Application of Palmer Drought Severity Index to Observed and Enhanced Greenhouse Conditions using CSIRO Mk3 GCM Simulations

F.S. Mpelasoka[1], M.A. Collier[2], R. Suppiah[2] and J. Peña Arancibia[1]

[1] CSIRO Land and Water, Canberra, ACT 2601, AUSTRALIA
[2] CSIRO Marine and Atmospheric Research, Aspendale, VIC 3195, AUSTRALIA
Email: Freddie.Mpelasoka@csiro.au

Keywords: *climate change, drought, Palmer Drought Severity Index (PDSI)*

EXTENDED ABSTRACT

During the past century some parts of Australia have experienced extended severe droughts affecting Australia's landscape, agricultural production and water resources. In addition, recent studies by CSIRO show that most Global Climate Models simulate decreases in future mean rainfall for most areas in Australia, with increases in variability and near-surface air temperature under enhanced greenhouse conditions. The erratic change in climate is likely to be visible in the cycle and intensity of extreme events such as droughts.

In this study, first, we investigate spatial and temporal characteristics of drought duration, frequency and severity over Australia using Palmer Drought Severity Index (PDSI) from 1951 to 2004. Second, we applied the PDSI to the 20th century, the committed climate change (commit) and the Special Report for Emissions (SRES) A2 experiments of CSIRO Mk3.5 GCM for the period 2051 to 2100. The basic boundary conditions for the three experiments are described by Meehl *et al.* (2005). The results showed that the CSIRO Mk3 GCM generally captures most of the characteristics of the observed drought events, except for relatively low spatial correlations. This can be attributed to spatial scale resolution mismatch between the model and observations. Figure 1 depicts PDSI time-series over four selected sites for 1951-2000 and 2051-2100. The frequency of periods with PDSI < 0 in the top panel of Figure 1 demonstrates the venerability of Australia to droughts. Under enhanced greenhouse conditions the model shows an increase in drought relative frequency, intensity and duration of droughts, particularly droughts defined by PDSI < -2 (moderate to severe droughts). Examples of drastic changes in severe drought characteristics are given in Table 1. Differences between commit and A2 simulations quantify the response to transient increase in anthropogenic greenhouse forcing through the 21st century. Changes in drought characteristics potentially have major implications for natural resource management, water security planning, water demand management strategies and drought relief payments.

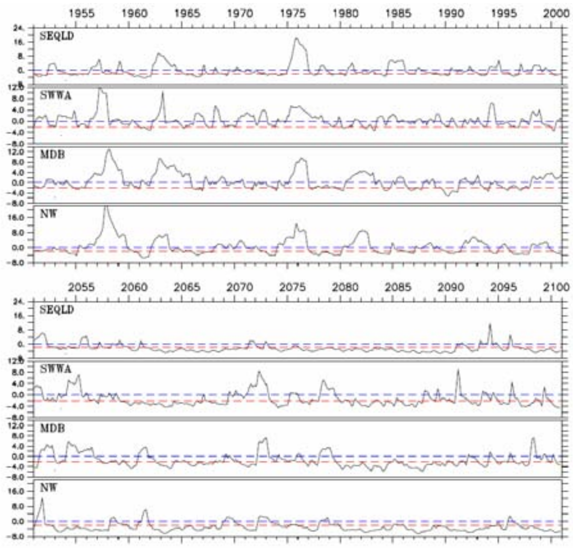

Figure 1: PDSI for four point locations, SEQLD, SWWA, MDB and NWWA, respectively, for 1951-200 (top) and 2051-2100 (bottom) periods. Blue and red lines represent 0 and -2 PDSI values respectively.

Table 1: Examples of changes in characteristics of severe droughts (PDSI < -4) in Australia for the 2051-2100 period with respect to 1951-2000.

