Hydrol. Earth Syst. Sci. Discuss., 6, 6181–6206, 2009
www.hydrol-earth-syst-sci-discuss.net/6/6181/2009/

Hydrology and
Earth System
Sciences
Discussions

Towards understanding hydroclimatic change in Victoria, Australia – why was the last decade so dry?

A. S. Kiem and D. C. Verdon-Kidd

Environmental and Climate Change Research Group, School of Environmental and Life Sciences, University of Newcastle, Australia

Received: 7 September 2009 – Accepted: 11 September 2009 – Published: 1 October 2009

Correspondence to: A. S. Kiem (anthony.kiem@newcastle.edu.au)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Since the mid-1990s Victoria, located in southeast Australia, has experienced severe drought conditions characterized by streamflow that is the lowest on record in many areas. While severe 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, which 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 extremely low streamflow (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. Murphy and Timbal, 2008; Pook et al., 2008; Cai and Cowan, 2008a,b) have pointed out that the majority of the SEA rainfall decline (~60%) 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; Kiem and Verdon-Kidd, 2009) and Cai and Cowan (2008b) have also pointed out 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. 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 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 available that are representative of “natural” streamflow conditions;
- “long” rainfall and streamflow records (preferably at least 60 yr to capture multi-decadal 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 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 REALM time series were included as they provide important information about inflows into key water storage reservoirs in Victoria. For each 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. It was also a requirement that the rainfall record cover 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

As mentioned in the Introduction, there has been a significant reduction in streamflow across much of Victoria since the mid-1990s. 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 streamflow over approximately the last decade is markedly lower than the long term average. This trend is consistent across all nine study catchments (only two shown here) and supports the findings of numerous previous studies (e.g. Murphy and Timbal, 2008; and publications produced as part of the SEA Climate Initiative (SEACI; http://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 similar 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 elevated and suppressed rainfall occurring over at least the last 87 yr.

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 yr 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 2.

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 "post-1997 climate shift" initiated closer to 1994 for the majority of Victoria. Importantly, as suggested by Fig. 2, other significant step-changes in rainfall were also identified. These varied from station to station but the most common "step-change years" are ~1935 switch to dry, ~1945 switch to wet, ~1975 switch to dry, ~1985 switch to wet. This demonstrates that the "post-1994 climate shift" is not unprecedented, at least in terms of annual rainfall across Victoria – this finding is supported by previous studies into SEA hydroclimatology (e.g. Murphy and Timbal, 2008; SEACI publications etc.) that have identified similarly dry epochs, with respect to rainfall and/or streamflow, occurring around 1895–1902 (the Federation drought) and 1936–1945 (Watkins, 2005).

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 extreme rainfall events that occurred in autumn 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 consistent with anecdotal evidence from SEA water resources managers who have been asking for several years "what has happened to the autumn rain?" This is an important question 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 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). 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 (2009) 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 (refer to Fig. 3 and associated discussion in Verdon-Kidd and Kiem, 2009) 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 (refer to Fig. 5 in Verdon-Kidd and Kiem, 2009).

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-1994 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- and post-1993. In particular, since 1994 there has been an increase in synoptic types representing a 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, 2009) which would prevent rain-bearing lows moving through south-east Australia – a result consistent with Fig. 4b and the recent work emanating from SEACI (http://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, 2009). Therefore, these results suggest 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 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 (Verdon-Kidd and Kiem, 2009) 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 3 – refer to Verdon-Kidd and Kiem (2009) for results relating to other seasons and for further details on the synoptic types.

Table 3 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. It can be seen from Table 3 that the Indian Ocean variability alone does not appear to have a great deal of influence on autumn synoptic types and is therefore unlikely to have contributed to the decrease in autumn rainfall. 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, 2009). Table 3 shows that the positive phase of the SAM strongly favours the occurrence of "dry" synoptic patterns (located at the bottom half of Table 3). Therefore, it seems that both SAM and ENSO play a role in modulating synoptic patterns and therefore rainfall during autumn. A timeseries of the SAM and ENSO is shown in Fig. 6.

