend to underestimate observed trends (e.g. Lu et al. 2007; CSIRO, 2012). There are therefore significant uncertainties about the timing and magnitude of associated reductions in mid-latitude rainfall. The overall implication, nevertheless, is that the traditional filling season for water supply systems across most of SEA, which historically was considered to run from about May to November, may not be as reliable in the future. Rather, replenishment of storages may in future be more dependent on warm season rainfall events which, in turn, will primarily depend on the status of the El Niño/Southern Oscillation (ENSO), the IOD and the Southern Annular Mode (SAM) (Verdon-Kidd and Kiem, 2009b; Gallant et al., 2012). However, future changes in these key climate influences (in particular ENSO) are also not certain, and it is unclear to what extent continuing reductions in cool season rainfall are likely to be offset by higher warm season rainfalls (which also suffer from higher evaporative losses). Without this understanding it is difficult to plan for future water availability in the region. For example, do we need to change the "baseline" estimation of climate to reflect an overall "new" drier climate state?

In the light of the experiences during the Big Dry and the significant uncertainties currently associated with future climate, adaptive management principles have been built into the water management and planning framework across SEA, and water trading arrangements have been modified, to assist in maintaining reliable water supplies in the face of a variable and changing climate (see for example McMahon et al., 2008; DSE, 2011; www.nccarf.edu.au/content/robust-optimization-urban-drought-security-uncertain-climate).

For example, in Victoria, prior to the Big Dry, the framework for maintaining an acceptable reliability of water supplies required water corporations to develop long-term strategies (aimed at balancing supply and demand over the next 50 yr) and comple-

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mentary short term drought response plans (aimed at managing short term deficits in supply) for each of the supply systems under their control. The flow scenarios considered over the 50 yr time frame included the continuation of historic conditions and low, medium and high climate change flow projections out 50 yr. These strategies were reviewed and updated every five years. As a consequence of the Big Dry, the possibility of the conditions of the drought returning in the immediate future, and persisting, is an additional scenario that is considered in long and short term planning processes. Given that flow reductions during the Big Dry exceeded medium to high climate change projections out to 2060, this means that a wide range of possible futures are considered. Water corporations are now also required to develop (in November every year) annual water security outlooks over a 1–5 yr time frame using a range of possible future flow scenarios and, in the light of an associated risk assessment, make decisions as to whether to implement any of the short or long term options to reduce demand and/or augment supplies. Water trading arrangements have also been modified to allow users to take allocations that are unused at the end of a season into the following season. This provides all water users – irrigators, urban water corporations, and environmental managers – with greater flexibility to manage their own water availability. All these measures help ensure an appropriate and timely response to variable and changing climatic conditions.

1.4 Objectives

This paper aims to establish if the Big Dry that impacted SEA from the mid-1990s to 2010 is related to the 1970s climate shift experienced in many regions of the Southern Hemisphere (Sect. 3) and in particular the step change in climate observed in SWWA (Sect. 4). The synoptic processes that contribute to the differences observed in SWWA and SEA since the 1970s are explored in Sect. 5, while the role of remote large-scale drivers are analysed in Sect. 6. Implications of the findings for water resource management in the region are analysed and discussed in Sect. 7 of the paper.

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2 Data

2.1 Gridded climate data

The daily NCEP/NCAR (National Centres for Environmental Prediction and the National Centre for Atmospheric Research) Reanalysis global gridded data sets (available 1948–present), from the US National Oceanic and Atmospheric Administration (NOAA, www.esrl.noaa.gov/psd/), are used to identify various synoptic patterns that influence the rainfall of SEA and to develop an understanding of Southern Hemisphere climatology during different climate epochs. The NCEP/NCAR Reanalysis data is derived from a global spectral model with a grid resolution of 2.5° latitude × 2.5° longitude global (144 × 73 grids). As with all reanalysis data, this data has various limitations, particularly in the Southern Hemisphere where historical recorded data tends to be sparse. Trenberth and Guillemot (1998) provide a review of limitations associated with the NCEP/NCAR reanalysis data, in particular the uncertainties inherent in the atmospheric moisture representation.

Gridded monthly precipitation data for Australia was obtained from the Australian Water Availability Project (AWAP), a joint initiative of the Bureau of Meteorology (BoM) and the Commonwealth Scientific and Industrial Research Organisation (CSIRO). In the daily/monthly AWAP dataset the observed daily/monthly rainfall from gauges within the BoM gauging network (i.e. up to approximately 7500 gauges, both open and closed) are decomposed into a monthly average and associated anomaly (Jones et al., 2009). The daily/monthly anomalies are interpolated using the Barnes successive correction technique, and the monthly climatological averages are interpolated using three dimensional smoothing splines (Jones et al., 2009). The rainfall grids are produced by multiplying the monthly climate average grids and daily/monthly anomaly grids. An unexplained microscale variance term is used in AWAP to allow for observational or measurement error, such that exact reproduction of gauged values at each gauge location is not expected (Jones et al., 2009). AWAP rainfall grids are freely available from 1900 onwards at http://www.bom.gov.au/jsp/awap/.

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2.2 Station-based rainfall data

The dry conditions during the Big Dry were largely confined to regions south of 30° (Verdon-Kidd and Kiem, 2009a). Therefore, in order to provide a spatial/geographical context to the recent dry conditions in SEA, and to ensure limitations of gridded rainfall datasets are not skewing our results (see Tozer et al., 2012), station-based rainfall data from regions south of 30° (shown in Fig. 1a) from the following data sets was also used:

- *Australia* – monthly station-based rainfall data was obtained from the Australian Bureau of Meteorology (http://www.bom.gov.au/climate/data/). Data chosen for analysis was at least 95 % complete and covered the period 1900–2009. Daily rainfall data was also obtained for eight stations located in SEA (see Fig. 1b) in order to further investigate the daily characteristics of the monthly rainfall totals (i.e. number of rain days, daily rainfall magnitude etc.). The stations chosen for analysis have sufficiently long records (i.e. at least 100 yr) and minimal missing data (at least 99 % complete).

- *New Zealand* – daily station data was obtained from the National Climate Database of the National Institute of Water and Atmospheric Research (NIWA, http://cliflo.niwa.co.nz/). Data chosen for analysis was at least 95 % complete and covered the period 1920–present. An additional station was chosen for analysis (located at Reefton on the west coast of New Zealand) that contained daily data from 1948 onwards in order to sufficiently represent the west coast of New Zealand, since the climatology there differs significantly from the east coast. Daily data was aggregated to monthly data prior to analysis.

- *South America and Southern Africa* – monthly rainfall data for South America and southern Africa was obtained from the Global Historical Climatology Network (GHCN, www.ncdc.noaa.gov/oa/climate/ghcn-monthly/index.php). The historical GHCN data has previously undergone rigorous quality assurance review (including pre-processing checks on source data, time series checks that identify spu-

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rious changes in the mean and variance, spatial comparisons that verify the accuracy of the climatological mean and the seasonal cycle, and neighbour checks that identify outliers from both a serial and a spatial perspective). GHCN-Monthly is used operationally by NCDC to monitor long-term trends in temperature and precipitation. It has also been employed in several international climate assessments, including the Arctic Climate Impact Assessment, and the "State of the Climate" report published annually by the Bulletin of the American Meteorological Society.

Despite the level of quality assurance, the rainfall data available through the GHCN for South America and southern Africa is not as complete as data from Australia and New Zealand, with the more recent data being particularly sparse, especially in southern Africa and South America. Given that the main focus of this study is on the 15 yr to 2009 (i.e. period covered by the Big Dry) and that only stations with complete data over this period were included in our analysis, the spatial coverage of the station-based rainfall data is poor in some regions (see Fig. 1).

3 Setting the context of recent dry conditions in SEA in terms of Southern Hemisphere variability

While it is well known that SEA experienced a prolonged drought from the mid-1990s to early 2010 (e.g. NWC, 2006; Murphy and Timbal, 2008; Verdon-Kidd and Kiem, 2009a, b; Kiem and Verdon-Kidd, 2010; Gallant et al., 2012), it is unclear if other regions of similar latitude also experienced a step change in climate (either to dry or wet) at this time. The NCEP/NCAR Reanalysis data sets described in Sect. 2.1 were used to study this as a first step towards identifying possible climate linkages in the Southern Hemisphere during this period. Figure 2a shows the annual difference in precipitable water during the period 1994–2009 compared to the period 1948–1993 (note that 1994 was used as a starting year for the drought as per the findings of Kiem and Verdon-Kidd, 2010; 1948

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was used as the start of the analysis period as this is restricted by the NCEP/NCAR data set). Tozer et al. (2012), and other references reviewed within, demonstrate that gridded rainfall data sets often do not capture extreme events particularly well (due to smoothing during the interpolation process, inadequate representation of topographical effects, uncertainties associated with remotely sensed data, density of available station data that varies in space and time etc.). Further, as mentioned in Sect. 2.2, rainfall data observations for the Southern Hemisphere tend to be sparser than the Northern Hemisphere, particularly for regions such as South America, southern Africa and Antarctica. Therefore, in order to ground truth the observations made using the gridded data set, the station-based monthly rainfall data (described in Sect. 2.2) was also used to compare the rainfall during the period 1994–2009 with the period 1948–1993 (the period which the NCEP/NCAR data covers). The results are shown in Fig. 2b.

Figure 2a shows that, for the period 1994–2009, there was a clear increase in precipitable water relative to 1948–1993 in the northwest of Australia, the northeast and northwest of South America and the northwest of southern Africa. Figure 2a also shows a corresponding decrease in precipitable water during this period in the southwest and southeast of Australia, New Zealand and central South America. The results using the station-based data (Fig. 2b) support the results obtained using the gridded data sets and indicate that since the mid-1990s there appears to be a southward migration of rain-bearing systems in the Southern Hemisphere resulting in a dry band across approximately 30–45° S (consistent with the findings of CSIRO, 2012).

As discussed in the Introduction, it is well known that the rainfall decline in SWWA began as early as the late-1960s/mid-1970s (IOCI, 2002; Hope et al., 2009), which corresponds to a time of significant changes in the climate system in the Southern Hemisphere. Therefore, it is possible that the drying trends observed in Fig. 2 from 1994–2009 are simply a continuation from an earlier step change in climate. To examine this, the rainfall analysis was repeated for the period 1976–1993 (i.e. the period prior to the mid-1990s step change in SEA) as shown in Fig. 3. The year 1976 was chosen as the start year of this analysis as this corresponds to a statistically significant

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change in ocean/atmosphere processes and a reorganisation of the climate system (Mantua et al., 1997).