Catchments	Change (%)		
	Probability	Intensity	Duration
QLD -136315	75.0	17.7	100.0
NSW -410047	29.1	5.7	33.3
VIC - 406213	62.4	15.7	200.0
TAS -3080003	91.1	22.8	140.0
WA - 603136	94.7	21.0	87.5

1. INTRODUCTION

Drought is a normal, recurrent phenomenon of climate variability in Australia and has significant environmental and socio-economic impacts. For example, the drought of 2002-2003 cost Australia US$7.6 billion (Adams *et al*. 2002) and had significant impacts on tourism which currently contributes to 4.5% of Australian Gross Domestic Product (Allen 2005). This emphasises Australia's vulnerability to climate variability and limitations of adaptive capacity (Mpelasoka *et al.* 2007).

Australia is relatively arid, with 80% of the land having less than 600 mm annual rainfall and 50% of the land area having less than 300 mm annual rainfall. Where soil quality is adequate, this relatively low rainfall is still sufficient to grow extensive crops and farm livestock over large regions of Australia. Most of the current GCMs' projections show a general decrease of mean rainfall over Australia coupled with increase in temperature (Suppiah *et al*. 2007).

However, a key feature of Australia's climate is not necessarily the amount of rainfall but the variability on inter-annual and intra-seasonal time scales. Drought is a period of abnormally dry weather sufficiently prolonged for the lack of precipitation to cause a serious hydrological imbalance and carries connotations of a moisture deficiency with respect to water use requirements (McMahon and Arenas 1982). Various operational drought indices have been reviewed (White, 2006). These indices are normally continuous functions of some hydrometeorological variables, including rainfall, temperature and potential evaporation. The Palmer Drought Severity Index (PDSI) is based on rainfall and temperature (Palmer 1965).

Theoretically, the PDSI is a standardised measure of surface moisture conditions, ranging from about -10 to +10 (see Table 1). PDSI allows comparisons across regions and time. Although the PDSI is widely used, there are some difficulties with this approach. In particular, it ignores the form of precipitation, such as snowfall and is insensitive to the time lag between precipitation and runoff.

In this study, first, we used the PDSI to investigate observed patterns of spatial and temporal characteristics of drought frequency, duration and intensity over Australia from 1951-2000. Second, the PDSI was applied to present-day climate simulations of the CSIRO Mk3 GCM for SRES A2. For validation the results were compared with observations over the same period. Finally, simulated changes in the characteristics of Australian droughts associated with increasing levels of greenhouse gases were determined from model results for 2051-2100 with respect to 1951-2000.

2. DATA AND METHODS

The Mark 3.5 (Mk3.5) is a version of the latest generation Global Climate Model (hereafter termed as "Mk3.5 GCM) developed by the Australian Commonwealth Scientific Research and Industrial Organisation (CSIRO) (Gordon *et al*. 2004, Smith 2007). A salient characteristic of the Mk3.5 GCM is that the long (1000+ year) control experiment conducted with it indicates a very small drift, for a long period, in the order of 1/10 (Collier *et al*. 2007). Three twentieth century experiments or ensembles conducted with the Mk3.5 GCM were initiated from points on the pre-industrial control experiment time-line, twenty years apart so as to have a set of independently initialised experiments.

For the calculation of PDSI we have used observed and simulated monthly values of air temperature, rainfall, specific humidity and incoming radiation. Soil-moisture capacity data were derived from the FAO soil digital map of the world (FAO 1995).

The PDSI requires monthly values of temperature, precipitation, potential evapotranspiration and soil moisture as inputs. Data for 1981 to 2000 were used for calibration. The original PDSI Fortran software was modified to override the internal computation of evapotranspiration by areal wet potential evaporation derived from Morton Evaporation Complementary Relationships Model (Morton,1983). The soil moisture computation was replaced by data read in from an offline simple lumped conceptual daily rainfall-runoff model (see Section 2.2). The PDSI is based around a supply and demand model of the soil moisture at a location. The supply is the amount of moisture in the soil plus the amount that is absorbed into the soil from rainfall. The demand, however, is not so as easy to see, because the amount of water lost from the soil depends on several factors, such as temperature and its derivatives, and the amount of moisture in the soil. Although the output from the PDSI analysis includes several moisture indices, only the PDSI was saved for further analysis in this study.

