Climate analyses for south-west Western Australia

A report to the Australian Government from the CSIRO South-West Western Australia Sustainable Yields Project


July 2010
South-West Western Australia Sustainable Yields Project acknowledgments

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Director’s Foreword

Following the November 2006 Summit on the southern Murray-Darling Basin (MDB), the then Prime Minister and MDB state Premiers commissioned CSIRO to undertake an assessment of sustainable yields of surface and groundwater systems within the MDB. The project set an international benchmark for rigorous and detailed basin-scale assessment of the anticipated impacts of climate change, catchment development and increasing groundwater extraction on the availability and use of water resources.

On 26 March 2008, the Council of Australian Governments (COAG) agreed to expand the CSIRO assessments of sustainable yield so that, for the first time, Australia would have a comprehensive scientific assessment of water yield in all major water systems across the country. This would allow a consistent analytical framework for water policy decisions across the nation. The South-West Western Australia Sustainable Yields Project, together with allied projects for northern Australia and Tasmania, will provide a nation-wide expansion of the assessments.

The CSIRO South-West Western Australia Sustainable Yields Project is providing critical information on current and likely future water availability. This information will help governments, industry and communities consider the environmental, social and economic aspects of the sustainable use and management of the precious water assets of south-west Western Australia.

The projects are the first rigorous attempt for the regions to estimate the impacts of catchment development, changing groundwater extraction, climate variability and anticipated climate change, on water resources at a whole-of-region-scale, explicitly considering the connectivity of surface and groundwater systems. To do this, we are undertaking the most comprehensive hydrological modelling ever attempted for the region, using rainfall-runoff models, groundwater recharge models, river system models and groundwater models, and considering all upstream-downstream and surface-subsurface connections.

To deliver on the projects CSIRO is drawing on the scientific leadership and technical expertise of national and state government agencies in Queensland, Tasmania, the Northern Territory and Western Australia, as well as Australia’s leading industry consultants. The projects are dependent on the cooperative participation of over 50 government and private sector organisations. The projects have established a comprehensive but efficient process of internal and external quality assurance on all the work performed and all the results delivered, including advice from senior academic, industry and government experts.

The projects are led by the Water for a Healthy Country Flagship, a CSIRO-led research initiative established to deliver the science required for sustainable management of water resources in Australia. By building the capacity and capability required to deliver on this ambitious goal, the Flagship is ideally positioned to accept the challenge presented by this complex integrative project.

CSIRO has given the Sustainable Yields Projects its highest priority. It is in that context that I am very pleased and proud to commend this report to the Australian Government.

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Executive Summary

This report describes the three climate scenarios used for hydrological modelling in the CSIRO South-West Western Australia Sustainable Yields Project. The three climate scenarios are the historical climate (Scenario A), recent climate (Scenario B) and future ~2030 climate (Scenario C). All three comprise 33 years of daily rainfall and Morton’s wet areal evapotranspiration (APET) data, i.e. the same record length as the Scenario A baseline.

The Scenario A historical climate sequence is the baseline against which the other scenarios are compared. It comprises a 33 year series (1 January 1975 to 31 December 2007) of daily observed rainfall and calculated APET on a 0.05 x 0.05 degree (~ 5 km x 5 km) grid over the project area. The Scenario A mean annual rainfall, averaged over the entire project area, is 716 mm/year. Rainfall is winter-dominated (June-August mean of 363 mm), with a strong spatial gradient from the south-west coast to the north-east inland. Rainfall is highest in the south-west (mean annual rainfall of up to 1278 mm/year) and along the Darling Range, and lowest in the north-east (as low as 301 mm/year). The corresponding mean annual APET is 1427 mm/year, with a strong spatial gradient ranging from 1658 mm/year in the north to 1184 mm/year in the south. APET is highest in summer, averaging 547 mm for the December-February season, reducing to an average of just 180 mm for winter.

The Scenario B recent climate sequence is a 33-year (same length as Scenario A) climate series with the rainfall and APET characteristics of the past 11 years (1 January 1997 to 31 December 2007). It was used to assess future water availability should the climate in the next few decades prove to be similar to that of the most recent past. In general, the 1997 to 2007 climate has been drier than that of the 22 years preceding 1997. Scenario B mean annual rainfall is 694 mm/year, 3 percent less than Scenario A. This recent reduction in rainfall has greatest statistical significance across the central portion of the project area, including the catchments containing several dams of the Integrated Water Supply Scheme (IWSS). Correspondingly, APET has increased over much of the project area over the recent period by an average of 1 percent.

The Scenario C future climate sequences are used to assess the range of possible climate conditions as projected by 15 global climate models (GCMs) for the climate of ~2030 relative to ~1990. Forty-five future climate variants, each of 33 years of daily climate, were used. These future climate variants were produced by scaling the Scenario A climate sequence to represent ~2030 climate, using 15 GCMs and three global warming scenarios based on the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2007). The scaling was applied to the Scenario A sequence on a seasonal basis and importantly took into account projected changes in the daily rainfall intensity such that different daily rainfall amounts were scaled differently.

Whilst there are considerable differences in the range of projected rainfall change between the 15 GCMs, and hence uncertainty, when averaged across the project area all but one project a decrease in mean annual rainfall under ~2030 climate relative to ~1990. All 15 of the GCMs agree that rainfall will decrease in winter and spring with 12 also agreeing that rainfall will decrease in autumn. Summer projections were more variable, with eight GCMs projecting decreases and seven increases. All 15 GCMs project increased APET by ~2030.

Three of the 45 future climate scenarios that projected the 10th, 50th and 90th percentile annual rainfall across the project area were selected to represent dry (Cdry), median (Cmid) and wet (Cwet) future conditions. Averaged across the project area, mean annual rainfall changed declines by 1 percent under Scenario Cwet, by 8 percent under Scenario Cmid and by 17 percent under Scenario Cdry. Combined with a median projected increase in APET of 2 percent, the climate is projected to move into a more water-limited state than has been the case over the last 33 years.

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1 Introduction

1.1 Overview

This report is one in a series of reports from the CSIRO South-West Western Australia Sustainable Yields Project (a full list of reports is given in Appendix A). The project estimated current and future water yields in each non-saline catchment and aquifer in South-West Western Australia (SWWA, project area in Figure 1-1) considering climate change, development (farm dams, plantations, increased water abstractions) and surface–groundwater interactions, and compares yields to those required to meet current and expected future demand. Results from the project are reported separately for groundwater (CSIRO, 2009a), surface water (CSIRO, 2009b) and for the ability of the combined yields to meet environmental and consumptive requirements across SWWA (CSIRO, 2009c).

The purpose of this report is to present background information on the climatology of the region (Section 1.2), justification for using post-1974 as the historical climate baseline (Section 1.3), and to describe in detail the methodology used to produce the three climate scenarios provided as input to the hydrological modelling. The three climate scenarios encompass historical climate (Scenario A), recent climate (Scenario B) and projected future climate (Scenario C). All have 33 years of daily climate data, corresponding to the length of the historical climate scenario (Scenario A).

The climate sequences used for all modelling were 66 years long, with the first 33 years in common, as the historical sequence, followed by the 33 year scenario sequence. In this way all model runs generated projections from a common starting condition, being that which the catchments and groundwater systems were in on December 31st, 2007.

Scenario A is the 1975 to 2007 daily rainfall and Morton’s wet areal evapotranspiration (APET) baseline against which other scenarios are compared. It was derived from SILO Data Drill (Jeffrey et al., 2001) daily climate data (Figure 1-1), as described in Chapter 2. The post-1974 period was chosen as the baseline climate because of evidence that there has been a climate shift that has affected surface and groundwater hydrology since about that time (Section 1.3).

The recent climate scenario (Scenario B) is used to assess future water availability should the climate in the future prove to be similar to that of the most recent past. Climate data for the last eleven years of Scenario A (1997 to 2007) was repeated three times to give a single 33-year daily climate sequence, as presented in Chapter 3.

The future climate scenarios (Scenario C) are used to assess a range of plausible climate conditions representing the climate of 2030, encompassing 45 future climate variants, each with 33 years of daily climate sequences. The 45 variants were obtained by scaling the 1975 to 2007 Scenario A climate data to represent projected 2030 climates. The scaling factors were obtained from 15 global climate models (GCMs) for three global warming scenarios, representing low, medium and high (0.7, 1.0 and 1.3°C, respectively) global warming relative to the 1990 GCM climate baseline. The GCMs and scaling methods used to produce the 45 Scenario C series are described in Chapter 4.

The use of the climate scenario data for hydrological modelling is described in the respective groundwater and surface water reports (CSIRO, 2009a, b). The groundwater recharge models were calibrated using station, rather than gridded, climate inputs. The station data were scaled to produce 2030 climate scenario data using methodology consistent with that described in this report (W. Dawes, pers. comm. 2009).
Figure 1-1. Geographic scope of the project area and SILO climate data grid
1.2 Climatological overview

SWWA experiences a ‘Mediterranean’ type climate with higher winter rainfalls than west coastal regions of other continents at comparable latitudes, and an intense summer drought. Up to 80 percent of annual rainfall falls in the winter half-year from May to October. The majority of winter rainfall is produced by mid-latitude (30º to 55ºS) frontal systems. A distinguishing feature of these frontal systems is their rapid northward spread and increase in intensity throughout May, and their slower southward retreat and decrease during August to October. Rainfall amounts are higher and the wet season is longer than similarly exposed regions in other continents owing to the advection of moist air by strong westerly winds, influenced by the presence of a warm southward flowing offshore current (Leeuwin Current) and the modest orographic uplift provided by the Darling Scarp, of 250 to 300 m elevation running parallel with the west coast for over 300 km (Gentilli, 1972).

The seasonal cycle in the procession of troughs, lows and high produces the marked seasonality and strong south-west to north-east gradient in SWWA rainfall. In summer (December to February), the frontal systems are too far south to affect the region. By April the northward extension of fronts to the west of the region begins to occur with increasing frequency. By late April/early May, the jet stream flows faster and mostly over southern Australia, the westerly circulation becomes more intense, and fronts come much closer to the southern coast. Well-developed fronts bring the first widespread rainfall to SWWA. Through winter (June to August), the fronts move increasingly northwards to reach their maximum northerly extent in July. By August, the fronts begin their southward movement and the rainfall progressively reduces (Gentilli, 1972).

1.3 Choice of post-1974 as the historical climate period

SWWA winter rainfall was previously considered the most consistent and reliable in Australia, with low inter-annual variability relative to any other region of the continent (Nicholls et al., 1997). However during the period post-1974 the region has experienced a decline in the May to July rainfall (Figure 1-2) of 10 to 15 percent, resulting in rainfall isohyets moving towards the south-west corner (Bates et al., 2008a). The rainfall decline has contributed to a severe reduction in runoff, with an average change in runoff of 2 to 3 percent for each 1 percent change in rainfall (Fu et al., 2007).

There have been several studies investigating the climate variability of the SWWA region in recent decades, under the impetus of government and water industry concern over the declining rainfall and inflow into Perth’s water supply dams. A leading example is the Indian Ocean Climate Initiative (IOCI), a research partnership between the West Australian Government, the Commonwealth Bureau of Meteorology and CSIRO, that was formed to address these concerns and the need for greater understanding of the region’s likely future rainfall trends (IOCI, 2006, Bates et al., 2008a).

Figure 1-2. Time series of rainfall in south-west Western Australia. Means for the periods 1900 to 1974 and 1975 to 2008 are represented by horizontal lines. The thicker solid lines are 11-year moving averages (Bureau of Meteorology data for the IOCI region south-west of a line joining 30ºS, 115ºE and 35ºS, 120ºE. Bates et al., 2008a)
Characterising climate on the basis of a 33 year sequence is statistically tenuous; however, there is a significant body of literature describing how the post-1974 climate of SWWA is different to that of the earlier period of record. It is especially clear that runoff generation has declined since 1975, and that this change occurred apparently very suddenly at this time (Petrone et al., 2010). This section summarises this literature to address concerns that characterising historical climate using only post-1974 data may not be scientifically justifiable.