The analysis presented here suggests that the trends in precipitation across the Southern Hemisphere observed in the post-1994 analysis are likely to be part of a longer term trend beginning around the mid-1970s, given the similarity in the anomaly patterns between the two time slices (for regions other than SEA). Figure 4 confirms that there has also been a corresponding decrease in meridional winds south of 30° and an increase in zonal winds since the mid-1970s. This would have the effect of pulling the storm tracks further south; hence stations located south of 45° show an increase in rainfall, while mid-latitude stations have experienced a decrease in rainfall. This observation is consistent with the findings of Frederickson et al. (2005, 2007) (noted above) regarding a reduction in winter storm formation in the three decades from 1969.

4 Comparison of rainfall anomalies in SEA and SWWA since the 1970s climate shift

A comparative analysis between SEA and SWWA rainfall was carried out using the station-based rainfall data as described in Sect. 2.2. Normalised rainfall anomalies for the period 1900–2009 were combined and the time series plotted for all SEA stations and all SWWA stations for each season (Fig. 5).

Figure 5 shows that, following below average summer rainfall and average autumn rainfall in the late-1970s in SEA, a series of eight consecutive back to back wetter than average winters occurred between 1984 and 1991 (actually 1983 is also slightly wetter than average but is not considered as "wet" in this analysis), along with a series of wetter than average autumns in 1988, 1989 and 1990. Therefore, while the dominant mid-latitude trend was towards dry since the mid-1970s, other factors acted to offset the trend for SEA during these wet autumn/winter seasons. Importantly, in terms of winter rainfall, the series of eight back to back wet events is unprecedented in the 100 yr

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instrumental record. It can also be seen from Fig. 5 that the mid-1980s to early-1990s autumn and winter rainfall relief did not occur simultaneously in SWWA; rather these seasons have consistently been dry since the mid-1970s for this region. The results presented here also indicate that, based on the station data used in our analysis, the cool season drying trend in SWWA occurred from the mid-1970s (rather than the late-1960s as reported by Hope et al., 2009).

The spatial nature of these wetter than average autumn and winter conditions is analysed in Fig. 6. In this figure "wet seasons" are defined as 1988–1990 for autumn and 1984–1991 for winter (based on the analysis presented above).

Figure 6a shows that the enhanced autumn rainfall during the period 1988–1990 occurred in a broad northwest to southeast band across the continent. Not all SEA regions experienced this elevated autumn rainfall however – as shown in Fig. 6a, southern regions of South Australia, Victoria and Tasmania actually experienced a decrease in rainfall during this time. Figure 6b shows that the elevated winter rainfall during 1984–1991 penetrated all of SEA (note SWWA did not receive this winter relief and hence the overall drying trend initiating in the mid-1970s continued without interruption in this region).

Thus far the rainfall has been analysed in terms of seasonal totals, however, changes in daily rainfall statistics (i.e. changes to the frequency, intensity, duration and/or sequencing of rainfall events) have important hydrological implications, as this will influence soil moisture and, in turn, the runoff generated. Therefore, daily characteristics of the seasonal rainfall during the elevated rainfall seasons identified above were analysed using the station-based daily rainfall data (refer to Sect. 2.2 and Fig. 1b). Figure 7 shows the daily rainfall intensity and percentage of rain days (defined as any day with rainfall greater than 1 mm) for the eight daily rain stations during autumn (1988/1989/1990) and winter (1984–1991) compared to the long term mean.

As shown in Fig. 7, the autumns of 1988–1990 were associated with both an increase in rainfall intensity and number of rain days for those stations located in the region where seasonal rainfall totals were shown to be elevated in Fig. 6. The sta-

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tions in the region where autumn rainfall decreases were experienced (Casterton and Melbourne) either show no change or a decrease in rainfall intensity and/or rain days during autumn. Overall, there is no evidence of increased rainfall intensity during the winters of 1984–1991 (with the exception of Queanbeyan and Sydney). The elevation in winter rainfall during this period is thus primarily a result of an increase in the number of rain days (i.e. the increase in rainfall appears to be due to the fact that it rained more often rather than due to an increase in daily intensity).

5 Synoptic processes driving increases in autumn and winter rainfall during the mid-1980s to the early-1990s in SEA

5.1 Identification of synoptic types using self-organizing mapping

Given that the majority of enhanced autumn/winter rainfall is due to increased rain days (with some evidence of elevated rainfall intensity for autumn) persistent climate system(s) are most likely responsible for the elevated rainfall occurrence. Therefore, we have used a process to identify daily synoptic systems that occurred during the period of elevated autumn/winter rainfall which can then be compared to the long term climatology. The method by which the synoptic systems have been identified is known as self-organizing maps (SOM). The SOM methodology has been shown to be successful in identifying key regional synoptic patterns that drive local climate in other regions of the world (e.g. Cavazos, 2000; Cavazos et al., 2002; Hewitson and Crane, 2002; Hope et al., 2006; Reusch et al., 2007; Verdon-Kidd and Kiem, 2009b). Importantly, the SOM methodology is less subjective than other forms of pattern recognition and the non-linear approach lends itself to regions where local climate is constantly changing due to large-scale climate variability.

Daily global sea level pressure (SLP) data for the years 1948–2009 was used to develop the SOM (see discussion of the NCEP/NCAR Reanalysis data in Sect. 2.1). This data set has been widely used in similar studies (e.g. Cavazos, 2000; Cavazos et

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al., 2002; Hope et al., 2006) and is considered to be the best SLP data available for the study region and type of analysis (see Hope et al., 2006 for a detailed discussion). In order to study the regional scale synoptic systems that are important for SEA, a subset of the global SLP data was extracted to carry out the SOM. This region was chosen so as to capture the synoptic patterns that influence autumn and winter rainfall in SEA. Two separate SOMs were generated – one for autumn (MAM) and another for winter (JJA). The location of the SLP field used in this analysis is 90–180° E, 0–60° S.

The size of the SOM array directly influences the range of synoptic patterns represented. A number of array sizes were trialled in order to determine the optimum number of synoptic patterns. It was determined that a 3 by 4 SOM (i.e. 12 types) was not large enough to adequately identify the subtle differences between types that are likely to be important in generating rainfall; however these subtleties were found to be captured by a 4 by 5 SOM (i.e. 20 types). Larger array sizes (e.g. a 5 by 6 SOM) resulted in further refinement of the transitionary synoptic types (resulting in very discrete differences between types) yet did not alter the extreme types. In addition, there was no improvement in the mean error per sample (calculated as the average Euclidian distance between the input vector and the synoptic types it best matches to) by increasing the size of the SOM array beyond 20 types. Given these findings, a 4 by 5 SOM was chosen for the synoptic typing performed in this study – this array size satisfactorily captures extreme types and a range of synoptic patterns with sufficient differences observed between types.

Twenty synoptic types (using a 4 by 5 grid) were generated using the daily SLP data, as shown in 8 (autumn) and Fig. 9 (winter). By virtue of the method, similar types are clustered together in the SOM, with the most dissimilar types located at the far corners of the SOM map.

A range of synoptic systems for both seasons were identified using the SOM methodology. In general the top half of the SOM represents systems with a westerly flow (since winds move in the direction of high to low pressure), while the bottom half of the SOM represents easterly flow. Systems with a westerly flow are more likely to bring rain into eastern Australia (particularly west of the Great Dividing Range); however, coastal stations may benefit from easterly systems if they are laden with moist air (for example, a "black nor–easter"). The westerly systems are more likely to deliver lower intensity, longer duration events, while the easterly systems are more likely to deliver rainfall in shorter more intense storm events (from cut off lows, east coast lows, etc). The types located along Row 3 of the SOM (Figs. 8 and 9) show a southward retraction of the Subtropical Ridge. This is likely to result in reduced rainfall across SEA (a more summer like pattern) due to the surface high pressure being located over southern Australia (Sturman and Tapper, 2004).

Autumn synoptic types located in the top left hand corner (1A, 1B, 2A) of Fig. 8 show a monsoon depression over eastern Australia, as seen by the strong "dip" in the isobars over eastern Australia (note also the low pressure trough over western Australia, known as the "west coast trough" that occurs at this time of year which results in dry conditions for SWWA). Monsoon depressions often have their origin in the northwest of the continent and move southeast bringing warm moist air that often results in prolonged rainfall (particularly west of the Great Dividing Range). This type of system was responsible for the breaking of the severe 1982/1983 drought (Tapper and Hurry, 1996) and more recently was the primary weather system that resulted in elevated rainfalls in 2010/2011. The strong surface high pressure system located to the south of Australia in the "Bight" is likely to block the propagation of the rain bearing systems into the southern regions and can even lead to a "cold outbreak" in southern Victoria and South Australia (Tapper and Hurry, 1996). Occasionally east coast lows can also form out of these monsoon depressions resulting in heavy recorded rainfall for east coast stations.

Similar synoptic patterns to those observed in autumn were identified for winter. However, some key differences were observed. In particular, as shown in Fig. 9, winter types 1C, 1D and 2D display a low pressure trough stretching from the northwest through to the southeast of the continent. This synoptic system represents conditions suitable for cloud band development (a system common in winter and spring and less

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common in autumn). The "northwest cloud bands", as they are known, often result in substantial rainfall across SEA in the winter and spring seasons. Similar to low pressure trough systems, the type of rainfall associated with northwest cloud bands tends to be of a lower intensity and longer duration than isolated low pressure systems (such as east coast lows, Tasman lows, etc).

5.2 Rainfall statistics associated with the 20 autumn and winter synoptic types

The daily rainfall associated with each autumn and winter synoptic type is shown in Fig. 10 (autumn) and Fig. 11 (winter). Note that days with zero rain were removed in this analysis in order to demonstrate how much rain is associated with each type when that type results in rainfall. The percentage of rain days associated with each synoptic type is shown in Fig. 12 (autumn) and Fig. 13 (winter).