2.1 Estimation of areal potential evaporation

Evapotranspiration is a large component of the water balance. However, despite its importance, evapotranspiration is almost impossible to measure or observe directly at a meaningful scale in space or time. There various methods for potential evaporation estimation, and there are significant differences in the results among methods. In this study we used Morton evaporation model. The model uses complementary relationships to draw the distribution of the area where the evapotranspiration is controlled by water availability (Morton 1983). The calculation requires rainfall, temperature, vapour pressure, and solar radiation. Areal potential evaporation (WVAP) is the evaporation that would take place, if there was an unlimited water supply, from an area so large that the effects of any upwind boundary transitions are negligible and local variations are integrated to an areal average. The WVAP was calculated using the observed data and Mk3.5 model outputs. To have consistent inputs for PDSI calculations, WVAP for both GCM and observed data sets was estimated using Morton model.

2.2 Estimation of soil-moisture

Soil-moisture data were derived using a simple lumped conceptual daily rainfall-runoff model (SIMHYD). In SIMHYD, daily rainfall first fills the interception store, which is emptied each day by evaporation. The excess rainfall is then subjected to an infiltration function that determines the infiltration capacity. Moisture that infiltrates is subjected to a soil moisture function that diverts the water to the stream (interflow), groundwater store (recharge) and soil moisture store. Evapotranspiration from the soil moisture store is estimated as a linear function of the soil wetness, but cannot exceed the atmospherically controlled rate of areal potential evapotranspiration. The soil moisture store has a finite capacity.

3. RESULTS AND DISCUSSION

The important aspects of droughts are intensity, frequency, duration and severity. The combined effects of these aspects are often used to quantify drought events over a region. While drought intensity is directly quantified by the magnitude of negative PDSI, drought severity is a more complex function of duration, intensity and time scales of the impacted processes. The basic classification of PDSI for different categories of wet and dry spells derived by Palmer (1965) is shown in Table 2. These categories are used as guidelines to define and identify drought events from PDSI time series.

On the basis of the results of PDSI a quantitative definition of a drought event was adopted, only to include drought events, likely to cause a significant downturn in, for example, farm income over a prolonged period. Therefore, in our analysis, a drought event is a period in which the PDSI is continuously negative and reaches a value of -2.0 or less. In this case, a drought event commences when the PDSI first reaches -2 or below and ends when the PDSI following a value of -2.0 or less is greater than -2. Drought intensity is defined based on the PDSI given in Table 2.

Table 2: Categories of moisture status based on PDSI scale (Palmer 1965).

PDSI ≥ 4.0	Extreme wet spell
4.0 < PDSI > 3.0	Severe wet spell
3.0 ≥ PDSI > 2.0	Moderate wet spell
2.0 ≥ PDSI > 1.0	Mild wet spell
1.0 ≥ PDSI > 0.5	Developing wet spell
0.5 ≥ PDSI > -0.5	Normal
-0.5 ≤ PDSI > -1.0	Developing dry-spell
-1.0 ≤ PDSI > -2.0	Mild dry-spell
-2.0 ≤ PDSI > -3.0	Moderate dry-spell
-3.0 ≤ PDSI > -4.0	Severe dry-spell
PDSI ≤ -4.0	Extreme dry-spell

The frequency and duration of events were tracked through the identification of their distinct commencement and cessation points in the time series. For example, Figure 1 shows PDSI time series of four selected locations (NWWA, SEQLD, MDB and SWWA) which correspond to A, B, C and D in Figure 2a. Where SEQLD is south-east Queensland, SWWA is south-west West Australia, MDB is the Murray-Darling Basin and NW is the north-west Australia. In Figure 1, the results for 1951-200 above the 2051-2100 experimental results. These results are based on a single realisation ‘Run2’. The simulation during the second half of the 21st century is dominated by droughts with extended periods. This tendency of increased drought persistence is interrupted by occasional extreme wet short spells with progressively increasing intensity. There are drastic differences in time series structure (periodicity and amplitude) between the 1951-200 and 2051-2000 that can be attributed to global warming signal. These structural differences in the temporal evolution suggest that the effect of the global warming signal gets pronounced from the second half of the 21st century.