Figure 6 shows that the SAM has been in a positive phase during autumn from 1994 to 2008 in every year except 2002. In addition, there has also been a distinct lack of La Niña events since the early 1990s. More importantly, when a La Niña has occurred since 1994 (negative ONI) 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 Niñ a 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 dry conditions, due mostly to the strong El Niño event occurring at that time. However, in comparison to the current SEA drought, the 1982/83 drought was relatively short-lived (i.e. less than 12 months) across most of eastern Australia.

Therefore, the results presented here indicate that the observed decrease in autumn rainfall since 1994 is related to both the state of ENSO and the SAM 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 less frequent wet types (and vice versa for negative SAM and/or La Niña). 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 explaining how ENSO and SAM interact to either produce or block rain producing systems is 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 also 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 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. 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, 2009b).

There are numerous factors besides, or in addition to, increasing temperature that could explain the trend in flow not attributable to changes in annual or seasonal rainfall totals. These include increasing loss to groundwater, re-vegetation post-bushfire or changes to fire management strategies, change in land-use or vegetation type, increasing irrigation and/or farm dam extractions, 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 7a compares the pre-1994 and post-1993 exceedance probabilities of daily 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 rainfall at each station is scaled by the mean of that stations daily rainfall during autumn) – refer to Kiem and Franks (2003) for details on the derivation of this "Statewide Index".

Figure 7a shows that the probability of receiving daily rainfall between 5 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. 7b shows that the chance of experiencing "wetter than average" days 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, 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. 7c, 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. 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 3). 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 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 autumn rainfall, which in turn is linked to changes in the frequency and timing of the regional synoptic patterns that drive Victorian climate. In particular, 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 ENSO-SAM 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 into the interaction between large-scale and regional-scale climate drivers, such as those summarized here obtained, should inferences be made about future hydrological conditions under anthropogenic and/or natural climate change.

Acknowledgements. This work was partially funded by the Victorian Department of Sustainability and the Environment (DSE). The authors wish to thank Rae Moran (DSE), Peter Hill (SKM), Rory Nathan (SKM), and Shaun Berg (DSE) for their involvement in discussions relating to this paper.

References

Ashok, K., Guan, Z., and Yamagata, T.: Influence of the Indian Ocean Dipole on the Australian winter rainfall, Geophys. Res. Lett., 30, 1821, doi:10.1029/2003GL017926, 2003.

Ashok, K., Tam, C.-Y., and Lee, W.-J.: ENSO Modoki impact on the Southern Hemisphere storm track activity during extended austral winter, Geophys. Res. Lett., 36, L12705, doi:10.11029/12009GL038847, 2009.

Cai, W. and Cowan, T.: Dynamics of late autumn rainfall reduction over southeastern Australia, Geophys. Res. Lett., 35, L09708, doi:10.01029/02008GL033727, 2008a.

Cai, W. and Cowan, T.: Evidence of impacts from rising temperature on inflows to the Murray-Darling Basin, Geophys. Res. Lett., 35, L07701, doi:10.01029/02008GL033390, 2008b.

Cai, W. and Cowan, T.: La Niña Modoki impacts Australia autumn rainfall variability, Geophys. Res. Lett., 36, L12805, doi:10.11029/12009GL037885, 2009.

Kiem, A. S. and Franks, S. W.: On the identification of ENSO-induced rainfall and runoff variability: a comparison of methods and indices, Hydrol. Sci. J., 46, 715–727, 2001.

Kiem, A. S., Franks, S. W., and Kuczera, G.: Multi-decadal variability of flood risk, Geophys. Res. Lett., 30, 1035, doi:10.1029/2002GL015992, 2003.