From Figs. 10 and 11 it is clear that daily rainfall distributions vary markedly for different synoptic types at the same site (and for the same synoptic type across the different sites). For example, the most intense rainfall in autumn is associated with type 5B at Ivanhoe and Kerang, 4A at Sydney and Omeo, 2B at Queanbeyan, 5C at Corowa, 3A/4C at Casterton and 4B at Melbourne. These types are clustered in the bottom left corner of the SOM in Fig. 8 (strong easterly flow).

There is also a clear trend in the number of rain days associated with each synoptic type as demonstrated by Figs. 12 and 13. For those stations located in the northern part of the study region (e.g. Sydney and Ivanhoe) there is a general increase in rain days in both autumn and winter for those synoptic types located in the bottom half of the SOM, while for stations located in the south of the study region (e.g. Corowa, Casterton, Omeo and Melbourne) the opposite is true (i.e. a greater number rain days occur for synoptic types located in the top half of the SOM). This indicates that the more southern stations benefit most from westerly flow, while those located further north benefit from easterly systems. The four stations located in the south of the study region are within the "Victorian" region as defined by Timbal et al. (2010) which, according to the authors, is most strongly influenced by local mean sea level pressure in autumn and

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winter, with the Southern Annular Mode (i.e. westerly flow) also playing a significant role in winter. The stations in our study that are located further north correspond to the regions defined as "Central" and "Eastern" by Timbal et al. (2010) which, according to the authors, are most strongly influenced by the Pacific driver (i.e. ENSO) which affects easterly systems.

5.3 Relative occurrence of synoptic types during the wetter than average autumns of 1988–1990 and winters of 1984–1991

Next we investigate how frequently each synoptic type occurred during the wetter than average autumns (1988–1990) and winters (1984–1991) in order to determine which (if any) types were responsible for the elevated rainfall during these seasons. The relative percentage of each synoptic type occurring during the wetter than average autumns of 1988–1990 and winters of 1984–1991 are shown in Fig. 14 compared to the long term climatology (based on the period 1948–2009).

Figure 14a shows a large increase in type 1A during the wet autumns of 1988–1990 (result statistically significant at < 10 % (p value 0.07) using a Student's t test), representing a monsoon depression over eastern Australia. As noted previously, this system often results in substantial rainfall across SEA (however the presence of a west coast trough is associated with dry conditions in SWWA). There is also a general increase in synoptic types representing westerly flow (as opposed to easterly flow).

Based on Fig. 14b there appears to be two separate weather systems that were more common than usual during the wet winter period of 1984–1991. Increases in synoptic types located along the first row of the SOM indicate that, as for autumn, monsoon trough systems over the east coast were more frequent, along with cloud band development. These systems are also associated with strong westerly flow. In addition, an increase in types located in the bottom right corner of the SOM (representing systems with a very strong easterly flow) would have resulted in rainfall being generated from the Pacific in the form of cut off lows, which are closed low pressure systems which have become completely displaced from the basic westerly current which flows across

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Australia's southern oceans (Tapper and Hurry, 1996). While these increases were not found to be statistically significant using a Student's t test, a small increase in "wet" synoptic types may have a larger impact on the seasonal rainfall totals.

An assumption that has been made thus far is that the likelihood of rainfall for a given synoptic type is stationary and consistent in time. In order to analyse the validity of this assumption, the percentage change in the likelihood of rainfall occurrence (i.e. a day with rain > 1 mm) for a given synoptic type during the wet autumns of 1988/1989/1990 compared to the long term climatology was calculated (Table 1). Similarly, results for winter (1984–1991 compared to the long term mean) are shown in Table 2. Note that a small deviation is not unexpected given the reduced sample size of daily synoptic types during the "wet" seasons compared to the long term climatology.

Table 2 shows that the likelihood of rain for a given synoptic type during winter is fairly consistent for the time periods being analysed. However, in autumn 1988–1990 there does appear to be a trend towards more rain days for a given synoptic type (up to 50 % more in some cases), as shown in Table 1. An initial investigation into climate variables other than sea level pressure has highlighted some interesting findings that may help explain why some stations received so much rain during this period. For example, Fig. 15 shows precipitable water anomalies, SST anomalies, scalar windspeed and outgoing longwave radiation, during the wet autumns of 1988–1990.

Figure 15a shows that a pool of precipitable water was centred over southern Qld, NSW and northern Vic during the autumns of 1988–1990, which is likely to have increased the chance of rain for a given synoptic system. Another reason for an increased chance of rain in autumn (for Sydney in particular) may be due to warmer than average SSTs (shown in Fig. 15b) off the west coast of Australia feeding moisture to the westerly winds. Thirdly, the outgoing longwave radiation (Fig. 15c) is particularly low along eastern Qld and NSW during this time. Low longwave radiation is typically associated with increased storm activity and subsequent rainfall. Therefore, both the moisture source and the atmospheric processes that actually deliver the rainfall were available during this time.

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While some preliminary insights have been gained, the reason why Sydney received so much rainfall during the autumns of 1988–1990 requires further investigation. Indeed it is likely that local climate phenomena not studied here may have played a role (i.e. phenomena that are too small to be captured based on the synoptic types using NCEP/NCAR grid resolution).

6 Role of large-scale climate phenomena in driving enhanced autumn and winter rainfall during the mid-1980s to the early-1990s in SEA

Numerous studies have demonstrated that the four most influential climate modes on SEA's climate are:

- El Niño/Southern Oscillation (ENSO; Chiew et al., 1998; Kiem and Franks, 2001; Verdon et al., 2004). ENSO is represented by the Oceanic Niño Index (ONI) from the United States National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Centre (CPC) (www.cpc.ncep.noaa.gov). The ONI is a 3 month running mean of ERSST.v3b SST anomalies in the Niño 3.4 region, centered on 30 yr base periods updated every 5 yr. For historical purposes cold (La Nina) and warm (El Nino) episodes are defined when the threshold (±0.5°) is met for a minimum of 5 consecutive over-lapping seasons;
- Inter-decadal Pacific Oscillation (IPO; Power et al., 1999; Kiem et al., 2003; Verdon et al., 2004; Power and Colman, 2006) – Both the raw and the smoothed time series of Power et al. (1999) are used in this study in order to identify epochs of positive and negative IPO;
- Indian Ocean Dipole (IOD; Saji et al. 1999; Ashok et al. 2003; Verdon and Franks, 2005) – SST anomalies to the northwest of Australia are used here rather than the IOD as previous studies have shown that warming to the northwest of Australia (i.e. the eastern pole of the IOD) is most important for cloud band development

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and is strongly related to above average rainfall in SEA (e.g. Verdon and Franks, 2005), while the need for an anomaly further west has not been demonstrated. In fact the poles of the IOD are not negatively correlated as one would expect (Dommenget and Latif, 2001; Gallant et al., 2012) and intermittent decoupling of the east and west pole of the IOD can lead to false classification of events;

- Southern Annular Mode (SAM; Thompson and Wallace, 2000; Thompson et al., 2000; Ho et al., 2012) – The positive phase of SAM has been associated with reduced winter rainfall in SEA (e.g. Risbey et al., 2009) and also reduced autumn SEA rainfall via a reduction in frontal systems (e.g. Verdon-Kidd and Kiem, 2009b; Nicholls, 2009). In this study the NOAA CPC version of the AAO is used when it exists (i.e. from 1979 onwards) and the Thompson and Wallace (2000) AAO data is used prior to that (1948 to 1978). Overlapping periods (1979 to 2002) of the two versions of the AAO were compared and the difference found to be negligible ($R^2 = 0.95$, $N = 288$).

It is well known that the 1970s change in climate observed in the Southern Hemisphere (and parts of the Northern Hemisphere) corresponds to changes in both ENSO and IPO (e.g. Mantua et al., 1997; Power et al., 1999; Kiem and Franks, 2004; Verdon and Franks, 2006). Changes in Indian Ocean SSTs also occurred during this time (Verdon and Franks, 2005; Samuel et al., 2006). It has also been established that these large-scale climate modes modulate the frequency and timing of synoptic systems in Australia, at least at a monthly timescale (Verdon-Kidd and Kiem, 2009b). The question remains, however, whether these modes either collectively or individually can explain the increase in rainfall observed during autumn and winter of the late-1980s/early-1990s. Table 3 shows the state of each of the large-scale climate drivers during this wetter than average autumn and winter period. Note that while typically an ENSO event does not establish until after autumn (and therefore is unlikely to be a driver of autumn rainfall), the La Niña of 1988 was particularly long lasting and extended through the following autumn and winter of 1989.

Based on the analysis presented in Table 3 it may appear that SSTs to the northwest of Australia were primarily responsible for the elevated rainfall; however, it must be noted that in fact this region has been warmer than average during the entire period from the mid-1970s (including during the recent drought where autumn and winter rainfalls have been lower than average). What is clear from the analysis presented in Table 3 is that, for every wet season identified (except winter 1987) at least one of the four large-scale climate drivers was in a "wet phase". This indicates that, while a single climate mode can sometimes dominate, it is more often the interaction between drivers that is most important (Kiem and Verdon-Kidd, 2010). It also appears that the SAM plays an important role in the autumn rainfall relief (in that SAM is not positive during any of the wet autumns) but that a negative SAM on its own is not usually enough to ensure wetter than average conditions. This possibly explains why previous studies which analyse correlation relationships between SEA rainfall and SAM on its own conclude that SAM has minimal influence in autumn (e.g. Cai and Cowan, 2008a, b; Risbey et al., 2009). Based on the findings presented here (also Kiem and Verdon-Kidd, 2010) we suggest that this is unlikely to be true, and that SAM does indeed play an important role in modulating autumn/winter rainfall in SEA; however, this modulating effect is dependent on the phase of the Pacific and Indian Ocean drivers (see Kiem and Verdon-Kidd, 2010 for more details).

Of particular interest is the winter of 1991, which was extremely wet and the only climate mode in a wet phase at the time was the SAM, demonstrating that SAM does indeed have an influence; however, this result also indicates that correlation studies of SAM and rainfall may be skewed by this one very wet winter and negative SAM. Also of interest is the winter of 1987 where ENSO was in a dry phase, and the Indian and Southern Modes were neutral (indicating that rainfall would be expected to be average to below average). The rainfall for this season was only slightly elevated (whereas the other seven winters were substantially above average). However, this result points to the fact that it is also possible that other climate drivers may have played a role that has not been considered here – for example upper atmosphere phenomena or small scale synoptic systems.

