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Comparison of suitable drought indices for climate change impacts assessment over Australia towards resource management

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ABSTRACT: Droughts have significant environmental and socio-economic impacts in Australia. This emphasizes Australia's vulnerability to climate variability and limitations of adaptive capacity. Two drought indices are compared for their potential utility in resource management. The Rainfall Deciles-based Drought Index is a measure of rainfall deficiency while the Soil-Moisture Deciles-based Drought Index is a measure of soil-moisture deficiency attributed to rainfall and potential evaporation. Both indices were used to assess future drought events over Australia under global warming attributed to low and high greenhouse gas emission scenarios (SRES B1 and A1F1 respectively) for 30-year periods centred on 2030 and 2070. Projected consequential changes in rainfall and potential evaporation were based on results from the *CCCma1* and *Mk2* climate models, developed by the Canadian Climate Center and the Australian Commonwealth Scientific and Industrial Research Organisation (CSIRO) respectively. A general increase in drought frequency associated with global warming was demonstrated by both indices for both climate models, except for the western part of Australia. Increases in the frequency of soil-moisture-based droughts are greater than increases in meteorological drought frequency. By 2030, soil-moisture-based drought frequency increases 20–40% over most of Australia with respect to 1975–2004 and up to 80% over the Indian Ocean and southeast coast catchments by 2070. Such increases in drought frequency would have major implications for natural resource management, water security planning, water demand management strategies, and drought relief payments.

KEY WORDS drought; drought index; meteorological drought; agricultural drought; hydrological drought; rainfall deficiency; soil-moisture deficiency; Australia

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1. Introduction

Drought is a normal, recurrent feature of climate variability. It differs from aridity, which is restricted to low rainfall regions as a permanent feature of climate. It is a hazard of nature that occurs in virtually all climate zones, although its characteristics vary significantly from one region to another. Drought is a period of abnormally dry weather sufficiently prolonged because of a lack of precipitation that causes a serious hydrological imbalance and has connotations of a moisture deficiency with respect to water use requirements (McMahon and Arenas, 1982). The deficiencies have impacts on both surface and groundwater resources and lead to reductions in water supply and quality, reduced agricultural productivity, diminished hydro-electric power generation, disturbed riparian and wetland habitats, and reduced opportunities for some recreation activities (Riebsame *et al.*, 1991).

As shown in Table I, there is abundant evidence of drought impacts in Australia (Heathcote, 1969), emphasizing the country's vulnerability to climate variability and the limitations of adaptive capacity. Drought relief payments have cost the government an average of A$100 million per year for the 1992–1999 period (DoE&H, 2001b).

Droughts fall into four disciplinary definitions incorporating meteorological, hydrological, agricultural, and socio-economic perspectives (Palmer, 1965; American Meteorological Society, 1997; Botterill and Wilhite, 2005). The longer and the more spatially extensive a meteorological drought is, the more likely the occurrences of other types of drought. The soil-moisture status links various characteristics of a meteorological drought to agricultural and hydrological droughts, by accounting for rainfall shortages and differences between actual and potential evapotranspiration. Indices of meteorological drought identify periods with deficiencies with respect to specific thresholds of some measures reflecting rainfall departures from climatology (Wilhite and Glantz, 1985). Drought vulnerability and related socio-economic events increase as water supply and

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Table I. Examples of major drought impacts in Australia.

Period	Areal coverage	Losses
1864–1866	All States except Tasmania	50% of sheep population 40% of cattle population 19 million sheep
1911–1916	Widespread	2 million cattle
1918–1920	All States except Western Australia	Not available
1939–1945	Widespread	30 million sheep 40% drop in wheat production 20 million sheep
1963–1968	Widespread	\$300–500 million farm income
1972–1973	Mainly eastern Australia	Not available Billions of farm income
1982–1983	The most intense, widespread	\$590 million in terms of relief \$10 billion farm income
2002–2003	Widespread	70 000 jobs

Source: BoM, 2006 and Adams *et al.*, 2002.

demand trends converge (American Meteorological Society, 1997).

Various operational drought indices have been formulated to provide quantitative measures of when, how long, or how severe droughts are (White, 2006). These indices are normally continuous functions of some hydrometeorological variables, including rainfall, temperature, and potential evaporation. For example, the Palmer Drought Severity Index (PDSI) based on rainfall and temperature (Palmer, 1965); Crop Moisture Index (CMI), (Palmer, 1968), a modified PDSI to measure short-term drought on a weekly scale for quantification of drought's impacts on agriculture during the growing season; the Surface Water Supply Index, (Shafer and Dezman, 1982), for drought conditions in snow-pack run-off areas; the Standardized Precipitation Index (SPI) based solely on rainfall data (McKee *et al.*, 1993); the Keetch and Byram Drought Index (KBDI) based on amount of precipitation necessary to return soil moisture to full field capacity (Keetch and Byram, 1968), for assessment of potential forest fires; and the Rainfall Deciles-based Drought Index (RDDI) based on ranked monthly totals of rainfall distribution constructed from long-term records (Gibbs and Maher, 1967).

Drought indices have a wide range of applications including drought monitoring, quantitative assessment, drought prediction, and the development of management strategies under the current climate (Karl, 1983) as well as under future climate change associated with global warming (Le Houerou, 1996). Although none of the 'major' drought indices is inherently superior to the rest in all circumstances, some indices could be better than others in terms of providing useful information from a management perspective. For example, PDSI has little applicability outside the USA (Kogan, 1995). In particular, PDSI does not perform well in regions where there are extremes in the variability of rainfall or run-off, such as in Australia and South Africa (Smith *et al.*, 1993; Burke *et al.*, 2006; White, 2006). The use of different time scales by the SPI allows the effects of rainfall deficit on different water-resources components to be accounted for, making it robust. However, since it does not consider water balance aspects, it is commonly used in data-limited areas for pragmatic reasons (Smakhtin and Hughes, 2004; White, 2006). Similarly, the RDDI widely used in Australia is solely based on rainfall, and therefore potentially provides information on drought that is of limited use to resource managers.

Worldwide, governments have generally perceived drought as a natural risk to be mitigated through crisis management (i.e. short-term solutions). This perception forms the basis for subsequent governmental drought relief. However, often this perception favours poorer drought risk managers and climatologically marginal areas as recipients of drought relief assistance (Smith *et al.*, 1993). Restriction of relief only to areas declared to be under drought as *Exceptional Circumstances* by Australia's National Drought Policy, introduced in 1992, is an attempt to take a more realistic view of the highly variable nature of Australia's climate (Wilhite, 2005).

