A method for estimating climate change impacts on mean and extreme rainfall and runoff

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EXTENDED ABSTRACT

This paper compares runoff simulations for historical rainfall (1901-1998) and rainfall scenarios for 2035 and 2085 for six catchments in Australia, each in a different GCM grid square. Runoff is simulated using the conceptual daily rainfall-runoff model SIMHYD. Rainfall scenarios are estimated from the CSIRO Mark 2 General Circulation Model (GCM) simulations for A2 emissions (a mid to high greenhouse gas emission scenario), using a scaling method that considers daily patterns of rainfall change simulated by the GCM, and regresses these changes against global temperature. The patterns of change at the GCM scale are applied to the historical catchment rainfall to produce the rainfall scenarios.

The methodology described and implemented in this paper (the "daily scaling method") is designed to consider changes in extreme daily rainfall and changes in the frequency of wet days, not just changes in average rainfall. The daily scaling method applies different scaling to different rainfall amounts, compared to the commonly used "constant scaling method" that scales all the daily rainfall by a constant factor that is based on changes in average rainfall at the GCM scale. The daily scaling method involves ranking GCM daily rainfall for a given grid square and a given month, over 30 year periods (say 1961-1990 and 2071-2100). Changes in the ranked GCM rainfall are used to scale ranked catchment or point rainfall. An improvement to the daily scaling method, which is implemented in this paper, is to consider 41 overlapping 30-year periods from transient GCM runs that span the period 1871-2100, to calculate maximum GCM rainfall and percentiles of GCM rainfall at each of the 41 timesteps, and to regress these values against global warming. This gives a robust smoothed pattern of change in the GCM rainfall, with each component of the pattern having a linear response to global warming.

The results presented in this paper show decreases in mean annual rainfall with global warming in five of the six catchments, while extreme rainfall increases in five of the six catchments. Changes in rainfall are amplified in runoff, leading to significant decreases in mean annual runoff in five of the six catchments.

The potentially different impact of global warming on different rainfall amounts highlight the advantage of the daily scaling method over the constant scaling method. This is particularly important because the climate change projections indicate increases in extreme rainfall, even at locations where mean annual rainfall is projected to decrease. Because rainfall-runoff is a threshold process, where most of the runoff is generated as a result of high rainfall events, the constant scaling method overestimates decreases in runoff where there is a decrease in mean annual rainfall, and underestimates increases in runoff where there is an increase in mean annual rainfall.

The advantage of the daily scaling method over the constant scaling method in more accurately estimating extreme rainfall and therefore extreme runoff is also important because floods and the generation of sediments and pollutant loads are directly related to extreme runoff events.

The analysis presented here is based on a single GCM and emissions scenario, and as such it should only be considered as an example to illustrate the methodology. Many GCMs and emissions scenarios exist, and the uncertainties associated with these are high. Exploration of the ranges of uncertainty associated with climate projections should be considered in any full assessment of the impacts of climate change.

1. INTRODUCTION

A simple and widely implemented methodology for applying climate changes simulated by global-scale climate models to catchment runoff involves three steps:

1. Calculation of changes in GCM rainfall and potential evapotranspiration (PET);

2. Scaling of catchment-scale rainfall and PET to reflect the changes at the GCM scale; and

3. Using a rainfall-runoff model to convert the "climate change impacted" rainfall and PET into catchment runoff.

Because hydrologic model simulations have low sensitivity to day-to-day variability in PET (Chiew and McMahon 2002), it is appropriate to use monthly or seasonal scaling factors that are based on averages for evaporation in step 2 above. However, runoff is sensitive to changes in extreme rainfall, as demonstrated by Chiew et al. (2003). The use of averages to scale rainfall does not allow for the possibility that changes in extreme rainfall can be quite different to changes in average rainfall. Harrold et al. (2005) demonstrated that the maximum daily rainfall in January (as modelled in the CSIRO Mark 2 GCM) increased due to global warming over all regions in Australia, even in regions where the average rainfall decreased with warming. Moreover, the strength of the climate change signal (as measured by regression against global temperature) was much stronger for increases in extremes than for changes in average rainfall.

Chiew et al. (2003) used the pattern of change found in ranked GCM daily rainfalls in step 1 above, and applied this pattern to scale historical catchment daily rainfall. This "daily scaling" took into account changes in daily rainfall (in particular extreme daily rainfalls) and the frequency of wet days simulated in the GCM. The rainfall scenarios were then fed through a rainfall-runoff model, and the changes in runoff were assessed. However Chiew et al. (2003) compared statistics between just two 30-year periods (i.e. 1961-1990 compared to 2021-2050), and this methodology was subject to significant variability in the climate change signal. When similar statistics (which were not presented in the 2003 paper) were calculated for 2071-2100, the results were not always consistent with the 2021-2050 results because of this variability.

