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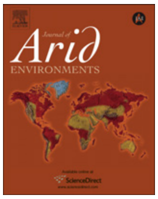

Characteristics of Australian droughts under enhanced greenhouse conditions: Results from 14 global climate models

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ABSTRACT

This paper presents characteristics of droughts simulated by global climate models (GCMs) under enhanced greenhouse gases conditions. We used a drought index called the Reconnaissance Drought Index (RDI) which takes both rainfall and potential evapotranspiration into account to investigate variations of droughts among 12 regions in Australia. The RDI was applied to simulated climate variables from 14 GCMs performed for the IPCC 4th Assessment Report.

The results show a general increase in drought areal extent and/or frequency for most regions. However, the increases are not significant over the North West, North Queensland, Queensland East Coast and Central Queensland. For most regions, the change beyond 2030 is larger than that prior to 2030, but the uncertainty in the projections also increases with time. By 2030, there is a *likely* (>66% probability) risk of twice or more drought affected area and/or twice as often drought frequency over South West Western Australia. By 2050, this will include the Murray-Darling Basin, South Australia and Victoria, and by 2070 this will extend to New South Wales and Tasmania. For North Queensland such a risk is *unlikely* (<33% probability) for the next 100 years. This information can be considered indicative in long-term planning focussing on sustainability.

1. Introduction

The hydroclimatic variability in Australia is among the highest in the world (McMahon et al., 1992; Nicholls et al., 1997) and droughts are a normal component of the climate of Australia (McKernan, 2005). A number of major droughts events are well documented including the Federation drought (1895–1902), the World War II drought (1937–1945), and the recent drought (post-1995) that has lasted for almost a decade, particularly over the southeastern Australia. These droughts had significant impacts on the Australian environment (Bond et al., 2008; Humphries and Baldwin, 2003; Recher et al., 2009) and the country's economy (Productivity Commission, 2008; BoM, 2009a). For example, in the World War II drought there was loss of nearly 30 million sheep between 1942 and 1945 (BoM, 2009a), and the drought in the southeast Australia in 1994, 2002 and 2006 reduced the agricultural Gross National Product by about 30% (ABARE, 2008).

The cost of droughts to Australian government occur mainly through monetary payments, subsidies to agricultural and industrial sectors, exit assistance for farmers, professional advice and planning grants, counselling and so on (www.daff.gov.au). The decision-making process for the provision of such assistance are assisted by the exceptional circumstances (EC) evaluation. The EC application process requires State or Territory Governments to determine if there is an EC occurring in their jurisdiction that may warrant EC assistance (DAFF, 2008). For the declaration of EC, six core criteria need to be satisfied: meteorological conditions, agronomic and stock conditions, water supplies, environmental impacts, farm income levels, and the scale of the event (DAFF, 2008; White et al., 1998). The agreed framework stated that EC would be declared when the combined impact on farmers of these core criteria constituted a rare and severe occurrence and that meteorological conditions would be the threshold or primary condition (DAFF, 2008).

With regard to meteorological conditions, the event must be rare, that is, it must not have occurred more than once on average in every 20–25 years and be of >12 months duration. Meteorological drought condition can be defined based on rainfall data using, for example, the Rainfall Deciles (RDDI) method (Gibbs and Maher, 1967; BoM, 2009b) and the Standardised Precipitation Index (SPI) (Baros and Bowden, 2008; McKee et al., 1993). However, an analysis of the 2002–2003 drought in Australia indicated that

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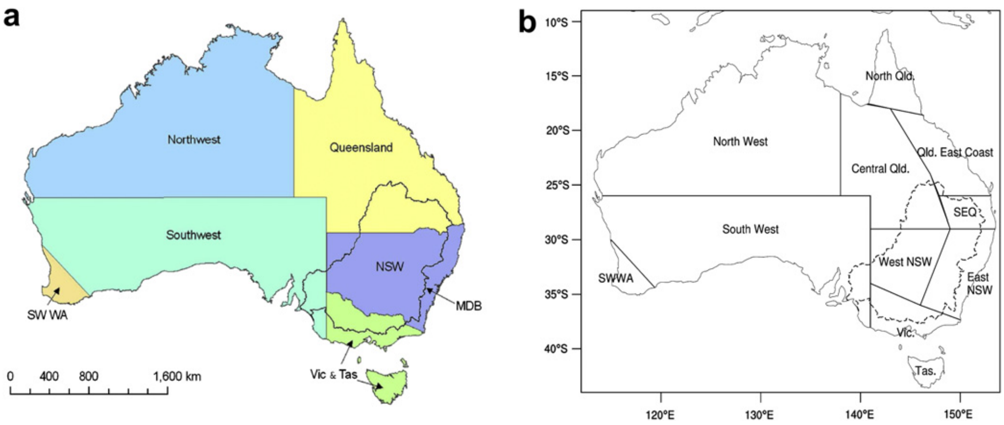

Fig. 1. a) Maps of the 7 regions considered in Hennessy et al. (2008); b) Maps of the 12 regions considered in this study. The region shown as dashed line is the Murray-Darling Basin (MDB).

meteorological drought indices based on rainfall alone may fail to include the important contribution of temperature via the evaporation (Nicholls, 2004) emphasising the need to include two of the key factors in determining meteorological drought occurrence, i.e. rainfall and evapotranspiration (Blekinsop and Fowler, 2007). Nicholls (2004) reported that, with regard to the 2002–2003 drought event, the very high day-time temperature clearly reflected the combination of inter-annual climate variability and long-term (global) warming and probably led to the drought being more severe despite its rainfall was not obviously drier than previous drought.

