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Towards understanding hydroclimatic change in Victoria, Australia – preliminary insights into the "Big Dry"

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Abstract. Since the mid-1990s the majority of Victoria, Australia, has experienced severe drought conditions (i.e. the "Big Dry") characterized by streamflow that is the lowest in approximately 80 years of record. While decreases in annual and seasonal rainfall totals have also been observed, this alone does not seem to explain the observed reduction in flow. In this study, we investigate the large-scale climate drivers for Victoria and demonstrate how these modulate the regional scale synoptic patterns, which in turn alter the way seasonal rainfall totals are compiled and the amount of runoff per unit rainfall that is produced. The hydrological implications are significant and illustrate the need for robust hydrological modelling, that takes into account insights into physical mechanisms that drive regional hydroclimatology, in order to properly understand and quantify the impacts of climate change (natural and/or anthropogenic) on water resources.

1 Introduction

Since the mid-1990s Victoria, in southeast Australia (SEA), has experienced several years of below average streamflow conditions (e.g. NWC, 2006; Murphy and Timbal, 2008). The decrease in streamflow corresponds, at least partially, to a decrease in SEA rainfall, with annual SEA rainfall totals for the period 1997–2006 only 86% of the 1961-1990 climate "base-line" adopted by the World Meteorological Organization (WMO). Many studies (e.g. Cai and Cowan, 2008a, b; CSIRO, 2008; Murphy and Timbal, 2008; Pook et al., 2008; Potter et al., 2008, and publications produced as part of the SEA Climate Initiative (SEACI; www.mdbc.gov.au/subs/seaci)) have pointed out that the majority (∼60%) of the total SEA annual rainfall decline is due to drier autumns (March–May), which is the crucial season for "wetting up" Victorian catchments so as to ensure satisfactory streamflow throughout the rest of the year (Pook et al., 2008). The dynamics behind the SEA rainfall decline are still highly uncertain (e.g. Murphy and Timbal, 2008; Cai and Cowan, 2008a; CSIRO, 2008; Kiem and Verdon-Kidd, 2009) and it has also been shown that the decrease in annual and/or seasonal streamflow totals in many SEA areas is not totally explained by the observed decrease in annual and/or seasonal rainfall totals (e.g. Cai and Cowan, 2008b; CSIRO, 2008; Murphy and Timbal, 2008; and numerous SEACI publications). Therefore, in this study we analyze the characteristics of the most recent step change in Victorian rainfall and streamflow. We extend this analysis by investigating relationships between the recent Victorian drought (i.e. the "Big Dry") and both large-scale and regional climate drivers. This is followed by an investigation into the hydrological implications of the recent change in rainfall regime and some discussion as to the possible reasons why the decrease in Victorian streamflow since the mid-1990s appears exaggerated when compared with rainfall.

2 Data

2.1 Study catchment selection

Historical daily flow and rainfall data was obtained for nine study catchments (see Fig. 1) based on the following criteria:

- historical streamflow records are representative of "natural" streamflow conditions (i.e. observed streamflow with minimal upstream diversion or modelled streamflow where upstream diversions have been quantified and re-added to "naturalise" the flow data);

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Fig. 1. Location of study catchments and streamflow gauges (or inflow node).

- "long" rainfall and streamflow records (preferably at least 60 years to capture multidecadal variability);
- spatially distributed across Victoria to ensure several different regions are analysed.

2.2 Streamflow data

The locations of the streamflow gauges are illustrated in Fig. 1 and the characteristics of the streamflow data are summarised in Table 1. Mean observed daily flow data was obtained from Thiess Services for all stations except Goulburn and Yarra, which were obtained from the REsource ALlocation Model (REALM). REALM is a generalised computer program used to simulate the operation of both urban and rural water supply systems across many regions of SEA. The observed flow at Goulburn and Yarra is so heavily impacted by human activities it is not possible to use observed flow from these sites for any meaningful climate impact analysis as any impact due to climate variability/change is significantly outweighed (and clouded) by the impact of extractions upstream. Therefore, the Goulburn and Yarra flow data used in this study has been simulated (or "naturalised") by REALM. That is, REALM was used to convert observed (i.e. human impacted) flow at the Goulburn and Yarra sites into "natural" flow by calculating, and re-adding, extractions due to reservoir operations, farm dams, and water allocations. While it is not ideal to use modelled data in a study such as this, it was decided to include REALM simulations of "naturalised" Goulburn and Yarra flows rather than have zero information about two key Victorian catchments. Furthermore, the REALM simulations have been rigorously checked and similar data has been utilised in many previous studies (e.g. Cai and Cowan, 2008b; CSIRO, 2008).

For each streamflow site, the daily flow data was aggregated into monthly totals with months containing more than five days of missing (or poor quality) data excluded from the analysis. While various methods exist by which missing streamflow can be "infilled" it was decided not to "infill" the gauged data records due to the sensitive nature of the streamflow-climate relationships being investigated, and the potential for introduction of bias and/or artificial relationships.

2.3 Rainfall data

Historical daily rainfall data was obtained from the Australian Bureau of Meteorology for the nine study catchments. A single rainfall station, as close as possible to the catchment centroid, was used to represent each catchment (see Table 2). It was also a requirement that the rainfall record covers the period of streamflow data. As for streamflow, monthly rainfall totals were used, with months containing more than five days of missing data excluded from the analysis.

3 Step changes in Victorian rainfall and runoff

Figure 2a shows the timeseries of annual inflows at Mitta Mitta (Site 4) and Goulburn (Site 8) during the period 1920 to 2006. It can be seen that annual average streamflow over approximately the last decade is markedly lower than the

Table 1. Study catchments and streamflow gauges.