Gallant et al. (2007) reviewed recent research investigating observed Australian rainfall trends, citing 10 studies published since 1992 that have included an analysis of SWWA rainfall. These studies found:

- decreases in SWWA winter rainfall since the 1970s (Nicholls and Lavery, 1992);
- decrease in southern winter half-year rainfall of 18mm/century for 1890-1992 (Lavery et al., 1997);
- decrease in total and heavy rainfall in the winter half-year in SWWA (Suppiah and Hennessy, 1998);
- total and heavy rainfall decreases and declines in rain days in SWWA (Hennessy et al., 1999);
- decreases in autumn rainfall for south-west Australian quadrant (Plummer et al., 1999);
- decreases in total rainfall, rain days and extreme rainfall in SWWA (Haylock and Nicholls, 2000);
- decreases in extreme intensity and frequency in SWWA (Manton et al., 2001);
- increases in total rainfall over much of Australia except SWWA (Collins and Della-Marta, 2002);
- decreases in SWWA rainfall during the winter half-year (Smith, 2004); and
- 1951-2005: strong decreases in southwest winter rainfall (Alexander et al., 2007).

Gallant et al. (2007) concluded ‘large decreases for both seasonal and annual rainfall [means and extremes] since the 1950s in the … southwest region … primarily due to the southward shift in rain-bearing synoptic circulations since the 1970s, which has been partly attributed to natural variability, the enhanced greenhouse effect and stratospheric ozone depletion (IOCI, 2002; Hope et al., 2006).’

IOCI’s detailed investigations (IOCI, 2006; Bates et al., 2008a) also concluded that the enhanced greenhouse effect has contributed to the rainfall decrease experienced since the mid 1970s. However definitive attribution of the relative contribution of climate change versus natural climate variability is still an active area of research.

There is also increasing evidence that large-scale atmospheric circulation changes occurred in the late 1960s to mid-1970s on a global and hemispherical scale (e.g. Baines and Folland, 2007; Frederiksen and Frederiksen, 2007). These circulation and resultant storm track changes have resulted in declines in winter rainfall amounts and inter-annual variability. Li et al. (2005) examined station extreme daily rainfall, finding 1965 to be a change point for winter rainfall reduction. The distinct separation between the distributions of 1930 to 1965 versus 1966 to 2001 extreme daily rainfall is noticeably evident in their analysis (see Figure 6 in Li et al., 2005).

Frederiksen and Frederiksen, 2007) concluded that the post 1974 rainfall reduction over SWWA has been caused by large-scale changes to southern hemisphere circulation resulting in a reduction in the intensity of cyclogenesis (i.e. fewer and weaker low pressure systems and associated cold fronts) with storms being deflected southward. They suggest these observed changes are physically consistent with expected changes due to increased anthropogenic greenhouse forcing. Correspondingly, a weakened Leeuwin Current (Feng et al., 2004) has been linked to a weakening in the Indonesian Throughflow caused by a 1976 ‘shift’ in Pacific Ocean sea surface temperatures (Wainwright et al., 2008). Two recent studies have concluded that these changes are likely due to the enhanced greenhouse effect, rather than natural multi-decadal variability (Alory et al., 2007; Vecchi et al., 2006).

Comparison between 1975 to 1994 and 1949 to 1968 synoptic climatology has determined that a 20 percent decrease in subtropical jet strength over Australia has reduced storm development over SWWA (IOCI, 2006). Hope et al., (2006) concluded that both decreases in the frequencies and intensities of early-winter rain-bearing synoptic systems accounted for 80 percent of the observed June to July rainfall declines.

Cai and Cowan (2007) compared observed rainfall to an ensemble of 71 climate model runs and determined that 50 percent of the SWWA winter rainfall decline was attributable to the enhanced greenhouse effect, with factors such as
multidecadal variability accounting for the other 50 percent. They concluded ‘One of the most consistent results from climate models is that as CO₂ continues to increase, SWWA rainfall will continue to decrease … If multidecadal variability plays a significant part in the observed rainfall reduction, it means that there will be a period in which CO₂-induced reduction will be temporally mitigated by the opposite phase of variability. On the other hand, it also means that CO₂ and multidecadal variability could conspire to produce an even greater rate of rainfall reduction in the future.’

Summarising these and other IOCI research findings, Bates et al., 2008a) highlighted the consistencies between baroclinic instability theory (Frederiksen and Frederiksen, 2007), self-organised maps (Hope et al., 2006) and statistical downscaling (Charles et al., 2004) applied across hemispheric, regional and local scales, respectively. Bates et al., 2008a) concluded that the strong consistencies between these three methods were evidence that the observed mid-1970s rainfall decline was, at least in part, attributable to changes in large scale circulation and synoptic activity. As will be seen in Chapter 4, the observed rainfall declines are consistent with the majority of GCM-derived scenarios for a drier projected 2030 climate.

Given the consistency of such findings, it is evident that the mid 1970s stand out as a period when SWWA rainfall (totals and extremes) declined. Given the significant contribution of studies showing that SWWA climate changed in the mid-1970s, and the corresponding consistency with climate change projections of further drying (Bates et al., 2008b), it is justifiable to accept 1975 to 2007 as a climate baseline for this project.

There is no expectation of a return to the wetter conditions of pre-1975 in the literature. Although natural variability will result in sequences of both wet and dry years, the overall evidence is that SWAA is in a different climate regime to that pre-1975 and that climate change projections are consistent with observed trends. Therefore, the 33-year period from 1 January 1975 until 31 December 2007 has been chosen as the historical climate series given climatologists and water planners judgement that there was a significant climate shift in the mid-1970s that makes using earlier climate data unrepresentative.

1.4 References


CSIRO (2009a) Groundwater yields in south-west Western Australia. A report to the Australian Government from the CSIRO South-West Western Australia Sustainable Yields Project. CSIRO Water for a Healthy Country Flagship, Australia.

CSIRO (2009b) Surface water yields in south-west Western Australia. A report to the Australian Government from the CSIRO South-West Western Australia Sustainable Yields Project. CSIRO Water for a Healthy Country Flagship, Australia.

CSIRO (2009c) Water yields and demands in south-west Western Australia. A report to the Australian Government from the CSIRO South-West Western Australia Sustainable Yields Project. CSIRO Water for a Healthy Country Flagship, Australia.


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2 Historical climate scenario data (Scenario A)

2.1 Gridded historical climate data

Historical daily climate data from 1 January 1975 to 31 December 2007, on 0.05° x 0.05° (~ 5 km x 5 km) grid cells, were used to produce Scenario A for the South-West Western Australia Sustainable Yields Project modelling area. The source of this data was the SILO Data Drill of the Queensland Government Department of Environment and Resource Management (<http://www.longpaddock.qld.gov.au/silo> and Jeffrey et al., 2001). SILO Data Drill data prior to the Scenario A period, as well as individual station data from the SILO Patched Point Dataset, were also used in the analysis presented.

The SILO Data Drill provides gridded daily climate data interpolated from point measurements made by the Bureau of Meteorology, Commonwealth of Australia. The variables used are rainfall and, for the calculation of daily Morton’s wet areal evapotranspiration (APET), total daily incoming shortwave solar radiation (Rs), daily mean vapour pressure (ea), maximum air temperature (Tmax) and minimum air temperature (Tmin). As point observations of rainfall are highly discontinuous in space and time, interpolation of rainfall is particularly challenging. To maximise the accuracy of the SILO Data Drill rainfall (Jeffrey, 2006) implemented an interpolation strategy where a rainfall normalisation parameter was interpolated with ordinary kriging and, after removal of stations with large residuals, the revised dataset was re-interpolated and the normalisation reversed. Surfaces for the other climatic variables were interpolated using a tri-variate thin plate spline as a function of longitude, latitude and elevation (Jeffrey et al., 2001).

The observations used as input to the gridded data have been quality checked by the Bureau of Meteorology and have been subject to error checking by the Queensland Department of Environment and Resource Management (Jeffrey et al., 2001). Nevertheless, it is inevitable that errors remain in the data and the interpolation routines can introduce further errors. In general, the data accuracy is expected to be higher in areas where the observation density is high relative to the climate gradients. Although rainfall is more spatially variable than the other climate variables, this is offset to some extent by the generally higher density of the rainfall observation network (e.g. compare Figure 2-1 for rainfall with Figure 2-3 for temperature).

An index that assesses spatial and temporal dynamics was developed to provide a guide to confidence in the data used in the construction of Scenario A. On a decadal basis, both the distance between each grid cell to the nearest ten Bureau of Meteorology stations and the completeness of the records of these ten closest stations were combined into a single metric. This ‘distance-completeness’ index is dimensionless and scaled consistently over the entire record, providing a quantitative measure of the spatio-temporal quality of the underpinning observation network. The completeness of record for each decade of the nearest ten stations to each grid cell was weighted using a Gaussian distance function:

$$w = \exp\left(-\frac{d}{h}\right)^2$$

where $w$ is the vector of weighting factors for the nearest ten stations; $d$ is a vector of the distance between the grid cell and the nearest ten stations and $h$ is the ‘bandwidth’, which for this case was set to approximately 250 km (defined as fifty 0.05° grid cells). The choice of bandwidth was somewhat subjective, aiming to reasonably account for the zone of influence around a recording station, i.e. we assume that any grid cell greater than 250km from a station would have minimal input from that station. Whilst results would be sensitive to choice of bandwidth, the overall and relative patterns would be similar.

The network of Bureau of Meteorology stations recording daily rainfall are summarised, by decade, in Figure 2-1. Figure 2-2 shows the corresponding distance-completeness index for the SILO gridded rainfall derived from these stations. The analysis reveals that coverage of stations recording rainfall is plentiful and consistent across the decades of Scenario A (1975 to 2007).
Figure 2-1. Coverage and completeness of Bureau of Meteorology stations recording daily rainfall for the decades 1960 to 2000. The decade labelled 1960 is defined as the period 1 January 1960 to 31 December 1969, and so on.
Whilst characterising rainfall confidence is of primary interest, due to its influence on daily rainfall-runoff and groundwater recharge modelling, the confidence in measurement coverage of factors affecting APET is also significant. As an example, the decadal station network and distance-completeness index for maximum daily air temperature are shown (Figure 2-3 and Figure 2-4 respectively). Over time, the distance-completeness index for maximum daily air temperature has generally increased as the density of Bureau of Meteorology stations recording temperature has increased. The distance-completeness index for maximum daily air temperature is sparser than that of rainfall, but there is coverage over most of the region for the Scenario A period and given that temperature gradients are a lot smoother than rainfall gradients this does not necessarily imply that the station network for temperature is deficient relative to that for rainfall.
Thus the contrast between rainfall and temperature distance-completeness reflects the fact that the Bureau of Meteorology has established and maintains a denser rainfall observation network than the air temperature observation network (e.g. compare Figure 2-1 to Figure 2-3) because of the importance and spatial inhomogeneity of rainfall relative to that of air temperature.

Figure 2-3. Coverage and completeness of Bureau of Meteorology stations recording daily maximum air temperature for the decades 1960 to 2000. The decade labelled 1960 is defined as the period 1 January 1960 to 31 December 1969, and so on.
Historical climate scenario data (Scenario A)

Figure 2-4. Distance-completeness index for daily maximum air temperature for the decades 1960 to 2000. A value of 1.0 means the location is at a station with a complete temperature record, and the index decreases with distance away from stations and with decreasing completeness of temperature record. The decade labelled 1960 is defined as the period 1 January 1960 to 31 December 1969, and so on.
2.2 Rainfall

Figure 2-5 shows the mean annual, summer (December to February), autumn (March to May), winter (June to August) and spring (September to November) rainfall across SWWA under Scenario A from 1975 to 2007. Mean rainfall across the project area is 716 mm/year with a clear south-west to north-east rainfall gradient, with rainfall highest in the south-west and along the Darling Scarp (maximum mean annual rainfall of 1278 mm/year), and lowest in the north-east (minimum mean annual rainfall of 301 mm/year). The winter dominance and summer drought are strongly evident.

Figure 2-6 shows corresponding 1975 to 2007 linear trends in annual and seasonal rainfall, i.e. the mean rate of change per year for the 1975 to 2007 period. Here and elsewhere in this report, linear trends were calculated as the slope of the line of best fit through the annual and seasonal time-series. Figure 2-7 presents the statistical significance (p-values) of these trends. Statistical significance of the slope of trends has been determined using a standard t-test. Overall only small isolated areas have statistically significant trends. These, and the trends and significance for rain-days and intensity presented later, should be interpreted with caution because they are based on data interpolated from an observational network that changes as stations open and close. Thus small or isolated areas of change are likely to be the result of interpolation inconsistencies rather than actual underlying trends in the climate. Longer term trends (i.e. prior to 1975) were not investigated as there are many published studies referring to the decline in SWWA rainfall that occurred around 1975, as was summarised in Section 1.3.