Kiem, A. S., and Verdon-Kidd, D. C.: Climatic drivers of Victorian streamflow: Is ENSO the dominant influence?, Aust. J. Water Res., 13, 17–30, 2009.

Mauget, S. A.: Multidecadal regime shifts in U.S. streamflow, precipitation, and temperature at the end of the Twentieth Century, J. Clim., 16, 3905–3916, 2003.

Murphy, B. F., and Timbal, B.: A review of recent climate variability and climate change in southeastern Australia, Int. J. Clim., 28, 859–879, 2008.

NWC: Australia's Water Supply Status and Seasonal Outlook, National Water Commission (NWC), Canberra, ACT, 2006.

Pook, M., Lisson, S., Risbey, J., Ummenhofer, C., McIntosh, P., and Rebbeck, M.: The autumn break for cropping in southeast Australia: trends, synoptic influences and impacts on wheat yield, Int. J. Climatol., Published online in Wiley InterScience (www.interscience.wiley.com) doi:10.1002/joc.1833, 2008.

Roderick, M. L. and Farquhar, G. D.: Changes in Australian pan evaporation from 1970 to 2002, Int. J. Clim., 24, 1077–1090, doi:1010.1002/joc.1061, 2004.

Roderick, M. L., Hobbins, M. T., and Farquhar, G. D.: Pan Evaporation Trends and the Terrestrial Water Balance – 1. Principles and Observations, Geogr. Compass, 3, 746–760, 2009a.

Roderick, M. L., Hobbins, M. T., and Farquhar, G. D.: Pan Evaporation Trends and the Terrestrial Water Balance – 2. Energy Balance and Interpretation, Geogr. Compass, 3, 761–780, 2009b.

Saji, N. H., Goswami, B. N., Vinayachandran, P. N., and Yamagata, T.: A dipole mode in the tropical Indian Ocean, Nature, 401, 360–363, 1999.

Taschetto, A. S., and England, M. H.: El Niño Modoki impacts on Australian rainfall, J. Clim., 22, 3167–3174, 2009.

Taschetto, A. S., Ummenhofer, C. C., Sen Gupta, A., and England, M. H.: Effect of anomalous warming in the central Pacific on the Australian monsoon, Geophys. Res. Lett., 36, L12704, doi:10.11029/12009GL038416, 2009.

Verdon-Kidd, D. C. and Kiem, A. S.: On the relationship between large-scale climate modes and regional synoptic patterns that drive Victorian rainfall, Hydrol. Earth Syst. Sci., 13, 467–479, 2009,
http://www.hydrol-earth-syst-sci.net/13/467/2009/.

Verdon, D. C. and Franks, S. W.: Indian Ocean sea surface temperature variability and winter rainfall: Eastern Australia, Water Res. Res., 41, W09413, doi:10.01029/02004WR003845, 2005.

Watkins, A. B.: The Australian drought of 2005, WMO Bull., 53, 156–162, 2005.

Wooldridge, S. A., Franks, S. W., and Kalma, J. D.: Hydrological implications of the southern oscillation: variability of the rainfall-runoff relationship, Hydrol. Sci. J., 46, 73–88, 2001.

Table 1. Study catchments and streamflow gauges.

Site	Gauge names (number/source)	Catchment area (km^2)	Record start and finish	Record Length (yr)
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)	1357	Jul 1946–Oct 2006	61
7	Werribee River at Ballan (231209) 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

Table 2. 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

Table 3. 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 blue. “Dry” types are in red. Refer to Verdon-Kidd and Kiem (2009) 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	Dry at far eastern stations (Buchan and Mitta Mitta)
2D	2	1	4	3	1	3	0	4	3	Dry at far eastern stations (Buchan and Mitta Mitta)
3A	1	2	0	1	2	0	0	1	2	Wet at far eastern stations (Buchan and Mitta Mitta)
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	0	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	