Site	Gauge names (number/source)	Catchment area (km^2)	Record start and finish	Record Length (yrs)
1	Buchan River at Buchan (222206)	822	Apr 1926–Sep 1930 Nov 1947–Dec 2006	81
2	Macalister River at Licola (225209)	1233	Aug 1952–Dec 2006	55
3	Mount Emu Creek at Skipton (236203)	1251	Jul 1920–Dec 1933 Dec 1943–Dec 2006	87
4	Mitta Mitta River at Hinnomunjie (401203)	1533	Jul 1925–Dec 2006	82
5	Campaspe River at Redesdale (406213)	629	Nov 1953–Dec 2006	54
6	Wimmera River at Glynwylln (415206) Werribee River at Ballan (231209)	1357	Jul 1946–Oct 2006	61
7	Werribee River at Ballan (Upstream of old Western Highway) (231225)	106	Aug 1943–Dec 2006	64
8	Eildon/Goulburn (REALM model input from 2006 GSM Update)	3872	Jan 1891–Jun 2006	116
9	O'Shannassy/Yarra (REALM model input from Melbourne Water)	119	Jan 1915–Dec 2006	92

annual long term average (1920–2006). This trend is consistent across all nine study catchments and supports the findings of numerous previous studies (e.g. CSIRO, 2008; Murphy and Timbal, 2008; Potter et al., 2008, and publications produced as part of the SEACI (www.mdbc.gov.au/subs/seaci)). This reduction in streamflow has also been accompanied by a reduction in rainfall as shown in Fig. 2b.

Also immediately apparent from Fig. 2 is that, while Victorian rainfall and streamflow have been below average since the mid-1990s, there are other similarly dry epochs in the historical record (particularly ∼1935 to ∼1945). Again, this is consistent across all nine study catchments, illustrating the highly variable nature of rainfall in SEA, with interannual to multidecadal cycles of above or below average rainfall occurring over at least the last 87 years.

In order to further examine the occurrence of step changes in Victorian hydroclimatology the annual (January to December) rainfall totals were analyzed using a moving window of 20 years to identify significant epoch shifts. Each window was subjected to a Mann-Whitney U test to determine the statistical significance of any step changes. This test has previously been used to detect multidecadal regime shifts in hydroclimatological variables (e.g. Mauget, 2003). Years where significant step changes were identified in annual rainfall totals are shown in Table 3.

The literature indicates some uncertainty about the start of the current "dry" period in SEA – with reference to the shift beginning anywhere from 1990 to 1998. The statistical test applied here identifies 1994 as the first year of the current "dry" phase for six out of the nine study sites. The exceptions were the two far eastern stations, Buchan and Mitta Mitta (where 1996 was identified as the first year of the current "dry" phase) and Goulburn (where 1993 was identified as the first year of the current "dry" phase). This demonstrates that, with respect to rainfall, the so-called "Big Dry" (e.g. Ummenhofer et al., 2009; Verdon-Kidd and Kiem, 2009b) initiated closer to 1994 for the majority of Victoria as opposed to 1997 as is commonly reported (e.g. Murphy and Timbal, 2008). Other significant step-changes in rainfall were also identified (see Fig. 2 and Table 3). These varied from station to station but there is reasonable agreement that the mid-1930s to mid-1940s were drier than average (3 out of 4 sites for which there was data), mid-1940s to mid-1970s were wetter than average (5 out of 5 sites), and the mid-1980s to mid-1990s were also wetter than average at 4 out of 9 sites. This demonstrates that the mid-1990s climate shift is not unprecedented, at least in terms of significant changes from wet to dry epochs across Victoria – this finding is supported by previous studies into SEA hydroclimatology (e.g. Watkins, 2005; CSIRO, 2008; Murphy and Timbal, 2008; Potter et al., 2008; Verdon-Kidd and Kiem, 2009b) that have

Table 2. Study catchments and rainfall gauges.

Site	Catchment	Rainfall gauge name, BOM gauge number and location	Record length
1	Buchan	084005 Buchan (Post Office) (37.5° S, 148.17° E)	Apr 1925–Apr 2007
2	Macalister	083033 Woods Point (37.57° S, 146.25° E)	Aug 1951–Apr 2007
3	Mt Emu Crk	089005 Beaufort (37.45° S, 143.37° E)	Jul 1919–Apr 2007
4	Mitta Mitta	083025 Omeo Comparison (37.10° S, 147.60° E)	Jul 1924–Apr 2007
5	Campaspe	088042 Malmsbury Reservoir 37.20° S, 144.37° E)	May 1957–Apr 2007
6	Wimmera	079031 Moonambel (36.99° S, 143.27° E)	Jul 1945–Apr 2007
7	Werribee	087006 Ballan (Post Office) (37.6° S, 144.23° E)	Aug 1942–Apr 2007
8	Goulburn	088023 Lake Eildon (37.23° S, 145.91° E)	Jan 1919–Apr 2007
9	Yarra	086090 Warburton (O'Shannassy Reservoir) (37.71° S, 145.79° E)	Jan 1919–Apr 2007

Table 3. Significant step changes in annual rainfall totals (January to December) for each of the nine rainfall stations.

Site 1 Buchan	Site 2 Macalister	Site 2 Mt Emu Crk	Site 4 Mitta Mitta	Site 5 Campaspe	Site 6 Wimmera	Site 7 Werribee	Site 8 Goulburn	Site 9 Yarra
1934 (to dry)	*	1933 (to dry)	*	*	*	*	1936 (to dry)	
1946 (to wet)	*	1946 (to wet)	1945 (to wet)	*	*	*	1945 (to wet)	1946 (to wet)
				1976 (to dry)				1976 (to dry)
	1986 (to wet)					1985 (to wet)	1986 (to wet)	1984 (to wet)
1996 (to dry)	1994 (to dry)	1994 (to dry)	1996 (to dry)	1994 (to dry)	1994 (to dry)	1994 (to dry)	1993 (to dry)	1994 (to dry)

*Timeseries too short to identify step change for this period

identified similarly dry epochs, with respect to rainfall and/or streamflow, occurring around 1895–1902 (the so-called Federation drought) and 1937–1945 (the so-called World War II drought).

