Production of climate scenarios for Tasmania


A report to the Australian Government from the CSIRO Tasmania Sustainable Yields Project

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Photo on cover: Irrigated field near Cressy (CSIRO)
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 Tasmania Sustainable Yields Project, together with allied projects for northern Australia and south-west Western Australia, will provide a nation-wide expansion of the assessments.

The CSIRO Tasmania 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 Tasmania.

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.

Dr Tom Hatton
Director, Water for a Healthy Country
National Research Flagships
CSIRO
Executive summary

The purpose of this report is to describe the production of the three climate scenarios used for the hydrological modelling in the CSIRO Tasmania Sustainable Yields Project. The three climate scenarios are historical climate (Scenario A), recent climate (Scenario B), and future (~2030) climate (Scenario C). All three climate scenarios have 84 years of daily climate data.

The historical climate sequence (Scenario A) is taken to be the observed climate (rainfall and areal potential evapotranspiration (APET)) from 1 January 1924 to 31 December 2007. It was derived on a 0.05 x 0.05 degree (~ 5 km x 5 km) grid over the whole of Tasmania, corresponding to 3352 grid cells. Under Scenario A, the mean annual rainfall averaged over Tasmania is 1266 mm. Rainfall is winter-dominated, with mean maximum monthly rainfall occurring in July or August and mean minimum monthly rainfall occurring in January or February. The seasonal differences are greatest in the north-west of Tasmania and reduce moving towards the south-east. There is a clear east–west rainfall gradient across Tasmania, where rainfall is highest in the west (mean annual rainfall of more than 4000 mm for the wettest grid cell) and lowest in the east (mean annual rainfall of just over 450 mm for the driest grid cell). The mean annual APET averaged across Tasmania is 989 mm, ranging from over 1100 mm on Flinders Island in the north-east to less than 850 mm in the south of the state. APET is highest in summer averaging 403 mm, reducing to an average of 104 mm in winter.

The recent climate scenario (Scenario B) is based on an 84-year climate series (same length as Scenario A) generated from the rainfall and APET characteristics from 1 January 1997 to 31 December 2007. In general, the climate over the recent period (1997 to 2007) has been drier than that over the historical period (1924 to 2007). For the whole of Tasmania, mean annual rainfall under Scenario B is 1193 mm (a 6 percent reduction). This reduction in rainfall is greatest across the north-east of the state with the Pipers-Ringarooma region showing a 12 percent reduction. The severity of the reduction in rainfall is lessened moving towards the south with the Arthur-Inglis-Cam region showing an 9 percent reduction, the South Esk region an 8 percent reduction, the Mersey-Forth region a 7 percent reduction, and the Derwent-South East region a 6 percent reduction. The reductions in rainfall are not distributed evenly throughout the year, with the largest reductions across every region occurring in autumn (with a maximum 21 percent reduction in autumn rainfall across the Pipers-Ringarooma region). The next largest seasonal reductions are in summer for all regions except the Pipers-Ringarooma region which experiences a 14 percent reduction in winter and 12 percent in summer. Changes in spring are minimal, ranging from a 2 percent reduction in the Arthur-Inglis-Cam region to a 2 percent increase in the Mersey-Forth region.

The future (~2030) climate scenario (Scenario C) is derived by modifying the historical climate sequence (Scenario A) based on 15 global climate models (GCMs) and one dynamically downscaled projection of ~2030 climate. Changes in APET under Scenario C relative to Scenario A are derived directly from the GCMs. The magnitude of the changes in rainfall between Scenario A and Scenario C are also derived from the GCMs; however, the spatial patterns of the changes in rainfall are taken from the GFDL 2.0 GCM which was dynamically downscaled using the CCAM model. In addition, to account for changes in the future daily rainfall distribution, different daily rainfall amounts are scaled differently. These are also based on the GFDL 2.0 GCM which was dynamically downscaled using the CCAM model.

While there are considerable differences in the rainfall projections for ~2030 between global climate models, the majority of global climate models show a decrease in future mean annual rainfall, particularly across the northern half of Tasmania where almost all models agree that drying occurs. Even in southern Tasmania, one-half to two-thirds of the models agree that drying occurs. The vast majority of the models agree that rainfall decreases in spring and summer, again particularly across the northern half of Tasmania. Most models also agree that rainfall decreases in autumn, with around two-thirds projecting drier conditions across the northern half of Tasmania and over one-half projecting drier conditions across the southern half of Tasmania. Most models also agree that drying occurs in winter across the northern half of Tasmania, but that rainfall increases across the southern half of Tasmania.

The second wettest, median and second driest future models were defined as scenarios Cwet, Cmid and Cdry respectively. On average, for the whole of Tasmania, mean annual rainfall increases by 1 percent under Scenario Cwet, decreases by 2 percent under Scenario Cmid, and decreases by 6 percent under Scenario Cdry. Under Scenario Cwet, the largest increases in rainfall occur in summer and winter. Under Scenario Cmid, decreases in rainfall occur in summer, autumn and spring with a slight increase in winter. Under Scenario Cdry, the largest decrease in rainfall occurs in summer and spring but with drying all year round.
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1 Introduction

This report is one in a series of technical reports from the CSIRO Tasmania Sustainable Yields Project. The terms of reference for the project are to estimate current and future water availability in each catchment and aquifer in Tasmania considering climate change, forestry, groundwater and irrigation development, and to compare the estimated current and future water availability to that required for meeting the current levels of extractive use. These terms of reference are covered in a series of region reports (see back cover for a full listing) which provide a detailed account of all modelling and assessments undertaken by the project as illustrated in Figure 1. The role of this and other technical reports is to provide an appropriate scientific background to the results presented in the region reports.

Figure 1. Project framework

The purpose of this report is to describe the production of the three climate scenarios used for the hydrological modelling in the project. The three climate scenarios are historical climate, recent climate, and future climate. All three climate scenarios have 84 years of daily climate data.

The historical climate scenario (Scenario A) is based on the observed climate (rainfall and areal potential evapotranspiration (APET)) from 1 January 1924 to 31 December 2007. For modelling river flows under this scenario, the current level of surface and groundwater development was assumed. Scenario A was used as the baseline against which assessments of relative change were made. The historical climate data are described in Section 2.

The recent climate scenario (Scenario B) is based on the rainfall and APET characteristics of the past 11 years (1 January 1997 to 31 December 2007). For modelling river flows under this scenario, the current level of surface and groundwater development was used. Scenario B was therefore used to assess the water availability of the last 11 years. The recent climate scenario is described in Section 3.

The third scenario (Scenario C) is a future climate scenario. It encompasses three global warming scenarios applied to a number of global climate models (GCMs) and dynamically downscaled projections of ~2030 climate. Modelling river flows under this scenario used the current level of surface and groundwater development. The future climate scenario is described in Section 4.
In this report, climate is considered across the whole of Tasmania. However, other reports from this project (see back cover for a full listing) report changes in water availability for five reporting regions: Arthur-Inglis-Cam (including Flinders and King islands), Mersey-Forth, Pipers-Ringarooma, South Esk and Derwent-South East. These reporting regions are shown in Figure 2. Note that a significant portion of Tasmania, labelled as ‘west coast’ on Figure 2, is not included for analysis of water availability in this project, hence reporting is limited for that area.