7 Implications for water resource management in SEA

There is evidence that changes in the dominant Southern Hemisphere climate drivers experienced during the mid-1970s created a shift to drier than average conditions across most of the mid-latitude belt. However, a series of wetter than average winters in SEA during 1984–1991 (and three wet autumns), due to weather systems originating primarily from the tropical Indian Ocean (i.e. north west cloud bands and monsoon depressions) prevented, delayed or interrupted this change in climate in SEA.

What would have happened to water resources and supplies in the region in the absence of these wet winters and autumns? Given the experience of SWWA and the findings presented here, it is suggested that this should be considered as a possible "scenario" in terms of water management planning, and indeed water corporations in Victoria are using an immediate return to the dry conditions of the Big Dry as a possible future scenario alongside climate change projections (DSE, 2011).

To demonstrate the importance of considering such a scenario, a simple analysis of the effects on soil moisture and streamflow has been carried out. To achieve this, the observed rainfall sequences were altered such that the elevated rainfall totals actually experienced during the winters of 1984–1991 were replaced by the long term mean winter rainfall. Similarly, the autumns of 1988, 1989 and 1990 were replaced with the long term autumn mean rainfall. This perturbed synthetic rainfall sequence was then used to calculate the monthly value of the Palmer Drought Severity Index (PDSI, Palmer, 1965), a physically based index of meteorological drought that takes into account precipitation, evapotranspiration and soil moisture conditions, all of which are determinants of agricultural drought (Alley, 1984). Droughts are classified based on PDSI value between −10 (extreme drought) and +10 (extremely wet). The calculation of the PDSI also requires maximum temperature data (which was sourced from the BoM for the locations at the rainfall gauges). Sheffield et al. (2012) highlighted significant issues with the PDSI in terms of overestimation of drought (albeit on a global scale) given that the index uses a simplified model of potential evaporation that responds only to changes in temperature (see Mishra and Singh, 2010 for a comprehensive review of drought indices). In the absence of local meteorological data required to calculate potential evaporation using the Penman-Monteith method (a physically based estimate of potential evaporation), a second measure of drought, the Standardized Precipitation Index (SPI, McKee et al., 1993) was calculated to compare with the PDSI results. The SPI is a purely statistical measure of meteorological drought that requires only precipitation as input, where negative values of the SPI indicate dry conditions (values < -2 represents extreme drought). It is acknowledged that all indices used to measure drought are only proxies (with associated pros and cons); however, the analysis presented here is simply to demonstrate the potential changes in drought conditions that could have been experience had the elevated rainfalls in autumn/winter of the later 1980s and early 1990s not occurred.

Figure 16 shows the time series of the PDSI for Queanbeyan, Kerang and Melbourne in SEA (see Fig. 1b for locations) calculated using the instrumental record and then again using the “altered” rainfall sequence. Figure 17 shows the SPI time series for the same locations. Note drought indices are shown from 1976 only, however the long term indices were calculated over the entire instrumental record.

Figures 16 and 17 confirm that drought conditions (varying degrees of severity) associated with the Big Dry occurred between the mid-1990s through to 2009 at Kerang and Melbourne, while the drought appears to be less severe for Canberra (based on the PDSI and SPI). Based on both the PDSI and SPI time series for Melbourne (the most southerly station analysed here), the period from 1976 through to the late 1980s was also consistently dry, similar to SWWA.

It can be seen from Figs. 16 and 17 that replacing the wetter than average autumn and winters of the 1980s and early-1990s with average rainfall impacts on the drought index time series at all stations for both indices to varying degrees. The largest impact

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on drought conditions was obtained at Kerang (the most inland station analysed here), particularly for the PDSI. It can be seen from Fig. 16 that, in the absence of wetter than average winters (1984–1991) and autumns (1988–1990), the return to "wet" soil moisture conditions (i.e. PDSI > 0.5) experienced between ∼ 1984–1991 at Kerang would not have occurred. Based on the recorded data (actual time series) dry (PDSI < −0.5) conditions prevailed 33 % of the time between 1984–1991 compared to 55 % of the time for the time series with wet seasons replaced by averages. Indeed, if the rainfall had been average during these seasons, the entire period post 1982 would have been characterised by predominantly dry conditions (PDSI < −0.5).

The altered (i.e. wet winter and autumns replaced by the seasonal average) rainfall sequence for Omeo (see Fig. 1 for location) was also run through a simple hydrological model (Kiem et al., 2007) to determine the impact this scenario would have on streamflow for the Mitta Mitta River (see Fig. 18). Mitta Mitta River feeds Dartmouth Dam, the largest capacity dam in Victoria, storing water for irrigation and domestic and stock use in Victoria and New South Wales. The model simulates changes in the soil moisture storage deficit over a monthly period with fluxes in rainfall, evaporation and overflow represented. A rainfall-runoff regression converts the estimated soil moisture deficit to streamflow (overall R^2 of model = 0.8).

Figure 18 shows that the impacts of replacing the wet autumns/winters of the late 1980s and early 1990s with average conditions are magnified (compared to meteorological drought analysis) for streamflow. Rather than streamflow reductions occurring around the mid-1990s (as was experienced during the Big Dry), the streamflow simulation for Mitta Mitta River (Fig. 18) shows the possibility for streamflows to have been reduced from the mid-1980s (in the absence of the wet winter/autumns). Given the stresses placed on SEA water supply systems during the Big Dry (i.e. critical storage levels reached in ∼ 2006 in numerous places) an extra ten years of low streamflow would have been very challenging for water managers, bringing forward the need for the types of contingency measures that were implemented from 2006 and, potentially, further additional major system augmentations as the drought progressed.

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8 Discussion

Based on the findings presented in this paper we suggest that the Big Dry (or Millennium Drought) is in fact likely to be connected to the widespread Southern Hemisphere climate shift that began in the mid-1970s (also resulting in a notable decrease in SWWA winter rainfall). Since the mid-1970s there has been a general decrease in meridional winds south of 30° and an increase in zonal winds, effectively shifting the storm tracks further south; hence stations located south of 45° show an increase in rainfall, while mid-latitude stations have experienced a decrease in rainfall. However, the effects in SEA were shown to be masked due to smaller-scale synoptic processes which resulted in elevated autumn and winter rainfall during the mid to late-1980s and early-1990s (a crucial period for SEA hydrology). The elevation in rainfall occurrence during this time was subsequently linked to an increased frequency of monsoon depressions and systems with strong westerly flow in autumn while, during winter, cloud band development and strong easterly flow (that would have resulted in rainfall being generated from the Pacific in the form of cut off lows) appear to be the dominant drivers of the increased rainfall. From the mid-1990s to 2010 the frequency of these synoptic processes decreased, resulting in a return to drier than average conditions and the onset of the Big Dry.

While we have gained insight here into the synoptic processes responsible for the delayed response in the 1970s climate shift in SEA, the probability of this situation occurring needs to be established in order to properly quantify drought risk – and importantly, the chances of a drought being broken. An analysis of how the large-scale drivers (e.g. ENSO, IPO, IOD and SAM) may have influenced this period of elevated rainfall for SEA, but which was not experienced elsewhere around the Southern Hemisphere, was inconclusive. However, what was made clear from the analysis is the importance of the interaction between drivers that operate on an inter-annual to annual timescales, with the majority of elevated rainfall events occurring during periods where more than one climate mode was in its “wet” phase. It is also suggested that other

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large-scale processes may have played a role in the elevated rainfall period – for example upper atmosphere phenomena such as the seasonal long wave trough (which should be the subject of future research).

Current projections for SEA are for continued drying of the region (CSIRO, 2010, 2012) primarily as a result of reduced storminess (increased stability) in the mid-latitudes in winter and a southward shift of rain bearing systems (Frederiksen et al., 2011), along with a projected weakening and poleward expansion of the Hadley circulation (Lu et al., 2007), continuing observed trends (Lucas et al, 2012). During 2010/2011 and 2011/2012 austral summer rainfall totals were above average in SEA, breaking the long running hydrological drought. However, this rainfall was primarily tropical in origin and winter rainfall in SEA was still below average, with spring and summer being the greatest contributors to this rainfall relief. The wet spring/summer conditions were in part related to strong La Niña events in the Pacific combined, in 2010/2011 only, with warm SSTs off north-western Australia (i.e. negative IOD). Therefore, establishing the likelihood of repeat events (such as those that occurred in spring/summers of 2010/2011 and 2011/2012) in the next few years to decades is of crucial importance to water resource managers in the region.

9 Conclusions and recommendations

As discussed in Sect. 1.3, in the light of the experiences during the Big Dry and the significant uncertainties associated with future climate, changes have been made to the water management and planning framework across SEA, and water trading arrangements to better manage supplies in the face of a variable and changing climate. The effectiveness of these planning processes would nevertheless be facilitated by better understanding the full risk profile associated with drought (that is how dry can it get and for how long). This can only be achieved by improving our understanding of the drivers of drought (both in the short and long term) using all available information (instrumental, palaeoclimate, stochastic modelling, climate models etc.).

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Finally, the findings presented here also have implications for climate change attribution studies, since many assume or aim to prove the Big Dry is due to increasing CO_2 emissions. However if this climate shift is part of a much longer (and more widespread) change in climate since the mid-1970s, the "goal post" (in terms of timing) for studies examining the potential role of CO_2 (and other non-CO_2 drivers) is somewhat shifted.

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Table 1. Percentage change in the likelihood of a rain day (greater than 1 mm) for a given synoptic type during autumn 1988–1990 compared to the 1948–2009 period (substantial deviations from the long term mean (> 20 % or < −20 %) are highlighted in bold).