3.1 Seasonality of the mid-1990s shift to a dry epoch across Victoria

Figure 3 illustrates the seasonality of the mid-1990s climate shift by showing the seasonal rainfall totals for the periods 1948 to 1993 (the most recent "wet" epoch) and 1994 to 2007 for the nine study catchments. It is evident from Fig. 3 that the majority of the decrease in annual rainfall since 1994 is due to a large reduction in autumn (and to a lesser degree winter and spring) rainfall – this finding supports the results of several previous studies (e.g. Murphy and Timbal, 2008; Pook et al., 2008; Cai and Cowan, 2008a, b). Importantly, not only is there an obvious decrease in median rainfall, the extremely wet autumn rainfall totals that occurred in pre-1994 have not occurred post-1993. Figure 4a shows that the reduction in autumn rainfall is not just limited to the study sites and in fact extends across the entire SEA region and is also accompanied by a rising trend in sea level pressure (Fig. 4b).

So it is clear that since the mid-1990s Victoria has experienced marked, but not unprecedented, reductions in rainfall, and that most of this reduction has occurred in autumn. This is important given that rainfall in the autumn months, known as the "autumn break" (e.g. Pook et al., 2008), is crucial for establishing the antecedent soil moisture conditions

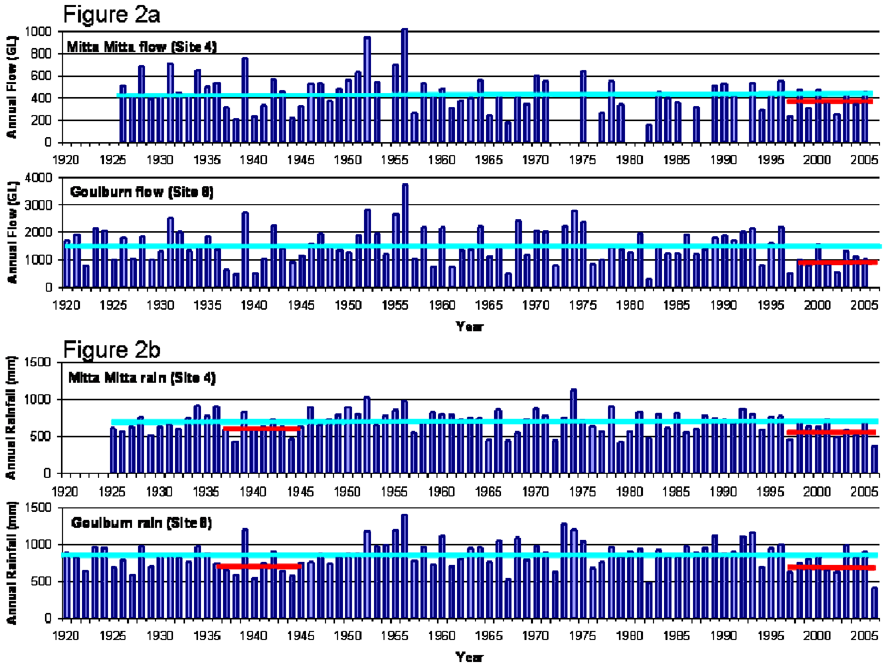

Fig. 2. Historical annual **(a)** streamflow and **(b)** rainfall at Mitta Mitta (Site 4) and Goulburn (Site 8). Long-term (1920–2006) averages are indicated by the light blue lines while the red lines indicate the post-1997 average and, for rainfall, the average for a similarly dry decade beginning in the mid-1930s (1937 for Mitta Mitta and 1936 for Goulburn).

necessary for reasonable flows throughout the remainder of the year. As expected, the reduction in rainfall has been accompanied by reductions in streamflow, however, in some locations the decrease in streamflow totals is reportedly unprecedented in historical records (i.e. since about 1920). There is limited understanding as to why the autumn rainfall has declined so dramatically and also why the decrease in Victorian rainfall does not seem to explain the exaggerated decrease in streamflow (e.g. Cai and Cowan, 2008b; CSIRO, 2008; Murphy and Timbal, 2008; and numerous SEACI publications). These issues are addressed in the Sects. 4 and 5, respectively.

4 What is causing the decrease in autumn rainfall?

4.1 Regional-scale synoptic patterns

Figure 4b demonstrates that sea-level pressures (SLPs) across SEA during autumn have been higher post-1993 than they were pre-1994, with the centre of this pressure increase focused on western Victoria. It is anticipated that this is related to changes in the regional-scale synoptic patterns that actually deliver Victoria's rainfall. Verdon-Kidd and Kiem (2009a) identified 20 key regional synoptic patterns important for Victoria using a non-linear classification methodology known as self-organizing maps (SOM). The synoptic types identified using this technique were shown to capture a range of significant synoptic features identified by previous studies (e.g. Pook et al., 2008) as being important influences on the climate of Victoria. The synoptic features identified include, the seasonal trend in the location and intensity of the semi-permanent Pacific and Indian Ocean high pressure systems associated with the Sub-tropical Ridge (STR), variability in the strength and location of the east coast trough (located between the two semi-permanent high pressure systems), as well as an off-shore trough, pre-frontal trough and blocking high. Rainfall distributions were assigned to each of the 20 patterns for nine rainfall stations (the same stations that are used in this study), resulting in clear distinctions between wet and dry synoptic types at each station.

Given that the majority of the "post-1993" reduction in Victorian rainfall has occurred in autumn, this is where we concentrate our analysis. An investigation into the relative frequency of the 20 key synoptic types was performed to determine whether the changes in post-1993 autumn rainfall totals can be explained by changes in the seasonality/timing of regional synoptic patterns (Fig. 5). Note that the analysis is restricted to 1948 onwards as that is when the monthly global SLP data, required for the SOM, begins.