The work of Harrold et al. (2005) provides a way to significantly reduce the effect of variability and provide a smooth and consistent climate change signal. Harrold et al. (2005) present statistics for overlapping 30-year periods throughout a transient GCM run for 1871-2100. Regression of these results against global warming gives a much more reliable climate change signal, with each component of the signal varying linearly with global warming. In this current paper, the regression results of Harrold et al. (2005) are applied to generate catchment rainfall for the same six catchments used in Chiew et al. (2003), and the impacts on runoff are assessed.

The daily scaling methodology discussed in this paper is relatively simple compared to alternative approaches for generating rainfall scenarios at fine spatial and temporal scales. These include the stochastic weather generator (Bates et al. 1994) and stochastic downscaling approaches (Charles et al. 1999). Daily scaling only considers changes in daily rainfall magnitudes (including extremes, which is its major advantage) and wet day frequency. It assumes no change in the temporal distribution of events, and does not consider changes in the relative frequency of weather patterns (such as fronts and thunderstorms) that produce rainfall. However, because of its simplicity, daily scaling can be easily applied using different GCMs and different emissions scenarios. This is an important consideration because of the significant uncertainty in: i) projected scenarios of greenhouse gas emissions; ii) sensitivity of the earth's climate to changes in greenhouse gas levels; and iii) the parameter sets used in GCMs. Exploration of the ranges of uncertainty associated with climate projections should be considered in any assessment of the impacts of climate change.

2. CATCHMENT DATA, RAINFALL-RUNOFF MODELLING, SCALING PET

Results from six catchments in different GCM grids are presented in this paper (Figure 1). The catchment areas range from 100 to 600 km^2, while the grid size of the GCM used here (CSIRO Mark 2) is about 3.2 degrees latitude by 5.6 degrees longitude (roughly 350km by 450km).

The daily conceptual rainfall-runoff model SIMHYD is used to estimate runoff in the six catchments from daily rainfall and monthly average areal potential evapotranspiration (APET) data. Chiew et al. (2002) provide a description of the model, input data and an earlier calibration of the model for 331 Australian catchments (note that the APET data has been revised and the models recalibrated in 2005).

Daily rainfall data were available from 1901 to 1998, and the optimised parameter values in SIMHYD were used to estimate daily runoff from 1901 to 1998. For the climate change impact simulations, the historical rainfall and APET were modified to reflect climate change. The modified data were then used to run SIMHYD, with the same optimised parameter values, to estimate daily runoff in a greenhouse-enhanced environment.

The methodology for generating climate impacted rainfall is described in the next section. Based on changes in temperature, the historical APET values were scaled by a constant factor of 4% for 2035 and 11% for 2085.

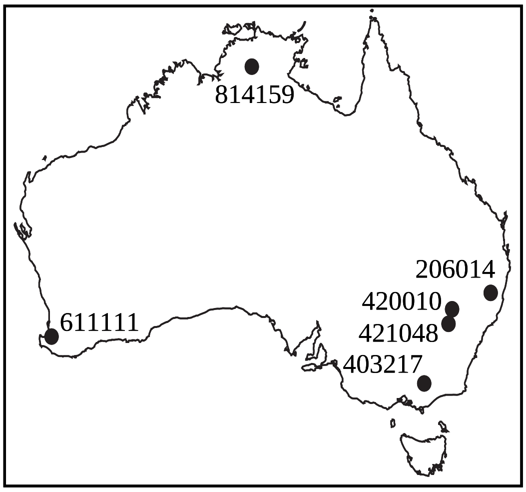

Figure 1. Locations of catchments.

3. GENERATION OF CLIMATE CHANGE IMPACTED RAINFALL

Figure 2 (adapted from Chiew et al. 2003) illustrates the principle of "daily scaling", which applies relative changes in the distribution of daily rainfall at the GCM scale to rainfall at the catchment scale, in order to produce a scenario of "climate change impacted" catchment rainfall. Panels a and b show ranked GCM daily rainfalls for current and future conditions respectively. Panel c shows the ranked differences expressed as ratios relative to current values. This "daily pattern of change" can then be used to scale the catchment rainfall (panel d) to provide the rainfall scenario (panel e).