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

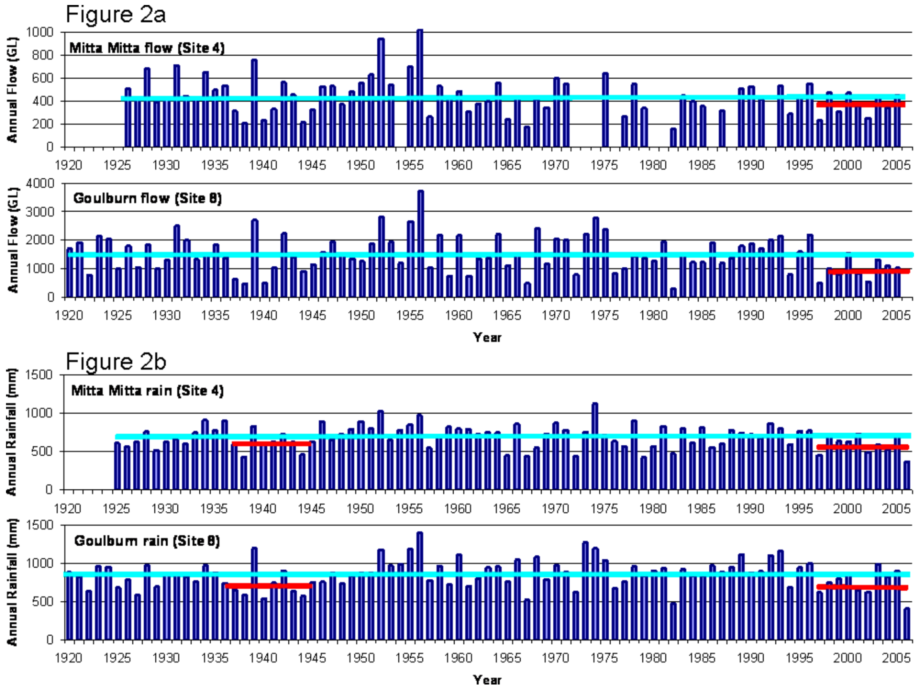

Fig. 2. Historical annual **(a)** streamflow and **(b)** rainfall at Mitta Mitta (Site 4) and Goulburn (Site 8). Long-term (1920–2006) averages are indicated by the light blue lines while the red lines indicate the post-1997 average and, for rainfall, the average for a similarly dry decade beginning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