Figure 5 demonstrates that there have been marked changes in the frequency of synoptic types occurring in autumn pre-1994 and post-1993. In particular, post-1993 there has been an increase in synoptic types representing a

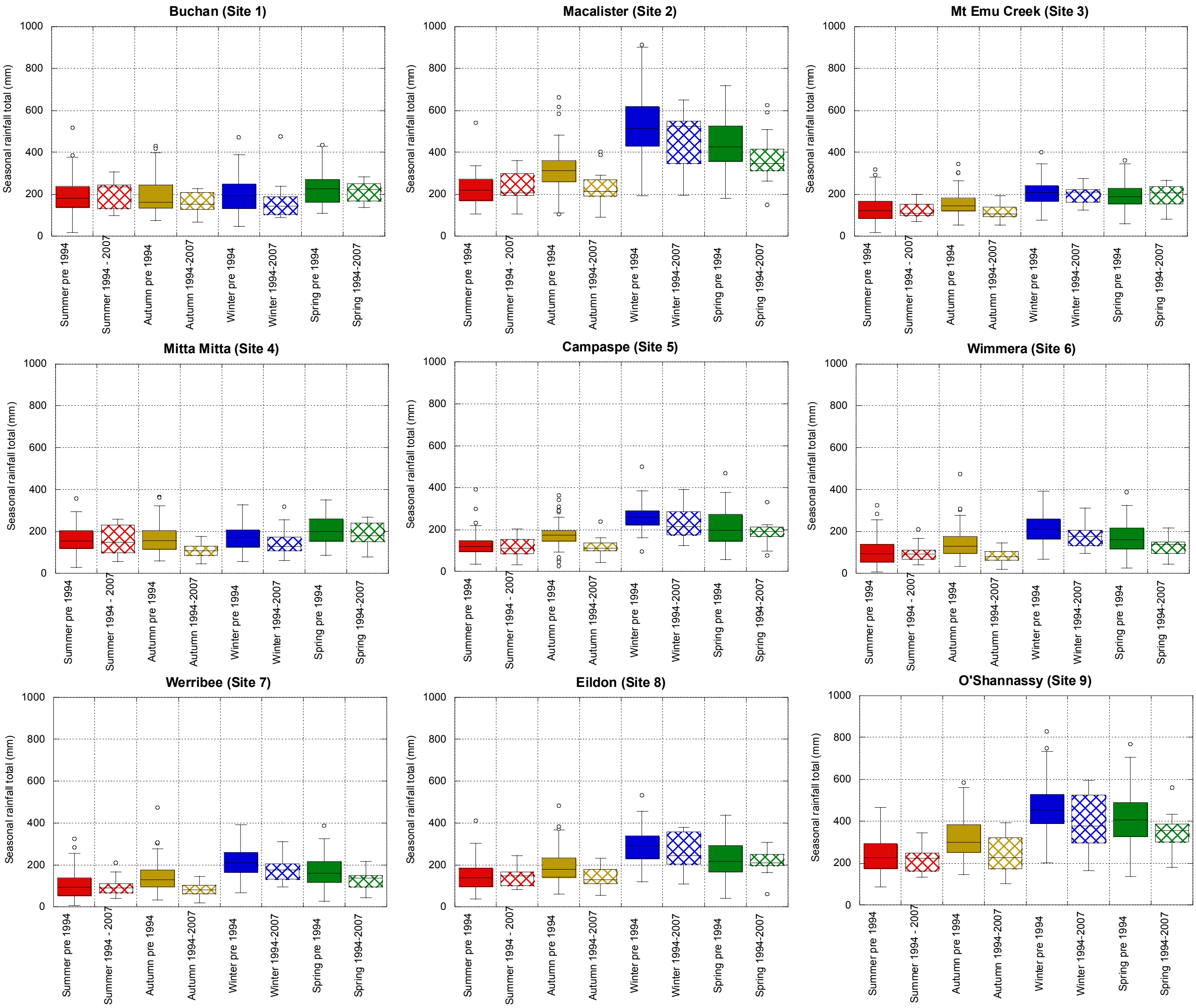

Fig. 3. Seasonal rainfall totals for the periods 1948–1993 (pre-1994) and 1994–2007 at each study location. Each box encloses 50% of the data with the median value displayed as the horizontal line within the box. The Interquartile Distance (IQD) is the difference between the value at the top (UQ) and bottom (LQ) of the box. The vertical lines coming out of the boxes ("whiskers") represent the highest/lowest data point within an acceptable range (in this case less than UQ +1.5* IQD and greater than LQ −1.5* IQD). Values outside this range (circles) are considered outliers.

southward movement and strengthening of the central high pressure system associated with the STR (noted as types 3D, 4D and 5D in Verdon-Kidd and Kiem, 2009a) which would prevent rain-bearing lows moving through south-east Australia – a result consistent with Fig. 4b and the recent work emanating from SEACI (www.mdbc.gov.au/subs/seaci/). In addition, post-1993 there has been a complete absence of synoptic types representing pre-frontal troughs, which would normally allow rain producing southern ocean cold fronts to penetrate into the south of the state (noted as type 1A and 1B in Verdon-Kidd and Kiem, 2009a). Therefore, these results support previous work (e.g. Drosdowsky, 2005; Timbal et al., 2007; Larsen and Nicholls, 2009; Williams and Stone, 2009) suggesting that the "post-1993 autumn rainfall decline" can be attributed to a strengthening and southward movement of the STR during autumn and a reduction in the frequency of rain producing troughs.

4.2 Large-scale climate modes

The change in synoptic frequency is thought to largely explain the reduction in autumn, and therefore annual, rainfall. However this raises the question, why have the

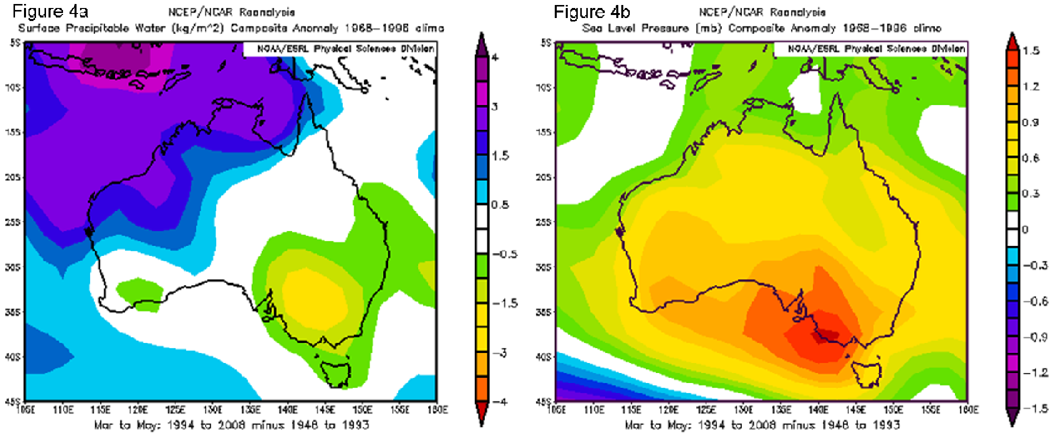

Fig. 4. **(a)** Difference in autumn surface precipitable water 1994–2008 compared with 1948–1993. **(b)** Difference in autumn sea level pressure 1994–2008 compared with 1948–1993 (Source: NCEP/NCAR Reanalysis Data, http://www.esrl.noaa.gov/).