The averaged Model and observed PDSI values for four points in Table 3 illustrate model biases with respect to the observed, ranging from 0.5% over SWWA to 92.6% NWWA. A gradual trend of the PDSI towards bigger negative values suggests a tendency for increased intensity of droughts. For all four locations, the A2 PDSI values are substantially higher in magnitude than those associated with the Commit experiment. The difference of 38%, 64%, 90% and 83% by the A2 over Commit are exhibited for SEQLD, SWWA, MDB and NWWA respectively for the 2051-2100 period.

Table 3: Observed versus model mean drought intensity (PDSI < 0) for four locations as shown in Figure 2.

	SEQLD	SWWA	MDB	NW
Period				
	Observed			
1951-2000	-1.40	-2.20	-1.44	-1.76
	Modelled			
1951-2000	-2.49	-2.21	-1.67	-3.39
	Commit			
2001-2025	-1.82	-1.70	-1.87	-2.64
2026-2050	-1.75	-1.74	-1.71	-2.44
2051-2075	-1.87	-1.56	-1.78	-2.52
2076-2100	-2.28	-1.46	-1.92	-2.77
2051-2100	-2.09	-1.51	-1.51	-1.85
	SRES A2			
2001-2025	-2.06	-1.82	-1.87	-2.46
2026-2050	-2.55	-1.57	-2.03	-2.47
2051-2075	-2.60	-2.41	-2.58	-3.15
2076-2100	-3.51	-2.53	-3.12	-3.60
2051-2100	-2.89	-2.47	-2.87	-3.39

3.1 Drought intensity

The spatial patterns of drought intensity for both observed and modelled cases are shown in Figure 2. The 1951-2000 observed average intensity ranges from -2.3 to -16.0 but a vast majority of Australia has typical values of -2.5 to -3 (area average of -2.8). The most significant regions affected by intense and extreme droughts are found in coastal regions of NSW extended through parts of central and coastal Victoria and Adelaide (-3 to -4), Cape York Peninsula (-3 to -5) and other isolated coastal regions in Queensland (-3 to -3.5), Northern Arnhem Land (-3 to -4), isolated regions of northern and Southern Western Australia (-3 to -4). Simulated intensity values are similar to the observed values. However, there are significant differences between observed and simulated spatial patterns. The spatial correlation between the observed and modelled severity is 0.42 and the ratio of the modelled to the observed spatial variance is 1.38. The modelled average intensity ranges from -2.2 to -8.9 (area average of -2.6).

Simulated intensity is shown in Figure 2c and 2d for the Commit and A2 experiments averaged over the years 2051-2100. The values for the Commit experiment range from -2.4 to -8.6 (area average of -2.9) and for the A2 -2.7 to -9.1 (area average of -3.3). The droughts associated with the A2 experiment are more intense over most of the Australian continent, except for northern NT, a small region in northern coastal Queensland and the extreme south eastern Australia, where slight decreases in intensity are simulated. The largest increases in intensity are projected mostly in south-eastern Australia, particularly in southern Victoria and Tasmania. However there are isolated increases in severity in both the Northern Territory and New South Wales.

3.2 Drought frequency

The PDSI values derived from long-term historical rainfall and potential evaporation records give a spatial pattern that represents a "normal" condition for an area and also how much variation might be expected to constitute extreme events such as droughts. There is little chance that all Australia could be in drought at the same time, since there is a strong spatial variation in climate, particularly due variations in rainfall. Some droughts are long-lived; some are short and intense, causing significant damage. Some can be localised while other parts of the country enjoy bountiful rain (BoM 2007).