Given the likely increase in the area of the globe affected by droughts in future Hennessy et al. (2008) assessed how human induced climate change may affect the concept of a one in 20–25 year event into the future for Australia. In their study, simulated annual data from 13 global climate model (GCMs) had been used to examine the areal extent and frequency of exceptionally high temperatures, low rainfall and low soil moisture for seven regions (Fig. 1a) for up to the next 30 years. The areal extent and frequency of exceptionally hot years have been increased in recent decades and that the trend is expected to continue in each region. According to the rainfall analyses, the mean projections for 2030 (2010–2040) indicate that more declarations of EC would be likely, and over large areas, in the SW, SWWA and Vic&Tas regions, with relatively no detectable change in other regions, and the same is true for low soil moisture. The study recommended a more detailed analyses of projected changes in drought in sub-regions, e.g. southeast Queensland. Also, an assessment beyond the next 20–30 years would be required to meet long-term planning horizons of some enterprises and the focus on sustainability.

Table 1
List of 14 GCMs used.

GCM	Modelling group, Country	Horizontal resolution (km)
CCCMA T47	Canadian Climate Centre, Canada	~250
CCCMA T63	Canadian Climate Centre, Canada	~175
CSIRO-MK3.0	CSIRO, Australia	~175
CSIRO-MK3.5	CSIRO, Australia	~175
GISS-AOM	NASA/Goddard Institute for Space Studies, USA	~300
GISS-EH	NASA/Goddard Institute for Space Studies, USA	~400
GISS-ER	NASA/Goddard Institute for Space Studies, USA	~400
IAP-FGOALS	LASG/Institute of Atmospheric Physics, China	~300
INMCM	Institute of Numerical Mathematics, Russia	~400
IPSL	Institut Pierre Simon Laplace, France	~275
MIROC-H	Centre for Climate Research, Japan	~100
MIROC-M	Centre for Climate Research, Japan	~250
MRI	Meteorological Research Institute, Japan	~250
NCAR-CCSM	National Centre for Atmospheric Research, USA	~125

The main objective of this paper is to extend Hennessy et al.'s (2008) analyses to cover more regions (12 regions as shown in Fig. 1b) over a longer time period (up to 2100). The delineation of the 12 regions were based on some considerations including climatic zones, geographical variations in rainfall trends (1950–2008) and geo-political boundaries. Recalling the fact that it is crucial to include both rainfall and evapotranspiration in a drought analysis, this study used the Reconnaissance Drought Index (RDI) which considers both rainfall and potential evapotranspiration (*PET*). This index, recently introduced by Tsakiris and Vangelis (2005), is suitable in cases of change environment (Tsakiris et al., 2007) and is appropriate for climate change scenarios-drought related study (FAO/NDMC, 2008; Rossi et al., 2008).

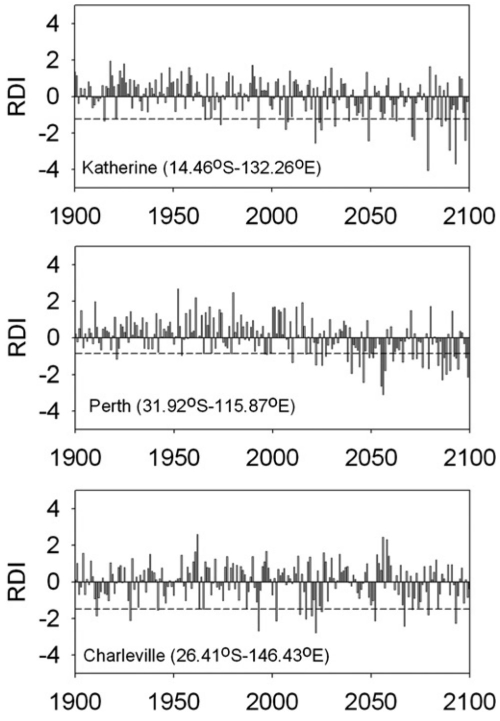

Fig. 2. Time series of the RDI, as modelled by CSIRO-MK3.0, at three selected sites. The dashed lines represent the 5th percentile for the period of 1900–2007.

Similar to that in Hennessy et al.'s (2008) study, the development of regional drought projections is facilitated by the use of global climate model (GCM) simulations since, in the absence of fine resolution climate simulation (which may be capable of better representing some of the topographical and other interactions more accurately), GCMs are the only available tools for estimating the future response of regional climates to anthropogenic radiative forcing. Despite some conjecture that GCM simulations of future climate are not yet ready, particularly for direct application to long-term water management and adaptation planning (Kundzewicz and Stakhiv, 2010; Wilby, 2010), there is also considerable confidence that the GCMs provide credible quantitative estimates of future climate change, particularly at continental and larger scales (IPCC, 2007). It seems likely that "the real climate system will respond to increased greenhouse gas concentrations in many respects in a way similar to that models suggest" (Räisänen, 2007), thus supporting previous suggestion that climate models are useful tools at least to sub-continental scales (McAvaney et al., 2001).