The multiplicity of drought index definitions, the measurement of these indices, and the existence of climate trends pose problems for drought risk management and relief strategies in the context of *Exceptional Circumstances* (DoAFF, 2006). The current guidelines for *Exceptional Circumstances* state that the event must be rare and severe. The effects of the event must result in a severe downturn in, for example, farm income over a prolonged period; and the event must not be predictable or part of a process of structural adjustment. A rare event has to be one that occurs, on average, once in every 20–25 years. The event is severe if it lasts for a prolonged period (greater than 12 months) and is of a scale that affects a significant proportion of operations in a region. The severity of an event is determined by assessing the impact on the industry and overall value of production. Therefore, a robust drought index that can potentially supplement other objective evidence for the declaration of *Exceptional Circumstances* is sought. This is particularly important for the quantification of future droughts over Australia in the wake of climate change.

This paper presents a comparative study of a Meteorological Drought Index and a Soil-Moisture-based Drought Index for present and future drought assessment. The Meteorological Drought Index is based on rainfall decile 1, and the Soil-Moisture Decile 1-based Drought Index is derived from rainfall and potential evaporation.

2. Data and methods

Drought events over Australia under the current climate were identified using observed daily precipitation and pan evaporation data for 1970–2004. These data, on a $0.25^\circ \times 0.25^\circ$ grid, were downloaded from climate datasets maintained by the Queensland Department of Natural Resources and Mines Data Drill, Australia (Jeffrey *et al.*, 2001). The investigation of future drought events was based on projections of monthly mean rainfall and potential evaporation from two climate models developed by the Canadian Climate Center (Boer *et al.*, 2000) and the Australian Commonwealth Scientific and Industrial Research Organisation (CSIRO) (Gordon *et al.*, 2002), *CCCma1* and *Mark2* respectively. The fine-grid observed daily time series were scaled by model-derived changes in monthly means to produce fine-grid scenarios for 2030 and 2070.

2.1. Rainfall Deciles-based Drought Index (RDDI)

The RDDI was constructed according to the criteria for serious rainfall deficiency set by the Australian Bureau of Meteorology (Gibbs and Maher, 1967). The Australian Bureau of Meteorology produces summaries of the climate of Australia, which include information on drought on a 3-monthly basis. Therefore, drought was identified by comparing rainfall accumulations for 3-month periods with accumulations for the same 3-month period of a baseline 'normal' annual cycle to see whether they lie below the first decile (lowest 10% in the 1970–2004 record). Once a 3-month period was classified as a drought, the drought persisted until the total amount of rainfall for a subsequent 3-month period was above the seventh decile (highest 30% in the 1970–2004 record). In Australia, 'drought years' often run from April to March following the typical El Niño cycle.

2.2. Soil-Moisture Deciles-based Drought Index (SMDDI)

We extend the RDDI to include evapotranspiration in order to produce a measure of soil-moisture deficit. This is referred to as the Soil-Moisture Deciles-based Drought Index (SMDDI) potentially reflecting rather pseudo-conditions of both agricultural and hydrological droughts, since we have not accounted for regional variations in hydrological characteristics and soil type or the variable susceptibility of crops.

Soil-moisture deficit was calculated using a soil-moisture balance model (Jones *et al.*, 2001) driven by daily inputs of rainfall and potential evaporation. The model represents the deep percolation of soil moisture to the water table and its discharge as baseflow. It is assumed that the ratio of actual evapotranspiration (E_a) to potential evapotranspiration (E_p) is a function of soil-moisture storage and soil transmissivity. Only three processes, E_a, percolation (B), and precipitation (P), affect soil moisture in the model. Percolation is represented as in Equation (1).

$$B = \mathrm{KQ}\left(\frac{\mathrm{SC} - \mathrm{SWP}}{\mathrm{SM} - \mathrm{SWP}}\right)\mathrm{SS} \tag{1}$$

where SS is the current soil-moisture storage, SC is the threshold soil-moisture storage, SWP is the soil-moisture wilting point, SM is maximum soil-moisture storage, and KQ is a dimensionless constant.

The soil-moisture capacity was set to 150 mm to represent the topsoil SWP and SM set to 1000 mm. Soil-moisture storage is reduced by actual evapotranspiration from the surface and percolation to groundwater. The current soil-moisture storage, SC, was determined from Equation (2)

$$\mathrm{SC} = \frac{E_p \mathrm{SM}}{E_m} \tag{2}$$

where E_m is maximum potential evapotranspiration, which was set to 9.0 mm/day.

If the previous soil moisture, ST, equalled or exceeded SC, the evapotranspiration will have occurred at a potential rate, as in Equation (3):

$$E_a = E_p \tag{3}$$

Conversely, E_a was given by Equation (4), when $\mathrm{SC} > \mathrm{ST}$.

$$E_a = \frac{E_m \mathrm{ST}}{\mathrm{SM}} \tag{4}$$

Finally, the current soil-moisture storage was calculated using Equation (5):

$$\mathrm{SS} = \mathrm{ST} - E_a + P \tag{5}$$

A drought is defined as a period of extremely low soil moisture. In order to compare RDDI- and SMDDI-defined droughts, the same moving window-period and decile definitions were used for starting and ending a drought event, as defined in Section 2.1. While the RDDI is commonly used by the Australian Bureau of Meteorology, soil-moisture status is used operationally in the monitoring and assessment of conditions of the extensive Australian grazing lands in Aussie Grass Project (Hobbs *et al.*, 1994; Hall *et al.*, 2001).

2.3. Models and projections

Despite international efforts to reduce emissions of greenhouse gases, substantial increases in carbon dioxide concentrations are inevitable during the course of the 21st century and continued global warming and climate change will occur (Whetton and Jones, 2004). Global Climate Models (GCMs) are considered to be the only credible tools currently available for simulating the response of the global climate system to increasing greenhouse gas concentrations. Coupled atmosphere–ocean GCMs have been validated by comparing the observed 20th century climate variability with that simulated by climate models driven by historical forcing due to solar variations, volcanic eruptions, stratospheric ozone depletion, and increases in greenhouse gases and aerosols. The observed variability in global average temperature is generally well reproduced (IPCC, 2001). Regional temperature variability is reasonably well captured by the

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models, but regional rainfall variability is more challenging. The *CCCma1* and CSIRO *Mark 2* models used in this study have been chosen because they performed well in simulating patterns of 1961–1990 average temperature, rainfall, and mean sea level pressure over the Australian region (Whetton *et al*., 2005).