Figure 2. Project extent and reporting regions
2 Historical climate data (Scenario A)

2.1 Gridded historical climate data

Scenario A consists of historical daily climate data from 1924 to 2007 at 0.05 x 0.05 degree (~ 5 km x 5 km) grid cells across Tasmania. The source of the data is the SILO Data Drill of the Queensland Department of Environment and Resource Management (QDERM) (<http://www.nrw.qld.gov.au/silo> and Jeffrey et al., 2001). The SILO Data Drill provides surfaces of daily rainfall and other climate data (here, only temperature, relative humidity and solar radiation were used) interpolated from point measurements made by the Australian Bureau of Meteorology.

The rainfall surfaces were interpolated using a trivariate thin plate smoothing spline with latitude, longitude and elevation as independent variables. The temperature, relative humidity and solar radiation surfaces after 1957 were also interpolated using the same method, but a different interpolation algorithm was used for the period prior to 1957 because most of the available data before then are not in digital format (see <http://www.nrw.qld.gov.au/silo/CLIMARC>).

The gridded climate data were derived from observations that have been quality checked by the Australian Bureau of Meteorology and have been subject to error checking by QDERM. Nevertheless, it is inevitable that there were errors in the data, and the interpolation routines can also introduce errors. In general, the data accuracy is expected to be lower in areas where the observation density is low relative to the climate gradients. In this context, it should be noted that rainfall varies spatially more than the other climate variables, but this is compensated by the generally denser rainfall observation network.

2.2 Observed rainfall

Figure 3 shows the annual rainfall for the whole of Tasmania and each of the five reporting regions from 1924 to 2007. The 11-year centrally weighted mean and the long-term mean are also shown. Each region shows much the same temporal pattern with wetter conditions in the 1950s and 1970s and drier conditions in the 1960s and most recent decade. Figure 4 shows the mean annual, summer (December to February), autumn (March to May), winter (June to August), and spring (September to November) rainfall across Tasmania from 1924 to 2007.

The mean annual rainfall averaged over Tasmania is 1266 mm. Rainfall is winter-dominated, with maximum mean monthly rainfall occurring in July or August and minimum mean monthly rainfall occurring in January or February. The seasonal differences are greatest in the north-west of Tasmania and reduce towards the south-east (see Figure 36 in Section 4.7 for monthly averages).

There is a clear east–west rainfall gradient across Tasmania where rainfall is highest in the west (mean annual rainfall of more than 4000 mm for the wettest grid cell) and lowest in the east (mean annual rainfall of just over 450 mm for the driest grid cell) (see Figure 4).

Rainfall is the most important driver of the rainfall-runoff process. Rainfall is also much more variable, both temporally and spatially, than other climate variables. Figure 5 shows the density of rainfall stations used to generate the SILO Data Drill rainfall data for 20-year time slices from 1920 to the present. In general there is a good coverage of rainfall stations across the entire period of record, with the number being considerably higher from 1980 to the present. During earlier decades the number of stations is less, but the spatial coverage is similar. An analysis of rainfall-runoff patterns across the state indicates that rainfall may be underestimated in the south-west where the distribution of rain gauges is the poorest. However, as the project is not evaluating water availability in the south-west, this should not affect the results of the project greatly. The minimum number of operational stations occurred in the 1920s when 303 stations were operating, and the maximum number occurred in the 21st century when 526 were operating. Note that the points which appear to be in the ocean on Figure 5 are in fact rainfall stations on small islands off the coast.
Figure 3. Annual rainfall under Scenario A, averaged across (a) whole of Tasmania, (b) Arthur-Inglis-Cam, (c) Mersey-Forth, (d) Pipers-Ringarooma, (e) South Esk and (f) Derwent-South East. The dark blue line shows the 11-year centrally weighted mean and the red line shows the mean.
Figure 4. Spatial distribution of mean annual and seasonal rainfall across Tasmania under Scenario A
Figure 5. Locations of rainfall stations used to generate SILO Data Drill rainfall for various decades
2.3 Areal potential evapotranspiration

Daily rainfall and areal potential evapotranspiration (APET) are required as input data for the rainfall-runoff modelling. The daily APET was calculated from 0.05 x 0.05 degree (~5 km x 5 km) grid-based climate data from the SILO Data Drill consisting of temperature; relative humidity (calculated as actual vapour pressure divided by saturation vapour pressure); and incoming solar radiation. APET was calculated using Morton’s wet environment evapotranspiration algorithms (<http://www.bom.gov.au/averages>; Morton, 1983; Chiew and Leahy, 2003).

The 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, and local variations are integrated to an areal average. The APET is therefore conceptually the upper limit to actual evapotranspiration in the rainfall-runoff modelling.

The rainfall-runoff modelling results are much less sensitive to errors in the APET data than they are to errors in the rainfall data. It is also easier to provide reliable APET data for the rainfall-runoff modelling, because compared to rainfall, APET is less variable in both space and time.

Figure 6, Figure 7, and Figure 8 show the mean annual, summer, autumn, winter, and spring surface air temperature, average relative humidity, and incoming solar radiation respectively across Tasmania under Scenario A. These are used to calculate the APET, shown in Figure 9. The mean annual APET averaged across Tasmania is 989 mm, ranging from over 1100 mm on Flinders Island in the north-east to less than 850 mm in the south of the state. APET is highest in summer averaging 403 mm, reducing to an average of 104 mm in winter.
Figure 6. Spatial distribution of mean annual and seasonal temperature across Tasmania under Scenario A
Figure 7. Spatial distribution of mean annual and seasonal relative humidity across Tasmania under Scenario A.
Figure 8. Spatial distribution of mean annual and seasonal incoming solar radiation across Tasmania under Scenario A.
Figure 9. Spatial distribution of mean annual and seasonal areal potential evapotranspiration across Tasmania under Scenario A.
3 Recent climate data (Scenario B)

3.1 Method

The recent climate scenario (Scenario B) is used to assess the water availability of the past 11 years (1997 to 2007). To create the Scenario B rainfall, the climatic sequence of the past 11 years was repeated seven times, and the years between 2001 and 2007 were added to the beginning of the sequence in order to create an 84-year sequence of rainfall and areal potential evapotranspiration (APET). While this is a very simple way of creating an 84-year sequence of climate, it has the advantage of producing a sequence which reflects the characteristics of the past 11 years without needing to specify exactly which characteristics are to be reflected, for example, the importance of annual rainfall versus seasonal or monthly rainfall, or the necessity of replicating the sequence of dry-wet days. This information would be required in a more complex approach, and as we do not know exactly which characteristics of the rainfall may be important, it is not a question which can easily be answered. An 84-year sequence was used in preference to an 11-year sequence since it allows for an easier comparison to the 84-year Scenario A sequence. For example, some storages will not reach equilibrium after an 11-year dry period. Thus, an 84-year dry period is required in order to assess the implications of a long-term drought.