The simulations inherit uncertainties, however, which are linked to uncertainties in global greenhouse gas emissions and global climate sensitivity to these emissions, as well as regional climate sensitivity. Given such uncertainty, one should opt for decisions that are robust, over the range of potential future outcomes. Thus, to be useful for such exercise, this study also

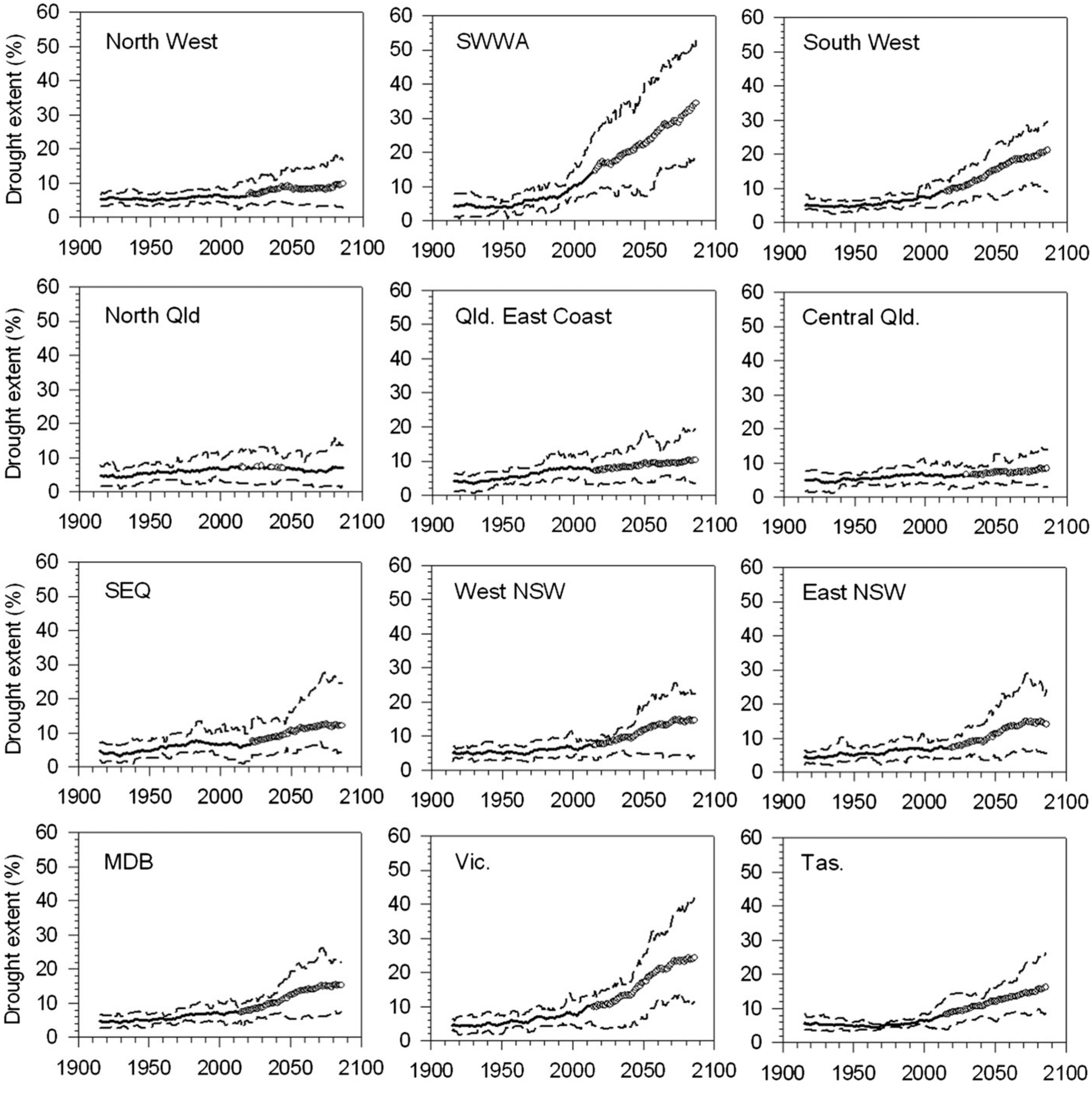

Fig. 3. Simulated percentage area affected by drought in the twelve regions for 1900–2100, based on 14 GCMs. The solid lines are the multi-model means while the dashed lines show the range between the lowest and highest 10% of model results, all smoothed by thirty-year averages. Circle symbols denote that the mean drought extent at that particular period statistically differs (with $p < 0.1$) to the mean of drought extent in 1900–2007.