Type	Ivanhoe	Sydney	Queanbeyan	Kerang	Corowa	Casterton	Omeo	Melbourne
1A	5	10	8	3	7	−10	3	−6
1B	19	8	10	0	−11	−8	1	8
1C	**52**	**46**	**46**	7	**40**	8	16	−9
1D	−2	**30**	−2	0	−4	−10	−3	−11
2A	5	−2	14	−2	−10	−20	−2	−2
2B	7	**34**	18	−11	−11	−4	−17	**−24**
2C	15	−9	13	**21**	1	−10	6	3
2D	−3	18	−5	−2	4	−17	1	3
3A	−6	**25**	−3	1	−10	**−27**	−3	1
3B	−7	14	6	−4	−4	−13	−4	−8
3C	**26**	11	6	13	19	**−23**	**22**	17
3D	10	**22**	8	11	11	−13	12	11
4A	−10	**38**	11	−9	−3	−7	−5	−16
4B	**50**	**37**	**30**	3	**43**	**−21**	**21**	−4
4C	−10	10	−17	−13	−3	−4	−7	−7
4D	6	**25**	5	4	3	6	17	−5
5A	12	**21**	**23**	2	3	−12	16	3
5B	1	17	−3	4	1	**−30**	−2	−18
5C	**22**	2	**29**	15	**37**	−10	**20**	−1
5D	6	**41**	3	12	10	**−30**	**24**	**22**

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Table 2. Percentage change in the likelihood of a rain day (greater than 1 mm) for a given synoptic type during winter 1984–1991 compared to the 1948–2009 period (substantial deviations from the long term mean (> 20 %) are highlighted in bold).

Type	Ivanhoe	Sydney	Queanbeyan	Kerang	Corowa	Casterton	Omeo	Melbourne
1A	−1	−2	1	−3	8	−10	2	1
1B	5	7	−2	5	5	−8	2	7
1C	0	8	−11	−1	−7	−8	−3	9
1D	4	−3	−3	0	0	2	−5	−5
2A	1	−6	−10	6	2	−11	**−22**	6
2B	−4	−4	−9	−4	−1	−13	1	4
2C	2	13	12	−2	2	−14	5	12
2D	1	3	4	12	14	6	**21**	−2
3A	11	10	−1	9	15	−16	4	−4
3B	8	−5	3	13	4	**−24**	13	11
3C	11	4	−4	12	11	0	11	5
3D	0	−10	0	11	10	1	2	12
4A	−2	3	−2	3	−1	0	2	12
4B	5	4	−10	−3	3	−6	−2	3
4C	8	−5	−7	10	9	7	−1	6
4D	16	−2	4	19	19	−12	18	18
5A	4	3	0	4	−1	2	3	1
5B	9	−3	0	−6	5	0	0	1
5C	4	12	5	−3	6	−5	0	−1
5D	4	1	1	7	8	−12	5	5

Table 3. State of large-scale drivers during "wet seasons".

Autumn	ENSO	IPO (smooth)*	IPO (raw/annual)	Northwest of Australia SSTs	SAM
1988	Neutral	Positive	Positive	*Warm SSTs*	*Negative*
1989	*La Niña*	Positive	*Negative*	*Warm SSTs*	Neutral
1990	El Niño	Positive	*Negative*	*Warm SSTs*	Negative
Winter					
1984	Neutral	Positive	*Negative*	Neutral	Negative
1985	Neutral	Positive	*Negative*	*Warm SSTs*	Positive
1986	El Niño	Positive	Positive	*Warm SSTs*	Positive
1987	El Niño	Positive	Positive	Neutral	Neutral
1988	*La Niña*	Positive	*Negative*	*Warm SSTs*	*Negative*
1989	Neutral	Positive	*Negative*	*Warm SSTs*	Neutral
1990	El Niño	Positive	*Negative*	*Warm SSTs*	Neutral
1991	El Niño	Positive	Positive	Neutral	*Negative*

* Power et al. (1999a) applied a spectral filter with a 13 yr cut-off to the raw IPO (i.e. annual value) to generate a smoothed (or slowly varying) IPO timeseries.

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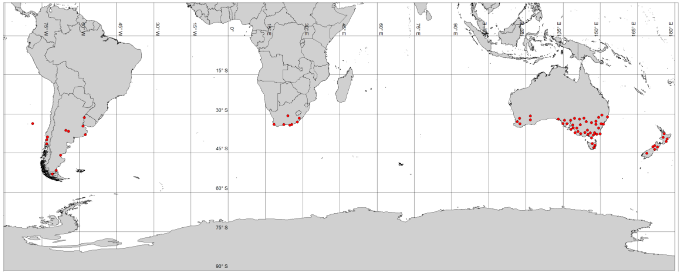

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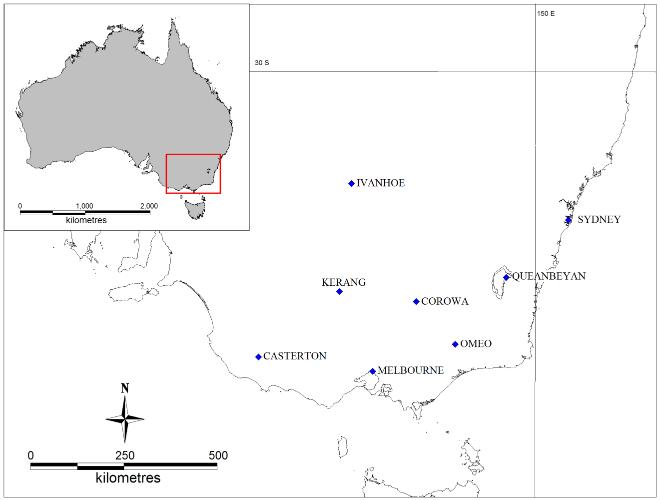

b)

Fig. 1. Location of **(a)** monthly rainfall stations (red circles) and **(b)** eight high quality daily rainfall stations in SEA (blue diamonds). Note monthly station data varies in length with all stations containing data from at least 1920 to 2009 (with the exception of two stations from Argentina that include data from 1931 onwards, which were included in order to improve the spatial coverage of the east coast of South America).

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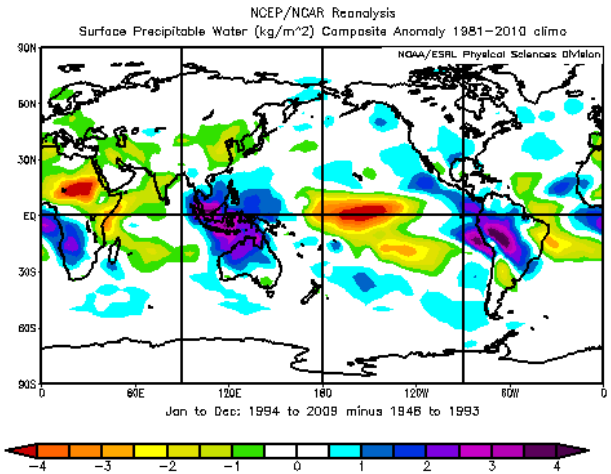

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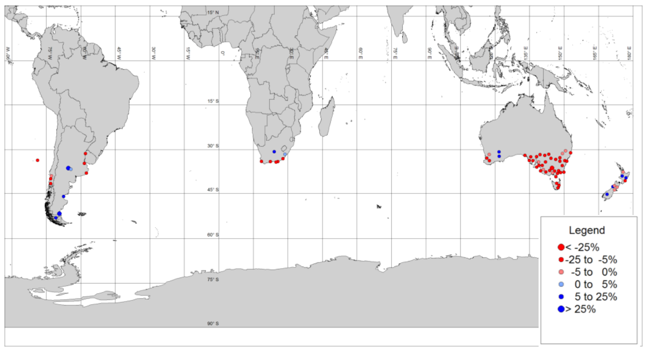

b)

Fig. 2. Difference in annual **(a)** precipitable water anomalies and **(b)** station-based rainfall (shown as a percentage change) for the period 1994–2009 compared to the period 1948–1993.

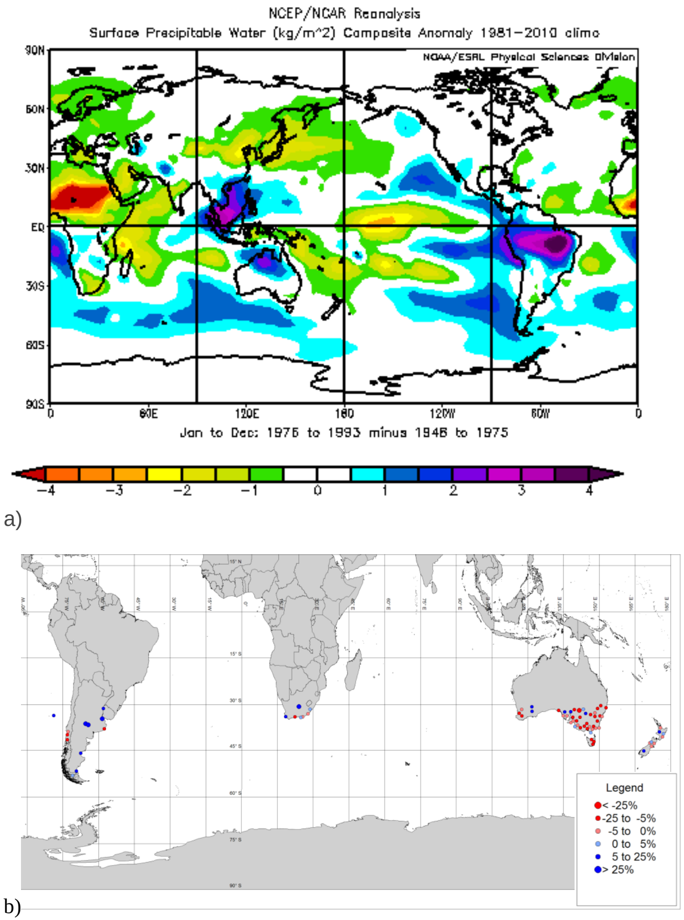

Fig. 3. Difference in annual **(a)** precipitable water anomalies and **(b)** station-based rainfall (shown as a percentage change) for the period 1976–1993 compared to the period 1948–1975.