Figure 3 depicts the distribution of probabilities of extreme drought (PDSI $\leq$ -4) over Australia. Comparing Figures 3a and 3b the model does not capture the observed spatial pattern so well, as indicated by a pattern correlation of 0.24 (based on a single realisation). This can be mainly attributed to the spatial resolution mismatch between the observations and model data. However the magnitudes of observed and simulated drought are similar as shown by a high ratio of variance of 0.98 as a measure of relative amplitudes. Similar results have been obtained by (Burke *et al*.,2006) using the Hadley Centre Model. Figures 3c and 3d show future probabilities of droughts associated with commit and A2 climate scenarios. The results based on commit experiment range from 0.09 to 0.52 (area average of 0.18) whilst the A2 range from 0.10 to 0.52 (area average of 0.23). Most pronounced differences occur in the Western Australian central plateau extending right across to the western coast. Differences with a smaller spatial extent include the northern parts of Western Australia, the southern coastal regions of Queensland, western coast of Victoria and most of Tasmania. On average, for 2051-2100 period the probability of drought occurrences over Australia under A2 is about 1.3 of that under commit.

3.3 Drought duration

The duration considered was that of the extreme droughts defined by PDSI $\leq$ -4. A comparison between observed and simulated drought duration in Figures 4a and 4b shows that the model simulates the drought duration reasonably well for the present-day climate period (1951-2000). For example, the extended period of droughts in northern Western Australia through to northern Queensland, and in south-eastern Australia, Victoria and central to coastal New South Wales are fairly well simulated. A spatial correlation from a single realisation is 0.24 with a standard deviation ratio of 1.21. Figures 4c and 4d show the duration of drought in months for experiments conducted based on Commit and A2 emission scenarios. The Commit experiment results range from 0 to 38 (area average of 4.0) whilst the A2 results range from 0 to 56 (area average of 13.0). Almost all of Australia indicates higher average duration under A2 emission scenario than the Commit (up to 35 months). This is particularly evident over the Murray Darling Basin, most of Victoria, Tasmania, central and north-eastern West Australia, portions of the Northern Territory and parts of Queensland.

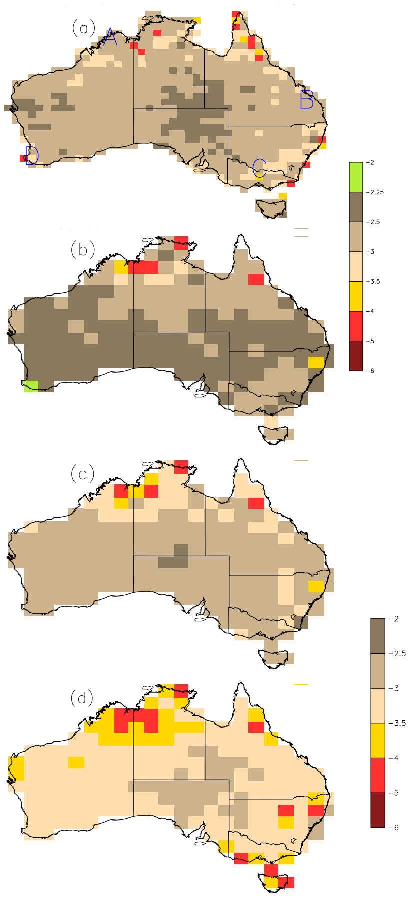

Figure 2. Observed (a) and modelled (b) drought intensity (PDSI) for the period 1951-2000. Modelled Commit (c) and A2 (d) drought intensity (PDSI) for the period 2051-2100.