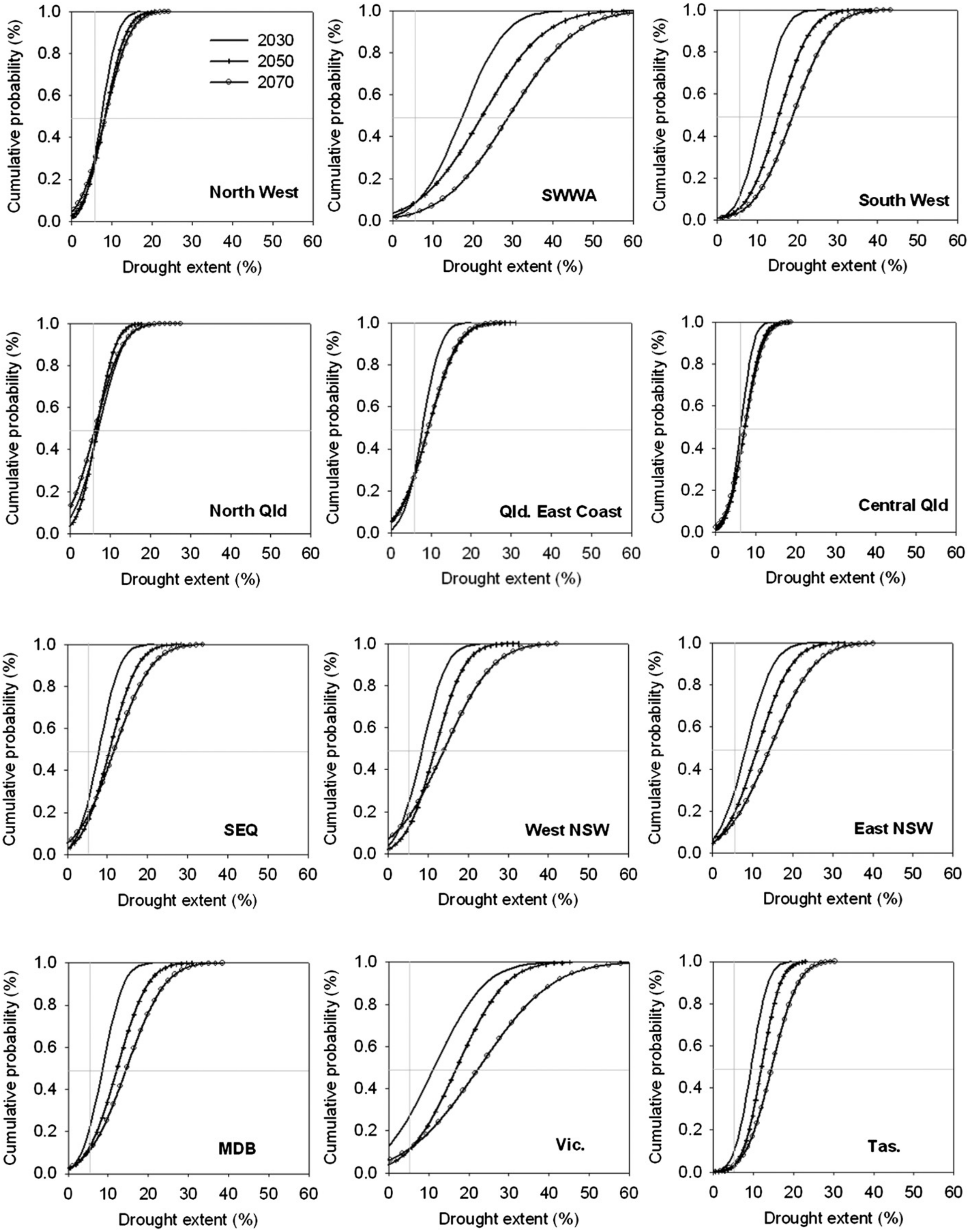

Fig. 4. Probability distribution for drought extent in 2030, 2050, 2070 based on 14 GCMs.

conducts a simple risk analysis so that uncertainty in future drought projections can be expressed in units of probability or likelihood. Details about the methods and data used in this study are described in the following section.

2. Methodology

2.1. The Reconnaissance Drought Index (RDI)

The RDI is based on the ratio between two aggregated quantities of rainfall (P) and PET. It is similar to the "Aridity Index" proposed by the United Nations (FAO/UNESCO/WMO, 1977; Jones and Reid, 2001). A mathematical representation of the RDI is as summarised below (Equations (1) through (3)), and a detailed representation of the RDI can be found in Tsakiris and Vangelis (2005) and Tsakiris et al. (2007). The RDI can be calculated for any period of time from 1 month to the entire year, but this paper focuses on the 12 month (annual) RDI. The initial value of annual RDI (α_o) is calculated as

$$\alpha_{oi} = \sum_{j=1}^{12} P_{ij} \Big/ \sum_{j=1}^{12} PET_{ij} \qquad (1)$$

where P_{ij} and PET_{ij} represent rainfall and potential evapotranspiration of the jth month of the ith years and N is the total number of years of the available data. The normalised RDI can then be calculated as:

$$RDI_n^{(i)} = \left(\alpha_0^{(i)}/\bar{\alpha}_0\right) - 1 \qquad (2)$$

and the standardised RDI is calculated as:

$$RDI_{st}^{(i)} = (y_i - \bar{y}_i)/\sigma \qquad (3)$$

where the $\bar{\alpha}_0$ is the arithmetic mean of α_o values calculated for N *years* of data and y_i is the $\ln(\alpha_0^{(i)})$, $\bar{y}_i$ is its arithmetic mean and σ is the standard deviation of y_i. The above formulation is based on the assumption that α_o values follow a lognormal distribution. The choice of the lognormal distribution is not constraining but it assists in devising a unique procedure instead of various procedures depending on the probability distribution function, which best fits the data (Tsakiris et al., 2007). All analyses and results presented on this paper are based on the standardised RDI (henceforth is referred as RDI for abbreviation).

2.2. Data

We use monthly data of 14 GCMs (Table 1) out of the 23 GCMs because they have climate variables needed for the calculation of PET. The data of the 23 GCMs are available in the database of the Coupled Model Intercomparison Project 3 (CMIP3) (http://www-pcmdi.llnl.gov). Most of the GCMs used in this study fairly well capture the observed climatological patterns over the Australian continent (Suppiah et al., 2007; Watterson, 2008) and therefore we have used simulations from the 14 GCMs to investigate simulated changes in the characteristics of droughts in Australia. The PET was derived using offline calculations from monthly time series of climate variables (temperature, humidity, solar radiation, and rainfall) using the Morton model (Morton, 1983). The Morton model was used to construct the Australian Bureau of Meteorology atlas for evaporation (BoM, 2001) and future projections for potential evaporation (CSIRO, 2001; CSIRO and BoM, 2007).

For 1900–2000, the simulations were based on observed atmospheric emissions of greenhouse gases and sulphate aerosols, while for 2001–2100, the simulations were forced by the SRES-A1B (IPCC, 2000) emission scenario for eleven GCMs and by the SRES-A2 emission scenario for three GCMs. This provides a representation of some of the uncertainties related to greenhouse gas emissions and regional climate sensitivity to global climate – resulted from the change in those emissions scenarios.