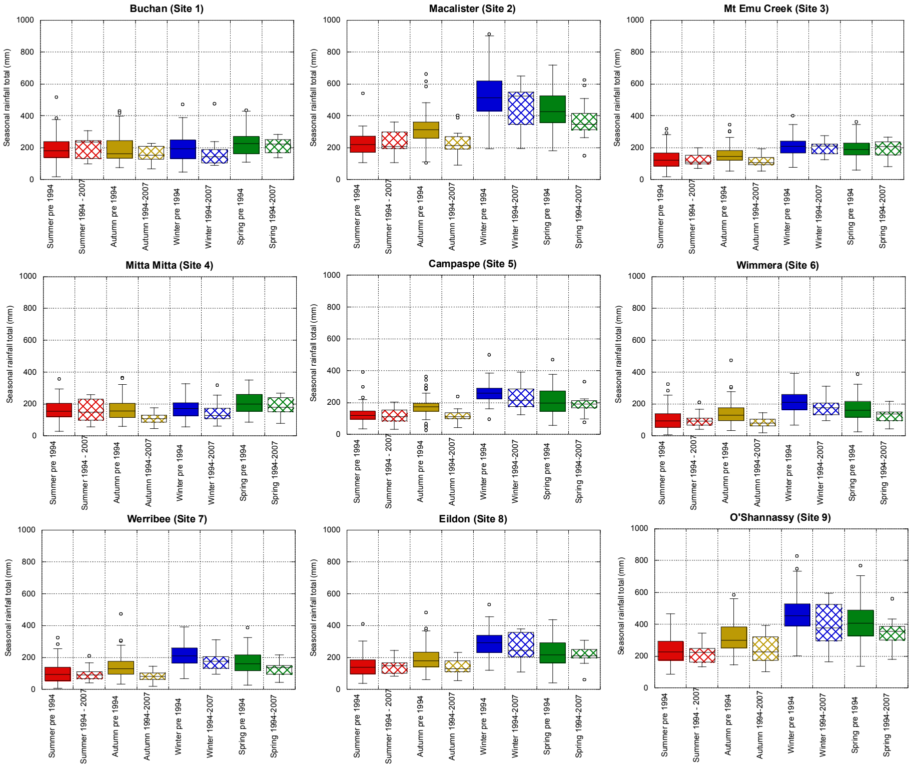

Fig. 3. Seasonal rainfall totals for the periods 1948–1993 and 1994–2007 at each study location.

Title Page
Abstract
Introduction
Conclusions
References
Tables
Figures
◀|
|▶
◀
▶
Back
Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

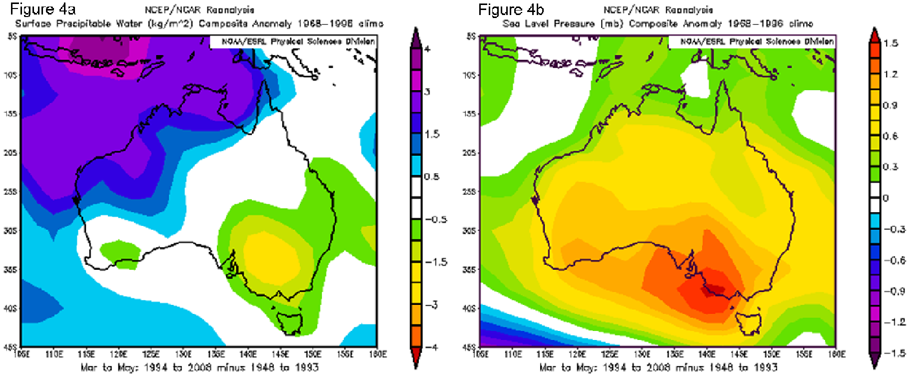

Fig. 4. (a) Difference in autumn surface precipitable water 1994–2008 compared with 1948–1993. **(b)** Difference in autumn sea level pressure 1994–2008 compared with 1948–1993. (Source: NCEP/NCAR Reanalysis Data).

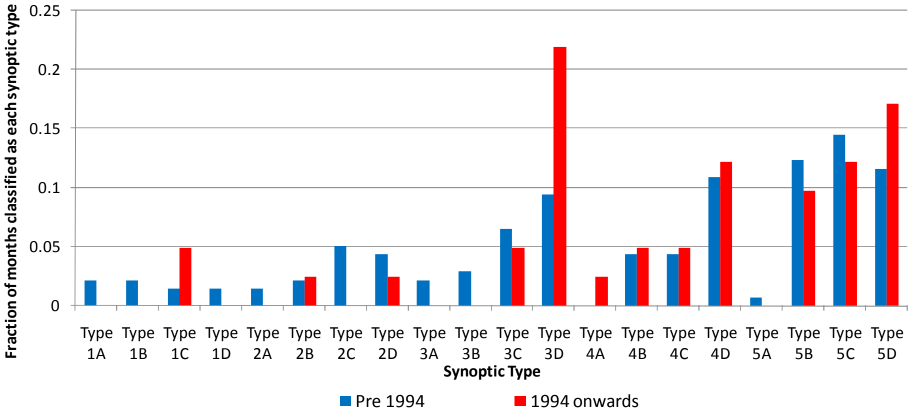

Fig. 5. Fraction of each synoptic type during autumn (MAM): post-1993 versus pre-1994.