The mean, trend and trend significance of the number of rain days (defined as a grid with a daily rainfall greater than zero) and rainfall intensity (i.e. rainfall amount on rain days) are shown in Figure 2-8 to Figure 2-13. The interpretation of rain-days for gridded rainfall requires caution. It is sensitive to the density of observations and, as it only takes one station to record rainfall for surrounding grids to have an interpolated rainfall amount, is likely to be an overestimate of the actual number of rain days. The mean number of rain days has a strong north to south gradient, is greatest along the south coast and is winter dominated (Figure 2-8). The mean rainfall intensity is also winter-dominated, but has a spatial distribution more influenced by the orographic effect of the Darling Scarp, as evident particularly in winter but also in spring and autumn (Figure 2-11). The trends in rain day frequency, although small, show most of the region is experiencing a decreasing trend with small pockets of increase (Figure 2-9) and correspondingly the trends in intensity are small and localised (Figure 2-12). The rain day frequency shows more areas of significant trend (Figure 2-10) than the corresponding rain intensity trend significance (Figure 2-13). This indicates that significant trends in the number of rain days are relatively more widespread than those for rainfall intensity over the post 1974 period.
Figure 2-5. Spatial distribution across the project area of mean annual and seasonal historical (1975 to 2007) rainfall.
Figure 2-6. Spatial distribution across the project area of trends in mean annual and seasonal historical (1975 to 2007) rainfall.
Figure 2-7. Spatial distribution across the project area of significance of trends in mean annual and seasonal historical (1975 to 2007) rainfall

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Figure 2-8. Spatial distribution across the project area of mean annual and seasonal historical (1975 to 2007) rain days.
Figure 2-9. Spatial distribution across the project area of trend in mean annual and seasonal historical (1975 to 2007) rain days.
Figure 2-10. Spatial distribution across the project area of significance of trends in mean annual and seasonal historical (1975 to 2007) rain days.
Figure 2-11. Spatial distribution across the project area of mean annual and seasonal historical (1975 to 2007) rain intensity.
Figure 2-12. Spatial distribution across the project area of trend in mean annual and seasonal historical (1975 to 2007) rain intensity.
Ten representative stations were selected to represent spatial variation in rainfall trends across the project area. The ten stations provide a north to south transect, including both coastal and inland locations (Figure 2-14). They were selected based on their high quality station data with minimal infilling. Station data, rather than grid values, were used in order to remove the possibility that trends were influenced by variations in the quality of the interpolated data due to non-meteorological factors such as stations opening or closing. The time-series of annual and seasonal rainfall for these stations are shown in Figure 2-12. Data are presented from 1960, in order to show examples of wetter years prior to the Scenario A period. Inclusion of this earlier wetter period results in all stations having negative linear trends in their annual
and winter rainfalls (Table 2-1). The coefficient of variation of annual and seasonal rainfall (CV in Table 2-1) tends to decrease from north to south and be highest for summer and lowest for winter. The significance of the linear trends are presented as P-values, which can be compared to any significance level of choice (Table 2-1). For example Geraldton, Perth Airport, Cape Leeuwin, Donnybrook, Dwellingup and Cowaramup all have annual trends significant at the 5 percent level (i.e. P-values less than 0.05). Virtually all winter trends are significant at the 10 percent level, with the exception of Strawberry North with a P-value of 0.104.

Figure 2-14. Locations of the ten climate stations reported in Figure 2-15. The shaded region, adopted following the Indian Ocean Climate Initiative, is used to produce the mean rainfall in south-west Western Australia shown in Figure 1-2.
Historical climate scenario data (Scenario A)
Figure 2-15. Time series of annual and seasonal rainfall for ten climate stations (locations shown in Figure 2-14). Lines are annual and seasonal eleven-year moving averages.
Table 2-1. Observed 1960 to 2007 rainfall statistics for ten representative stations

<table>
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<tr>
<th>Station</th>
<th>Mean (mm)</th>
<th>CV</th>
<th>Trend (mm/y)</th>
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</table>
2.3 Morton’s wet areal evapotranspiration

In addition to daily rainfall, Morton’s wet environment areal evapotranspiration (APET) daily series were produced for input into surface water and groundwater modelling. APET is defined as the evapotranspiration that would take place if there was unlimited water supply, from an area large enough that the effects of any upwind boundary transitions are negligible, with local variations integrated to an areal average. The APET is therefore conceptually the upper limit to actual evapotranspiration estimates in the surface water and groundwater modelling.

Hydrological modelling results are much less sensitive to errors in APET estimation than to errors in rainfall data. It is also easier to provide reliable APET data than for rainfall because APET is relatively homogeneous spatially and temporally. The daily APET was calculated from 0.05° x 0.05° climate data from the SILO Data Drill (temperature; relative humidity, calculated as actual vapour pressure divided by saturation vapour pressure; and incoming solar radiation) using Morton’s wet environment evapotranspiration algorithms (<http://www.bom.gov.au/averages>; Morton, 1983; Chiew and Leahy, 2003).

Figure 2-16 to Figure 2-19 show the mean annual and seasonal SWWA air temperature, relative humidity, incoming solar radiation and calculated APET, respectively. The mean air temperature (Figure 2-16) is the average of the daily maximum and minimum temperatures. Its spatial distribution has a strong north to south gradient, with a less pronounced gradient with distance from the coast. Coastal moderation effects are particularly evident in winter. Relative humidity similarly has a strong north to south gradient and distance from coast gradient, as expected given that onshore flow is the major source of atmospheric moisture (Figure 2-17). Solar radiation (Figure 2-18), in contrast, shows predominantly a north to south variation with little coastal influence.

The APET surfaces (calculated from these data using the method outlined in Appendix B) have a mean annual APET averaged across the project area of 1427 mm/year, ranging from 1658 mm/year in the north to 1184 mm/year in the south. The spatial and seasonal variations are shown in Figure 2-19, emphasising the strong north to south gradient, as expected given the corresponding gradients in the contributing variables. The trend in APET is shown in Figure 2-20 with the corresponding trend significance in Figure 2-21. A large proportion of the study area is shown to have experienced a significant increasing trend in spring, including most of the northern and south-eastern portions of the project area with smaller areas of significant trend seen in winter, predominantly along the north-west coast and in the south-east. However, as with rainfall discussed earlier, these trends should be interpreted with caution because they are based on data interpolated from an observational network that changes as stations open and close and more so given the sparser observing network for the variables used in APET calculation. Thus many of these changes are likely to be the result of interpolation inconsistencies rather than actual underlying trends in the climate. Also, as Morton’s wet areal evapotranspiration formulation does not take into account changes in wind speed, and noting observed wind field changes (McVicar et al., 2008), Donohue et al. (2009) caution against placing too much confidence in such trends.

Figure 2-22 shows the difference between mean rainfall (Figure 2-5) and APET (Figure 2-19). This highlights the extent to which the region is water limited, with effective rainfall (i.e. rainfall greater than APET) in winter only. The corresponding trend in effective rainfall is shown in Figure 2-23, showing the dominance of a drying trend across most of the region. Only small areas have trends that are statistically significant (Figure 2-24), and the caveats related to observing station changes apply equally here also. It is important to remember these are post-1974 trends and so are in addition to the step change to drier conditions that occurred around 1975 (as discussed in Section 1.3).
Figure 2-16. Spatial distribution across the project area of mean annual and seasonal historical (1975 to 2007) temperature
Figure 2-17. Spatial distribution across the project area of mean annual and seasonal historical (1975 to 2007) relative humidity.
Figure 2-18. Spatial distribution across the project area of mean annual and seasonal historical (1975 to 2007) incoming solar radiation.
Figure 2-19. Spatial distribution across the project area of mean annual and seasonal historical (1975 to 2007) Morton’s wet areal evapotranspiration.
Historical climate scenario data (Scenario A)

Figure 2-20. Spatial distribution across the project area of trends in mean annual and seasonal historical (1975 to 2007) Morton’s wet areal evapotranspiration.
Figure 2-21. Spatial distribution across the project area of significance of trends in mean annual and seasonal historical (1975 to 2007) Morton’s wet areal evapotranspiration.
Figure 2-22. Spatial distribution across the project area of mean annual and seasonal historical (1975 to 2007) rainfall deficit (rainfall minus Morton’s wet areal evapotranspiration).
Figure 2-23. Spatial distribution across the project area of trend in mean annual and seasonal historical (1975 to 2007) rainfall deficit (rainfall minus Morton’s wet areal evapotranspiration)
Figure 2-24. Spatial distribution across the project area of significance of trends in mean annual and seasonal historical (1975 to 2007) rainfall deficit (rainfall minus Morton’s wet areal evapotranspiration).
2.4 References


3 Recent climate scenario data (Scenario B)

3.1 Method

The recent climate scenario (Scenario B) is a 33-year daily climate sequence used to assess future water availability should the climate in the future prove similar to that of the past 11 years (1997 to 2007). It is recognised that 11 years is too short to adequately capture the variability within a climate sequence, however, there is some evidence that this period is different from previous decades and hence it is used as a scenario for hydrological modelling comparisons with results from Scenario A and C. Scenario B was generated by repeating the last 11 years (1997 to 2007) of Scenario A daily rainfall and Morton’s wet areal evapotranspiration (APET) three times, to produce a 33-year sequence of the same length as Scenario A.

3.2 Comparison with historical data

The mean annual rainfall averaged over the South-West Western Australia Sustainable Yields project area under Scenario B is 694 mm/year, which is 3 percent less than the full Scenario A period (1975 to 2007) mean of 716 mm/year. Correspondingly, the mean annual APET is 1437 mm/year for the Scenario B period compared to 1427 mm/year for Scenario A, an increase of nearly 1 percent.

Figure 3-1(a) shows the percentage difference, and (b) the absolute difference, between the mean annual rainfall of the Scenario B (1997 to 2007) and the period 1975 to 1996. An overall drying trend is evident over much of the area, with some smaller areas of increase in the southern areas. Figure 3-1(c) shows where these changes are statistically significant. Relatively few annual rainfall decreases are statistically significant (e.g. Peel-Harvey area) and none of the rainfall increases are statistically significant. The Scenario B APET changes relative to the prior 22 years are predominantly increases (Figure 3-2). A large proportion of the northern part of the project area (Northern Perth Basin) has experienced a statistically significant increase in APET, as have smaller areas along the south coast.

The statistical significance p-values in Figure 3-1(c) and Figure 3-2(c) were determined using a two-sided, non-overlapping two-sample t-test with equal (pooled) variances across the two time periods. The reported changes and their statistical significance should only be interpreted as general indications of possible trends because they are based on data interpolated from an observational network that changes as stations open and close. Thus small or isolated areas of change are likely to be the result of interpolation inconsistencies rather than actual underlying trends. For example, the APET increase in the north-west region is likely to be a spurious result of a station recording inputs used in APET calculation opening or closing on the coast.
Figure 3-1. (a) Percentage difference, (b) absolute difference (mm); and (c) statistical difference (P-value) between mean annual rainfall for 1997 to 2007 (Scenario B) and 1975 to 1996

Figure 3-2. (a) Percentage difference, (b) absolute difference (mm) and (c) statistical difference (P-value) between mean annual APET for 1997 to 2007 (Scenario B) and 1975 to 1996
4 Future climate scenario data (Scenario C)

4.1 Global warming

This section summarises the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) global warming projections used to derive the scenarios used in the project. A comprehensive presentation of the current state of knowledge of global and regional climate change can be found in the IPCC AR4 reports (IPCC, 2007). A recently released report (CSIRO and Australian Bureau of Meteorology, 2007) provides greater detail on climate projections and drivers of climate variability and trends for Australia.

International research reviewed by the IPCC (2007) indicates a warming world is leading to significant changes in regional climate. Eleven of the twelve years to 2007 rank among the twelve warmest years in the post-1850 instrumental record of global surface temperature, with a linear global warming trend over the last 50 years of about 0.13°C per decade (IPCC, 2007) increasing to 0.18°C per decade since the mid 1970s (WMO, 2006). The global average temperature over the last 150 years is shown in Figure 4-1. Based on many lines of evidence, including the widespread warming of the atmosphere and ocean, together with ice mass loss, the IPCC (2007) concludes that most of the observed increase in global average temperature since the mid-20th century is very likely attributable to the observed increase in anthropogenic greenhouse gas concentrations.