Also, these models exhibited the smallest errors at local scales in the performance scrutiny by the Coupled Model Inter-comparison Project (Meehl *et al*., 2000).

The model projections were applied to observed daily data for 1974–2004. The low and high global warming values by the Intergovernmental Panel on Climate Change for the SRES B1 and A1F1 emission scenarios allowed results from the models to be scaled for the years 2030 and 2070. The global warming was 0.54–1.17 °C in 2030 and 1.24–3.77 °C in 2070, relative to 1990.

Climate change scenarios were developed using a 'pattern scaling' method. For each model, grid-point changes in monthly mean rainfall and potential evaporation were regressed against global average temperature, taking the gradient of the relationship at each grid-point as the estimated change per degree of global warming. These trend patterns can then be linearly scaled by the global warming values from the Intergovernmental Panel on Climate Change for any selected year. This method has been used by CSIRO since 2001 (Whetton and Hennessy, 2001) and is considered robust (Mitchell, 2003). The benefits of using the approach, which include a generation of scenarios of the same scale as the observations being scaled with coarse GCMs' projections, are described by Whetton *et al*. (2005).

3. Results and discussion

The rainfall- and soil-moisture-based drought indices provided an understanding of drought characteristics and the probability of recurrence of drought across Australia. The drought events observed during the period 1970–2004 were consistently captured by both indices. For example, during the 1974/1975 La Niña cycle, a drought-free period for most of the country was well illustrated as was the major drought event in 2002/2003 attributed to El Niño (Botterill, 2003). The 2002/2003 drought concentrated in eastern Australia, with the Murray-Darling Basin (the Nation's agricultural heartland) receiving its lowest recorded March–November rainfall and its highest maximum recorded temperature (Nicholls, 2004). High temperatures caused a marked increase in evaporation rates, which sped up soil-moisture depletion and the drying of vegetation and watercourses.

Differences in decadal averages of the number of consecutive months/year under SMDDI- and RDDI-based droughts for the 1970–1979, 1980–1989, and 1990–1999 periods were used in the estimation of trends in drought persistence across Australia. The trends ranged from −1.4 to +1.2 and −4.6 to +1.8 months/year per decade for the SMDDI and RDDI respectively. Depicted in Figure 1(a) and (b) is the spatial variability of the tendencies of drought duration for RDDI- and

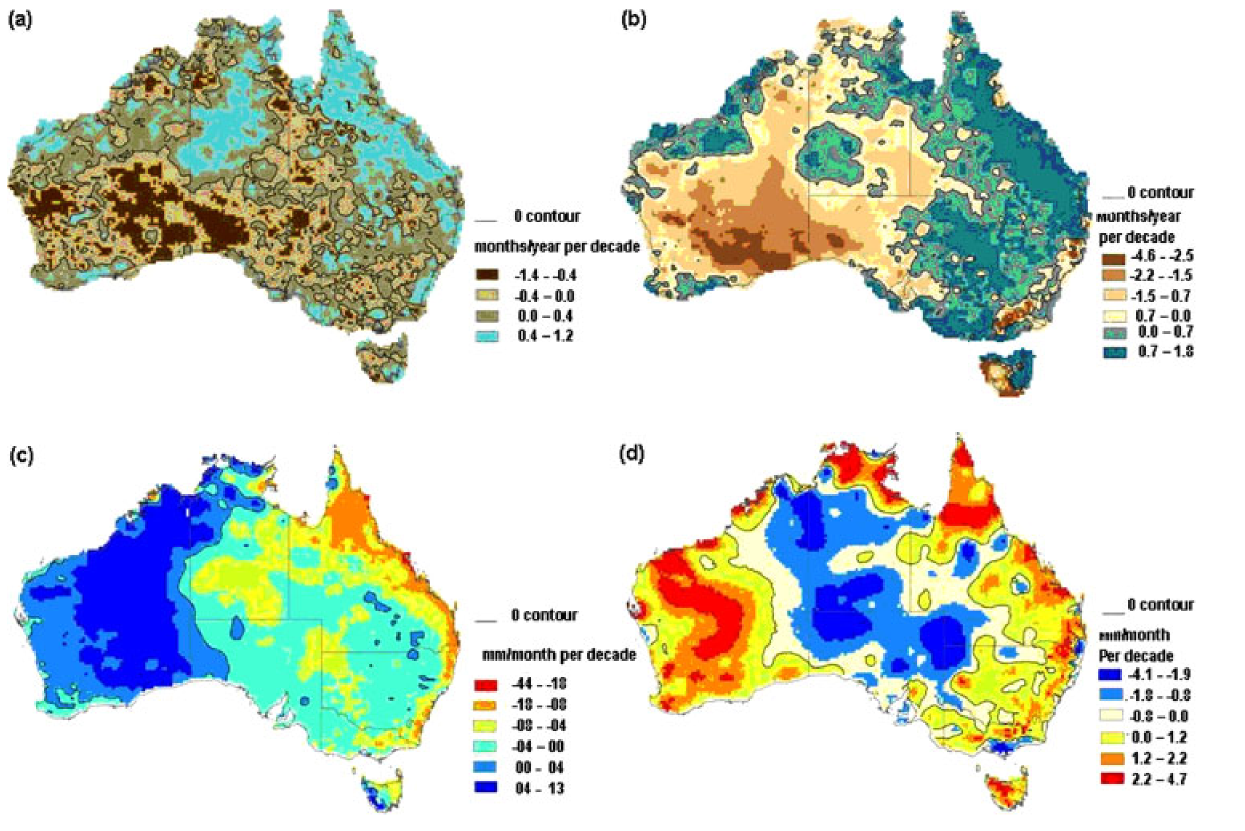

Figure 1. Spatial distribution of estimated drought persistence trends (months/year per decade) for the first RDDI (panel a) and SMDDI (panel b) together with trends in rainfall (panel c) and trends in potential evaporation (panel d) for the 1970–1999 period.

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SMDDI-based droughts respectively. Both indices show similar general trend patterns but differ significantly in trend magnitudes. The trends in drought persistence by the SMDDI are greater than those captured by the RDDI. Reductions in drought duration were exhibited over the western areas with droughts becoming more persistent over most of the remaining areas of the country, particularly in the central and south-eastern regions. This is more consistent with the trends in rainfall than in potential evaporation, which in essence only exacerbates drought conditions and can be regarded as a secondary drought driver. Precipitation has tended to increase over Western Australia (WA) over the last three decades, except in the south–southwest and eastern areas which were generally dominated by negative trends, as shown in Figure 1(c) and (d).