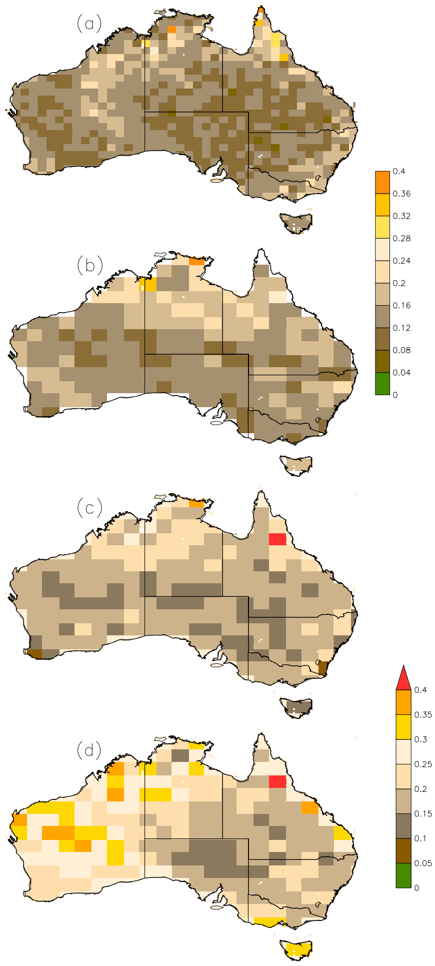

Figure 3. Observed (a) and modelled (b) probability of drought events for the period 1951-2000. Modelled Commit (c) and A2 (d) relative drought probabilities for the period 2051-2100.

4. CONCLUSION

In the present study, we have applied the Palmer Drought Severity Index (PDSI) to the observed and the CSIRO Mk3.5 GCM simulated data in order to assess the performance of the model in simulating various characteristics of drought and their projected changes under enhanced greenhouse conditions. The model experiments conducted using scenarios of greenhouse gases under A2 and a Commit have been used to quantify the differences in their associated future drought characteristics and the changes for 2051-2100 with respect to 1951-2000.

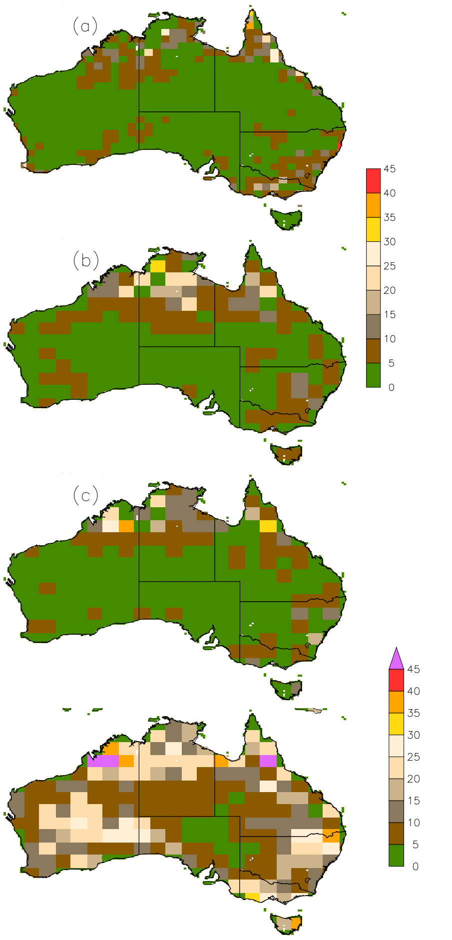

Figure 4. Observed (a) and modelled (b) extreme drought maximum duration (months) for the period 1951-2000. Modelled Commit (c) and A2 (d) extreme drought maximum duration (months) for the period 2051-2100.

For the second half of the 21st century, the simulations exhibit a tendency of increasing duration and intensity for extreme droughts with decreasing frequency. The spatial patterns of PDSI < 0 show bigger changes in drought characteristics under 'Business-As-Usual' than under 'Commitment' by about 30%, 96%, and 125% in drought relative frequency, intensity and duration of extreme droughts, respectively.