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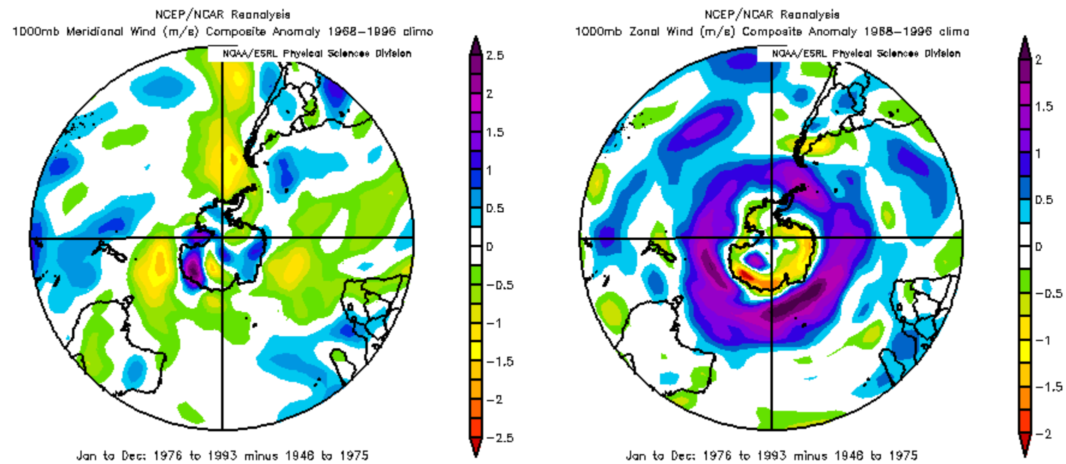

a) b)

Fig. 4. Difference in annual **(a)** meridional and **(b)** zonal wind anomalies during the period 1976–1993 compared to 1948–1975.

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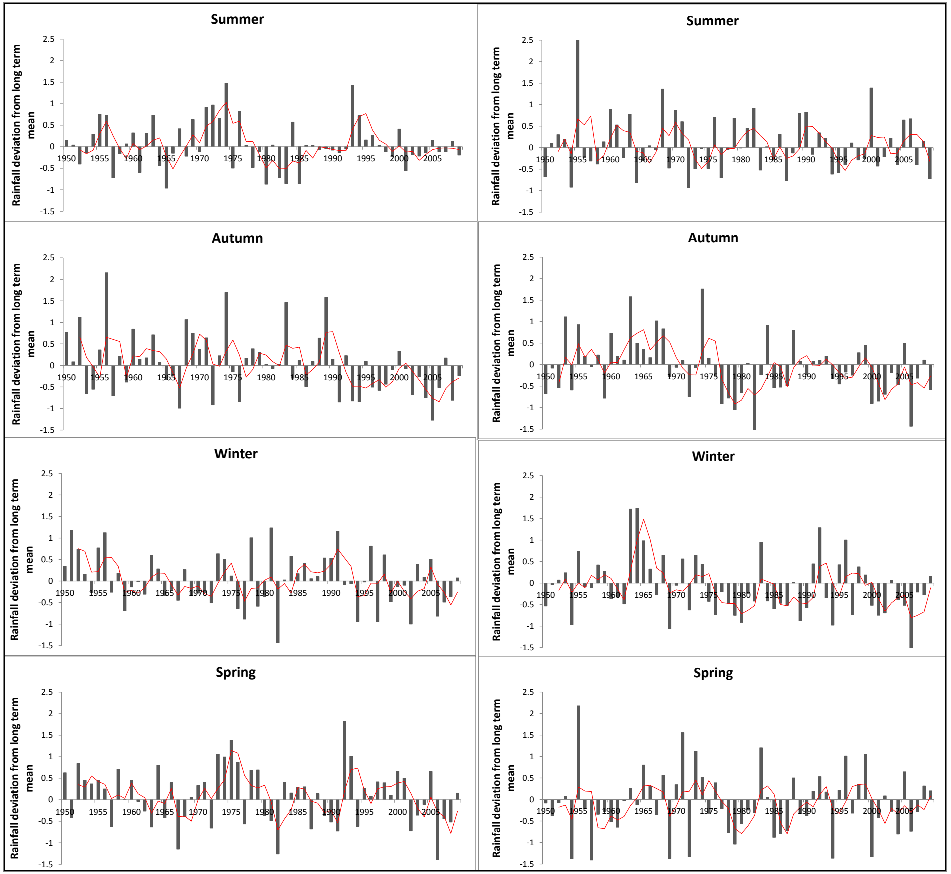

a) b)

Fig. 5. Rainfall deviation from the long term mean (1900–2009) for **(a)** all SEA (left panels) and **(b)** all SWWA stations (right panels) combined. Note anomalies displayed from 1950 onwards.

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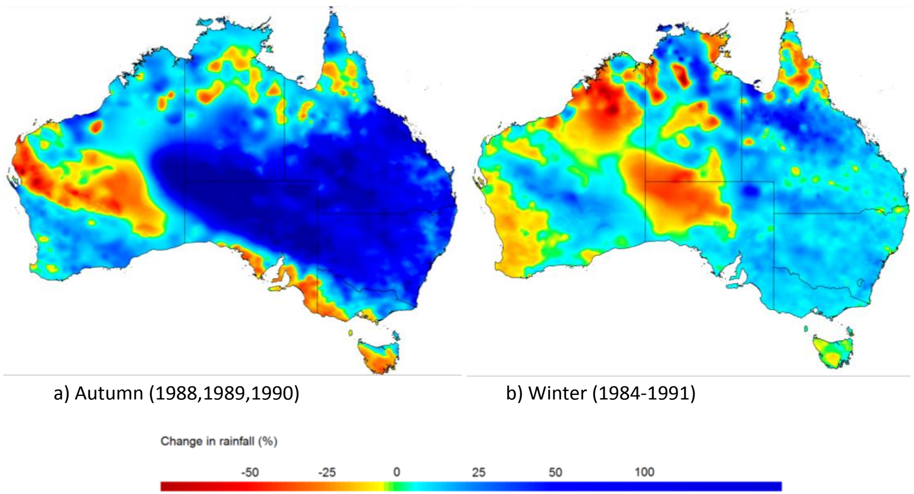

Fig. 6. Difference in **(a)** autumn and **(b)** winter rainfall during “wet seasons” compared to the long term mean (1900–2009).

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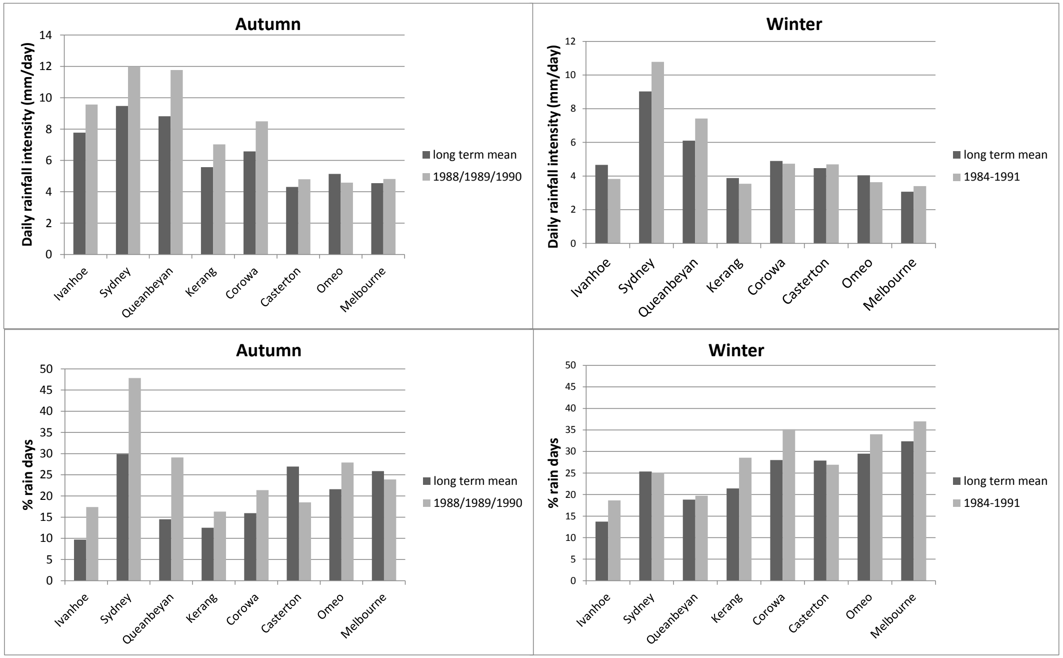

Fig. 7. Daily rainfall intensity and percentage of rain days for the eight selected high quality rainfall stations in SEA during wet years compared to long term mean (1900–2009).

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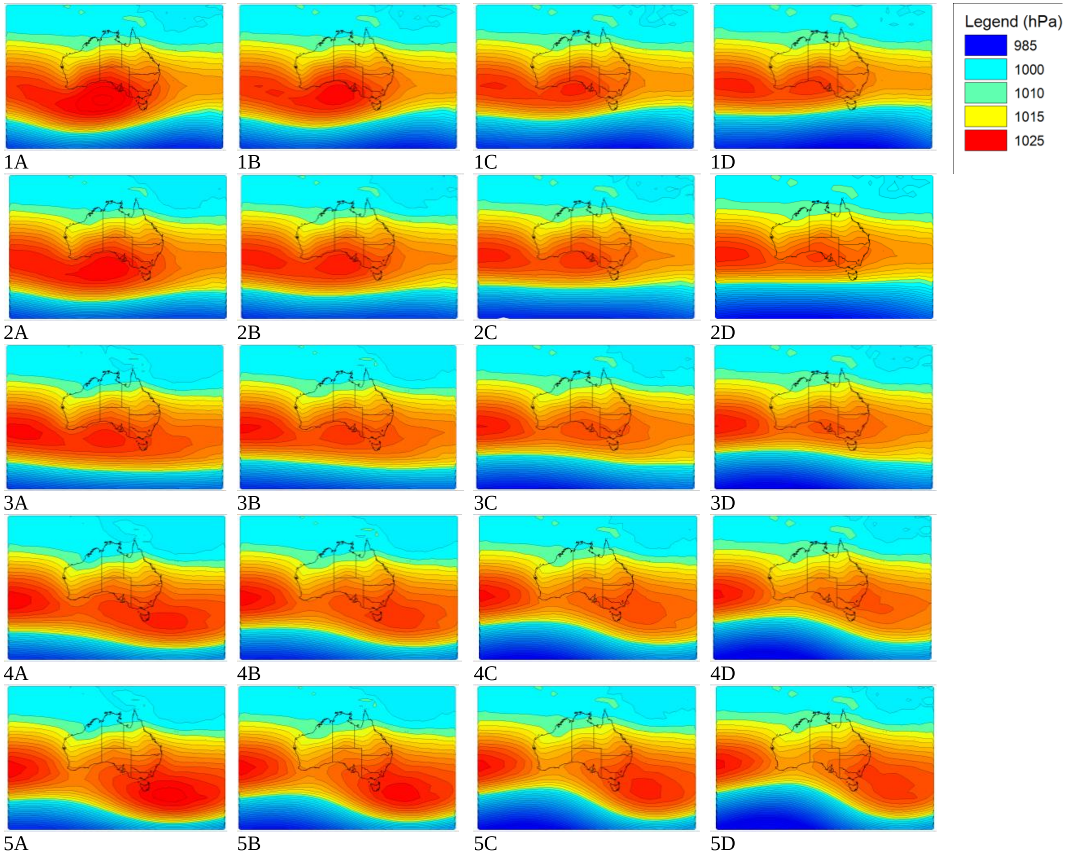

Fig. 8. 20 autumn synoptic types identified using SOM based on data from 1948–2009.