3.2 Comparison with historical data

The climate of the last 11 years (Scenario B) has been drier than that of the last 84 years (Scenario A). These changes in rainfall are not statistically significant at the 5 percent level. However, as described below, the reductions in rainfall over the last 11 years have been quite large and would be expected to impact on water availability. In addition, the mean annual rainfall for the last 11 years has seen a large decrease in variability as seen in Figure 3. This absence of large annual rainfalls over the last 11 years would also be expected to impact on water availability.

Mean monthly rainfall for the past 11 years compared to the past 84 years is shown in Figure 10 while the spatial distribution of these changes can be seen in Figure 11. Over the whole of Tasmania, mean annual rainfall under Scenario B is 1193 mm (a 6 percent reduction) but due to the reduction in rainfall being less over the south-west, over the regions covered by the project (see Figure 2) the reduction is even greater (at 8 percent). This reduction in rainfall is greatest across the north-east of the state with the Pipers-Ringarooma region showing a 12 percent reduction. The severity of the reduction in rainfall is lessened moving towards the south with the Arthur-Inglis-Cam region showing an 9 percent reduction, the South Esk region an 8 percent reduction, the Mersey-Forth region a 7 percent reduction, and the Derwent-South East region a 6 percent reduction. Almost all of the state had reduced rainfall over the past 11 years, with only a small patch in the south-west of the state showing an increase in rainfall (see Figure 11). However, as that area of the state has very few rain gauges located within it (see Figure 5) and an analysis of rainfall-runoff patterns indicated that rainfall here may be underestimated, this increase should be treated with some caution. As the south-west is excluded from an analysis of changes in water availability in this project, this possible anomaly will not affect the results.

The reductions in rainfall are not distributed evenly throughout the year with reductions everywhere during the months February to August. The largest reductions across every region occur in autumn (with a maximum 21 percent reduction in autumn rainfall across the Pipers-Ringarooma region). The next largest seasonal reductions are in summer for all regions except the Pipers-Ringarooma region with a 14 percent reduction in winter and 12 percent in summer. The next largest reductions occur in winter for all regions except for the Pipers-Ringarooma as stated above. Changes in spring are fairly minimal, ranging from a 2 percent reduction in the Arthur-Inglis-Cam region to a 2 percent increase in the Mersey-Forth region.
Figure 10. Mean monthly rainfall under scenarios A and B averaged across (a) Whole of Tasmania, (b) Arthur-Inglis-Cam, (c) Mersey-Forth, (d) Pipers-Ringarooma, (e) South Esk and (f) Derwent-South East
Figure 11. Spatial distribution of percent change in mean annual and seasonal rainfall across Tasmania under Scenario B relative to Scenario A.
4 Future climate data (Scenario C)

4.1 Method

Scenario C uses 45 variants of 84 years of daily climate series for a global average surface temperature in ~2030, guided by global climate models (GCMs) from the Fourth Assessment (AR4) of the Intergovernmental Panel on Climate Change (IPCC) for three global warming scenarios (IPCC, 2007). It also uses climate projections that are dynamically downscaled from the GFDL 2.0 GCM using the Conformal Cubic Atmospheric Model (CCAM) (McGregor, 2005).

The steps used to obtain the 45 variants of the 84-year daily climate series are summarised below.

- Three global warming scenarios under future climate projections were used: high, medium and low. These three scenarios were inferred from the AR4 and the latest climate change projections for Australia (CSIRO and Australian Bureau of Meteorology, 2007). This step is described in detail in Section 4.2.
- Archived monthly simulations from 15 AR4 GCMs were analysed to estimate the change in rainfall and other climate variables per degree of global warming. Each GCM was analysed separately. Data from each of the four seasons were also analysed separately. This step is described in detail in Section 4.3.
- The ability of the 15 GCMs to reproduce the current climate was assessed and the impact of removing one or more poor quality GCMs from the analysis was determined as described in Section 4.4.
- The percent changes in the climate variables per degree of global warming for each of the four seasons from the 15 GCMs were then multiplied by the change in temperature for each of the three levels of global warming to obtain the 45 sets of ‘seasonal scaling’ factors. The seasonal scaling factors were then used to scale the historical daily climate data from 1924 to 2007 differently in each season to obtain the 45 future climate variants, each with 84 years of daily climate data. The rainfall and other climate variables (temperature, relative humidity, solar radiation and areal potential evapotranspiration (APET)) under future climate projections are presented in Section 4.5.
- The spatial patterns of changes in rainfall from the dynamically downscaled CCAM model were determined in Section 4.6. These spatial patterns from the dynamically downscaled CCAM model were applied to the magnitude of changes from the GCMs to produce the finer-scale spatial patterns in the rainfall as described in Section 4.7.
- The changes in daily rainfall amounts were also considered by scaling the different daily rainfall amounts by different factors. This is described in Section 4.8.

These steps are summarised in Figure 12 which illustrates how the Scenario A climate data is modified by both the GCM-scale and dynamically downscaled climate projections to produce the final Scenario C data.
The method accounts for two types of uncertainties. The first uncertainty is in the global warming projection, due to the uncertainties associated with projecting greenhouse gas emissions and predicting how sensitive the global climate is to greenhouse gas concentrations. The second uncertainty is in GCM modelling of local climate in Tasmania. The method also takes into account changes in each of the four seasons as well as changes in daily rainfall amounts. The consideration of changes in daily rainfall amounts is important because many GCMs indicate that future extreme rainfall in an enhanced greenhouse climate is likely to be more intense, even in some regions where a decrease in mean seasonal or annual rainfall is projected. As high rainfall events generate large amounts of runoff and groundwater recharge, the use of simpler methods that assume the entire rainfall distribution changes in the same way would lead to an underestimation of total runoff and groundwater recharge.

The method used for this project is similar to, but not the same as, the approach used by CSIRO and Australian Bureau of Meteorology (2007) (<http://www.climatechangeinaustralia.gov.au>) to provide climate change projections for Australia. The key differences are that this project:

- used 15 of the 23 AR4 GCMs, while the CSIRO and Bureau of Meteorology projections use all 23 AR4 GCMs
- assesses the extreme range of global warming by ~2030
- also considers changes in daily rainfall amounts.

The method is also very similar to that used in the CSIRO Murray-Darling Basin Sustainable Yields Project (<http://www.csiro.au/partnerships/MDBSY.html>; Chiew et al., 2008), with the addition of dynamic-downscaling of one of the climate projections using CCAM to obtain finer-scale spatial patterns which were then applied to all 15 GCMs (see Section 4.6 for details).

As the future climate series (Scenario C) is obtained by scaling the historical daily climate series from 1924 to 2007 (Scenario A), the daily climate series for scenarios A and C have the same length of data (84 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 an 84-year daily climate series based on 1924 to 2007 data for projected global temperatures at ~2030 relative to ~1990.
4.2 Global warming

This section summarises the global warming projections leading to the three global warming scenarios used for this project. A comprehensive picture of the present state of knowledge on global climate change can be found in IPCC (2007). CSIRO and Australian Bureau of Meteorology (2007) provides detailed future projections of Australian climate and discusses past climate characteristics and drivers of Australian climate.