2.3. Definition of drought year

Following Hennessy et al. (2008), drought events are defined as being of one year duration and occurring once every 20 years, on average. If there were a hundred years of RDI data that were sorted from the driest to the wettest, the five driest years would fall below the 5th percentile and the five wettest above the 95th percentile. Here, the critical threshold for defining drought at a particular location is the 5th percentile of the RDI of that location for the period 1900–2007. For each grid cell of each GCM, the thresholds for drought were calculated. Projected changes at each grid cell for each GCM for the next 100 years were then calculated relative to these thresholds.

To illustrate this point, time series of RDI as modelled by CSIRO-MK3.0 are provided (Fig. 2) for three selected locations: Katherine (14.46°S–132.26°E), Perth (31.92°S–115.87°E) and Charleville (26.41°S–146.43°E). In this figure, the 5th percentile for the period of 1900–2007 is overlaid. Any year having an RDI of less than this threshold is categorised as a drought year. These three sites are representative of different climatic zones. According to a modified Koeppen climate classification system (BoM, 2009b) Katherine, Perth and Charleville are each located in tropical, temperate and grassland climatic zones, respectively. The annual average for rainfall (and evaporation) for each of these sites is around 1000 (2900), 800 (1800) and 490 (2400) mm, respectively (BoM, 2009b).

The 5th percentile varies with sites, i.e. −1.21, −0.86 and −1.49 for Katherine, Perth and Charleville, respectively. But by definition, the number of drought years within the period of 1900–2007 are the same for all the sites, i.e. around 6. From 2008 onward, the number of drought years vary with site and drought events are likely to occur more frequently in the future. For example, within the period of 2010–2030 the CSIRO-MK3.0 model suggests the occurrence of 3, 6 and 5 drought events at Katherine, Perth and Charleville, respectively.

2.4. Future projections

After time series of drought/non-drought year for each grid cell of each GCM were prepared, the projections for the areal extent and

Table 2
Likelihood to have 10% or more drought affected area in 2030, 2050 and 2070. (Likelihood scale are taken from IPCC (2007), i.e. *Very Likely* is >90% probability, *Likely* is >66% probability, *About as likely as not* is 33–66% probability, *Unlikely* is <33% probability, *Very unlikely* is <10% probability).

Regions	2030	2050	2070
North QLD	Unlikely	Unlikely	Unlikely
Central QLD	Very Unlikely	Unlikely	Unlikely
MDB	About as likely as not	About as likely as not	Likely
East NSW	About as likely as not	About as likely as not	Likely
West NSW	About as likely as not	About as likely as not	Likely
NW	Unlikely	About as likely as not	About as likely as not
QLD Coast	Unlikely	About as likely as not	About as likely as not
South West	About as likely as not	Likely	Likely
SEQ	Unlikely	About as likely as not	About as likely as not
SWWA	Likely	Likely	Very likely
Tas	About as likely as not	Likely	Likely
Vic	About as likely as not	Likely	Likely

frequency of droughts over each region can be constructed. The areal extent is calculated each year as the percentage area of a region affected by a drought event while the frequency is the regional-average number of drought years within a thirty-year period. Low, mean and high future scenarios are then given for each region. The mean is the 14-model average whereas the low and high scenarios are the lowest and highest 10% of the range of model results.

2.5. Risk analysis

There are inherent uncertainties in the projections associated with the future evolution of greenhouse gas concentrations in the atmosphere and the response of the climate of a region to such an increase in greenhouse gas. In the face of this problem, quantifying the uncertainties in climate change and its downstream consequences in units of probability or likelihood will help identify robust adaptation strategies. Thus in addition to the above projections, we also analyse the risks of experiencing a particular threshold in 2030, 2050 and 2070. In this paper, we choose a probability of having a double area affected by drought and/or having a drought that occur twice as often. Thus, the thresholds are 10% or more drought affected area and or a one in 10 year drought event. These thresholds, however, can be easily changed to suit any one needs.