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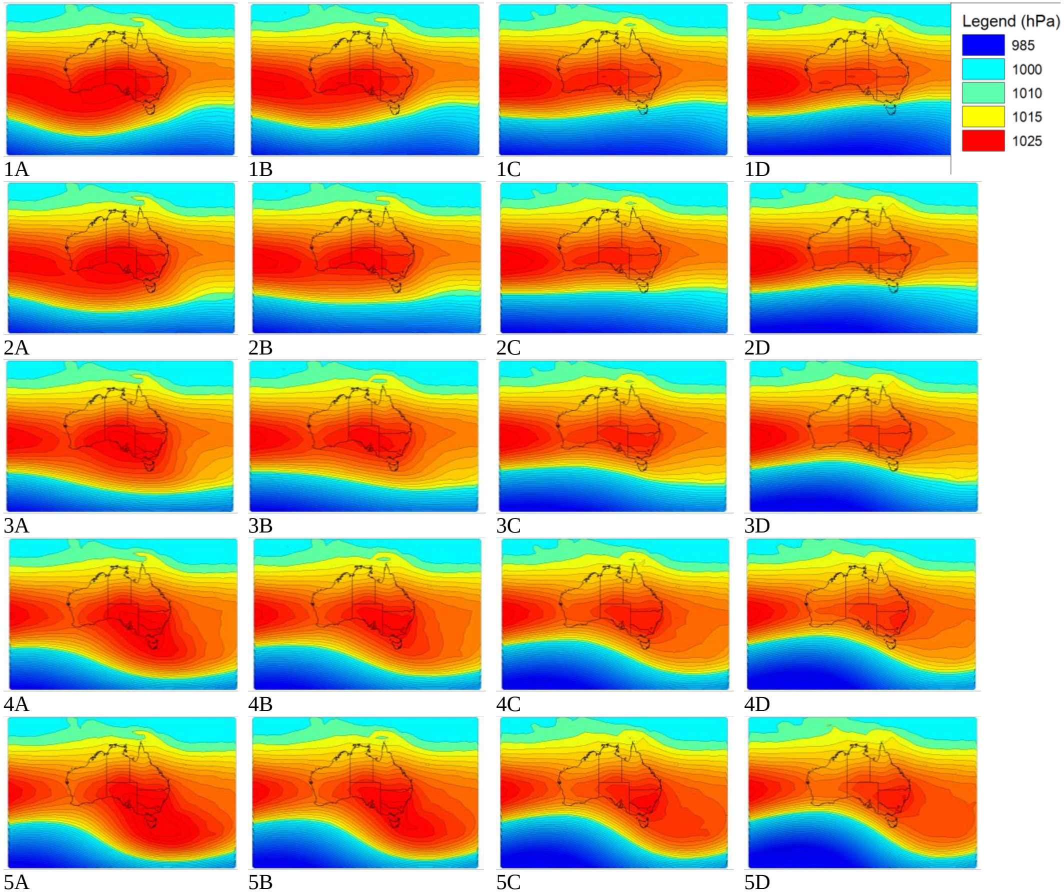

Fig. 9. 20 winter synoptic types identified using SOM based on data from 1948–2009.

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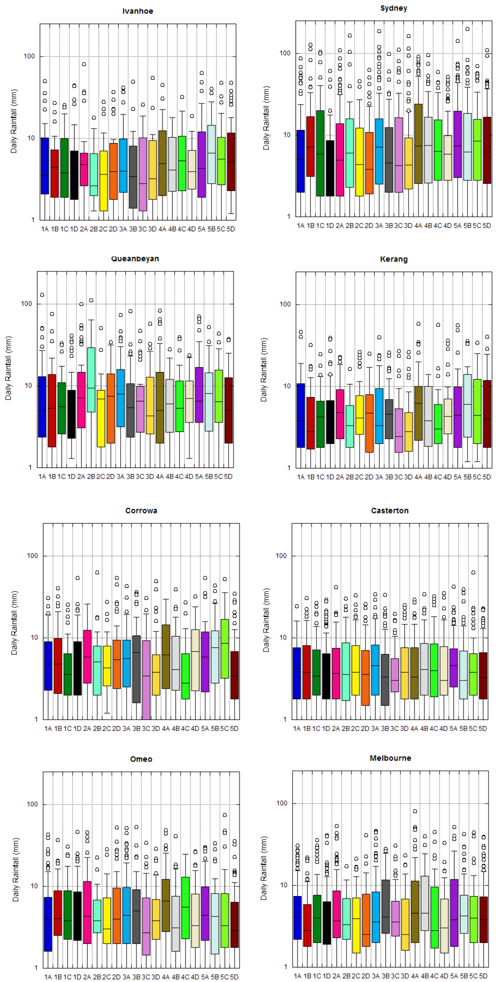

Fig. 10. Daily rainfall distributions associated with each autumn synoptic type.

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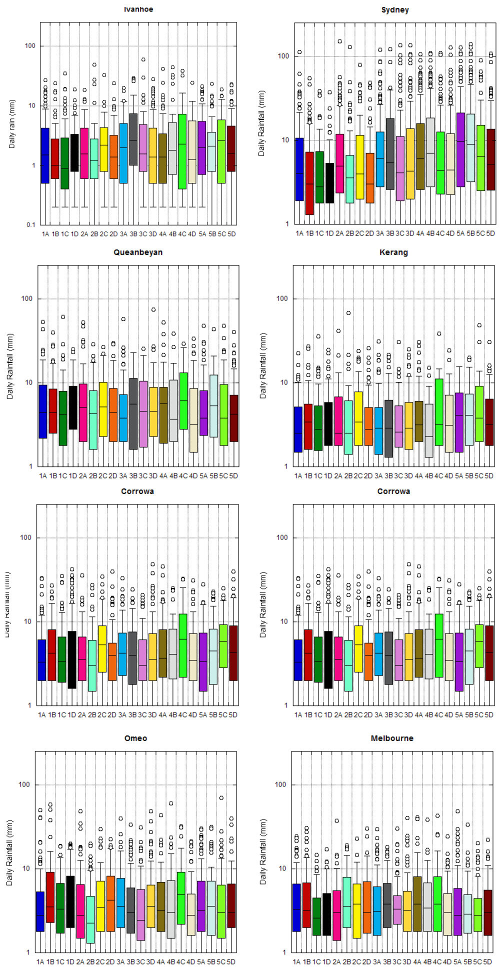

Fig. 11. Daily rainfall distributions associated with each winter synoptic type.

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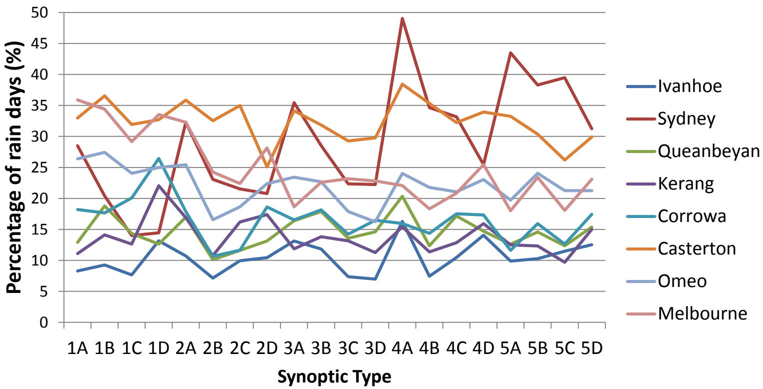

Fig. 12. Percentage of rain days associated with each autumn synoptic type.

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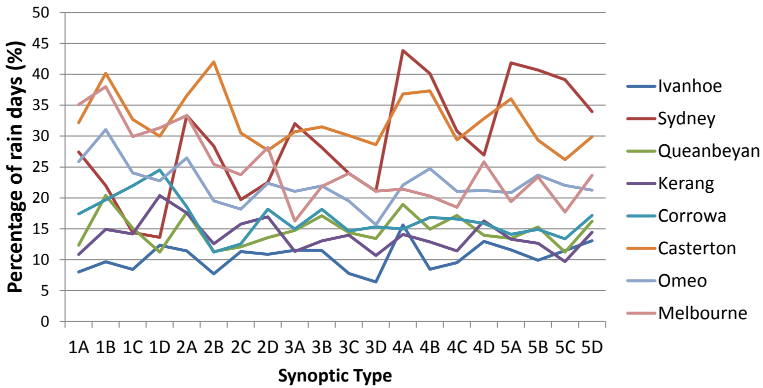

Fig. 13. Percentage of rain days associated with each winter synoptic type.