There is an increasing body of research that supports a picture of a warming world with significant changes in regional climate systems. Eleven of the last 12 years rank among the 12 warmest years in the instrumental record of global surface temperature (since 1850) and the linear warming trend over the last 50 years is about 0.13 °C per decade (IPCC, 2007). However, since 1976, the global temperature has risen more sharply at 0.18 °C per decade (WMO, 2006). The global average temperature over the last 150 years is shown in Figure 13. Based on many lines of evidence including the widespread warming of the atmosphere and ocean, together with ice mass loss, the IPCC (2007) concluded that most of the observed increase in the global average temperature since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations.

The global climate system is highly complex, and therefore it is inappropriate to simply extrapolate past trends to predict future conditions. To estimate future climate change, scientists have developed emission scenarios for greenhouse gases and aerosols. The greenhouse gas emissions considered here are those due to human activities, such as energy generation, transport, agriculture, land clearing, industrial processes and waste. To provide a basis for estimating future climate change, Working Group III of the IPCC prepared 40 greenhouse gas and sulfate aerosol emission scenarios for the 21st century that combine a variety of assumptions about demographic, economic and technological factors likely to influence future emissions. Described fully in the Special Report on Emission Scenarios (SRES) (IPCC, 2000), each scenario represents a variation within one of four ‘storylines’ (A1, A2, B1 and B2, see Table 1) with projected carbon dioxide, methane, nitrous oxide and sulfate aerosol emissions associated with each of the scenarios.

Increasing concentrations of greenhouse gases affect the radiative balance of the Earth. The balance between incoming solar radiation and outgoing heat radiation defines the Earth’s radiative budget and 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 and has a warming effect.

The AR4 Summary for Policymakers (IPCC, 2007) provides estimates of global warming for the year 2100 for six emission scenarios (B1, A1T, B2, A1B, A2 and A1F). The range of warming is based on 23 GCMs and comes from a hierarchy of AR4 models and observational constraints. Important uncertainties, including the possibility of significant further amplification of climate change due to carbon cycle feedbacks, are also considered. The lower end of the warming range corresponds to the mean warming minus 40 percent, while the upper end of the range is the mean warming plus 60 percent. The range of global warming by 2100 is 1.1 to 6.4 °C.

Equivalent global warming values for 2030 are not provided by the IPCC (2007). While global warming is dependent on future emission scenarios, there are little differences in global temperature by 2030 based on emission scenarios. Rather, global warming by 2030 is dependent on the possible range of global climate sensitivity to greenhouse gas concentrations (IPCC, 2007). The result is three predictions of the temperature change by ~2030 relative to ~1990: a low global warming of 0.7 °C, medium global warming of 1.0 °C, and high global warming of 1.3 °C. After 2030, emission scenarios outweigh global sensitivity to greenhouse gas concentrations as the dominant control on global temperature.
Table 1. Storylines from the Special Report on Emission Scenarios (source: IPCC, 2000)

<table>
<thead>
<tr>
<th>IPCC scenario</th>
<th>Storyline</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>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).</td>
</tr>
<tr>
<td>A2</td>
<td>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.</td>
</tr>
<tr>
<td>B1</td>
<td>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.</td>
</tr>
<tr>
<td>B2</td>
<td>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.</td>
</tr>
</tbody>
</table>

An illustrative scenario was chosen for each of the six scenario groups A1B, A1FI, A1T, A2, B1 and B2. All were considered equally sound by the IPCC.

The SRES scenarios do not include additional climate initiatives, which means that no scenarios are included that explicitly assume implementation of the United Nations Framework Convention on Climate Change or the emissions targets of the Kyoto Protocol.

Figure 13. Global average temperature over the last 150 years (source: IPCC, 2007, p37)
4.3 Change in climate variables per degree global warming

Global warming will lead to changes in regional climate. GCMs are the best tools available for simulating global and regional climate systems. There have been rapid improvements in climate modelling over the last few decades and the results from GCMs have been compared to a wealth of observational data. However, although GCMs have reasonable success in simulating past climate and therefore providing some confidence in their use for climate projections, the range of future climate predictions from different GCMs is often large.

To account for the uncertainty in GCM simulation of future climate across Tasmania, 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 were used because only 15 GCMs had readily available daily rainfall data (required for the daily scaling presented in Section 4.8). By comparison, CSIRO and the Bureau of Meteorology used data from all 23 GCMs to develop the climate change projections for Australia released in October 2007 (CSIRO and Bureau of Meteorology, 2007). That study also used weights to favour the use of GCMs that best reproduce the observed historical climate (rainfall, temperature and sea level pressure) across Australia. The weights in the CSIRO and Bureau of Meteorology study vary from 0.3 to 0.7, with the weights of the subset of 15 GCMs used in this project all being above 0.5.

The 15 GCMs used are listed in Table 2. Monthly rainfall and other climate data were available for these GCMs for the period 1870 to 2100. For each GCM, and for each season and each GCM grid cell, the simulated rainfall (or other climate variable) was plotted against simulated global average temperature. A linear regression was fitted through the data points and the slope of the linear regression gives the change in rainfall (or other climate variable) per degree of global warming (see Figure 14 for one example). The absolute change in the climate variable per degree of global warming was converted to a percent change per degree global warming relative to the model baseline climate of 1975 to 2004 (except in the case of temperature where the absolute value was used). In particular, the percent change was used for rainfall to reduce the effect of errors in the baseline climate on the magnitude of the simulated change (Whetton et al., 2005). One of the advantages of this method is that it decouples the model response from the particular emission scenario used in the simulation, and the resultant change per degree global warming can be rescaled by the global warming values for any scenario.

Combinations of results from many runs for the same GCM are 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 change in the climate variable per degree global warming.

<table>
<thead>
<tr>
<th>Global climate model</th>
<th>Modelling group, country</th>
<th>Horizontal resolution km</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCCMA T47</td>
<td>Canadian Climate Centre, Canada</td>
<td>250</td>
</tr>
<tr>
<td>CCCMA T63</td>
<td>Canadian Climate Centre, Canada</td>
<td>175</td>
</tr>
<tr>
<td>CNRM</td>
<td>Meteo-France, France</td>
<td>175</td>
</tr>
<tr>
<td>CSIRO-MK3.0</td>
<td>CSIRO, Australia</td>
<td>175</td>
</tr>
<tr>
<td>GFDL 2.0</td>
<td>Geophysical Fluid, Dynamics Lab, USA</td>
<td>200</td>
</tr>
<tr>
<td>GISS-AOM</td>
<td>NASA/Goddard Institute for Space Studies, USA</td>
<td>300</td>
</tr>
<tr>
<td>IAP</td>
<td>LASG/Institute of Atmospheric Physics, China</td>
<td>300</td>
</tr>
<tr>
<td>INMCM</td>
<td>Institute of Numerical Mathematics, Russia</td>
<td>400</td>
</tr>
<tr>
<td>IPSL</td>
<td>Institute Pierre Simon Laplace, France</td>
<td>275</td>
</tr>
<tr>
<td>MIROC-M</td>
<td>Centre for Climate Research, Japan</td>
<td>250</td>
</tr>
<tr>
<td>MIUB</td>
<td>Meteorological Institute of the University of Bonn, Germany</td>
<td>400</td>
</tr>
<tr>
<td>MPI-ECHAM5</td>
<td>Max Planck Institute for Meteorology DKRZ, Germany</td>
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</tr>
<tr>
<td>MRI</td>
<td>Meteorological Research Institute, Japan</td>
<td>250</td>
</tr>
<tr>
<td>NCAR-CCSM</td>
<td>National Center for Atmospheric Research, USA</td>
<td>125</td>
</tr>
<tr>
<td>NCAR-PCM1</td>
<td>National Center for Atmospheric Research, USA</td>
<td>250</td>
</tr>
</tbody>
</table>