There are substantial differences between RDDI- and SMDDI-based drought events in terms of duration and, to a lesser extent, in areal coverage (not shown). Illustrated in Figure 2(a) and (b) is the contrast in drought durations for the period 1970–2003 over the Murrumbidgee catchment. Evidently, the consideration of soil moisture had an integrating effect that resulted in less sensitivity to rainfall fluctuations, and hence reflected a more realistic evolution of water deficit. This suggests that in reality, a region can experience a drought later but remain in drought longer than would be suggested by an analysis of rainfall deficit alone (e.g. 1991–1997).

Frequencies of drought for the study period indicated more uniformly distributed drought probabilities, between 10 and 20%, for the rainfall-based index than for the soil-moisture-based index, which suggested probabilities ranging from 10 to 40% and exhibited a more fine-scale spatial structure. A comparison of the first deciles of long-term annual rainfall and soil-moisture for the Murrumbidgee and catchments of southwest WA (shown in Figure 3) exhibited significant spatial differences in the lag between phases of rainfall and soil moisture deciles across Australia. For example, Figure 4 depicts the contrast between the annual cycles of the first decile precipitation and the soil moisture of the Murrumbidgee (panel a) and catchments of southwest WA (panel b). It is shown that rainfall and soil-moisture deciles are out of phase by about 3 months in autumn and winter (relatively wet periods) and by about 6 months in spring and summer over the Murrumbidgee catchment. For the catchment of southwest WA, these deciles are out of phase by 6 months, and the annual soil-moisture cycle has a much lower amplitude compared to that of the Murrumbidgee. This can be attributed to spatial differences in both precipitation and evaporation (i.e. different climate regimes). Such differences can significantly contribute to the weakness in the characterization of drought events when they are based solely on meteorological drought indices.

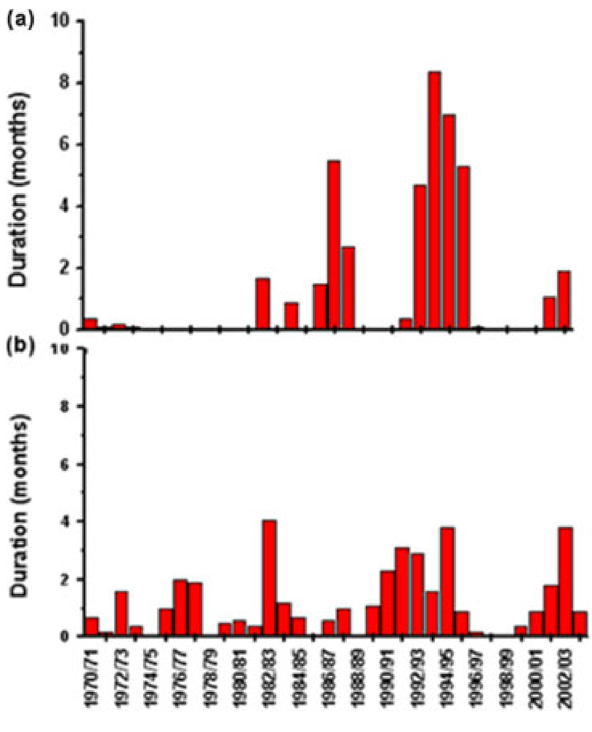

Figure 2. Duration of drought events over the Murrumbidgee catchment for the period 1970–2003 based on SMDDI (panel a) and RDDI (panel b). This figure is available in colour online at www.interscience.wiley.com/ijoc

In the context of the stress on commodity production as a result of drought, agricultural produce, including sugar cane, pasture growth, cereals, and fruit, is affected the most. About 20% of the wheat produced in Australia is produced in southwest WA in the 'Wheat Belt' in rain-fed fields (McFarlane, 2004) and is hence vulnerable to drought. Both irrigated and dry land agriculture in the Murrumbidgee catchment produce coarse grains (ABARE, 2004). Depicted in Figure 5 are statistics of wheat and coarse grain production in Australia (panel a) and catchment water yield (panel b) for the 1970–2003 period. Due to the multiplicity of constraints on agricultural production in addition to climate variability, no rigorous comparison of past drought events and production was made. However, the depicted correlation of yield and drought events captured by the drought indices was generally consistent with the well-documented recent drought impacts on agriculture and catchment water yield.

As depicted in Figure 5 (panel b), there is usually a significant time-lag between precipitation shortfall and the onset of a hydrological drought. The soil, including groundwater reserves and standing water bodies, may hold enough water to forestall hydrological drought while agricultural drought is occurring. The time-lag can also continue a hydrological drought well past the withdrawal of the precipitation deficit, making the comparison of past drought events with low flows more complex.

In the analysis of the characteristics of future drought events, changes in rainfall and potential evaporation for 2030 and 2070 were based on simulations from the *CCCma1* and CSIRO *Mark2* GCMs. Figure 6 shows relative changes in the frequency of droughts over Australia based on *Mark2*, with respect to a baseline frequency

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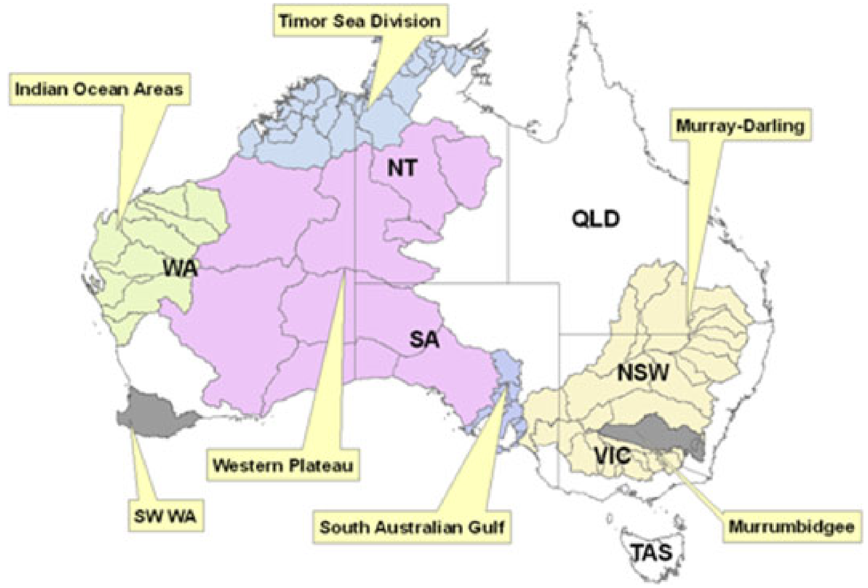