In the context of drought stress such changes will amount to extremely severe impacts of drought events. Drought severity is a complex interplay between duration, intensity and differing time scales of the impacted processes or systems. This emphasises the challenges ahead for improving productivity and efficiency of water use while maintaining healthy river and groundwater systems.

Acknowledgments

This work was co-funded by the Australian Greenhouse Office through the Australian Climate Change Science Program (ACCSP) and the South East Australian Climate Initiative (SEACI). The authors would like to acknowledge Mr Harvey Davies for his support in developing Tcl/NAP used extensively in the analysis and Dr David Post for his constructive criticism in the peer reviewing process of this paper.

5. REFERENCES

Adams, P.D., M. Horridge, J.R. Masden and G. Wittwer, (2002). "Drought, regions and the Australian economy between 2001-02 and 2004-05". Australian Bulletin of Labour, 28, 233-249.

Allen Consulting Group (2005). "Climate Change Risk and Vulnerability: Promoting an Efficient Adaptation Response in Australia". The Allen Consulting Group, 159 pp.

BoM, (2007). "Living with drought". Australian Bureau of Meteorology: http://www.bom.gov.au/climate/drought/livedrought.shtml. Accessed 21st August, 2007.

Burke, E. J., S.J. Brown and N. Christidis (2006). "Modeling the Recent Evolution of Global Drought and Projections for the Twenty-First Century with the Hadley Centre Climate Model" Journal of Hydrometeorology **7**: 1113-1125.

Collier, M. A., M.R. Dix and A.C. Hirst (2007). "CSIRO Mk3 Climate System Model and meeting the strict IPCC AR4 data requirements", MODSIM07.Christchurch, New Zealand.

FAO. (1995). "THE DIGITAL SOIL MAP OF THE WORLD" CD Version 3.5.

Gordon, H. B., L.D. Rotstayn, J.L. McGregor, M.R. Dix, E.A. Kowalczyk, S.P. O'Farrell, L.J. Waterman, A.C. Hirst, S.G. Wilson, M.A. Collier, I.G. Watterson and T.I. Elliott (2004). "The CSIRO Mk3 Climate System Model". Melbourne, CSIRO Marine and Atmospheric Research**:** pp 130.

Kallberg, P., A. Simmons, S. Uppala and M. Fuentest (2004). The ERA-40 Archive ERA-40 Project Report Series No. 17.

Kalnay, E., M. and others (1996). "The NCEP/NCAR 40-Year Reanalysis Project." Bulletin of American Meteorological Society **3**: 437–471.

McMahon, T. A. and Arenas., A.D. (1982). "Methods of computation of low streamflow". Paris, UNESCO**:** pp107.
Meehl G.A., et al. (2005). How more global warming and sea level rise? Science, 307: 1769-1772.
Morton, F. I. (1983). "Operational estimates of areal evapotranspiration and their significance to the science and practice of hydrology. ." Journal of Hydrology **66**: 1-76.
Mpelasoka F., Hennessy. K., Jones R. and Bates B. (2007). "Comparison of suitable drought indices for climate change impacts assessment over Australia towards resource management." International Journal of Climatology (In press).
Palmer, W. C. (1965). Meteorological drought, U.S. Weather Bureau**:** pp 58.
Smith, I. N. (2007). "Global climate modelling within CSIRO: 1981 to 2006." Australian Meteorological Magazine
Suppiah, R.,K. J. Hennessy, P. H. Whetton, K. McInnes, I Macadam, J. Bathols, J. Ricketts and C. M. Page (2007). Australian climate change projections derived from simulations performed for the IPCC 4th Assessment Report. Australian Meteorological Magazine (In press).
Taylor, K. E. (2001). "Summarizing multiple aspects of model performance in single diagram." J. Geophys. Res. **106**(D7): 7183-7192.
White, D., (2006). "The utility of seasonal indices for monitoring and assessing agricultural drought". Report to the Australia Bureau of Rural Sciences. pp 778.