Combinations of results from many runs for the same GCM are 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 change in the climate variable per degree global warming.
Figure 14. Example plots showing method used to estimate change in rainfall per degree global warming. Each point represents (a) summer and (b) winter rainfall for one year versus global average temperature from CSIRO-MK3.0 simulations for one grid cell for 2001 to 2100, with the slope of the regression line giving the rainfall change per degree global warming.

4.4 Global climate model assessment

Before choosing to use all 15 GCMs in this project, the models’ ability to simulate historical patterns of rainfall was evaluated. Figure 15 shows the observed mean annual rainfall and compares it with the rainfall as simulated by the 15 GCMs over the period 1975 to 2004. Three summary statistics are shown on the figure. These statistics summarise the spatial correlation (R), Nash-Sutcliffe efficiency (NSE) and root mean square error (RMSE) between the GCM simulated rainfall and the observed rainfall. Note that the first two statistics are calculated at the GCM grid cell scale and thus are not comparable across GCMs because of the differences in the number and size of GCM grid cells across Tasmania. This analysis was also carried out for each of the four seasons. Results were very similar to the annual results and are not reproduced here. Note that for this and all subsequent figures showing results from the GCMs, the order of presentation is from the driest projection of future climate to the wettest. This is to facilitate comparison between figures.

In general, while some of the GCMs are able to predict both the magnitude and spatial patterns of the observed annual and seasonal rainfall with a degree of accuracy, some do quite poorly. For example, the CSIRO-MK3.0 model does a reasonable job of predicting the spatial patterns of annual rainfall and has a RMSE of 334 mm (compared to an observed annual rainfall of 1266 mm). On the other hand, the CNRM model gets the spatial pattern of rainfall incorrect with greater rainfall in the east, and has a RMSE of 485 mm (Figure 15).
Figure 15. Spatial distribution of observed and simulated mean annual rainfall across Tasmania from 1975 to 2004 from the 15 global climate models.
Smith and Chandler (2009) and Suppiah et al. (2007) carried out analyses of the GCMs included in the AR4. Both assessments involved a comparison of the GCMs performance in reproducing a range of metrics over the Australian continent. Based on these comparisons, a weighted failure rate (Smith) and demerit points (Suppiah) were developed. These are shown in Table 3. Note that there are 22 models in this table (the 15 models used in the current project and another 7 models from the AR4). One model (not used in the current project) was excluded because of consistently poor results.

Table 3. Rankings for global climate models included in IPCC (2007). The 15 global climate models used in the project are ranked in order of their prediction of rainfall change for Tasmania from driest to wettest

<table>
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<tbody>
<tr>
<td></td>
<td>mm failure rate</td>
<td></td>
<td>demerit points</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CSIRO-MK3.0</td>
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<td>63</td>
<td>7</td>
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<td>No</td>
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<tr>
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<td>17</td>
<td>4</td>
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<tr>
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<td>44</td>
<td>2</td>
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<td>No</td>
</tr>
<tr>
<td>MRI</td>
<td>618</td>
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<td>37</td>
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<td>2</td>
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<td>Yes</td>
<td>Yes</td>
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<tr>
<td>CNRM</td>
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<td>71</td>
<td>4</td>
<td>Yes</td>
<td>No</td>
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<td>-</td>
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<td>Yes</td>
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<td>GFDL 2.1</td>
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<td>-</td>
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<td>No</td>
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<tr>
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<tr>
<td>UKMO-HadGEM1</td>
<td>-</td>
<td>33</td>
<td>2</td>
<td>No</td>
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</tr>
</tbody>
</table>

In general, the 15 models selected for analysis in this project cover the full range of weighted failure rates and demerit points (these 15 were selected as they had accessible daily rainfall which is needed to carry out the daily scaling – see Section 4.8). These 15 models also cover a wide range of projected change in annual rainfall (1990 to 2030) for Tasmania as shown in Figure 21. The question therefore arises: would the projected changes in annual rainfall be significantly different had only the better-performing models been chosen for use in the current project? The answer is seen in Figure 16 where the percent change in annual rainfall is plotted against the weighted failure rate, demerit points and RMSE.
It can be seen from Figure 16 that there is no relationship between the weighted failure rate of Smith and Chandler (2009), GCM demerit points of Suppiah et al. (2007), or the RMSE for Tasmania (from Figure 15), and the percent change in annual rainfall averaged across Tasmania. This lack of relationship means that choosing a subset of these 15 GCMs based on their ability to reproduce either Australian or Tasmanian climatology would have a negligible impact on the results and conclusions of the current project. For this reason, and to encapsulate all of the uncertainty implicit in the IPCC climate projections, all 15 GCMs have been retained in the project.

4.5 Global climate model scale climate change projections for the future (~2030)

The percent changes in the climate variables per degree global warming for each of the four seasons for each cell of the 15 GCMs in Section 4.3 were multiplied by the change in temperature for each of the three global warming scenarios in Section 4.2 (0.7, 1.0 and 1.3 °C) to obtain 45 sets of ‘seasonal scaling’ factors. The seasonal scaling factors were then used to scale the historical daily climate data from 1924 to 2007 to obtain the 45 future climate variants, each with 84 years of daily climate data.

The climate inputs required to run the rainfall-runoff model are daily rainfall and areal potential evapotranspiration (APET). The climate data are also used in the river system and groundwater recharge modelling. Rainfall is the main driver of runoff, with a 1 percent change in mean annual rainfall generally amplified to a 2 to 3.5 percent change in mean annual runoff. A 1 percent increase in mean annual APET generally leads to a 0.5 to 0.8 percent decrease in mean annual runoff (Chiew, 2006; Jones et al., 2006). These are very general rules of thumb, and the daily future climate series obtained here are used in the rainfall-runoff modelling to provide more accurate results (see Viney et al. (2009) for details of the rainfall-runoff modelling).

Figure 17, Figure 18 and Figure 19 show the absolute change in mean annual temperature, and the percent change in relative humidity and incoming solar radiation for ~2030 relative to ~1990 from the 15 GCMs for the medium global warming scenario. There is much better agreement in the future temperature projections from the 15 GCMs than the
The projections for the medium global warming scenario generally show a temperature increase of 0.3 to 1.2 °C across most of Tasmania. The GCMs indicate that the change in relative humidity by ~2030 relative to ~1990 is less than 1 percent and that the change in incoming solar radiation is less than 3 percent.