Figure 3. Location of example catchments and regions specifically referred to in the text, such as Murrumbidgee and southwest WA. This figure is available in colour online at www.interscience.wiley.com/ijoc

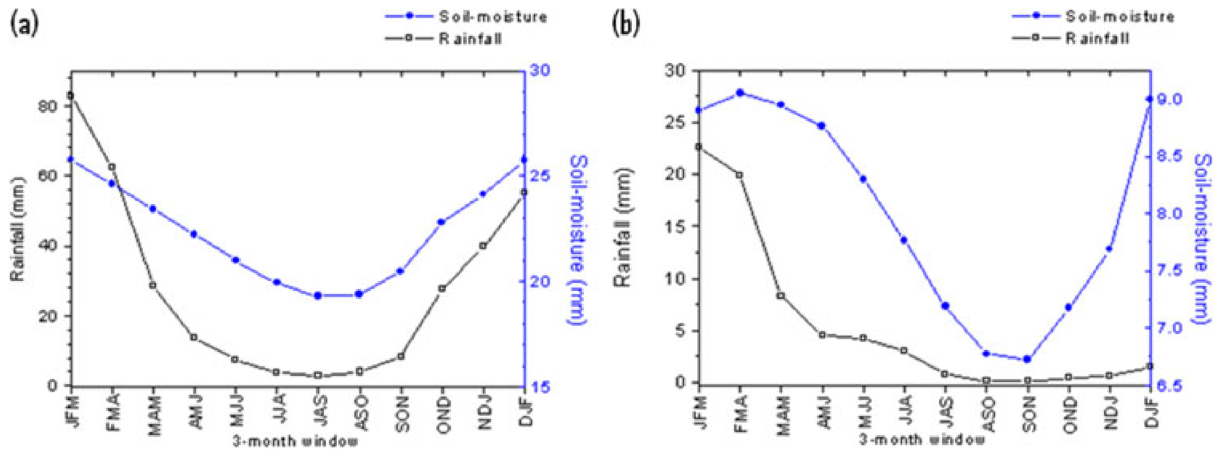

Figure 4. Long-term annual deciles 1 of rainfall and soil-moisture cycles for Murrumbidgee (panel a) and southwest WA (panel b). Rainfall and soil moisture are on different scales. This figure is available in colour online at www.interscience.wiley.com/ijoc

of droughts, for the 2030 and 2070 high scenarios. A comparative analysis of the changes in the probability of a drought event between Australian regions and the two GCMs with respect to baseline probabilities is summarized in Table II. For the frequency of RDDI-based droughts, the 2030 low scenario gives increases of 0–20% over most of Australia and decreases of 0–20% over south-eastern and central Australia. The 2030 high scenario is similar. The 2030 high and 2070 low scenarios are almost identical since their global warming values are similar. The 2070 high scenario for *Mark2* gives widespread increases of 0–20% while the 2070 high scenario for *CCCma1* gives increases of 0–20% over the eastern two-thirds of Australia, rising to 20–40% in the western one-third. The SMDDI suggests frequency increases of 0–20% for the 2030 low *Mark2* scenario in the eastern one-third and parts of WA with decreases of 0–20% elsewhere. The *CCCma1* 2030 low scenario gives increases of 0–20% over most of the continent. The 2030 high scenario is very similar to the 2030 low scenario, with slightly greater drought frequency. The 2070 low scenario is very similar to the 2030 high scenario. The 2070 high scenario for *Mark2* gives decreases of 0–20% in southeast WA, increases of 0–20% in most of the Murray-Darling basin, most of South Australia (SA), Northern Territory, and northwest WA, 20–40% in southeast Queensland, western Tasmania and southern New South Wales, 40–60% in northern Victoria, eastern Tasmania, southern SA and the WA wheat belt, and 60–80% in southern Victoria and southwest WA.

The inter-annual variability in rainfall and potential evaporation derived from historical time series were incorporated in the future climate scenarios. The characteristics of the scenarios can be heavily influenced by sampling variability from different periods of the historical time series. For example, one of the