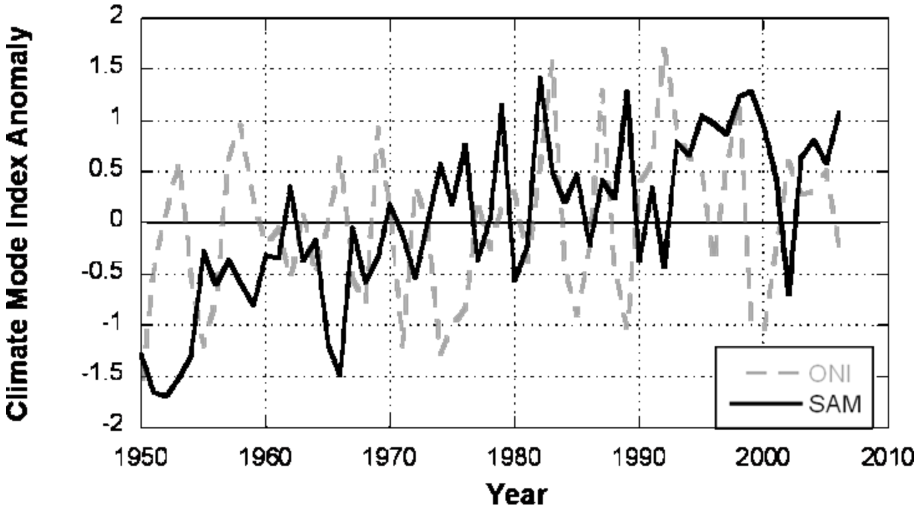

Fig. 6. Timeseries of autumn ONI (i.e. the ENSO monitor known as the Oceanic Niño Index) and autumn SAM index anomaly values. Index anomalies have been standardised to have a mean of zero and standard deviation of one across all months.

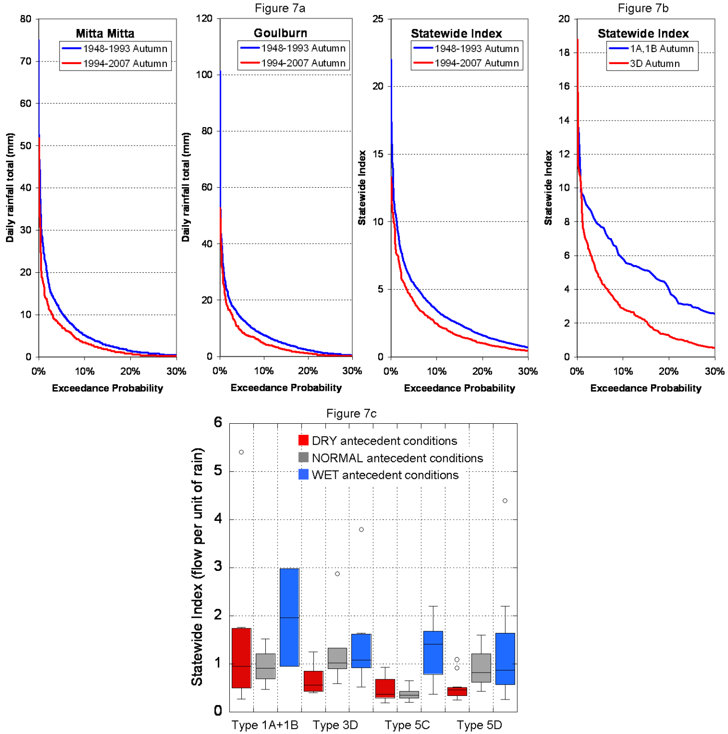

Fig. 7. Exceedance probabilities of daily rainfall **(a)** pre-1994 and post-1993 and **(b)** associated with synoptic types 3A and 3D for the period 1948–2007. In **(a** and **b)** the Statewide Index refers to the "normalized" daily rainfall averaged across the nine study sites – greater (less) than 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 **(c)** 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.