The temperature, relative humidity and incoming solar radiation were not used directly for the rainfall-runoff modelling, but rather were used to calculate the APET series required to run the rainfall-runoff models. In the analyses here, the daily historical temperature series from 1924 to 2007 was first increased by the temperature change shown in Figure 17 and the relative humidity and incoming solar radiation were scaled by the changes shown in Figure 18 and Figure 19 respectively, to generate 84 years of future (~2030) daily climate series. The future climate series was then used to calculate the future APET series using the evapotranspiration algorithms described in Section 2.3. The results indicate that the mean annual APET in ~2030 relative to ~1990 for the medium global warming scenario will increase by 1 to 4 percent as shown in Figure 20. It can be noted that some of the changes in both Figure 20 and Figure 21 do not exactly match the GCM grid scale. This is because these changes are calculated on a seasonal basis and then aggregated to an annual basis, scaled by the 0.05 degree seasonal SILO data. As a result, the changes in rainfall match the GCM grids on a seasonal basis, but not necessarily on an annual basis.

Figure 21 shows the percent change in mean annual rainfall for ~2030 relative to ~1990 from the 15 GCMs for the medium global warming scenario. These percent changes in annual and seasonal rainfall were scaled using the dynamically downscaled results in Section 4.6 to produce the final set of 14 km resolution pattern-scaled GCM projections which are the Scenario C data to be used across the remainder of the project components.

The question arises as to the statistical significance of these projected changes in mean annual and seasonal rainfall for ~2030 compared to ~1990. Figure 22 shows the statistical significance of the changes in mean annual rainfall shown in Figure 21. These were calculated by evaluating the statistical significance of the slope of the lines used to estimate change in rainfall per degree global warming as for example shown in Figure 14. It can be seen that the majority of the changes in mean annual rainfall are statistically significant, particularly for those grid cells that show the largest increases or decreases in rainfall. Seasonal results are similar to the annual results and are not shown here.
Figure 17. Spatial distribution of change in mean annual temperature across Tasmania for ~2030 relative to 1990 for the 15 global climate models under the medium global warming scenario.
Figure 18. Spatial distribution of percent change in mean annual relative humidity across Tasmania for ~2030 relative to 1990 for the 15 global climate models under the medium global warming scenario.
Figure 19. Spatial distribution of percent change in mean annual incoming solar radiation across Tasmania for ~2030 relative to 1990 for the 15 global climate models under the medium global warming scenario.
Figure 20. Spatial distribution of percent change in mean annual areal potential evapotranspiration across Tasmania for ~2030 relative to 1990 for the 15 global climate models under the medium global warming scenario.
Figure 21. Spatial distribution of percent change in mean annual rainfall across Tasmania for ~2030 relative to 1990 for the 15 global climate models under the medium global warming scenario.
Figure 22. Spatial distribution of statistical significance of the changes in mean annual rainfall across Tasmania for ~2030 relative to 1990 for the 15 global climate models under the medium global warming scenario.
4.6 Dynamically downscaled climate change projections for the future (~2030)

The dynamical downscaling model used in this project is the CSIRO Conformal Cubic Atmospheric Model (CCAM) (McGregor 2005; McGregor and Dix 2001, 2008). CCAM is a full atmospheric global general circulation model, formulated using a conformal-cubic grid which covers the globe but can be stretched to provide higher resolution in areas of interest. This gives more flexibility for downscaling experiments, allowing forcing of CCAM by sea surface temperatures (SSTs) as well as forcing by atmospheric fields from the host GCM (somewhat akin to the limited-area model style). In addition, it is possible to downscale from many of the AR4 climate models. The current project downscales the GFDL 2.0 GCM to 60 km, and then to 14 km over Tasmania for 140 years (1961 to 2100). As part of a collaborating project (Climate Futures for Tasmania, see <http://www.acecrc.org.au/drawpage.cgi?pid=climate_futures>), the CSIRO Mk 3.5, GFDL 2.1, Miroc-M, MPI-ECHAM5, and UKMO-HADCM3 models were also downscaled using CCAM. However, analysis of these models is still ongoing as part of the Climate Futures for Tasmania project and only the GFDL 2.0 results were used in the current project.

In the current application, CCAM was initially set up on a grid having a resolution of about 60 km over Australia. Outputs from these runs were then used to drive 14 km CCAM simulations. The 60 km simulations used monthly SSTs and sea-ice cover from the GFDL 2.0 GCM, which were smoothly interpolated in time. Most GCMs (including GFDL 2.0) have some significant biases in SST. Accordingly, average monthly biases relative to the Reynolds average SST were calculated for each month for the period 1961 to 2000. These biases were then subtracted from the monthly GCM SSTs to provide bias corrected SSTs throughout the relevant simulations. Note that the interannual variability and climate change signal are not altered by this bias correction. For the 14 km simulations, atmospheric forcing from the 60 km runs used a digital filter forcing (Thatcher and McGregor, 2009), where surface pressure, temperature and winds were replaced at large scale.

The ability of the 15 GCMs to reproduce the observed annual rainfall was shown in Figure 15 (Section 4.5). As expected at such a coarse resolution, only the most basic patterns were reproduced, and even then, not particularly well. To improve our predictions of the changes in future rainfall patterns across Tasmania, we compared the CCAM dynamically downscaled runs from the GFDL 2.0 GCM to the observed data. As expected, these dynamically downscaled runs performed much better in terms of reproducing observed annual and seasonal rainfall patterns and magnitude. These comparisons are shown in Figure 23.

As the dynamically downscaled model provides a better representation of historical climate, and as it incorporates processes at a finer scale than the GCMs, it was run through to 2100 to provide a finer resolution representation of future changes in rainfall. Figure 24 shows the percent change in mean annual, summer, autumn, winter and spring rainfall for 2030 relative to 1990 as derived from the CCAM-downscaled GFDL 2.0 GCM. These percent changes in rainfall were calculated in a very similar way to the method used at the GCM scale (Section 4.3) except that instead of plotting seasonal rainfall versus global mean annual temperature (as shown in Figure 14), seasonal rainfall was plotted against years from 2001 to 2100 from which the change in seasonal rainfall per year was derived. The results were virtually identical. This method was chosen as it does not rely on the global average temperature which could potentially have a different meaning for a downscaled model compared to a global model.
Figure 23. Spatial distribution of observed and simulated mean annual and seasonal rainfall across Tasmania from 1975 to 2004 from the CCAM-downscaled GFDL 2.0 global climate model
Figure 24. Spatial distribution of percent change in mean annual and seasonal rainfall across Tasmania for ~2030 relative to 1990 from the CCAM-downscaled GFDL 2.0 global climate model under the A2 climate scenario.
4.7 Scenario C future climate projections for hydrological modelling

While the CCAM dynamically downscaled runs from the GFDL 2.0 GCM produced a more realistic representation of current climate, and while they provided a higher resolution of rainfall changes in the future, these runs are a work-in-progress (see <http://www.acecrc.org.au/drawpage.cgi?pid=climate_futures> for details). In particular, at the time at which the Tasmania Sustainable Yields Project required final estimates of future rainfall changes (April 2009), only the GFDL 2.0 model had been downscaled (another five models have since been downscaled as described in Section 4.6). Obviously, this model represents only one projection of future climate compared to the range of projections from the 15 GCMs.