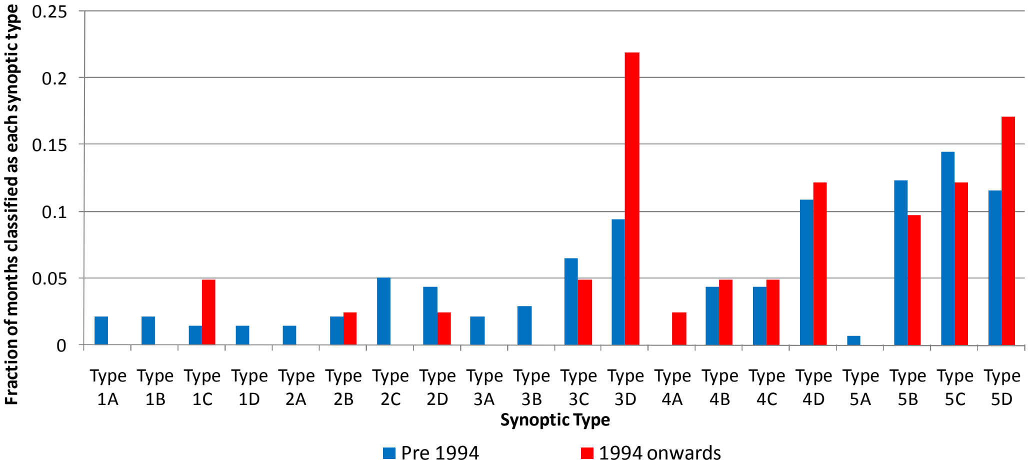

Fig. 5. Fraction of each synoptic type during autumn (MAM): post-1993 versus pre-1994.

frequency of synoptic types in autumn changed post-1993? Figure 4b illustrates that large-scale pressure patterns have also changed and the following sections extend this by examining the relationship between the key regional synoptic patterns for Victoria and the three large-scale climate modes thought to be most influential for Australia (i.e. the El Niño/Southern Oscillation (ENSO), the Indian Ocean variability and the Southern Annular Mode (SAM)). Refer to Kiem and Verdon-Kidd (2009) for an explanation of these climate modes, the indices used to represent them and how they are characterized. To investigate the relationship between the regional synoptic patterns and the large-scale climate modes, the occurrence of each of the 20 regional synoptic patterns within each climate state was determined and the results for autumn are shown in Table 4.

Table 4 shows that the "wet" synoptic type 1A (representing northward movement of the STR and a strong pre-frontal trough) only occurs in autumn in combination with a La Niña event, indicating that the "autumn break" (e.g. Pook et al., 2008) may be more reliable in a La Niña year. Table 4 also shows that the positive phase of the SAM strongly favours the occurrence of "dry" synoptic patterns (located at the bottom half of Table 4). This is further illustrated in Fig. 6, where the proportion of dry (bold in Table 4) and wet (itallic in Table 4) types occurring within each of the climate phases is shown. Figure 6c clearly shows that dry (wet) types are more likely when the SAM is positive (negative). Figure 6a also shows that wet types are less likely during El Niño events than they are in any other climate phase besides SAM positive. The likelihood of dry types occurring is also increased if Indian Ocean sea-surface temperature to the northwest of Australia is cooler than normal (Fig. 6b). However, as explained by

Table 4. Number of times each synoptic type has occurred in autumn for each climate state (1948–2006). EN/LN/N=El Niño/La Niña/Neutral phase of the ENSO, Pos/Neg/N=Positive/Negative/Neutral Indian Ocean SST or SAM phase. "Wet" synoptic types are in itallic. "Dry" types are in bold. Refer to Verdon-Kidd and Kiem (2009a) for further information regarding synoptic types.

Synoptic	ENSO			Indian Ocean SST			SAM			Exception to wet/dry response for each synoptic type
Type	EN	LN	N	Pos	Neg	N	Pos	Neg	N	
1A	*0*	*3*	*0*	*1*	*1*	*1*	*0*	*2*	*1*	
1B	*1*	*0*	*2*	*1*	*1*	*1*	*0*	*3*	*0*	
1C	*1*	*1*	*2*	*0*	*1*	*3*	*1*	*1*	*2*	
1D	*1*	*0*	*1*	*2*	*0*	*0*	*1*	*1*	*0*	Dry at far eastern stations (Buchan and Mitta Mitta)
2A	**0**	**1**	**1**	**0**	**0**	**2**	**0**	**2**	**0**	
2B	*0*	*2*	*2*	*1*	*1*	*2*	*0*	*1*	*3*	
2C	2	1	4	1	3	3	0	6	1	Mixed results
2D	2	1	4	3	1	3	0	4	3	Mixed results
3A	1	2	0	1	2	0	0	1	2	Mixed results
3B	0	0	4	1	1	2	0	3	1	Mixed results
3C	1	1	9	0	6	5	3	4	4	Mixed results
3D	**4**	**4**	**14**	**3**	**11**	**8**	**12**	**4**	**6**	
4A	**1**	**0**	**0**	**0**	**1**	**0**	**1**	**0**	**0**	
4B	**3**	**1**	**4**	**3**	**4**	**1**	**2**	**2**	**4**	Wet at Mitta Mitta
4C	*3*	*0*	*5*	*1*	*5*	*2*	*2*	*3*	*3*	
4D	**5**	**2**	**12**	**4**	**9**	**6**	**9**	**3**	**7**	
5A	*0*	*1*	*0*	*1*	*0*	*0*	*0*	*0*	*1*	Wet at far eastern stations (Buchan and Mitta Mitta)
5B	**0**	**9**	**12**	**9**	**7**	**5**	**7**	**5**	**9**	Wet at Buchan
5C	**7**	**8**	**10**	**5**	**15**	**5**	**9**	**2**	**14**	Wet at far eastern stations (Buchan and Mitta Mitta)
5D	**3**	**10**	**10**	**5**	**14**	**4**	**13**	**3**	**7**	