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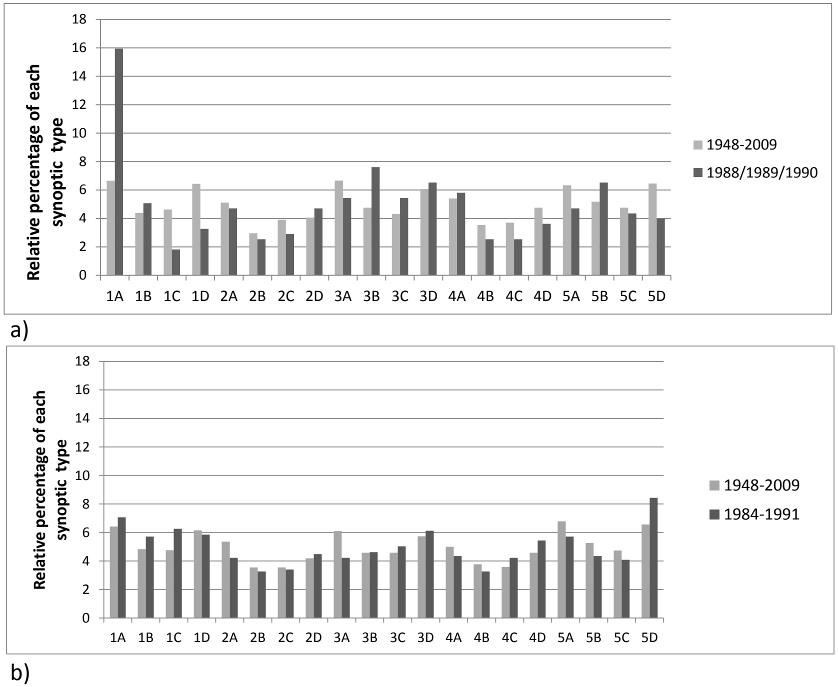
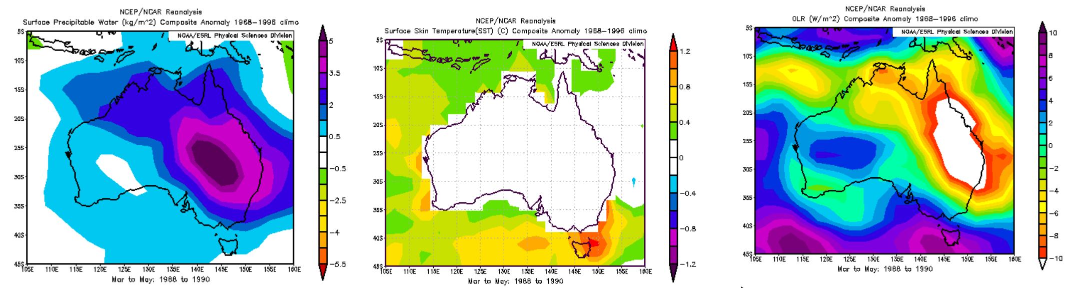


Fig. 14. Relative percentage (frequency of occurrence) for each synoptic type during **(a)** autumn 1988–1990 and autumn 1948–2009, **(b)** winter 1984–1991 and winter 1948–2009.



a) b) c)

Fig. 15. (a) precipitable water anomalies, **(b)** SST anomalies, **(c)** outgoing longwave radiation, during autumns of 1988–1990.

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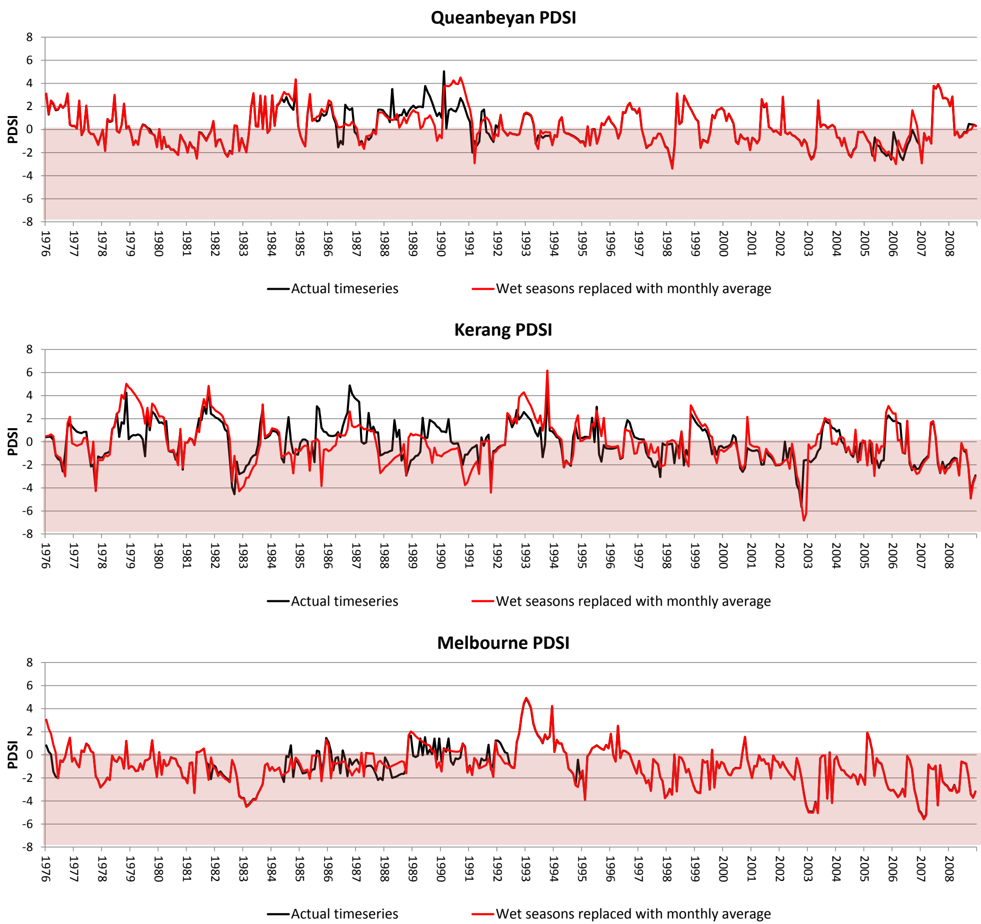

Fig. 16. Monthly time series of PDSI from 1976 to 2009 at Queanbeyan, Kerang and Melbourne (red shading shows PDSI values that indicate dry conditions).

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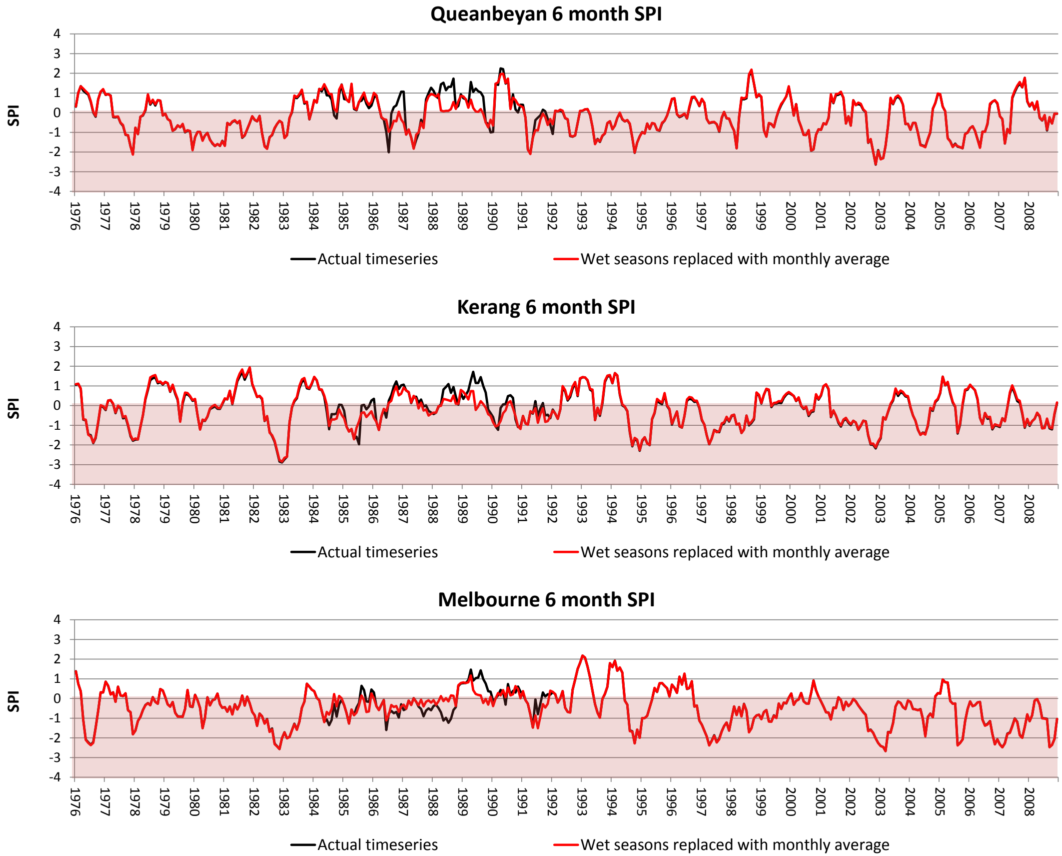

Fig. 17. Monthly time series of SPI from 1976 to 2009 at Queanbeyan, Kerang and Melbourne (red shading shows SPI values that indicate dry conditions).

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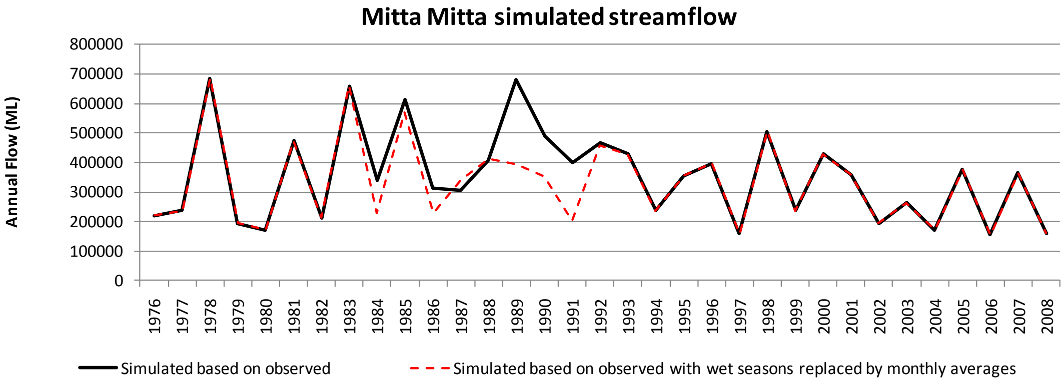

Fig. 18. Monthly simulated streamflow for Mitta Mitta Creek located in Victoria, Australia.

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