Thus, in order to maintain the range of possible future climate from the 15 GCMs, the spatial patterns from the CCAM-downscaled GFDL 2.0 GCM were scaled by the magnitude of the changes in rainfall as derived from the 15 GCMs. This was done for each of the three global warming scenarios over each of the reporting regions per season. As an example, across the Arthur-Inglis-Cam region, there are 15 projections of change in summer rainfall (1990 to 2030) for the AR4 medium global warming scenario, ranging from -11.2 percent for the IPSL model to +3.9 percent for the MIROC-M model (data not shown here). To produce the Scenario C data therefore, the patterns seen in the CCAM-downscaled GFDL 2.0 GCM were scaled such that for the medium global warming scenario over the Arthur-Inglis-Cam region, the percent change in summer rainfall equals -11.2 percent for the IPSL model, +3.9 percent for the MIROC-M model, and so on for each of the other 13 models. This was done for each of the three global warming scenarios for each season and for all 15 GCM-scale projections of change in rainfall. The results of this are shown in Figure 25, Figure 26, Figure 27, Figure 28 and Figure 29 for changes in mean annual, summer, autumn, winter, and spring rainfall respectively.

While there are considerable differences in the rainfall projections between GCMs, the majority of GCMs show a decrease in future mean annual rainfall, particularly across the northern half of Tasmania where almost all models agree drying will occur. Even in southern Tasmania, one-half to two-thirds of the models agree that drying will occur (Figure 30). The vast majority of the models agree that rainfall will decrease in spring and summer, again particularly across the northern half of Tasmania (Figure 29 and Figure 26). Most models also agree that rainfall will decrease in autumn, with around two-thirds predicting drier conditions across the northern half of Tasmania and over one-half predicting drier conditions across the southern half of Tasmania (Figure 27). Most models also agree that drying will occur in winter across the northern half of Tasmania, but that rainfall will increase across the southern half of Tasmania (Figure 28). Figure 30 summarises these results.

As there is too much information in the 45 (15 x 3) projections of future rainfall to use in the river and groundwater modelling, the notional 10th, 50th and 90th percentiles of future rainfall projections have been selected and will hereafter be referred to as the Cdry, Cmid and Cwet estimates. As the seasonal scaling factors for the 45 future climate variants are obtained by multiplying the percent changes per degree global warming obtained from the 15 GCMs by the change in temperature for low, medium and high global warming, the driest and wettest variant will generally come from the high global warming scenario while the median will come from the medium global warming scenario. For that reason, the dry case is defined as the second driest GCM from the high global warming scenario, while the wet case is defined as the second wettest GCM from the high global warming scenario. This is calculated on a grid cell basis across the whole of Tasmania for each season. Note that different GCMs have been selected as the Cwet, Cmid and Cdry scenarios for the surface water and groundwater modelling as these were selected on a regional basis based on changes in runoff and recharge respectively (see Viney et al., 2009 and Harrington et al., 2009 for details).

The median of the change in mean annual, summer, autumn, winter, and spring rainfall and the extreme range of changes for the 0.05 x 0.05 degree grid cells across Tasmania are shown in Figure 31, Figure 32, Figure 33, Figure 34 and Figure 35 respectively. The data in these figures is summarised in Table 4. On average, rainfall is projected to decrease by 2 percent under Scenario Cmid, but could increase by 1 percent under Scenario Cwet or decrease by 6 percent under Scenario Cdry. These changes are not evenly distributed across the year. Under Scenario Cwet, the largest increases in rainfall are projected to occur in summer and winter. Under Scenario Cmid, decreases in rainfall are projected for summer, autumn and spring with a slight increase in winter. Under Scenario Cdry, the largest decrease in rainfall is projected to occur in summer and spring. As the changes in rainfall were derived separately, both annually and
for each season, the seasonal averages in Table 4 do not combine to give the annual average. This is because Cwet may for example come from four different models – one for each of the four seasons. However, Cwet for the annual result comes from just one model.

The mean monthly rainfall for the whole of Tasmania and each of the five reporting regions is shown in Figure 36. It shows average conditions over the last 84 years (Scenario A) as well as the median and projected range for ~2030 (where the range is defined by Cwet and Cdry). Figure 36 shows that rainfall is projected to decrease across most regions (Cmid is lower than A) apart from the Derwent-South East where rainfall may increase in winter but decrease for the rest of the year. In addition, for most months in most regions, Scenario A is close to the top of the Scenario C range, implying that future conditions will be drier than past conditions.

It is not possible to compare Scenario B (Figure 10) with Scenario C (Figure 36). This is because Scenario B is based on an 11-year average, while Scenario A and Scenario C are based on 84-year averages. Scenario B can be compared with Scenario A as it is a subset of it. Comparison of Scenario C relative to Scenario A indicates that future conditions will be drier across large portions of the state. Comparison of Scenario B relative to Scenario A indicates that the last 11 years have been drier than the last 84 years across large portions of the state. This project does not consider short-term trends and therefore it is not possible to say whether the next 11 years will be wetter or drier than the most recent 11 years.

Table 4. Changes in rainfall under scenarios Cwet, Cmid and Cdry

<table>
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<td>16%</td>
<td>18%</td>
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<td>0.5%</td>
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<td>-10%</td>
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<td>97%</td>
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</tr>
<tr>
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<td>-15%</td>
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<td>-21%</td>
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<td>decrease</td>
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<tr>
<td>Percent change for</td>
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Figure 25. Spatial distribution of percent change in mean annual rainfall across Tasmania under Scenario C under the medium global warming scenario relative to Scenario A.
Figure 26. Spatial distribution of percent change in mean summer rainfall across Tasmania under Scenario C under the medium global warming scenario relative to Scenario A.
Figure 27. Spatial distribution of percent change in mean autumn rainfall across Tasmania under Scenario C under the medium global warming scenario relative to Scenario A.
Figure 28. Spatial distribution of percent change in mean winter rainfall across Tasmania under Scenario C under the medium global warming scenario relative to Scenario A.
Figure 29. Spatial distribution of percent change in mean spring rainfall across Tasmania under Scenario C under the medium global warming scenario relative to Scenario A.
Figure 30. Spatial distribution of number of 14 km resolution pattern-scaled global climate models showing a decrease (or increase) in future mean annual and seasonal rainfall across Tasmania (note that 15 global climate models are used)
Figure 31. Spatial distribution of percent change in mean annual rainfall across Tasmania under scenarios Cwet, Cmid and Cdry relative to Scenario A.

Figure 32. Spatial distribution of percent change in mean summer rainfall across Tasmania under scenarios Cwet, Cmid and Cdry relative to Scenario A.
Figure 33. Spatial distribution of percent change in mean autumn rainfall across Tasmania under scenarios Cwet, Cmid and Cdry relative to Scenario A.