Because of the highly complex and nonlinear nature of the global climate system, it is inappropriate to extrapolate observed trends to predict future conditions. Increasing concentrations of greenhouse gases affect the Earth’s radiation balance, with the balance between incoming solar radiation and outgoing heat radiation determining the Earth’s average temperature. Radiative forcing is the term given to an externally imposed change in the radiation balance, such as changes in atmospheric concentrations of greenhouse gases. Carbon dioxide dominates the radiative forcing, producing a warming effect. To estimate future climate change, scientists have developed emission scenarios for greenhouse gases and aerosols that account for future human activities such as energy generation, transport, agriculture, land clearing and industrial processes. The IPCC Special Report on Emission Scenarios (SRES) (IPCC, 2000) developed 40 greenhouse gas and sulphate aerosol emission scenarios for the 21st Century that combined a variety of assumptions about demographic, economic and technological factors likely to influence future emissions. Each scenario represented a variation within one of four ‘storylines’ (A1, A2, B1 and B2, see Table 4-1) giving projected carbon dioxide, methane, nitrous oxide and sulphate aerosol emissions until 2100.
Table 4.1. Storylines from the Intergovernmental Panel on Climate Change (2000) Special Report on Emission Scenarios (SRES)

A1. The A1 storyline describes a future world of very rapid economic growth, a global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1 storyline develops into three scenario groups that describe alternative directions of technological change in the energy system. They are distinguished by their technological emphasis: fossil intensive (A1FI), non-fossil energy sources and technologies (A1T), or a balance across all sources (A1B) (where balanced is defined as not relying too heavily on one particular energy source, on the assumption that similar improvement rates apply to all energy supply and end use technologies).

A2. The A2 storyline describes a very heterogeneous world. The underlying theme is self reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing population. Economic development is primarily regionally oriented and per capita economic growth and technological change more fragmented and slower than other storylines.

B1. The B1 storyline describes a convergent world with the same global population, that peaks in mid-century and declines thereafter, as in the A1 storyline, but with rapid change in economic structures toward a service and information economy, with reductions in material intensity and the introduction of clean and resource efficient technologies. The emphasis is on global solutions to economic, social and environmental sustainability, including improved equity, but without additional climate initiatives.

B2. The B2 storyline describes a world in which the emphasis is on local solutions to economic, social and environmental sustainability. It is a world with continuously increasing global population, at a rate lower than A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines. While the scenario is also oriented towards environmental protection and social equity, it focuses on local and regional levels.

The IPCC AR4 Working Group 1 Summary for Policymakers (IPCC, 2007) provides estimates of global warming for the year 2100 for six emission scenarios (A1FI, A1T, A1B, A2, B1, B2). The range of projected global warming was based on results from 23 global climate models (GCMs) that are subject to observational constraints and consider important uncertainties, including the possibility of significant further amplification of climate change due to carbon cycle feedbacks. The lower end of the projected warming range corresponds to the mean warming minus 40 percent, while the upper end of the range is the mean warming plus 60 percent, resulting in a range of global warming by 2100 of 1.1 to 6.4°C.

Equivalent global warming values for 2030 are not provided by the IPCC, so values required for this project and for broader Australian projections for 2030 have been derived in a way consistent with the approach used by the IPCC for 2100. The result is three projections of the temperature change by ~2030 relative to ~1990: a low global warming of...
0.7°C (low end of SRES B1), medium global warming of 1°C (average of the low and high global warming scenarios), and high global warming of 1.3°C (high end of SRES A1T).

4.2 Changes in regional climate variables

Regional climate change resulting from global warming is best assessed using GCM simulations. There have been rapid improvements in climate modelling over the last few decades and GCM results are continuously being verified against observational data. However, although GCMs have reasonable skill in simulating past climate and therefore providing some confidence in their use for climate projection, the range of future climate projections across GCMs is often the largest source of uncertainty at the regional scale (IPCC, 2007).

To account for the uncertainty in GCM simulation of future climate across SWWA, archived results from 15 of the 23 IPCC AR4 GCMs were used in this project. The GCM data were obtained from the Program for Climate Model Diagnosis and Intercomparison (PCMDI) website (<http://www-pcmdi.llnl.gov>). Data from only 15 of the 23 GCMs was used because daily future climate series, required to scale daily rainfall series, were only readily available for 15 GCMs. Australian climate change projections used data from all 23 GCMs and weighted GCMs according to their ability to reproduce observed historical climate (rainfall, temperature and sea level pressure) across Australia (CSIRO and Bureau of Meteorology, 2007). Weights varied from 0.3 to 0.7, with the weights for the 15 GCMs used in this project all above 0.5. In addition, we compare all 15 GCMs to a sub-set of nine selected as better performing according to metrics assessing their reproduction of current climate over the Australian region (see Section 4.4). The aim is to determine whether more consistent projections (i.e. a reduced uncertainty range) are obtained using GCMs judged to be better performing.

The 15 GCMs used are listed in Table 4-2. Monthly climate data were available for these GCMs for the period 1870 to 2100. For each GCM, season, and GCM grid point, the simulated rainfall (or climate variable used in Morton’s wet areal evapotranspiration calculation, i.e. temperature, solar radiation and relative humidity) was plotted against simulated global average temperature and the slope of the linear regression fitted through these data points gave the change in rainfall (or other climate variable) per degree of global warming. Combined results from many runs for the same GCM were used (generally all A1B simulations for rainfall and temperature, and a combination of A1B and A2 runs for the other climate variables) to estimate the climate variable’s change per degree of global warming.

The change in the climate variable per degree of global warming was converted to a percent change per degree global warming relative to the GCM climate of 1975 to 2004 (except in the case of temperature where the absolute change was used). In particular, using the percent change method for rainfall reduced the effect of baseline errors on the magnitude of the simulated change (Whetton et al., 2005). Another advantage is that it decouples model response from the particular emission scenario used in the simulation, so the resultant percent change per degree global warming can be rescaled by any global warming value required for any chosen scenario (e.g. 0.7, 1.0 and 1.3 °C as used in this project).
Table 4.2. Global climate models used (the nine in bold are relatively better performing, see Section 4.4)

<table>
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<tr>
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</tr>
<tr>
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</tr>
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<td>CNRM</td>
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<td>4</td>
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<tr>
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<tr>
<td>6</td>
<td>GISS-AOM</td>
<td>NASA/Goddard Institute for Space Studies, USA</td>
</tr>
<tr>
<td>7</td>
<td>IAP</td>
<td>LASG/Institute of Atmospheric Physics, China</td>
</tr>
<tr>
<td>8</td>
<td>INMCM</td>
<td>Institute of Numerical Mathematics, Russia</td>
</tr>
<tr>
<td>9</td>
<td>IPSL</td>
<td>Institut Pierre Simon Laplace, France</td>
</tr>
<tr>
<td>10</td>
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<td>Centre for Climate Research, Japan</td>
</tr>
<tr>
<td>11</td>
<td>MIUB</td>
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<td></td>
<td></td>
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<td>15</td>
<td>NCAR-PCM1</td>
<td>National Center for Atmospheric Research, USA</td>
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4.3 Scaling methodology

The method used to generate the Scenario C climate data originated from the Murray-Darling Basin Sustainable Yield project (Chiew et al., 2008a). There are a variety of possible methods to obtain future catchment-scale climate data to drive hydrological models, see Chiew (2006) for an overview. Statistical downscaling methods that relate large synoptic-scale atmospheric variables to catchment-scale rainfall, and dynamic downscaling, can potentially provide more realistic future rainfall inputs to drive hydrological models (Frost et al., 2010). However, the use of such downscaling methods was not possible in this project, due to time and resource constraints. Additionally, downscaling methods may not necessarily be able to provide future rainfall projections more reliably than the method used because downscaling research has not been used for hydrologic investigations at this scale and there are insufficient daily GCM data available for downscaling to cover the range of GCM uncertainty in future climate.

The future climate scenario (Scenario C) provides projections of relative conditions for 2030 climatology under three global warming scenarios. This was achieved by rescaling the Scenario A climate data for low (0.7°C), medium (1.0°C) and high (1.3°C) global warming for ~2030 relative to ~1990. The corresponding values used in the Murray-Darling project were 0.45, 1.03 and 1.60°C, respectively. The difference in values used here is due to increased understanding of global temperature rises associated with projected low, medium and high emissions. Such understanding continues to evolve as earth system science advances.

The steps involved in producing 45 (15 GCMs by 3 global warming scenarios) Scenario C series of daily rainfall and Morton’s wet areal evapotranspiration (APET) are as follows:

1. GCM daily rainfall time series for 1981 to 2000 and 2046 to 2065 and monthly climate time series for 1870 to 2100 for the 15 GCMs were extracted and processed.

2. The GCM monthly climate time series were used to calculate ‘seasonal scaling’ factors for changes in mean seasonal rainfall and other climate variables per degree global warming. Four seasons were used – December to February (summer), March to May (autumn), June to August (winter) and September to November (spring). The seasonal scaling factors were calculated by regressing the mean seasonal climate variables against global average temperature simulated by the GCM, where the gradient of the linear relationship gives the change in the climate variable per degree global warming (Mitchell et al., 2003; Mitchell et al., 1999; Suppiah et al., 2007; Watterson, 2008 and references therein). The seasonal scaling factors are expressed as a percentage change (except for temperature where an absolute change is used) per degree global warming by dividing the absolute change by the mean value of the variable over 1981 to 2000. These seasonal scaling factors were calculated for the four seasons for each GCM grid cell overlying the region for rainfall, temperature, relative humidity and incoming solar radiation.
3. In addition, for rainfall, distributional differences between 2046 to 2065 and 1981 to 2000 GCM daily rainfall were used to calculate ‘daily scaling’ factors (percentage change in daily rainfall percentile per degree of global warming) for each rainfall percentile class on a seasonal basis. To obtain smooth transitions in the daily scaling factors, the percent changes per degree global warming were estimated by averaging the rainfall amounts over percentile ranges: 99th percentile (all amounts greater than 98th percentile), 95th percentile (all amounts between 97.5th and 92.5th percentiles), 90th percentile (all points between 92.5th to 87.5th percentiles), and so on for every five percentile range to a final category, where all the small rainfall amounts were considered together. This category bound was defined by the percentile at which the observed rainfall was less than 1 mm, or the 70th percentile if the percentile at which the observed rainfall is less than 1 mm was below the 70th percentile. Therefore, if the final category bound was the 70th percentile, all rainfall amounts below the 70th percentile were lumped together and used to determine the single value of percent change per degree of global warming for rainfall amounts below the 70th percentile.

4. For each of the 15 GCMs and global warming scenarios, the daily scaling factors were used to scale the different daily rainfall amounts in the Scenario A daily rainfall series to obtain 45 sets of 33 year daily rainfall series for a ~2030 relative to ~1990 climate. This daily scaling approach accounted for different changes in the different rainfall amounts, but assumed that the future daily rainfall sequence of raindays was the same as in the historical sequence. The entire series was then re-scaled, using the seasonal scaling factors, to ensure that the mean rainfalls in the four seasons were the same as those resulting from seasonal scaling. This is done because the seasonal scaling factors were determined using a large amount of data (1871 to 2100) from several ensemble runs, whilst the GCM simulations used to estimate the daily scaling factors were only available for two 20-year time slices (2046 to 2065 and 1981 to 2000) from limited modelling runs.

Two sources of uncertainty were accounted for using this methodology. The first is global warming uncertainty associated with greenhouse gas emission projections and global climate sensitivity, accounted for by using three levels of global warming by 2030. The second is the uncertainty in GCM projections of local climate over SWWA, accounted for by using 15 GCMs.

The consideration of changes in the daily rainfall distribution is important because many GCMs indicate that future extreme rainfall in an enhanced greenhouse climate can be more intense, even in regions where a decrease in mean seasonal or annual rainfall is projected. As high rainfall events generate large amounts of runoff, the use of simpler methods that assume the entire rainfall distribution changes in the same way would lead to an underestimation of total runoff (Chiew et al., 2008b; Mpelasoka and Chiew 2008).

The seasonal scaling method is similar to that used by the CSIRO and the Bureau of Meteorology (2007) to provide climate change projections for Australia (<http://www.climatechangeinaustralia.gov.au>). The key differences are: (i) this project used 15 of the 23 IPCC AR4 GCMs, whilst the CSIRO and Bureau of Meteorology projections used all 23 GCMs; (ii) this project assessed a range of global warming by ~2030; and (iii) this project also considered changes in daily rainfall distribution.

As the future climate series (Scenario C) are obtained by scaling the historical daily climate series from 1975 to 2007 (Scenario A), the daily climate series for Scenarios A and C have the same length of data (33 years) and the same sequence of daily climate (for example, potential changes in the frequency and timing of daily rainfall were not considered). Scenario C is therefore not a forecast climate at 2030, but a 33-year daily climate series based on 1975 to 2007 data scaled for projected global temperature at ~2030 relative to ~1990.