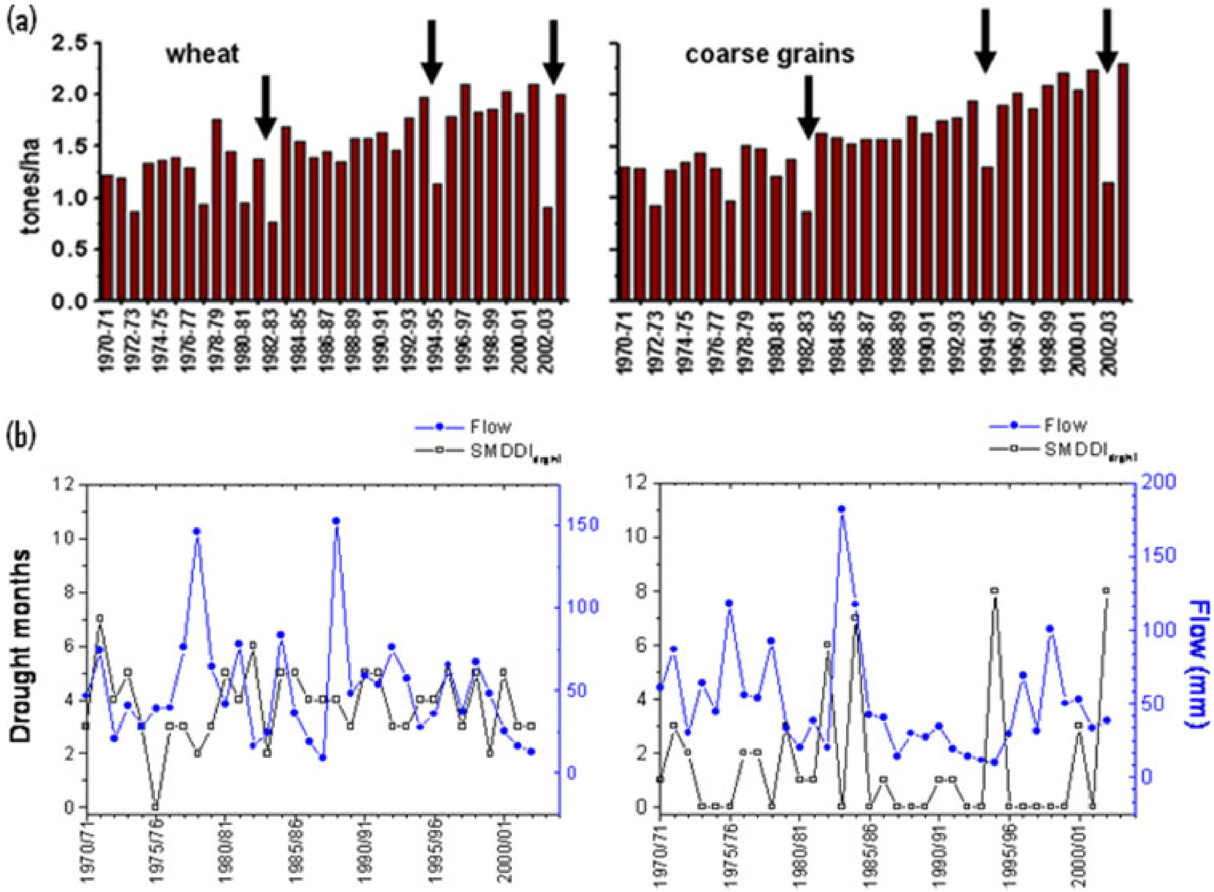

Figure 5. Wheat and coarse grains production in Australia (panel a) where arrows indicate the recent well-documented drought years in Australia; unregulated catchment water yield by the Denmark River catchment at Mt. Lindesay, WA (34.87oS, 117.31oE) on the left of panel b; and the Halls Creek catchment at Bingara, NSW (29.91oS, 150.58oE) on the right of panel b. *Sources:* ABARE, 2004, ABARE and Peel *et al*., 2000. This figure is available in colour online at www.interscience.wiley.com/ijoc

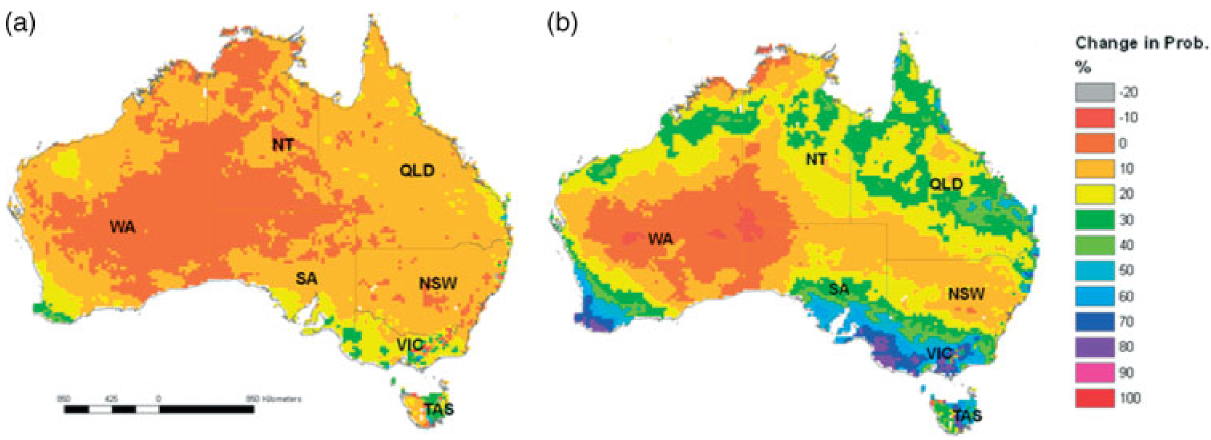

Figure 6. The 2030 and 2070 ‘High Scenario’ CSIRO *Mk2* model percentage change in drought frequency with respect to the baseline (1974–2003).

strongest climatological phenomena commonly linked to Australian rainfall variability is the El Nino Southern Oscillation (ENSO) (Dilley and Heyman, 1995). ENSO events themselves exhibit long-term variations that appear to be associated with decadal-to-century scale variations of sea surface temperatures in the Pacific and Indian Oceans (Power *et al*., 1999). In the 20th century there is evidence of the occurrence of extended ENSO events that lasted several years. The long ENSO event of 1990–1995 was followed by one of the strongest ENSO events on record during 1997/1998 (Trenberth and Hoar, 1996; Power *et al*., 1998).

Table II. Changes in drought frequency over Australia relative to the 1975–2004 baseline period, based on the SMDDI. Locations of specific areas mentioned are shown in Figure 3.

Model	2030 low	2030 high	2070 low	2070 high
MK2	An increase of 0–20% over most areas of Australia except for a decrease of 0–20% over the southern parts of the Murray-Darling Basin, the South Australian gulf areas, the south-eastern areas of the western plateau and Tasmania.	A general increase of 0–20% over Australia, except for scattered patches with decreases of 0–20% over the southern parts of the Murray-Darling Basin, the south-eastern parts of the western plateau, and Tasmania.	An increase of 0–20% over Australia, except for scattered patches with decreases of 0–20% over Tasmania, the southern parts of the Murray-Darling Basin, and the south-eastern parts of the western plateau.	A general increase of 0–20% with isolated patches of areas with a decrease of 0–20% over central western plateau and the northern parts of the Murray-Darling basin.
CCCma1	A 0–20% increase over most areas of Australia except for a decrease of 0–20% over the southern parts of the Murray-Darling Basin, the South Australian gulf areas, and Tasmania.	A 0–20% increase over most areas of Australia except for a decrease of 0–20% over the southern parts of the Murray-Darling Basin, the South Australian gulf areas, and Tasmania.	A 0–20% increase over most areas of Australia except for a decrease of 0–20% over Tasmania, the southern parts of the Murray-Darling Basin, and the South Australian gulf areas.	A 0–20% increase over three-quarters of the country to the east and Tasmania; 20–40% increases over the western areas with isolated patches of areas with increase up to 60%.
MK2	A 0–20% decrease over most of the western two-thirds of Australia, and increases of 0–20% in the eastern one-third.	A 0–20% decrease over most of the western half of Australia, and increases of 0–20% in the eastern one-third and parts of coastal WA.	A 0–20% decrease over most of the western half of Australia, and increases of 0–20% in the eastern one-third and parts of coastal WA.	A 0–20% decrease in southeast WA, increases of 0–20% over most of the remaining areas of Australia, but increases of 20–40% in parts of Qld and southern NSW, and increases of 40–80% in Victoria and southwest WA.
CCCma1	A 0–20% increase over most western areas of Australia and over two-thirds of the eastern areas. Patches of 0–20% decrease of the remaining areas including Timor Sea catchment.	A general increase of 0–20% over most areas; 20–40% increase over south-western coast catchment. Patches of decrease of 0–20% over Timor Sea areas and northeast coast catchment.	Mainly an increase of 0–20% over most areas; 20–40% increase over south-western coast catchment. Some patches of decrease of 0–20% over Timor Sea areas and northeast coast catchment.	An increase of 60–80% over the Indian Ocean and southwest coast catchments; 40–60% increase over the western plateau with 20–40% increase extending eastwards, and the southeast coast. A 0–20% increase over most of the Murray-Darling basin, the northeast coast catchment and Tasmania.