Figure 34. Spatial distribution of percent change in mean winter rainfall across Tasmania under scenarios Cwet, Cmid and Cdry relative to Scenario A.
Figure 35. Spatial distribution of percent change in mean spring rainfall across Tasmania under scenarios Cwet, Cmid and Cdry relative to Scenario A
4.8 Change in future daily rainfall amounts

To account for changes in future daily rainfall amounts, large daily rainfalls were scaled differently to small daily rainfalls. The scaling factors for the different rainfall amounts were determined by comparing daily rainfall simulations from the CCAM-downscaled GFDL 2.0 GCM for a SRES A2 run for two 20-year time slices: 2046 to 2065 and 1981 to 2000.

The method used is illustrated in Figure 37 showing spring rainfall simulations from a grid cell in south-west Tasmania. Figure 37a compares the 2046 to 2065 and 1981 to 2000 daily rainfall distributions for autumn, and Figure 37b shows the percent changes in 2046 to 2065 rainfall relative to 1981 to 2000 rainfall at the same daily rainfall exceedances. To obtain a smooth transition in the ‘daily scaling’ factors, the percent changes were estimated by averaging the rainfall amounts over exceedance ranges: 1st, 5th, 10th, and every 5 percent upwards to the 30th percent. However, if an observed daily rainfall of less than 1 mm was reached before the 30th percentile exceedance, it was used instead. The
percent changes at the discrete rainfall exceedance values were then interpolated to obtain the percent changes for all the rainfall exceedance values (see Figure 37). It can be seen that although future spring rainfall for this grid cell is projected to decrease slightly, the more intense rainfall events will actually increase.

Each of the four seasons is considered separately. As in the estimation of the seasonal scaling factors in Section 4.3, the changes for the different rainfall exceedances are expressed as a percent change per degree global warming, which are then multiplied by the change in temperature for each of the global warming scenarios for ~2030 relative to ~1990 to obtain changes for the different rainfall percentiles for the different global warming scenarios (0.7, 1.0 and 1.3 °C).

For each of the three global warming scenarios, the scaling factors described above were used to scale the daily rainfall amounts in the 1924 to 2007 daily rainfall series to obtain 84 years of daily rainfall series for a ~2030 climate relative to a ~1990 climate. The entire series was then scaled based on the spatial patterns from the CCAM dynamically downscaled GFDL 2.0 results, and then by the seasonal scaling factors from the 15 GCMs (procedure shown in Figure 12) to produce the final Scenario C rainfall time series.

![Figure 37. Example plots showing method used to estimate changes in the different daily rainfall amounts. (a) compares the 2046 to 2065 and 1981 to 2000 daily rainfall distributions. (b) shows the percent changes in the different rainfall exceedances for 2046 to 2065 relative to 1981 to 2000](image)

Figure 38 shows the percent change in annual, summer, autumn, winter and spring future extreme daily rainfall as derived from the CCAM-downscaled GFDL 2.0 GCM. It predicts more intense rainfall across most of Tasmania in all four seasons, although particularly in summer and spring, and less so in winter and autumn. The results are in broad agreement with those at the GCM grid scale. For this reason, and because the changes in rainfall intensity from the CCAM-downscaled GFDL 2.0 GCM are at a higher resolution, these were used in the current project. This approach is comparable with the decision to use the spatial patterns of rainfall changes from the CCAM-downscaled GFDL 2.0 GCM as described in Section 4.7.
Figure 38. Spatial distribution of percent change in annual and seasonal future extreme daily rainfall (1st percentile rainfall) as derived from the CCAM-downscaled GFDL 2.0 global climate model.
5 Conclusions

This report describes the production of the three climate scenarios used for the hydrological modelling in the CSIRO Tasmania Sustainable Yields Project. The three climate scenarios are historical climate (Scenario A), recent climate (Scenario B), and future (~2030) climate (Scenario C). All three climate scenarios have 84 years of daily climate data.

The historical climate sequence (Scenario A) is derived on a 0.05 x 0.05 degree (~5 km x 5 km) grid over the whole of Tasmania for the period 1924 to 2007. The mean annual rainfall for this period averaged over Tasmania is 1266 mm. Rainfall is winter-dominated, with mean maximum monthly rainfall occurring in July or August and mean minimum monthly rainfall occurring in January or February. The seasonal differences are greatest in the north-west of Tasmania and are reduced moving towards the south-east. There is a clear east–west rainfall gradient across Tasmania, with rainfall highest in the west (mean annual rainfall of more than 4000 mm for the wettest grid cell) and lowest in the east (mean annual rainfall of just over 450 mm for the driest grid cell).

The recent climate scenario (Scenario B) is based on an 84-year (same length as Scenario A) climate series created simply by repeating the climate of the past 11 years (1 January 1997 to 31 December 2007). In general, the climate of the last 11 years has been drier than that of the last 84 years. Over the whole of Tasmania, mean annual rainfall under Scenario B is 1193 mm (a 6 percent reduction). The reductions in rainfall are not distributed evenly throughout the year, with the largest reductions across every region occurring in autumn. The next largest seasonal reductions are in summer, followed by winter in almost all areas of the state. Changes in spring are minimal.

The future (~2030) climate scenario (Scenario C) is derived by modifying the historical climate sequence (Scenario A) based on 15 global climate models (GCMs) and dynamically downscaled projection of ~2030 climate. The magnitude of the changes in rainfall between Scenario A and Scenario C are derived from the GCMs; however, the spatial patterns of the changes in rainfall are taken from the GFDL 2.0 GCM, dynamically downscaled using the CCAM model. In addition, to account for changes in the future daily rainfall distribution, different daily rainfall amounts are scaled differently.

While there are considerable differences in the rainfall projections for ~2030 between GCMs, the majority of GCMs show a decrease in future mean annual rainfall, particularly across the northern half of Tasmania where almost all models agree drying will occur. Even in southern Tasmania, one-half to two-thirds of the models agree that drying will occur. The vast majority of the models agree that rainfall decreases in spring and summer, again particularly across the northern half of Tasmania. Most models also agree that rainfall decreases in autumn, with around two-thirds projecting drier conditions across the northern half of Tasmania and over one-half projecting drier conditions across the southern half of Tasmania. Most models also agree that drying will occur in winter across the northern half of Tasmania, but that rainfall increases across the southern half of Tasmania.

The second wettest, median and second driest climate models were taken as scenarios Cwet, Cmid and Cdry respectively. On average, for the whole of Tasmania, rainfall could increase by 1 percent under Scenario Cwet, decrease by 2 percent under Scenario Cmid or decrease by 6 percent under Scenario Cdry. Under Scenario Cwet, the largest increases in rainfall occur in summer and winter. Under Scenario Cmid, decreases in rainfall occur in summer, autumn and spring with a slight increase in winter. Under Scenario Cdry, the largest decrease in rainfall occurs in summer and spring but with drying all year round.
6 References


Tasmania Sustainable Yields Project reports

Region reports


Technical reports


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Enquiries
More information about the CSIRO Tasmania Sustainable Yields Project can be found at <www.csiro.au/partnerships/TasSY.html>. This information includes the full terms of reference for the project and all associated reporting products.