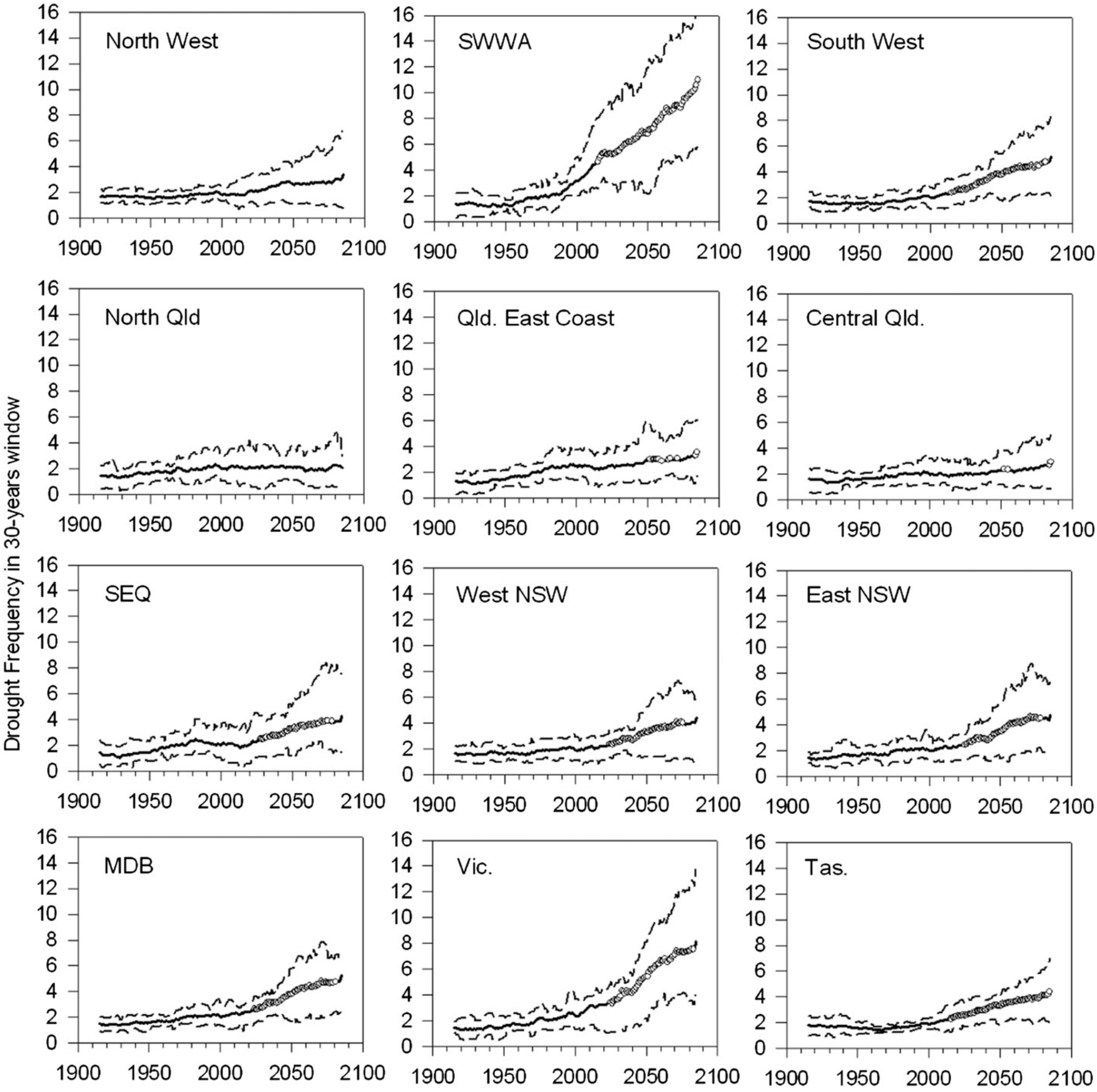

Fig. 5. Simulated drought frequency in a thirty-year window, based on 14 GCMs. The solid lines are the multi-model means while the dashed lines show the range between the lowest and highest 10% of model results. Circle symbols denote that the drought frequency at that particular 30-year period statistically differs (with $p < 0.1$) to the mean of drought frequency in 1990 (1975–2004).

To do this analysis, Monte Carlo techniques (repeated random sampling) were employed to stochastically generate probabilistic estimates of future drought extent and drought frequency. This random sampling was repeated 1000 times in year 2030, 2050, and 2070 to get an adequate sampling density over the projected range of uncertainty. Simulations samples were subsequently used to calculate cumulative distributions for future area affected by drought. We then used the IPCC's (2007) terminology for any likelihood of the outcome. For example, an outcome is *virtually certain* if its probability of occurrence is greater than 99%, and an outcome is *exceptionally unlikely* if its probability of occurrence is smaller than 1%.

3. Results

3.1. Estimated future variation in areal extent of drought

The percent area experiencing drought (as simulated by 14 climate models) for 1900–2100 is plotted in Fig. 3. This figure shows the multi-model mean and the range between the lowest and highest ten percent of multi-model results. In each region, about 5.6% of the area was affected by drought over the period 1900–2007. By 2030, the mean affected area indicates small change in most regions except SWWA (17.4%), South West (11.0%), Vic. (11.4%) and Tas (9.5%), and these are relatively consistent with results reported in Hennessy et al. (2008). By 2050, large increase in area can also be seen for SEQ (10.7%), West NSW (11.9%), East NSW (11.3%) and MDB (12.3%). By 2100, for most regions the mean area being doubled from about 5.6% to more than 10%. Exception is for North Qld region.

To examine whether the estimated future mean significantly differs to the estimated present (1900–2007) mean, we applied the *t*-test technique. The test returns the probability associated with a Student's *t*-Test to determine whether two samples (which in our case are the present and future period) are likely to have come from the same two underlying populations that have the same mean. From 2015 onward, the multi-model mean is assigned with a 'significance' symbol if the mean of drought extent at that particular period statistically differs to the mean of drought extent in 1900–2007. Apparently, the changes in mean area, relative to 1900–2007, are almost all statistically significant. The exceptions are the North Qld and Central Qld regions where the changes can be insignificant. In the North West, North Qld, Qld. East Coast, and Central Qld, the low and high scenarios are around 2–12% by 2100 whereas in other regions the low and high scenarios around 10–20% or more in 2100.

The probability of the most to the least likely drought extent in 2030, 2050 and 2070 are presented in Fig. 4. These cumulative probability graphs rank the data in the Monte Carlo simulation from the highest to the lowest value, and graph each point with its corresponding percentile. It indicates, for example, in 2030 there is around 18% probability that the drought extent in MDB will be similar to the present (i.e. about 5.6%) or less, suggesting the risk of increase in drought extent is relatively high. But by 2050 and 2070, the risk will be greater as there is only about 14% probability that the drought extent will remain the same as present or less in MDB. For North West, North Qld, and Central Qld, the chances of either increase or decrease in drought extent are almost even.

One can also use these results to examine the risk of a certain outcome. In this paper, the risks of having 10% or more drought affected area in 2030, 2050 and 2070 are presented in Table 2. Number of regions with *likely* risk (>66% probability) seems to increase with time. In 2030, the *likely* risk is shown for SWWA region only. By 2050, regions with *likely* risk will also include South West, Tas. and Vic., whereas by 2070 these will expand to MDB, West NSW and East NSW.