4.4 Assessment of global climate models

In order to determine whether there is a relationship between GCM performance and magnitude of projected change, several metrics used to assess the performance of GCMs (see Appendix C) have been related to GCM projected annual rainfall change over SWWA. Figure 4-2 compares annual rainfall changes projected by the 15 GCMs over SWWA according to three criteria:

(a) the weighted failure rate as described in Appendix C (Table C-2) that assesses GCM reproduction of a range of metrics;
(b) the demerit point ranking of Suppiah et al. (2007) based on reproduction of magnitude and spatial patterns of rainfall, temperature and mean sea level pressure over Australia; and

(c) the ability to reproduce the correct amount of rainfall over SWWA for current climate.

For each of these criteria, the better performing GCMs have lower values (i.e. to the left of the plots). Firstly, all three criteria show a noticeable relationship between performance and magnitude of projected change, with the GCMs that project the larger rainfall declines tending to be towards the left of each plot, i.e. the better performing GCMs. Secondly, there is consistency across the three criteria as to which GCMs are drier and better performing and which are less dry and poorer performing. For example, the GFDL 2.0 GCM (labelled ‘5’ in the plots) shows consistent relatively good performance and is one of the drier GCMs whilst the NCAR-PCM1 GCM (‘15’ in the plots) is consistently a poor performer and also projects a smaller relative rainfall decline. Across the three criteria, there is a cluster of better performing GCMs, ‘5’ (GFDL 2.0), ‘11’ (MIUB), ‘12’ (MPI-ECHAM5), ‘13’ (MRI) and ‘14’ (NCAR-CCSM) found towards the lower right hand corner of the plots, i.e. projecting relatively large rainfall declines. However there are also GCMs that perform inconsistently across the three criteria, for example ‘10’ MIROC-M which is a good performer for the weighted failure rate, a moderate performer for Suppiah’s demerit point criteria, and a poor performer for RMSE.

The nine GCMs shown in bold in Figure 4-2 are those which have a weighted failure rate less than 50, as described in more detail in Appendix C. Although 50 is an arbitrary cutoff, these nine are selected as a sub-set of all 15 for later comparison of how different the projections from a smaller set of GCMs, judged as relatively better performing, compare to those from the full set.

4.5 Climate change projections for ~2030

The climate variable percent changes per degree global warming for each of the four seasons for each cell of the 15 GCMs were multiplied by the change in temperature for each of the three global warming scenarios (0.7, 1.0 and 1.3°C) to obtain 45 sets of seasonal scaling factors, with additional daily scaling factors for rainfall. These scaling factors were
then used to scale the historical daily climate data from 1975 to 2007 to obtain the 45 Scenario C variants, each with 33 years of daily climate data.

The climate inputs required to run the hydrological models are daily rainfall and APET, with rainfall the main driver of runoff. Generally a 1 percent change in mean annual rainfall can lead to a 2 to 3.5 percent change in mean annual runoff whereas a 1 percent increase in mean annual APET can lead to a 0.5 to 0.8 percent decrease in mean annual runoff (Chiew, 2006; Jones et al., 2006). The 45 Scenario C daily climate series obtained here were used in the surface water and groundwater modelling to provide a detailed assessment of the hydrological responses to a range of projected climate change (see CSIRO, 2009a for details of the groundwater modelling and CSIRO, 2009b for details of the surface water modelling).

4.5.1 Rainfall change

Figure 4-3 to Figure 4-7 show the percent change in mean annual, summer, autumn, winter and spring rainfall, respectively for ~2030 relative to ~1990 from the 15 GCMs for the medium (1.0°C) global warming scenario. The results are ordered from the driest (top left) to the wettest (bottom right), the driest mean annual change being -13 percent, using scaling factors from CSIRO Mk3.0, and the wettest mean annual change being 1 percent from INMCM. INMCM was the only GCM to produce an overall increase in annual rainfall averaged over the region. Two GCMs (NCAR PCM1 and INMCM) project annual rainfall increases in the northern part of the project area, whereas the driest eight GCMs project larger relative decreases in the north. Seasonally, given the winter rainfall dominance, the spatial pattern and magnitude of relative winter change were similar to the annual change (Figure 4-6). Summer rainfall amounts are low, and the relative changes were not as consistent, with results from seven GCMs indicating increases and eight decreases (Figure 4-4). Autumn was generally similar to winter but with less intense changes; a notable exception being the strong increase from INMCM (Figure 4-5). Spring has very large relative decreases projected by the CSIRO Mk3.0 GCM (Figure 4-7).
Figure 4-3. Percent change in mean annual rainfall across the project area (~2030 relative to ~1990) from the 15 global climate models under the medium global warming scenario. Model order is from driest (top left) to wettest (bottom right).
Figure 4-4. Percent change in mean summer (DJF) rainfall across the project area (~2030 relative to ~1990) from the 15 global climate models under the medium global warming scenario. The ordering of models is the same as in Figure 4-3.
Figure 4-5. Percent change in mean autumn (MAM) rainfall across the project area (~2030 relative to ~1990) from the 15 global climate models under the medium global warming scenario. The ordering of models is the same as in Figure 4-3.
Figure 4-6. Percent change in mean winter (JJA) rainfall across the project area (~2030 relative to ~1990) from the 15 global climate models under the medium global warming scenario. The ordering of models is the same as in Figure 4-3.
Consistent with these mean changes, Figure 4-8 confirms that the projections from a significant majority of the 15 GCMs indicate decreased annual rainfall. Figure 4-8 also shows the number of GCMs projecting an increase (or decrease) in the highest 1, 5 and 10 percentiles of daily rainfall (i.e. the 99th, 95th and 90th percentiles respectively). This allows an assessment of how extreme daily rainfalls are projected to change relative to the mean projected changes. Only the highest 1 percent change indicates a different spatial pattern, with less consistency in the number of GCMs indicating a decrease, compared to the annual and highest 5 and 10 percentile results. For most of the region a majority of GCMs project a decrease for the highest 1 percentile rainfalls, however some small areas have more ambiguous results with approximately equal numbers of GCMs indicating an increase and a decrease (e.g. extreme south east of the project area).
Figure 4-8. Number of GCMs showing decreases (or increases) in future: (a) annual rainfall; (b) highest 1 percent of rainfall; (c) highest 5 percent of rainfall; and (d) highest 10 percent of rainfall, for ~2030 relative to ~1990 rainfall.
Three examples from the 45 Scenario C series are selected to represent 10th (dry), 50th (median) and 90th (wet) percentile projected rainfall change. Cmid, the median of the 15 medium (1°C) global warming Scenario C variants, was selected to represent the 50th percentile. CNRM was selected as the Cmid GCM. Note this will be different to the Cmid scenario selected for the groundwater and surface water modelling, as they were selected based on the 50th percentile of the regional recharge and runoff projections respectively (see CSIRO, 2009a and CSIRO, 2009b for details).

Cdry, the extreme dry projection, was chosen as the second driest GCM from the driest of the three global warming projections (GISS_AOM for the 1.3°C scenario). Cwet, the extreme wet projection, was chosen as the second wettest GCM from the wettest of the three global warming projections (NCAR_PCM for the 0.7°C scenario). Cdry and Cwet approximate the 10th and 90th percentiles of the range of projections. Figure 4-9 highlights the spatial contrasts, showing that for all three scenarios decreased rainfall predominates, with drying extending to even the Cwet scenario for the southern region of the project area.

Figure 4-9. Percent change in mean annual rainfall across south-west Western Australia (~2030 relative to ~1990) under the Cwet, Cdry and Cmid scenarios

Figure 4-10 compares monthly values of Cmid and the range between Cwet and Cdry (Crange) for ten locations (i.e. the grid cell overlying each of the ten representative stations). For each location, the left-hand plot uses all 15 GCMs to determine Cmid and Crange, whereas the right-hand plot uses only the nine better performing GCMs. The Cmid obtained using nine GCMs is very close to that from all 15 GCMs for all locations, whereas the range is often reduced. This suggests that selecting for better performing GCMs can potentially reduce the variability and corresponding uncertainty. The range of changes is greater for wetter months than drier months because of the multiplicative nature of the scaling methodology, resulting in greater absolute changes to larger values. There is also a tendency for the northern stations to have larger relative ranges than southern stations, a factor of the relative spatial patterns of change projected by the particular GCMs used for Cwet and Cdry (e.g. the Cwet GCM NCAR_PCM projects a relatively wetter north, see Figure 4-3). The reduced Crange results for the nine GCMs reflects the decreased relative difference between GCMs, as the difference between Cwet and Cdry GCMs for the nine are not as great as for the full 15 (e.g. contrast the 15 GCM Cwet NCAR_PCM with the nine GCM Cwet CCCMA T63 in Figure 4-3).
Figure 4-11 compares Scenario A, B, Cmid and Crange annual rainfall time-series. It is important to remember that these are not predictions or forecasts of actual climate over the next 33 years and so the years on the x-axis do not represent years when the particular rainfall totals are expected to occur. As they are scenarios of scaled historical climate (scaled according to projected GCM changes) the patterns of interannual variability, i.e. peaks and troughs, are the same as that of the historical records. Note also that the scaling is applied consistently across the record, i.e. there is no sense of climate change increasing over time in these plots. Thus they should only be interpreted in terms of the relative differences between the different scenarios, to highlight the consistency in and relative degree of the projected change over the region.
4 Future climate scenario data (Scenario C)

- Perth Airport 15 GCM
- Perth Airport 9 GCM
- Dwellingup 15 GCM
- Dwellingup 9 GCM
- Donnybrook 15 GCM
- Donnybrook 9 GCM
- Cowaramup 15 GCM
- Cowaramup 9 GCM

Monthly rainfall (mm)
Figure 4-10. Monthly average rainfall showing range of Scenario C, plus Cmid and mean historical (i.e., Scenario A – labelled A) rainfall reported for ten locations. The Scenario C values (Crange) are the Cwet to Cdry range from the 15 GCMs on the left and highest rated nine GCMs on the right.
4. Future climate scenario data (Scenario C)

- Geraldton
- Strawberry North
- Chelsea
- Perth Airport
- Dwellingup
- Donnybrook
- Cowaramup
- Cape Leeuwin
4.5.2 Areal potential evaporation – Morton’s wet areal evapotranspiration (APET)

Figure 4-12 to Figure 4-14 show the projected changes in mean annual temperature, relative humidity and incoming solar radiation respectively for ~2030 relative to ~1990 from the 15 GCMs for the medium (1°C) global warming scenario. There is a high level of consistency in future temperature projections from the 15 GCMs, with temperature increases of 0.6 to 1.2°C at individual grid cells. There is some indication of higher increases in the north and lower increases on the south coast. The projected changes in relative humidity are decreases of less than 2 percent, with most GCMs indicating a decrease (i.e. drier atmosphere). The change in incoming solar radiation (corresponding to a drier, i.e. more cloud free atmosphere) are increases of less than 2 percent for the majority of GCMs, with some GCMs projecting some areas of decrease.

The temperature, relative humidity and incoming solar radiation were not used directly in hydrological modelling; they were used to calculate the APET series required to drive the hydrological models. The mean annual APET in ~2030 relative to ~1990 for the medium global warming scenario is projected to increase by up to 4 percent at individual grid cells (Figure 4-15). There is a tendency for larger changes in APET to occur in the north of the region. The annual cycle of projected change in APET is hard to discern from the mean monthly values, as the projected changes are a relatively small proportion of the total (Figure 4-16). The multiplicative scaling methodology results in the absolute changes being greatest for the months of higher APET.