Verdon-Kidd and Kiem (2009b), Indian Ocean sea-surface temperature to the northwest of Australia has been warmer than average since the mid-1990s (i.e. conditions not associated with a high proportion of dry types) and therefore Indian Ocean variability appears unlikely to be the main causal mechanism behind the recent autumn rainfall decline across Victoria. This is consistent with research that has shown that Indian Ocean variability primarily impacts eastern Australian rainfall in winter and spring, when the Indian Ocean Dipole (IOD; Saji et al., 1999) is most active (e.g. Ashok et al., 2003; Verdon and Franks, 2005; Verdon-Kidd and Kiem, 2009a). In any case, the marked difference in proportion of dry or wet types occurring during autumn when SAM is positive compared to when it is negative (Fig. 6c) combined with the clouded nature of the ENSO (Fig. 6a) and Indian Ocean variability results (Fig. 6b) suggests that SAM plays the major role in modulating synoptic patterns, and therefore rainfall, during autumn across Victoria. The fact that the wettest type (e.g. 1A) only occurs during La Niña events also suggests that ENSO phase is important. A timeseries of the SAM and ENSO is shown in Fig. 7.

Figure 7 shows that SAM has been in a positive phase during autumn from 1994 to 2008 in every year except 2002, and has in fact been trending positive since 1950. In addition, there has also been a distinct lack of La Niña events (i.e. lack of negative ONI in Fig. 7) since the early 1990s. More importantly, when a La Niña has occurred since 1994 it has coincided with a positive SAM, thereby reducing the chance of the "autumn rainfall break" (refer to Kiem and Verdon-Kidd (2009) for further details about how Victoria, due to its relative location to the Pacific, Indian and Southern Oceans, is influenced by ENSO, Indian Ocean variability and SAM acting in concert rather than being dominated by one single driver). Note that from 1982–1989 the SAM is also positive in all but one year, however, unlike the post-1993 period 1982–1989 was not associated with significant persistent reductions in annual rainfall/flow totals (refer to Fig. 2). This is due to the fact that (a) there was a lower proportion of El Niño events 1982–1989 than there has been post-1993, (b) there was a higher frequency of La Niña events during the 1982–1989 period, and (c) the La Niña events that did occur 1982–1989 were not always associated with a strongly positive SAM. This is not to say that shorter droughts cannot occur within longer epochs of average to above-average rainfall. For example, 1982/83 was associated with extremely

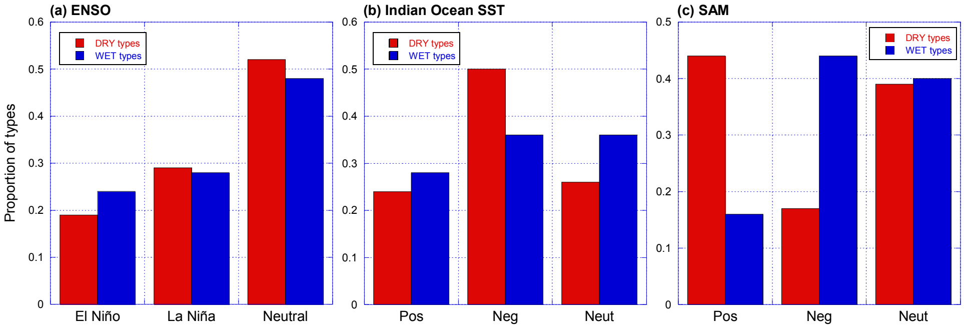

Fig. 6. Proportion of DRY and WET types occurring in autumn during different phases of **(a)** ENSO, **(b)** Indian Ocean variability and **(c)** SAM. DRY (WET) types are those in bold (italic) in Table 4.

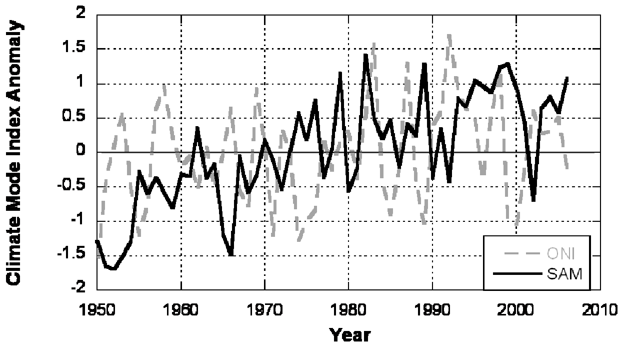

Fig. 7. Timeseries of autumn ONI (i.e. the ENSO monitor known as the Oceanic Niño Index) and autumn SAM index anomaly values. Index anomalies have been standardised to have a mean of zero and standard deviation of one across all months.

dry conditions, due to the Pacific being in El Niño mode, below average sea-surface temperature off northwest Australia and a positive SAM (i.e. all three modes locked into their dry phase). However, in comparison with the current SEA drought, the 1982/83 drought was relatively short-lived (i.e. less than 12 months) across most of eastern Australia.

The results presented here indicate that the observed decrease in autumn rainfall since 1994 is related to both the state of SAM and ENSO during this season. Both of these modes appear to modulate the regional synoptic patterns during this time with persistently positive SAM (and/or El Niño) conditions associated with more frequent dry types and/or less frequent wet types (and vice versa for negative SAM). Therefore, large-scale climate conditions, predominantly locked into the El Niño/SAM positive phase during autumn since 1994, potentially explain the mid-1990s change in rainfall (and runoff) regime across Victoria. The physical mechanism (s) explaining how SAM and ENSO interact to either produce or block rain producing systems is (are) yet to be fully understood. However it is suggested that the northward movement of the high pressure system associated with the Sub-tropical Ridge (STR) during a positive SAM, may negate the southward propagation of the South Pacific Convergence Zone (SPCZ) usually associated with La Nina events and therefore limit the above-average rainfall associated with La Niña events to regions north of Victoria (Kiem and Verdon-Kidd, 2009).