In each region, the risk of having 10% or more drought affected area is also greater throughout time. In SWWA a *likely* risk in 2030 will become a *very likely* risk in 2070 and in Central QLD a *very unlikely* risk in 2030 will become an *unlikely* risk in 2070. Exception is for North QLD where the risk of having 10% or more drought area will remain *unlikely* for the next 100 years.

3.2. Simulated future variation in frequency of drought

Fig. 5 depicts drought frequency in a thirty-year window period. This figure shows the multi-model mean and the range between the lowest and highest ten percent of multi-model results. From 2015 onward, the multi-model mean is assigned with a 'significance' symbol if the mean of drought frequency at that particular period statistically differs to the mean of drought frequency in 1990 (1975–2004). Increases in the frequency of drought occurrence are apparent, although for some regions the changes are not so clear. For North West, North Qld, Qld. East Coast and Central Qld, the future drought frequency in a thirty-year period is not significantly dissimilar from the frequency in the 1990 (1975–2004). The regions with possible significant increase include SWWA, South West, MDB and Vic where the mean drought frequency in the future differs significantly from that in 1990. The mean drought frequency for each of these regions is likely to be 4 or more by 2050. The low and high scenario suggests a frequency of around 2 to 6 or more. All of these indicate the possibility of more frequent drought event.

Cumulative probability of drought frequency in 2030, 2050 and 2070 as obtained from the Monte Carlo simulations are also constructed. Overall, they are relatively similar with those for the drought spatial extent shown in Fig. 4, namely: (a) the probability to have a certain outcome is greater with time, and (b) the chances of either increase or decrease in drought frequency are relatively even for North West, North Qld, and Central Qld (not shown here).

By 2030, there is no *likely* risk of having three drought events in a thirty-year period, hence a one in ten year drought event, except for SWWA region (Table 3). By 2050, there is a *likely* risk for MDB, South West, SWWA and Vic regions and there is *about as likely as not* or *unlikely* risk for the rest of the regions. By 2070, there is *very likely* risk for SWWA region and *likely* risk for MDB, East NSW, South West, Vic. and Tas.

Table 3
Likelihood to have a one in ten year drought event. (Likelihood scale are taken from IPCC (2007), i.e. *Very Likely* is >90% probability, *Likely* is >66% probability, *About as likely as not* is 33–66% probability, *Unlikely* is <33% probability, *Very unlikely* is <10% probability).

Region	2030	2050	2070
North QLD	Unlikely	Unlikely	Unlikely
Central QLD	Very Unlikely	Unlikely	About as likely as not
MDB	About as likely as not	Likely	Likely
East NSW	About as likely as not	About as likely as not	Likely
West NSW	Unlikely	About as likely as not	About as likely as not
NW	Unlikely	About as likely as not	About as likely as not
QLD Coast	Unlikely	About as likely as not	Unlikely
South West	About as likely as not	Likely	Likely
SEQ	About as likely as not	About as likely as not	About as likely as not
SWWA	Likely	Likely	Very likely
Tas	About as likely as not	About as likely as not	Likely
Vic	About as likely as not	Likely	Likely

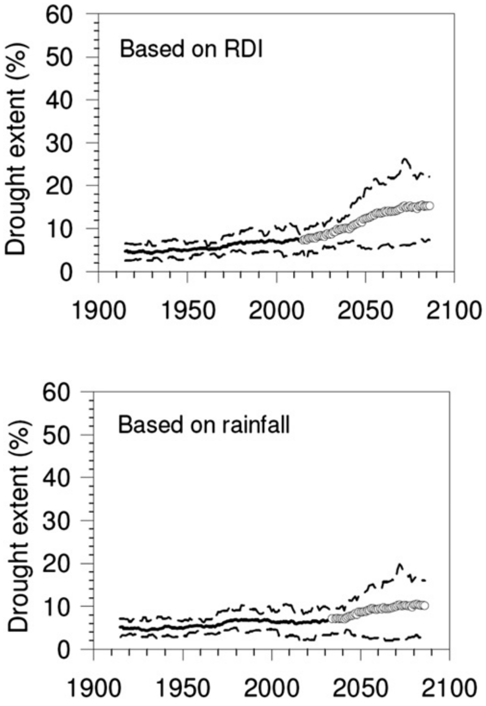

Fig. 6. Simulated percentage area affected by drought in the MDB region (based on 14 GCMs). The top and bottom panel is each based on the RDI and rainfall, respectively. The solid lines are the multi-model means while the dashed lines show the range between the lowest and highest 10% of model results, all smoothed by thirty-year averages. Circle symbols denote that the mean drought extent at that particular period statistically differs to the mean of drought extent in 1900–2007.

4. Discussions and conclusion

Drought is a regional phenomenon and given the size of Australia, the impacts of human induced climate change on drought may differ across regions. In this paper we have extended Hennessy et al.'s (2008) assessment on the impact of human induced climate change on the characteristics of Australian droughts. While the previous analysis was conducted for seven regions and for up to 2030, our study covered 12 regions and over a period of up to 2100. We used simulations from 14 GCMs to calculate a meteorological drought index called the Reconnaissance Drought Index (RDI) (Tsakiris et al., 2007). An advantage of this index is that it takes both rainfall and potential evapotranspiration (*PET*) into account.

Over Australia, a 3–5% decrease in future rainfall is projected (CSIRO and BoM, 2007). Also, a 1 °C warmer climate is expected, with potential evaporation may increase for 2–6% by 2030. The 2002–2003 severe drought experience tells us that the drought can be very severe, even though the rainfall may not be unusually low, likely because of warmer temperatures (Nicholls, 2004), suggesting that the relatively warm temperatures in the future can probably led to the drought being more severe. Thus, the inclusion of *PET* is necessary as meteorological drought indices based on rainfall alone may fail to include the important contribution of temperature via evaporation in Australia (Nicholls, 2004).