These changes are summarised in Table 4-3. The most hydrologically relevant difference between the fifteen and nine GCM results is the drier median rainfall change from -8.2 to -9.4 percent. The drier median annual projection obtained using the nine GCMs is a result of the median from the nine GCMs (NCAR CCSM) being a drier GCM than the median of the 15 GCMs (CNRM) (Figure 4-3). There is a reduced range in APET projections for the nine GCMs versus the 15 because the sub-set of nine excludes the three GCMs with the largest change (CSIRO-MK3.0, CCCMA-T47 and IPSL) and the two with the least change (CNRM and GISS-AOM). Thus selecting better performing GCMs removes outliers, leading to a reduction of uncertainty. Recall this is one rationale for GCM selection, because if selecting for better performing GCMs does not lead to reduction in the range of projections, then there would be little advantage in doing so.
Table 4-3. Projected annual changes (median and range of 15 or 9 GCMs) for the medium warming scenario

<table>
<thead>
<tr>
<th>Variable</th>
<th>All GCMs</th>
<th>Nine GCMs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rainfall Median (%)</td>
<td>-8.2</td>
<td>-9.4</td>
</tr>
<tr>
<td>Rainfall Range (%)</td>
<td>-13.4 to 1.4</td>
<td>-12.9 to 1.4</td>
</tr>
<tr>
<td>Temperature Median (°C)</td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td>Temperature Range (°C)</td>
<td>0.6 to 1.1</td>
<td>0.6 to 1.0</td>
</tr>
<tr>
<td>Solar Radiation Median (%)</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Solar Radiation Range (%)</td>
<td>-0.6 to 1.4</td>
<td>-0.6 to 1.4</td>
</tr>
<tr>
<td>Relative Humidity Median (%)</td>
<td>-0.8</td>
<td>-0.4</td>
</tr>
<tr>
<td>Relative Humidity Range (%)</td>
<td>-1.3 to 0</td>
<td>-1.2 to 0</td>
</tr>
<tr>
<td>APET Median (%)</td>
<td>2.4</td>
<td>2.2</td>
</tr>
<tr>
<td>APET Range (%)</td>
<td>1.6 to 3.3</td>
<td>1.9 to 2.8</td>
</tr>
</tbody>
</table>
Figure 4-12. Change (°C) in mean annual temperature across the project area (~2030 relative to ~1990) from the 15 global climate models under the medium global warming scenario. The ordering of models is the same as in Figure 4-3.
Figure 4-13. Percent change in mean annual relative humidity across the project area (~2030 relative to ~1990) from the 15 global climate models under the medium global warming scenario. The ordering of models is the same as in Figure 4-3.
Figure 4-14. Percent change in mean annual incoming solar radiation across the project area (~2030 relative to ~1990) from the 15 global climate models under the medium global warming scenario. The ordering of models is the same as in Figure 4-3.
Figure 4-15. Percent change in mean annual Morton’s wet areal evapotranspiration (APET) across the project area (~2030 relative to ~1990) from the 15 global climate models under the medium global warming scenario. The ordering of models is the same as in Figure 4-3.
4. Future climate scenario data (Scenario C)

Geraldton 15 GCM

Geraldton 9 GCM

Strawberry North 15 GCM

Strawberry North 9 GCM

Chelsea 15 GCM

Chelsea 9 GCM

Perth Airport 15 GCM

Perth Airport 9 GCM
4. Future climate scenario data (Scenario C)

- Dwellingup 15 GCM
- Dwellingup 9 GCM
- Donnybrook 15 GCM
- Donnybrook 9 GCM
- Cowaramup 15 GCM
- Cowaramup 9 GCM
- Cape Leeuwin 15 GCM
- Cape Leeuwin 9 GCM

Monthly APET (mm)

<table>
<thead>
<tr>
<th>J</th>
<th>F</th>
<th>M</th>
<th>A</th>
<th>M</th>
<th>J</th>
<th>A</th>
<th>S</th>
<th>O</th>
<th>N</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>60</td>
<td>120</td>
<td>180</td>
<td>240</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

C range
Cmid
A
Figure 4-16. Monthly average Morton’s wet areal evapotranspiration (APET) showing range of Scenario C, plus Cmid and mean historical (i.e., Scenario A – labelled A) rainfall reported for 10 locations. The Scenario C values (Crange) are the Cwet to Cdry range from the 15 GCMs on the left and highest rated 9 GCMs on the right.

4.6 References

CSIRO (2009a) Groundwater yields in south-west Western Australia. A report to the Australian Government from the CSIRO South-West Western Australia Sustainable Yields Project. CSIRO Water for a Healthy Country Flagship, Australia.
CSIRO (2009b) Surface water yields in south-west Western Australia. A report to the Australian Government from the CSIRO South-West Western Australia Sustainable Yields Project. CSIRO Water for a Healthy Country Flagship, Australia.


5 Conclusions

This technical report, one in a series of reports from the CSIRO South-West Western Australia Sustainable Yields Project (Appendix A), describes the climate data for the three climate scenarios used for the hydrological modelling in the project. The three climate scenarios were historical climate, recent climate and future climate. All three climate scenarios had 33 years of daily climate data at 0.05° x 0.05° (~ 5 km x 5 km) resolution grid cells across the project area.

In summary, this report has documented the data sources and methods implemented to develop the three climate scenarios, being historical climate (Scenario A), recent climate (Scenario B) and future climate (Scenario C). It has also provided key climate characteristics of the three scenarios to allow water resource managers to better understand the climate inputs to the systems they manage.

The historical climate scenario (Scenario A) was the baseline against which other scenarios were compared; it is a 33-year record of daily data spanning 1 January 1975 to 31 December 2007. It was based on the SILO data drill developed and maintained in real-time by the Queensland Climate Change Centre of Excellence. The recent climate scenario (Scenario B) was used to assess future water availability should the climate in the future prove to be similar to that of the most recent 11 years (i.e. 1 January 1997 to 31 December 2007). Climate data for the last 11 years were repeated three times to produce a 33-year daily climate sequences. The future climate scenario (Scenario C) was used to assess the range of projected climate conditions for 2030 climatology. Forty-five future climate variants, each with 33 years of daily climate sequences, were used. The future climate variants were produced by scaling the historical climate data to represent ~2030 climate, based on analyses of 15 global climate models (GCMs) and three global warming scenarios informed by the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2007).

The historical mean annual rainfall, averaged over the 33 year period for the entire South-West Western Australia Sustainable Yields Project area is 716 mm/year. There is a predominant south-west to north-east rainfall gradient over the region, where rainfall is highest along the south coast and Darling Range, and lowest in the inland north-east. Over the entire area, 50 percent of the rainfall occurs in the winter season (June to August).

The 33 year mean annual Morton’s wet areal evapotranspiration (APET), calculated following the method Morton (1983) gave for estimating wet areal evapotranspiration, averaged across the entire project area was 1427 mm/year. On a mean annual basis, as APET is greater than rainfall, almost all of the project area is a water-limited landscape. There was one small pocket on the south coast where on a mean annual basis rainfall was greater than APET and so hydrologically is considered energy-limited.

The mean annual rainfall averaged over the project area in the most recent 11 years is 694 mm/year, which is 3 percent lower than the 33 year mean. The largest decreases occurred in the region between coastal Mandurah and the Darling Scarp west of the town of Collie.

Although there is considerable uncertainty in the projections obtained from the 15 GCMs, as the range in projected rainfall change is large, there is overall consistency with the majority indicating a decrease in annual rainfall with a median decrease of 8 percent for ~2030 relative to ~1990. The projections show slightly more consistency using only the results from nine better performing GCMs and have median decreases in annual rainfall by 2030 of 9 percent. Combined with APET projected increases of 2 percent, the climate is projected to move into a more water-limited state than the last 33 years.

5.1 References


Appendix A  List of project reports

Methods report


CSIRO (2010) Description of project methods actually used in the South-West Western Australia Sustainable Yields Project. CSIRO Water for a Healthy Country Flagship, Australia. 87pp.

Main reports

1. CSIRO (2009) Surface water yields in south-west Western Australia. A report to the Australian Government from the CSIRO South-West Western Australia Sustainable Yields Project. CSIRO Water for a Healthy Country Flagship, Australia.


Technical reports


2. Silberstein et al. (2010, in prep.) Surface water yields in south-west Western Australia: technical report. A report to the Australian Government from the CSIRO South-West Western Australia Sustainable Yields Project. CSIRO Water for a Healthy Country Flagship, Australia.


Summary reports


3. CSIRO (2009) Water yields and demands in south-west Western Australia. Summary of a report to the
Australian Government from the CSIRO South-West Western Australia Sustainable Yields Project. CSIRO
Water for a Healthy Country Flagship, Australia. 16pp.

Factsheets

1. CSIRO (2008) Estimating the water yield of south-west Western Australia under a changing climate. CSIRO
Water for a Healthy Country Flagship, Australia. 4pp.

2. CSIRO (2009) Surface water yields in south-west Western Australia. CSIRO Water for a Healthy Country
Flagship, Australia. 4pp.

Flagship, Australia. 4pp.

Flagship, Australia. 4pp.

4pp.
APPENDIX B Calculation of daily APET

This Appendix outlines the methods used to calculate daily Morton’s wet areal evapotranspiration (APET) which is used in the South-West Western Australia Sustainable yields project as the estimate of potential evaporation for hydrological modelling. Relative humidity (%) was calculated from the SILO atmospheric water vapour pressure \(e_a\) as follows:

\[
\text{Rel Humidity} = 100 \left( \frac{e_s}{e_a} \right)
\]  

where Rel Humidity is the daily relative humidity (%) [McVicar, 1999 #1799]; \(e_a\) is the atmospheric water vapour pressure (kPa); and \(e_s\) is the saturation atmospheric water vapour pressure (kPa). The saturation vapour pressure \(e_s\) is calculated for the daily maximum air temperature (Tmax) or daily minimum air temperature (Tmin) as:

\[
e_s(T) = 0.6108 \exp \left[ \frac{17.27 \times T}{T + 237.3} \right]
\]  

and then averaged for use in equation (1) above [McVicar, 2007 #2127].

In most formulations of PET net radiation is needed as it is the primary source of energy for driving evaporation. Net radiation \(R_n\) units of MJ/m\(^2\)/day was defined here as the sum of the component longwave and shortwave fluxes:

\[
R_n = R_S \downarrow - R_S \uparrow + R_L \downarrow - R_L \uparrow
\]

where \(R_S \downarrow\) is the incoming shortwave radiation, \(R_S \uparrow\) is outgoing shortwave radiation, \(R_L \downarrow\) is incoming longwave radiation, and \(R_L \uparrow\) is outgoing longwave radiation (all with units of MJ/m\(^2\)/day). \(R_S \downarrow\) was obtained from the SILO database and \(R_S \uparrow\) was calculated as:

\[
R_S \uparrow = R_S \downarrow \times \alpha
\]

where albedo (\(\alpha\)) was set to 0.23 following Allen et al., 1998.

The net longwave \(R_{nL}\) radiation was calculated using the following equation, derived from Allen et al., 1998.

\[
R_{nL} = \sigma \left[ \frac{T_{\text{max}}^4 + T_{\text{min}}^4}{2} \right] \left[ 0.34 - 0.14 \sqrt{e_a} \left( 0.10 + 0.9 \frac{n}{N} \right) \right]
\]

where \(\sigma\) is the Stefan-Boltzmann constant (5.67 x 10\(^{-8}\) W/m\(^2\)/K\(^4\)), \(n\) is the bright sunshine hours and \(N\) is the number of daylight hours, with the ratio \(n/N\) being a measure of the atmospheric transmittance. The ratio \(n/N\) is calculated by inverting the Ångström–Prescott equation (Prescott, 1940).

\[
\frac{n}{N} = \frac{(R_S \downarrow / R_a - a)}{b}
\]

Where \(R_a\) is the extraterrestrial (or top-of-Earth atmosphere) solar radiation measured on a horizontal surface (MJ/m\(^2\)/day), with \(a\) and \(b\) being semi-empirical coefficients; \(a\) being the regression constant relating \(R_a\) to \(R_a\) for totally overcast days \((n = 0)\); and \(a + b\) being the atmospheric transmittance for totally clear days \((n = N)\). Following Allen et al. (1998), \(a = 0.25\), and as McVicar and Jupp (1999) showed that maximum Australian clear-sky atmospheric transmittance was 0.81, an Australian-specific value for \(b\) of 0.56 (calculated as 0.81 – 0.25 = 0.56) was used.

\(R_a\) was calculated as follows:

\[
R_a = \frac{I_0}{\pi} \int_0^{\varphi} \left[ e_{\omega} \sin(\varphi) \sin(\delta) + \cos(\varphi) \cos(\delta) \sin(\omega_s) \right] \, \text{d}d\varphi
\]

Where \(I_0\) is the solar constant (118.1 MJ/m\(^2\)/day), \(d\varphi\) is the inverse relative earth-sun distance \((d\varphi = 1 + 0.033 \cos (0.0172 \, \text{DOY})\), \(\omega_s\) is the sunset hour angle in radians (given by \(\omega_s = \arccos(-\tan(\varphi) \tan(\delta))\)), where \(\varphi\) is the latitude and \(\delta\) is the solar declination, both in radians and DOY is the Day Of Year from 1 (1 January) to 366 (31 December in a leap year).