It should be noted that several alternate indices and methods exist by which to characterise the state of the Pacific, Indian and Southern Ocean regions. Accordingly, the relationship identified between SEA hydroclimatology and the various large-scale climate drivers varies depending on the index and/or classification method chosen (Kiem and Franks, 2001). However, the conclusion that it is the interaction (s) between multiple large-scale climate phenomena that drives SEA climate is not sensitive to the choice of index or classification method. In addition, other ocean-atmosphere interactions besides those discussed here are likely to play a role, such as the recently documented impacts associated with ENSO Modoki (e.g. Ashok et al., 2009; Cai and Cowan, 2009; Taschetto and England, 2009; Taschetto et al., 2009). These studies present significant new insights, however, the disparity (and gaps) in some of the results, along with several unanswered questions and issues raised within and arising from the ENSO Modoki literature, highlights the fact that understanding into impacts associated with large-scale climate drivers (and their interactions) is in its infancy. Further investigation, similar to that presented here and in the ENSO Modoki literature mentioned above, is urgently required if we are to properly explain the causal climatic mechanisms behind the drought SEA is currently experiencing.

5 Hydrological implications of the post-1994 change in rainfall regime across Victoria

The fact that decline in annual runoff has occurred at the same time as a decline in annual rainfall, indicates that the mid-1990s reduction in runoff/inflows can, at least partially, be explained by the observed reduction in rainfall. However, Cai and Cowan (2008b) found that only ∼51% of the observed decline in runoff in the southern Murray

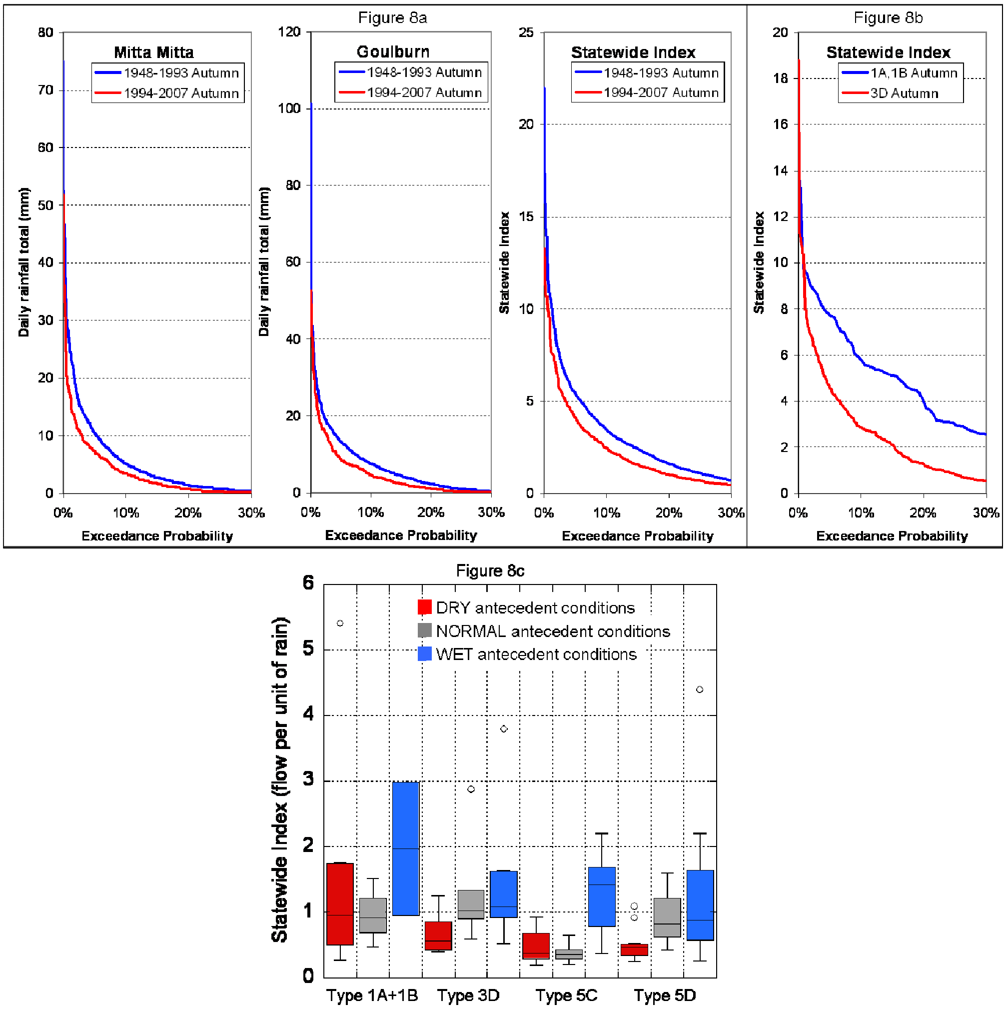

Fig. 8. Exceedance probabilities of daily rainfall during autumn **(a)** pre-1994 and post-1993 and **(b)** associated with synoptic types 1A+1B (wet types) and 3D (dry type) for the period 1948–2007. In Fig. 8a and b the Statewide Index refers to the "normalized" daily rainfall averaged across the nine study sites – greater (less) than 1 indicates above (below) average rainfall. **(c)** For the period 1948–2007, monthly flow (ML) per unit rainfall during autumn stratified according to selected synoptic types and antecedent flow conditions (DRY=previous 6 months more than 15% drier than average, WET=previous 6 months more than 15% wetter than average). In Fig. 8c the Statewide Index refers to the "normalized" monthly flow (ML) per unit rainfall averaged across the nine study sites – greater (less) than 1 indicates above (below) average monthly flow per unit rainfall.