To illustrate the above point, Fig. 6 plots the percent area affected by drought based on the RDI and based on rainfall for the Murray-Darling Basin (MDB). In the future, the mean affected area based on the RDI are larger than that based on the rainfall alone. In 2030, it is 8.6% and 6.5% for the former and the latter. In 2050 it is 12.3% compared to 8.7%, and in 2070 it is 14.7% compared to 9.9%. Such a difference in mean is also found in other regions (not shown here) and it tends to increase with time. In the early 21st century, the projected change in drought extent based on the RDI is generally 1% higher than that based on the rainfall. By 2100, such difference are likely to be around 3% or more depending on the region of interest. Implications of this result is that future projections of drought may depend on the specific index of drought used and research to address the sensitivity of projections of future drought to index definition is further required.

Some of the results in this study are in agreement with those obtained in Hennessy et al.'s (2008) study, i.e. there is a likely increase in future drought areal extent and frequency for most regions. However, there are some additional insights that can be offered from this study. First, a further breakdown of a region with large spatial variation in climate trends provides a clearer separation as to what the future will look like for each of the sub-regions. As an illustration, the projections for Queensland (Qld) as a whole indicate little change in both affected area and in frequency. When the Qld region is further broken into a number of sub-regions, the projections indicate little change in North Qld but rather large change in the Qld East Coast, Central Qld and South East Qld regions. This result is relatively consistent with the observed trend in rainfall (BoM, 2009b), i.e. positive in North Qld and negative in other three sub-regions.

Second, we applied *t*-test technique to determine whether the estimated future mean significantly differs to the estimated present mean. Although increases in estimated future mean area and frequency are statistically significant for most regions there are some exceptions including the North West, North Qld, Qld East Coast and Central Qld regions.

Third, for some regions the likely change beyond 2030 is larger than that prior to 2030. For example, during 2030 the mean projections indicate little change in the affected area of the MDB (Hennessy et al., 2008 and this study), but after 2030 the mean projections indicate a larger change. The uncertainty in the projections also increases with time and is linked to the increase in the uncertainty of anthropogenic emission scenarios, especially beyond 2030 (IPCC, 2000). Through a Monte Carlo analysis, we quantify the likelihood to experience a given outcome. In 2030 it is only SWWA region that shows a *likely* (>66% probability) risk of having 10% or more drought affected area and a *likely* risk of having a one in ten year drought event. By 2050, this will include MDB, South West and Vic regions, while by 2070, this will also cover NSW, and Tas regions. For North Qld such a risk is *unlikely* (<33% probability) for the next 100 years.

According to the existing Australian drought policy, an exceptional circumstance (EC) can be declared when the event is rare, i.e. must not have occurred more than once on average in every 20–25 years (DAFF, 2008). The above findings imply that the existing trigger for EC declaration may not be appropriate in the future for some regions (e.g. SWWA) but still be appropriate for other regions (e.g. North Qld). If the existing criteria will still be used in the future, say by 2100, then EC would be likely be declared over twice the area in MDB, West NSW, East NSW, South West, Tas. and Vic.

Following the IPCC's (2007) suggestion, that GCM provide credible quantitative estimates of future climate change, all of these findings assume that the GCMs used in this study are reliable. For example, most of the GCMs considered in this study fairly well capture the observed mean patterns of mean sea-level pressure, temperature and rainfall over the whole Australian region (Suppiah et al., 2007; Watterson, 2008). Previous studies also suggest that most models reproduced the observed probability density functions of daily rainfall, minimum temperature and maximum temperature in each of the 12 regions being studied (Perkins et al., 2007); most GCMs can reproduce the observed spatial mean annual rainfall pattern across the Murray-Darling Basin and southeast

Australia and the observed daily rainfall distribution (Chiew et al., 2009); some GCMs can generally reproduce the observed spatial mean annual rainfall and *PET* across each of the 12 regions considered here even though there is a tendency for GCMs to underestimate and/or fail to simulate the observed inter-annual variability and/or long-term trend (Kirono and Kent, 2010); and that few GCMs are able to reproduce the observed changes in the Southern Hemisphere circulation related to the genesis of the storms that affect southern Australia (Frederiksen et al. 2010). Since many of the major droughts in Australia, particularly over eastern and northern Australia have been associated with El Niño Southern Oscillation (ENSO) events, it is crucial that GCMs to adequately simulate ENSO and its teleconnections with rainfall over a given region. A study by Cai et al. (2009) suggest that the majority of GCMs produce the observed teleconnection between Australian rainfall and the ENSO, even though the modelled teleconnection is relatively weaker than observation. As a broad assessment of the response of the selected 12 Australian region to the enhanced greenhouse gases, therefore, results from this work can be regarded as indication for the future. It is also worthnothing that the overall results of this study appear to be consistent with those projected globally (Dai, 2010).

The changes in the areal extent and frequency of droughts can have big implications on water management, agriculture industry and aquatic ecosystems. It is hoped that drought projections from this study can be useful information for long-term planning for some enterprises. The probability or likelihood of areal extent and drought frequency presented here can be subsequently considered in risk-based impact assessment and management, whereby thresholds for climatic changes and/or specific impacts are integrated with probability distributions for climate, environmental, and socioeconomic variables that influences system outcomes (Jones, 2001). This in turn will help for identifying robust decisions in the face of the inherent uncertainties associated with climate variability and anthropogenic climate change.

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