However, the characteristics of ENSO over Australia may have changed during the past 25 years (Nicholls, 2004). Since the mid-1980s, annual rainfall in eastern Australia has increased slightly, contrary to the observed trend in ENSO, suggesting a weakening relationship between ENSO and rainfall over Australia (DoE&H, 2001a; Suppiah, 2004).

Recent studies at the Australian CSIRO indicate that ENSO explains only 25% of the variability of climate over eastern Australia (Hennessy *et al.*, 2004). Over southern Australia, climate variability is also attributed to variations in the characteristics of frontal activity. This poses a challenge in the construction of future climate scenarios, particularly for the 'pattern scaling' and similar approaches that assume that future climate variability will resemble past climate variability. Another assumption of this approach relates to the issue of spatial scale. The methodology assumes that the relative pattern of change is scale invariant, i.e. a relative pattern of change calculated at the GCM grid-scale can be applied at any point within a GCM grid-box. The validity of this assumption is yet to be tested with a dense network of observed point data that is area-averaged to various spatial scales.

4. Conclusions

Two drought indices have been assessed for Australia. The SMDDI appears to be more relevant to resource

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management than the Meteorological Drought Index in that it accounts for the 'memory' of water status. Consideration of soil-moisture delays and prolongs droughts, relative to meteorological droughts, and tends to indicate a realistic severity and persistence for drought events. Meteorological drought indices *per se* are inadequate for the reliable assessment of drought. Evapotranspiration, and thus air temperature, is important in determining the severity of droughts, and will be even more important as the climate changes in a warmer world. Projected changes in rainfall and potential evaporation for 2030 and 2070 based on results from two climate models driven by scenarios of increasing greenhouse gas concentrations suggest increases in drought frequency. However, the quantification of future drought characteristics in Australia can be rather subjective and complex when using 'pattern scaling' and similar approaches of scenario construction that assume that future climate variability will resemble past climate variability.

The projected changes in drought characteristics will potentially have major implications for natural resource management, water security planning, water demand management strategies, and drought relief payments. The projected warmer and drier conditions over Australia emphasize the challenges ahead for improving productivity and efficiency of water use while maintaining healthy river and groundwater systems. The difference in the results from the two GCMs illustrates another source of uncertainty in the characterization of future regional droughts, in addition to often ill-defined drought indices, of which water resource managers and planners should be more aware.

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References

ABARE. 2004. *Australian Commodity Statistics*. Australian Bureau of Agricultural and Resource Economics: Canberra; 45 and 216.

Adams PD, Horridge M, Masden JR, Wittwer G. 2002. Drought, regions and the Australian economy between 2001-02 and 2004-05. *Australian Bulletin of Labour* **28**: 233–249.

AFFA. 2006. *Australian Government Drought Assistance*. Department of Agriculture Fisheries and Forestry: http://www.affa.gov.au/content/output.cfm?ObjectID=D0C19333-3B03-4933-91BAE3D 3975BE27C&contType=outputs, Accessed 21 June 2006.

American Meteorological Society. 1997. Meteorological drought–policy statement. *Bulletin of the American Meteorological Society* **78**: 847–849.

Boer GJ, Flato GM, Ramsden D. 2000. A transient climate change simulation with historical and projected greenhouse gas and aerosol forcing: projected climate for the 21st century. *Climate Dynamics* **16**: 427–450.

BoM. 2006. *Living with Drought*. Australian Bureau of Meteorology: http://www.bom.gov.au/climate/drought/livedrought.shtml, Accessed 14 April 2006.

Botterill LC. 2003. Uncertain Climate: The Recent History of Drought Policy in Australia. *Australian Journal of Politics and History* **49**(1): 61.

Botterill LC, Wilhite D (eds). 2005. *From Disaster Response to Risk Management: Australia's National Drought Policy*. Springer; 209.

Burke EJ, Brown SJ, Christidis N. 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.

Dilley M, Heyman BN. 1995. ENSO and disaster: droughts, floods and El Nino/Southern Oscillation warm events. *Disasters* **19**(3): 181–193.

DoAFF. 2006. *Drought and Exceptional Circumstances*. Australian Department of Agriculture, Fisheries and Forestry: http://www.affa.gov.au/content/output.cfm?ObjectID=D2C48F86-BA1A-11A1-A2200060B0A06289, Accessed 21 June, 2006.

DoE&H. 2001a. *Department of the Environment and Heritage: Australia State of the Environment Report*. http://www.deh.gov.au/soe/2001/publications/theme-reports/atmosphere/index.html, Accessed 5 January, 2007.

DoE&H. 2001b. *Department of the Environment and Heritage: Australia State of the Environment, Independent Report to the Commonwealth Minister for the Environment and Heritage*. http:/www.ea.gov.au/soe/2001/publications, Accessed 5 January, 2007.

Gibbs WJ, Maher JV. 1967. *Rainfall Deciles as Drought Indicators, Bulletin No. 48*. Bureau of Meteorology: Melbourne, Australia.

Gordon HB, Rotstayn LD, McGregor JL, Dix MR, Kowalczyk EA, O'Farrell P, Waterman LJ, Hirst AC, Wilson SG, Collier MA, Watterson IG, Elliott TI. 2002. *The CSIRO Mk3 Climate System*. CSIRO Atmospheric Research technical paper no. 60: 130.