The method used to calculate \(\delta\) is:
\[ \delta = 0.409 \sin \left( \frac{2\pi}{365} \text{DOY} - 1.39 \right) \]  

(8)

Implementing the above equations produced daily \( R_n \) suitable for use in modelling APET as described below.

Morton's wet areal evapotranspiration (APET) was calculated for an 'equilibrium' temperature that is iteratively determined by simultaneously solving the vapour transfer and energy balance equations. Potential evaporation was then calculated for the equilibrium temperature. The first step (equations 9 to 11) is to calculate three coefficients. The stability factor \( (\zeta) \) is:

\[
\frac{1}{\zeta} = 0.28 \left( 1 + \frac{\theta_a}{\theta_s} \right) + \frac{\Delta R_n}{\gamma (P_s/P)^{0.5} f_z (\theta_a - \theta_s)}
\]  

(9)

Here \( \theta_a \) is the actual vapour pressure (kPa), \( \theta_s \) is the saturated vapour pressure (kPa) calculated as \( \frac{1}{2} \theta_s(T_a) + \frac{1}{4} \theta_s(T_{\text{max}}) + \frac{1}{4} \theta_s(T_{\text{min}}) \) (Eq. 2), \( R_n \) (MJ/m²/day) (Eq. 3), \( P_s \) is mean sea level pressure (101.3 kPa), \( P \) is surface pressure given by \( 101.3(293-0.0065z/293)^{5.26} \), where \( z \) (elevation, m) is derived from a national 9-second DEM, and \( f_z \) is 24.19 MJ/m²/day/kPa for air temperature \( (T_a) \) at or above 273.16 K and 27.82 MJ/m²/day/kPa for \( T_a \) below 273.16 K.

The vapour transfer coefficient \( (F, \text{MJ/m}^2/\text{day/kPa}) \) is

\[
F = \left( \frac{P_s}{P} \right)^{0.5} \frac{f_z}{\zeta}
\]  

(10)

and the heat transfer coefficient \( (H, \text{kPa}/\degree C) \) is

\[
H = \gamma + \frac{1.804 \times 10^{-8} (T_a + 273.16)^3}{F}
\]  

(11)

where \( \gamma \) is the psychrometric constant (kPa/°C) and the coefficient \( 1.804 \times 10^{-8} \) is the value of \( 4 \varepsilon \sigma \) where \( \varepsilon \) is the land surface emissivity (here taken to be 0.92) and \( \sigma \) is the Stefan-Boltzmann constant (4.903 x 10⁻³ MJ/K⁴/m²/day). \( T_a \) is average daily temperature calculated as \( (T_{\text{max}} + T_{\text{min}})/2.0 \).

The second step (equations 12 to 17) was to iteratively calculate the equilibrium temperature, \( T_p \) (°C). This was done by initially setting \( T_p \) to \( T_a \) (°C), setting the equilibrium vapour pressure, \( e_p \), to \( \theta_a \), and setting the equilibrium vapour pressure slope, \( \Delta p \), to \( \Delta \). A temperature increment \( (\delta T) \) was calculated according to:

\[
\delta T = \frac{R_n/F + H(T_a - T_p) + \theta_a - \theta_p}{\Delta p + H}
\]  

(12)

Estimates of equilibrium temperature \( (T_p') \), vapour pressure \( (e_p') \) and vapour pressure slope \( (\Delta p') \) were derived in each iteration:

\[
T_p' = \delta T + T_p
\]  

(13)

\[
e_p' = 0.6108e_p \left( \frac{17.277T_p'}{T_p'+237.3} \right)
\]  

(14)

and

\[
\Delta p' = \frac{4098e_p'}{(T_p'+237.3)^2}
\]  

(15)

However, if \( T_p' \) is below 0.0°C, then

\[
e_p' = 0.6108e_p \left( \frac{21.887T_p'}{T_p'+265.5} \right)
\]  

(16)

and
\[ \Delta_p' = \frac{5809e'_p}{(T_p + 265.5)^2} \]  

\( T_p \) was then set to \( T_p' \), \( e_p \) to \( e_p' \) and \( \Delta_p \) to \( \Delta_p' \) and the iteration (contained in equations 12 to 17) was repeated until the absolute value of \( \delta T \) is less than 0.01°C. Morton’s point potential evapotranspiration (PPET units of MJ/m²/day) was calculated as follows.

\[ PPET = R_n - HF(T_p - T_a) \]  

Then \( R_{np} \) (MJ/m²/day) was calculated, this is the net radiation that would occur at the equilibrium temperature

\[ R_{np} = PPET + \gamma F(T_p - T_a) \]  

Then APET (MJ/m²/day) was calculated as follows:

\[ APET = 1.2096 + 1.2R_{np}\left(\frac{\Delta_p}{\Delta_p + \gamma}\right) \]  

Finally the APET is converted from energy units of MJ/m²/day to depth of mm/day by multiplying by 0.408. This was determined by dividing the energy unit by the latent heat of vaporisation (2.45 MJ/kg) and density of water (1000 kg/m³ – at a standard atmosphere); see Allen et al., 1998 for full details.

References


Prescott JA (1940) Evaporation from water surface in relation to solar radiation. Transactions of the Royal Society of South Australia, 64, 114-125.
APPENDIX C  Global Climate Model selection for regional studies

Introduction

This appendix is based on a need to better identify methods for selecting GCM results for use in regional impacts studies. It builds on an approach adopted by several published assessment studies, described by Smith and Chandler (2009) (hereafter referred to as SC9), and discussions held at the CSIRO Climate Adaptation Flagship’s ‘GCM Selection for Regional Studies Workshop’ Melbourne, 23-24 October, 2008.

In addressing the problem of GCM selection, it seems logical to assume that a necessary condition for utilising climate change results from a GCM is that it provides a credible representation of the present day climate. Recent studies have indicated that some GCMs suffer relatively large errors associated with simulations of present day climate and that these raise doubts about the quality of their results for climate change, particularly at regional scales. Whether these particular results should be included in any sample used to generate climate change projections is a decision for others. However, there is a definite need for some form of overall assessment which can assist researchers in their selection of GCMs. The aim here is to provide just such an assessment so that researchers can choose to reject or accept weighted model results.

Not all available GCM results are equal

Even though GCMs are physically based using the equations of motion and physics of transport and exchange of heat, momentum and mass, this does not guarantee reliability. The CMIP3 data set (<https://esg.llnl.gov:8443/>) contains the results from over 20 different GCMs which were used to provide climate change simulations for the IPCC Fourth Assessment Report (IPCC, 2007). These results supersede those generated for the Third Assessment Report (IPCC, 2001). While the more recent GCMs represent an overall improvement over the AR3 GCMs, it is also true that the CMIP3 sample contains results from GCMs which can be identified as inferior to some of those of the earlier AR3 GCMs. Therefore, the idea that the CMIP3 sample represents the optimum sample for producing climate change projections, while desirable, is not strictly true. However, the climate change community generally assumes this to be the case since they invariably ignore the results from the AR3 models in favour of more recent and, it is assumed, better performing models.

Major differences between GCMs include

- Horizontal resolution, ranging from 400 km to 125 km
- Physics, e.g. interactive sea ice versus prescribed sea ice
- Parameterisations, e.g. convection
- Flux adjustments
- Corrupted outputs
- Model Flaws: These are hard to detect but are likely to be present in one form or another.

The effects of the above factors can often be detected when comparing the GCM results with observations of present day climate. In general, the GCMs provide reasonably good (and progressively improving) simulations of global-scale average quantities such as temperature, mean sea level pressure (MSLP) and rainfall. However, it must be recognised that the GCMs are developed and tuned to do exactly this. Tuning for global-scale averages does not guarantee the results at regional scales, nor for all fields. It is apparent, when comparing the results for multiple fields at large scales or single fields at regional scales, that there exist some relatively poorly performing GCMs. The differences with observations can be quite large in some cases, sometimes sufficiently large to cast doubt about their appropriateness for inclusion in any climate change projections.

This is also recognised by the fact that methods have been adopted which weight some model results in favour of others depending on their level of ‘skill’. The issue of weighting models based on performance is a controversial topic, with
some arguing for no weighting on the grounds that there is no consensus concerning suitable metrics (Stainforth et al., 2007; Tebaldi and Knutti, 2007) or that, for any given metric, it often makes little sense to calculate a weighting factor for a poorly performing model that is greater than that of a very poorly performing model. Raisanen (2007) and Stainforth et al. (2007) recommend rejecting model results when it can be demonstrated that they suffer from large biases with respect to current climate.

Here we summarise the results from a range of GCM model assessments and indicate which of the 15 GCMs used in this project can be described as consistent underperformers, irrespective of variable, region or scale of interest. It is argued that consistent failure across these assessments indicates potentially serious flaws which can be regarded as sufficient to render these GCMs inappropriate for climate change projections. Furthermore, we also provide values for various rankings and metrics which can be used to detect evidence of clustering, or model agreement.

Methods of assessment

Quantifying model performance can be difficult because of the range of metrics, variables, spatial scales and temporal scales of interest. It is fair to say that any measure of performance can be subjective, simply because it will tend to reflect the priorities of the person conducting the assessment. When different studies yield different measures of performance, this can be a problem when deciding how to interpret a range of results in a different context. On the other hand, there is evidence that some models consistently perform poorly, irrespective of the type of assessment.

One method for combining the results of various models is referred to as the reliability ensemble average (REA) approach (Giorgi and Mearns, 2002, 2003) and allows for weightings which reflect model performance and which also penalise outliers, or results that appear to be very different from the sample mean. This last step has been severely criticised (e.g. Raisanen, 2007) and the method has been refined over time in order to remove this criterion (Tebaldi and Knutti, 2007).

Reichler and Kim (2008) demonstrated that, on average and at the global scale, the errors associated with simulations of current climate tend to reduce with subsequent generations of models. However, it is also true that the errors associated with some models from previous generations are less than the errors associated with some models of subsequent generations and the errors associated with some models can easily be described as unacceptable. They assessed the biases of 21 models using annual average values of 14 atmospheric and oceanic variables across the globe as a guide. Their results clearly demonstrated the fact that the errors of the poorer performing models can be up to twice those of the better performing models (and that one model in particular stands out as very much poorer than the rest).

Whetton et al. (2007) demonstrated that model performance, based on the simulation of the current climate, is relevant to the performance of simulations of the future climate. The similarity between different models was quantified by comparing simulated regional and global patterns of seasonal average temperature, MSLP and precipitation. Using the results from 17 models they found that, for most extra-tropical regions of the globe, models with similar patterns for the current climate tended to yield similar change patterns of change. They found powerful cross-variable connections (e.g. current climate precipitation was the best variable for discriminating temperature change) and that comparing global patterns of current climate can be as useful for discriminating regional patterns of change as comparing regional patterns of current climate. These features can include simple long-term averages at the grid point scale, spatial patterns at the continental scale, the annual cycle (based on average monthly values), interannual variability (e.g. El Nino Southern Oscillation (ENSO) events) where this is important and, finally, although not considered here, recent long-term trends which may, or may not, be the result of greenhouse gas forcing of the global climate.

Several studies have been published that involve the development of projections for Australia and all adopt different methods. Suppiah et al. (2007) (referred to hereafter as S7) assessed the performance of 23 models with respect to how well they reproduced patterns of seasonal average temperature, MSLP and rainfall over the Australian continent. They reduced the sample to 15 by rejecting those models which frequently failed to meet certain root mean square error (RMSE) and spatial correlation thresholds across the four seasons. They then generated climate change projections based on the average and range of this 15-member sample without discriminating between the results.

Watterson (2008) described a method for generating projections using PDFs that allow for the weighting of model results via the M-statistic of Watterson (1996), determined from simulated and observed patterns of seasonal average temperature, MSLP and rainfall over the Australian continent. An M value between 1 (perfect match) and 0 (no-skill) was
obtained for each of 23 models for each of the three variables for each of the four seasons. The average of the twelve M skill scores for each model ranged from about 0.3 to 0.7.

Perkins et al. (2007) assessed 14 models based on their ability to simulate daily rainfall and daily minimum and maximum temperatures for 12 regions of Australia. They focussed on the ability of the models to reproduce the frequency distribution functions of the three variables. They noted that some of the models exhibited considerable skill and that it was possible to identify relatively poorly performing models. Maximo et al. (2007) took the same approach but focussed on a single region of Australia, the Murray-Darling Basin (MDB). They assessed 17 models, showing that some models were clearly flawed, with only four recommended for use in impact assessments over this region. Pitman (pers. comm.) used the results of the Perkins et al. (2007) assessment to exclude poorly performing models and obtained less uncertain projections of changes to daily temperatures and rainfall, even though the mean changes were not substantially different to those previously reported. Charles and Fu (2009) also assessed model performance over the MDB but focussed on the ability of the models to simulate both daily MSLP patterns and the seasonal cycle of monthly average MSLP. Of the 11 AR4 models and two other models assessed, four were clearly superior to the others.