Darling Basin (i.e. a large proportion of Victoria) since 1950 could be "explained" by the decline in rainfall and suggested that the reduction in runoff not attributable to the reduction in rainfall is largely due to increases in temperature. However, the rainfall-runoff regression relationships used by Cai and Cowan (2008b) do not take into account any soil moisture carryover and therefore the inherent non-linearity in the rainfall-runoff relationship (e.g. Wooldridge et al., 2001), and the importance of antecedent soil moisture conditions (e.g. Kiem and Verdon-Kidd, 2009), is likely to have been underestimated (e.g. CSIRO, 2008). In addition, while Cai and Cowan (2008b) show a statistical relationship between inflow variations and fluctuations in temperature, the physical mechanisms by which rising temperatures contribute to enhance the reduction in streamflow are not clear, particularly given previous studies that show a decreasing trend in evaporation across much of SEA over the last fifty years (e.g. Roderick and Farquhar, 2004; Roderick et al., 2009a, b).

There are numerous factors besides, or in addition to, increasing temperature that could possibly explain the trend in flow not attributable to changes in annual or seasonal rainfall totals. These include increasing loss to groundwater (e.g. CSIRO, 2008), re-vegetation post-bushfire or changes to fire management strategies (e.g. Mannik et al., 2009), change in land-use or vegetation type (e.g. CSIRO, 2008), increasing irrigation and/or farm dam extractions (e.g. CSIRO, 2008), increased air pollution (Rosenfeld, 2000), increased sunshine hours (Lockart et al., 2009) and, of specific interest for this study, changes in the seasonality of rainfall – in particular, changes in the way seasonal totals are compiled (i.e. changes to the frequency, intensity, duration and/or sequencing of rainfall events). Figure 8a compares the pre-1994 and post-1993 exceedance probabilities of daily autumn rainfall at Mitta Mitta (Site 4), Goulburn (Site 8) and across Victoria using a Statewide Index. The Statewide Index, in this case, is the average across the nine study sites of the "normalized" daily rainfall (i.e. autumn daily autumn rainfall at each station is scaled by the mean of that stations daily rainfall during autumn so that a value greater (less than) one indicates above (below) average daily autumn rainfall) – refer to Kiem and Franks (2003) for details on the derivation of this "Statewide Index".

Figure 8a shows that the probability of receiving daily autumn rainfall between 5 mm and 25 mm at Mitta Mitta and Goulburn, or between 2 and 10 times the daily average (based on the Statewide Index), has decreased markedly post-1993. For example, the probability of exceeding a Statewide Index of five (i.e. on average across the state daily rainfall that is five times the daily mean) pre-1994 (6.0%) is almost double that of post-1993 (3.3%). As suggested in Sect. 4.1, the likely reason for this is the change in frequency of the synoptic patterns that bring rainfall to Victoria. For example, Fig. 8b shows that the chance of experiencing "wetter than average" days during autumn is much higher when a strong pre-frontal trough is evident (as captured by synoptic types 1A and 1B) compared to when the central high pressure of the STR is located further south over Victoria (as captured by synoptic type 3D). Importantly, as demonstrated in Fig. 5, during autumn since 1994 there has been a marked increase in type 3D and an absence of type 1A and 1B.

The impact of changes in "seasonal rainfall makeup" on the rainfall-runoff relationship is further illustrated in Fig. 8c, where it is shown that monthly streamflow per unit rainfall during autumn varies dramatically depending both on the antecedent conditions (six months prior) and the dominant synoptic pattern for a given month. Note that this analysis only included situations where no data was missing during the month being analysed and the six months antecedent period. The five synoptic types chosen were selected because types 5C and 5D are the most dominant autumn types (each occurring approximately 14% of the time), type 3D is an example of a "dry" type that has increased in frequency since 1994, and types 1A and 1B are examples of "wet" synoptic patterns that have been absent since 1994 (refer to Fig. 5). Of particular interest is that if antecedent conditions during the six months leading up to autumn are "dry", as has been the case in most years since 1994, then below average flow per unit rainfall is almost certain unless a pre-frontal trough occurs (synoptic type 1A and/or 1B) – which is unlikely to happen if SAM and ENSO are locked in their respective positive phases (refer to Table 4 and Fig. 6). It is therefore recommended that, "seasonal rainfall makeup" and antecedent conditions be further investigated and accounted for, via robust hydrological modelling, before attributing declines in annual or seasonal streamflow, not explained by declines in seasonal rainfall totals, to increasing air temperatures.

6 Conclusions

After investigating the mid-1990s step-change in rainfall and runoff across Victoria it has been determined that:

1. The step change in annual Victorian rainfall occurred in ∼1994 for the majority of the state and similar shifts (wet to dry and vice versa) have occurred previously;
2. The majority of the annual rainfall decrease is due to a reduction in mean autumn rainfall (due to both a reduction in the number of rain days and an absence of extremely wet events), which in turn is linked to changes in the frequency and timing of the regional synoptic patterns that drive Victorian climate. In particular, during autumn there has been an increase in intensity and southward propagation of the STR preventing rain-bearing lows moving through south-east Australia, combined with an absence of pre-frontal troughs which would normally allow rain producing southern ocean cold fronts to penetrate into the south of the state;
3. The change in regional synoptic patterns during autumn is linked to the phases of SAM and ENSO (at least), with post-1993 drought conditions brought about due to SAM and ENSO during autumn months being simultaneously locked into multi-year "dry" phases of their respective cycles. Although three La Niña events have occurred during this time, these events failed to deliver substantial rainfall as they coincided with the positive (dry) phase of SAM (see Kiem and Verdon-Kidd, 2009).

We suggest that a significant proportion of the amplified runoff reduction observed post-1993 is due to altered daily/seasonal rainfall distributions (and sequencing of rainfall events), which in turn is attributable to the SAM-ENSO induced changes in the frequency of key synoptic patterns. There are likely to be several other contributing factors and only through detailed hydrological modelling can conclusions be made as to the relative importance of each. Based on the preliminary findings here it is recommended that such hydrological modelling be performed at a minimum of a daily time step (so as to capture changes to daily rainfall distributions which may not show up in monthly or seasonal totals) and should realistically incorporate antecedent conditions. Only after such hydrological modelling exercises are satisfactorily completed, and further understanding is gained into the interactions between large-scale and regional-scale climate drivers, should inferences be made about future hydrological conditions under anthropogenic and/or natural climate change.

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