Hall WB, Bruget D, Carter J, McKeon G, Peacock A, Brook K. 2001. *Australian Grassland and Rangeland Assessment by Spatial Simulation (Aussie Grass)*. Final Report for the Climate Variability in Agriculture Program, April 2001: http://www.longpaddock.qld.gov.au/AboutUs/Publications/ByType/Reports/AussieGRASS-FinalReport/index.html.

Heathcote RL. 1969. Drought in Australia: A problem of perception. *Geographical Review* **59**(2): 175–194.

Hennessy KJ, Page CM, McInnes KL, Jones RN, Bathols JM, Collins D, Jones D. 2004. *Climate Change in New South Wales. Part 1, Past Climate Variability and Projected Changes in Average Climate*. CSIRO Atmospheric Research Report no. 46.

Hobbs TJ, Sparrow AD, Landsberg JJ. 1994. A model of soil moisture balance and herbage growth in the arid rangelands of central Australia. *Journal of Arid Environment* **28**: 281–298.

IPCC. 2001. Climate Change 2001: *The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*. Houghton JT, Ding Y, Griggs DJ, Noguer M, van der Linden PJ, Dai X, Maskell K, Johnson CA (eds). Cambridge University Press: Cambridge, United Kingdom and New York, NY, USA; 881.

Jeffrey SJ, Carter JO, Moodie KM, Beswick AR. 2001. Using spatial interpolation to construct a comprehensive archive of Australian climate data. *Environmental Modelling and Software* **16**(4): 309–330.

Jones RN, McMahon TA, Bowler JM. 2001. Modelling historical lake levels and recent climate change at three closed lakes, Western Victoria, Australia (c. 1890–1990). *Journal of Hydrology* **246**(1): 159–180.

Karl TR. 1983. Some spatial characteristics of drought duration in the United States. *Journal of Climate and Applied Meteorology* **22**: 1356–1366.

Keetch JJ, Byram GM. 1968. A drought index for forest fire control. Paper SE-38, Forest Service Research, U.S. Department of Agriculture.

Kogan FN. 1995. Droughts of the late 1980s in the United States as derived from NOAA polar-orbiting satellite data. *Bulletin of the American Meteorological Society* **76**(5): 655–668.

Le Houerou HN. 1996. Climate change, drought and desertification. *Journal of Arid Environment* **34**(2): 133–185(53).

McFarlane M. 2004. Avon River Basin 2050 Brochure. Wheatbelt Development Commission.

McKee TB, Doesken NJ, Kleist J. 1993. The relationship of drought frequency and duration to time scales. In *Eighth Conference on Applied Climatology*, 17–22 January, Anaheim, CA, 179–184.

McMahon TA, Arenas AD. 1982. *Methods of Computation of Low Streamflow*. Paris, UNESCO Studies and Reports in Hydrology 36, 107.

Meehl GA, Boer GJ, Covey C, Latif M, Stouffer RJ. 2000. The Coupled Model Intercomparison Project (CMIP). *Bulletin of the American Meteorological Society* **81**(2): 313–318.

Mitchell TD. 2003. Pattern scaling – an examination of the accuracy of the technique for describing future climates. *Climatic Change* **60**: 217–242.

Nicholls N. 2004. The changing nature of Australian droughts. *Climatic Change* **63**(3): 323–336.

Palmer WC. 1965. Meteorological Drought. *US Weather Bureau Technical Paper* **45**: 1–58.

Palmer WC. 1968. Keeping track of crop moisture conditions, nationwide: the new Crop Moisture Index. *Weatherwise* **21**: 156–161.

Peel MC, Chiew FHS, Western AW, McMahon TA. 2000. Extension of unimpaired monthly streamflow data and regionalisation of parameter values to estimate streamflow in ungauged catchments. *Report Prepared for the National Land and Water Resources Audit*, in Australian natural Resources Atlas website, http:/audit.ea.gov.au/anra/water/docs/national/Water_Streamflow.htm.

Power S, Tseitkin F, Torok S, Lavery B, Dahni R, McAvaney B. 1998. Australian temperature, Australian rainfall and the Southern Oscillation Index, 1910–1992: coherent variability and recent changes. *Australian Meteorological Magazine* **47**: 85–101.

Power S, Tseitkin F, Mehta V, Lavery B, Torok S, Holbrook N. 1999. Decadal climate variability in Australia during the twentieth century. *International Journal of Climatology* **19**: 169–184.

Riebsame WE, Changnon SA, Karl TR. 1991. Drought and natural resources management in the United States: impacts and implications of the 1987–89 drought. *Westview Press* 174.

Smakhtin VU, Hughes DA. 2004. Review, automated estimation and analyses of drought indices in South Asia. Working Paper 83. International Water Management Institute: Colombo, Sri Lanka.

Smith DI, Hutchinson MF, McArthur RJ. 1993. Australian climatic and agricultural drought: payments and policy. *Drought Network News* **5**(3): 11–12.

Suppiah R. 2004. Trends in the Southern Oscillation phenomenon and Australian rainfall and changes in their relationship. *International Journal of Climatology* **24**: 269–290.

Trenberth KE, Hoar TJ. 1996. The 1990–1995 El Niño-Southern oscillation event: longest on record. *Geophysical Research Letters* **23**: 57–60.

Whetton PH, Hennessy KJ. 2001. Climate change projections for the Australian region. In *MODSIM 2001: International Congress on Modelling and Simulation: Proceedings, Australian National University*, Ghassemi F and others (eds). Modelling and Simulation Society of Australia and New Zealand: Canberra, ACT; 647–654.

Whetton PH, Jones RN. 2004. The impacts of climate change and variability on Australia: Climate change–can agriculture take the heat? *Farm Policy Journal* **1**(3): 4–12.

Whetton PH, McInnes KL, Jones RN, Hennessy KJ, Suppiah R, Page CM, Bathols J, Durack PJ. 2005. *Australian Climate Change Projections for Impact Assessment and Policy Application: A Review*. CSIRO Marine and Atmospheric Research Paper 001 December 2005.

White D. 2006. *The Utility of Seasonal Indices for Monitoring and Assessing Agricultural Drought*. Report to the Australia Bureau of Rural Sciences, 778.

Wilhite DA. 2005. Drought policy and Preparedness: The Australian experience in an international context. In *From Disaster Response to Risk Management: Australia's National Drought Policy*, Courtenay Botterill L, Wilhite DA (eds). Springer: Dordrecht, The Netherlands; 157–176.

Wilhite DA, Glantz MH. 1985. Understanding the drought phenomenon: The role of definitions. *Water International* **10**: 111–120.