SC9 adopted a similar approach to that used by S7 with several crucial differences. S7 assessed the performance of models with respect to how well they reproduced observed seasonal patterns of temperature, MSLP and rainfall over the Australian continent. S7 argued that a multivariate assessment is important since it can help identify those models that may be able to provide good simulations of current rainfall (for example) but for the wrong reasons if they cannot reproduce the observed MSLP patterns (for example). S7 calculated values for both RMSE and spatial correlation ($r_s$) in conjunction with visual examination of maps of the patterns. They then decided on a threshold value for RMSE of 2°C, 2 hPa and 2 mm day$^{-1}$ for temperature, MSLP and rainfall respectively, followed by an $r_s$ threshold value of 0.80 for all three variables. Model performance was then quantified in terms of ‘demitre points’, which effectively indicated how many of the 12 patterns (4 seasonal patterns for 3 variables) each model either exceeded the relevant RMSE threshold or fell below the 0.80 $r_s$ threshold. The fewer demitre points, the better performing the model. On this basis they judged that 15 out of the 23 CMIP3 models performed satisfactorily insofar as they had accumulated less than eight demitre points.

While it is apparent that this approach is fairly subjective, it is unclear whether this is an important issue. For example, S7 provide little justification for their choice of RMSE and $r_s$ thresholds or for eight demitre points as the cut-off for finally selecting models. In fact, choosing 2 mm day$^{-1}$ as the RMSE threshold for rainfall is questionable since this does not appear to provide any effective discrimination of model performance. According to their Figure 6, all models satisfy this threshold for autumn, winter and spring, and only six models fail this threshold in summer. Similarly, the 2°C RMSE threshold for temperature also appears to contribute little to discriminating the models since only four fail this in summer, only three fail in autumn, only six fail in winter and only four fail in spring. On the other hand, a 2 hPa RMSE threshold for MSLP is far more discriminatory since, apart from autumn, the majority of models fail. A different situation appears to be the case for the $r_s$ threshold since this is most effective with regard to rainfall, especially in spring when the majority of models fail the 0.80 threshold. In the case of temperature, no models fail this threshold in any season while only a small proportion fails this threshold for MSLP. As a result, it appears that the S7 methodology for selecting models takes very little account of RMSE for rainfall, and is strongly influenced by the performance of the models with regard to RMSE for MSLP.

In contrast SC9 were only interested in rainfall, so they only considered thresholds for rainfall RMSE and $r_s$. Unlike S7, they argue that because they are only interested in rainfall projections, then rainfall is the only variable that should be used to assess model performance. They state it seems difficult to justify giving credence to models whose rainfall simulations are relatively poor, yet those for temperature, MSLP, winds, etc. may be relatively good. Furthermore, SC9 argue that it is highly unlikely that a model can provide a credible simulation of rainfall without having a credible simulation of humidity, temperature, winds, MSLP, etc. In other words, as concluded from their global study, precipitation is the best single validation variable.

SC9 only focus on Australian rainfall, as it is difficult to justify the inclusion of a model which performs well over, say, northern Europe, but not over Australia. SC9 also argue that the Australian continent as a whole is sufficiently large and varied that it provides a good test bed for assessing the performance of models. It comprises a wide range of climate regimes including the very dry interior compared to very wet tropics, the dry west compared to the wetter east, a summer regime dominated by monsoon circulations, tropical cyclones, Madden-Julian Oscillations, thunderstorms etc. compared to a winter regime dominated by frontal events, cut-off lows, etc. Australia is also unique in that the climate is strongly affected by the Pacific Ocean (via ENSO events) and, to a lesser extent, the Indian Ocean.
Summary of GCM assessments

Table C–1 summarises the performance of the 15 GCMs used in this project based on various criteria adopted in a number of studies. Column A reflects the performance of the GCMs for their ability to capture key features of Australian seasonal rainfall only, according to the criteria adopted by SC9. The values represent the number of demerit points (or failures) based on RMS error and spatial correlation thresholds. There are two thresholds for each season and only four models (0 in Column A of Table C–1) pass both criteria in all four seasons.

Column B represents the assessment by S7 and also represents demerit points (in this case the maximum is 24, comprising two metrics, three variables and four seasons). The best performing GCM in this assessment is MPI-ECHAM5 (1 demerit point) while the worst is IPSL (14 demerit points).

Column C shows the skill scores (or ‘M-statistic’) calculated by Watterson (2008) and represents how well each GCM captures features of the rainfall, temperature and MSLP fields over Australia in each of the four seasons. In this case the best performing GCM is again MPI-ECHAM5 (700) and the worst CCCMA T63 (478).

Column D indicates which GCMs satisfactorily captured features of the daily temperature and daily rainfall probability distributions over 12 Australian regions according to the criteria of Perkins et al. (2007). Note that only 11 of the 15 GCM results were assessed.

Column E represents an assessment based on simulations of the ENSO phenomenon. According to the assessment of van Oldenborgh et al., (2005) only GFDL 2.0, MIROC-M and MPI-ECHAM5 provide credible representations of ENSO. The ENSO performance criteria may appear to be severe but, in the case of Australia, it is difficult to argue for the inclusion of model results for several decades into the future when it has been judged that the model appears incapable of adequately simulating important changes to the climate system that occur on a time scale of just a few years. Column F indicates which GCMs satisfied criteria for North Pacific SST variability according to Overland and Wang (2007).
### Table C–1. Summary of model assessments with relatively poor performance highlighted in yellow.

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
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<td>Aus</td>
<td>Aus</td>
<td>Aus</td>
<td>ENSO</td>
<td>North Pacific</td>
<td>MDB</td>
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<td>NH</td>
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<td>601</td>
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<td>No</td>
<td>Yes</td>
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<td>No</td>
<td>14</td>
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<td>Yes</td>
<td>No</td>
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<td>Yes</td>
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<td>No</td>
<td>4</td>
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<tr>
<td>MIUB</td>
<td>0</td>
<td>4</td>
<td>632</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MPI-ECHAM5</td>
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<td>700</td>
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<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
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<td>3</td>
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<td>No</td>
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<td></td>
<td>7</td>
</tr>
<tr>
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<td>11</td>
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<td>No</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>10</td>
</tr>
</tbody>
</table>

A. Number of rainfall criteria failed (SC9)
B. Demerit points based on criteria for rainfall, temperature and MSLP (S7)
C. M-statistic representing goodness of fit at simulating rainfall, temperature and MSLP over Australia (Watterson, 2008)
D. Satisfied criteria for daily rainfall over Australia (Perkins et al., 2007)
E. Satisfied ENSO criteria (Min et al., 2005; van Oldenborgh et al., 2005)
F. Satisfied criteria for SST variability (Overland and Wang, 2007)
G. Satisfied criteria for daily rainfall over MDB region (Maximo et al., 2007)
H. Satisfied criteria for MSLP over MDB region (Charles and Fu, 2009)
I. Below median errors for 14 variables (Reichler and Kim, 2008).
J. Below median rankings for temperature, MSLP and precipitation over NH (Walsh et al., 2008).

Column G represents the results of a similar assessment to Perkins et al., (2007) carried out for the MDB region of south-eastern Australia (Maximo et al., 2007). Column H represents the results of the assessment by Charles and Fu (2009), also for the MDB region, but focusing on daily and seasonal MSLP patterns.

Column I classifies GCMs as above or below median performing GCMs according to the assessment by Reichler and Kim (2008) in which 14 different variables were assessed at the global scale. Column J represents an assessment of GCM performance over the northern hemisphere in terms of the number of below-median rankings for temperature, MSLP and rainfall (Walsh et al., 2008).

While Table C–1 provides a detailed overview of GCM performance against a variety of metrics, variables and spatial scales, not all GCMs were included in all the assessments. Because the individual assessments are not completely independent, there is some degree of overlap in the results which could skew any overall assessment based on simple averaging, particularly as most of them are based on results over the Australian continent. If we group the assessments into those over Australia (Columns A, C, D and E) those over the relatively small MDB region (F and G), those over the Pacific Ocean (B and I) and those over the globe and/or hemispheres (H and J), we can partly account for some of this interdependence. For each geographic region we firstly calculate the average failure rate, and then form the average of these four values to provide an overall failure rate, shown in Table C–2. Here the results have been ranked and the GCMs grouped into three subjective classes with models deemed to be poor performers those with failure rates greater than 50 percent (highlighted in red), fair performers with failure rates greater than 25 percent and less than 50 percent (highlighted in yellow) and better performers those with failure rates less than or equal to 25 percent (highlighted in blue).
While this process is relatively crude and the boundaries between these three classes are subjective, a similar ranking is achieved by simply calculating the simple average failure rate across all the columns of Table C–1.

Table C–2. GCM rankings based on a weighted average of the Table C–1 assessment. The top nine (in bold) are selected as better performing (# in 1st column from Table 4-2). Highlighted colours represent three subjective classes of relatively better (blue), fair (yellow) and poor (red) performing GCMs.

<table>
<thead>
<tr>
<th>#</th>
<th>GCM ID</th>
<th>Weighted failure rate (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>GFDL 2.0</td>
<td>17</td>
</tr>
<tr>
<td>10</td>
<td>MIROC-M</td>
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<td>13</td>
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<tr>
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<td>MIU-B</td>
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<td>MPI-ECHAM5</td>
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<td>9</td>
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<td>75</td>
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<tr>
<td>15</td>
<td>NCAR-PCM1</td>
<td>100</td>
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</table>

Discussion

Is it possible that we are interpreting relative performance as an indication of absolute performance? That is, are we unfairly penalising GCMs for being ranked lowly when, in fact, all the GCMs may be perfectly adequate? While our simple methodology can be criticised, we argue that the relative rankings of the GCMs is unlikely to be significantly altered by the employment of more sophisticated methods.

Uncertainty associated with derived climate change projections can potentially be reduced by identifying and omitting the poorer performing GCMs. This effect can be partly detected by plotting the projected changes from each GCM as a function of some measure of model performance, as is done in Section 4.4. Evidence of clustering of projected changes amongst the better performing models may indicate that the poorer performing models may be a source of uncertainty, i.e. if the better performing models tend to agree, then this can be construed as evidence that GCM performance is relevant to the variable and region of interest. Otherwise there is little point in attempting to distinguish between the different results and the uncertainty remains.

Finally, one argument against penalising available model results, based on subjective measures of performance, is that, we cannot really know at this point in time which models provide the best results (since we must wait for the passage of time to make this assessment). Therefore it is folly to penalise models which may, in fact, contain correct climate change signals. The answer to this argument is, simply, that at this point in time we are more interested in a practical question (that end-users typically ask of scientists): ‘Given a wide range of climate model results, which do you regard as being the most reliable and why?’ In effect, we are not concerned so much with being proved ‘right’ or ‘wrong’ with regard to climate change projections at the end of the 21st century, as with providing expert advice that is both transparent, and can be acted on now. If the methodology used to sort the available information and generate advice is sound, then the important point is that due diligence is followed. There is no point in contemplating the fact that some (unspecified) apparently poor model results have been penalised and may contain correct climate change signals since this would imply some particular unrecognised skill. If this cannot be recognised now, using fairly simple and logical criteria, then it
is pointless arguing that all model results need to be treated equally, otherwise, in an extreme sense, there would be no point in excluding the results of a random number generator.

Conclusions

We have summarised a number of GCM assessments which compare features of the simulated climate from the 15 GCMs used in this project. The result is a ranking of the GCMs (Table C–2) which indicates some consistently well performed GCMs and some consistently poorly performed GCMs.

On a practical level, it is recommended that researchers:

1. Consider excluding the results from the poorer performing GCMs. This assessment provides evidence to indicate that the GCMs that fail more than 50% of the weighted criteria could be excluded on the basis of this study.
2. Plot projected changes as a function of GCM rankings (as done in Section 4.4) in order to detect evidence of clustering. This can potentially lead to less uncertain results (i.e. a smaller range in projection uncertainty).

References


Charles S and Fu G (2009) Statistical downscaling of coupled model historical runs. SEACI Project Report SEACI, 24 pp. Available at <http://www.seaci.org/docs/reports/1.5.2_1.5.3_final.doc>


Description of Project Methods
South-West Western Australia Sustainable Yields Project

November 2008