The daily scaling methodology was developed using an ensemble of five transient runs (1871-2100) of the CSIRO Mk2 GCM for the A2 greenhouse gas emission scenario (Watterson and Dix, 2003). This GCM was produced in Australia, with emphasis on calibrating the model over the Australian region, and it has been shown to have a mid-range sensitivity to changes in greenhouse gases and other forcings compared to other GCMs (CSIRO 2001). The A2 emissions scenario is a mid- to high-range scenario of future greenhouse gas emissions that is commonly considered in change studies.

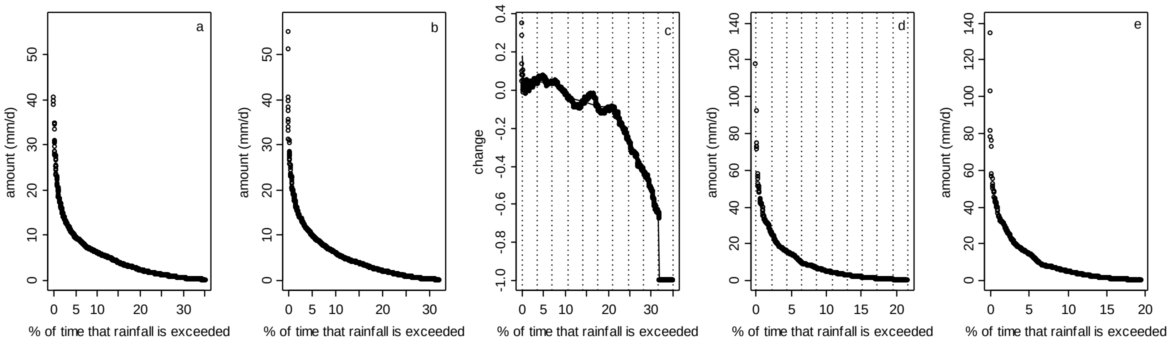

Figure 2. Illustration of the daily scaling method for January rainfall for East Victoria and Catchment 403217 (a) ranked GCM daily rainfall for 1961-1990, (b) ranked GCM daily rainfall for 2021-2050, (c) pattern of change in ranked daily GCM rainfall, (d) ranked catchment rainfall (over 1901-1998), (e) scaled catchment rainfall to reflect 2021-2050 climate

Harrold et al. (2005) improved the daily scaling methodology by applying a regression approach. Analysis is based on overlapping 30-year periods extracted at 5-year intervals spanning the entire timespan of the transient GCM ensemble, rather than comparison of just two 30-year periods. In addition to this, regression is made against global average temperature. This “per degree global warming” approach standardises the results and makes the simplifying assumption that changes are a linear function of the global temperature.

The regression approach is illustrated in Figures 3 to 5. Figure 3 shows how global average temperature increases with time for the CSIRO Mark 2 GCM for the A2 emissions scenario. Figure 4 shows the GCM daily maximum rainfall in January (mm/day, average of the 5 most extreme values) for the east Victoria grid square. Each datapoint in the panel is for a 30-year period centred on that (year, global average temperature). The 30-year period is shifted by five years at a time, giving 41 datapoints centred on 1885 through to 2085. In Figure 5, regression is made against the global average temperature.

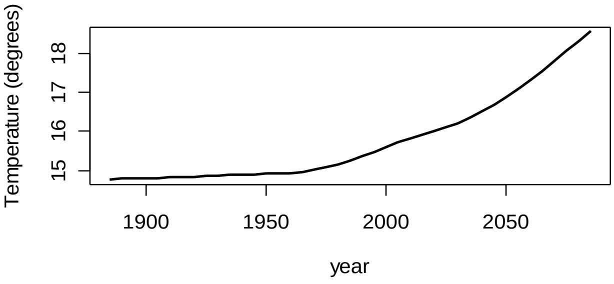

Figure 3. Global annual mean surface temperature (°C) for the CSIRO Mark 2 GCM.

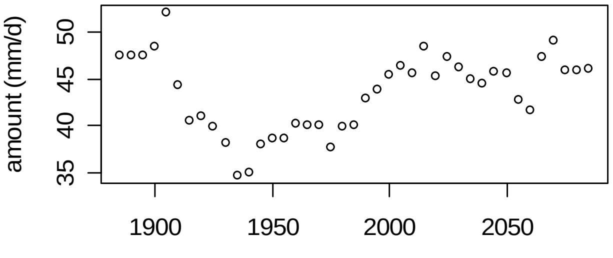

Figure 4. GCM maximum daily rainfall in January (mm/day) for the east Victoria grid square.

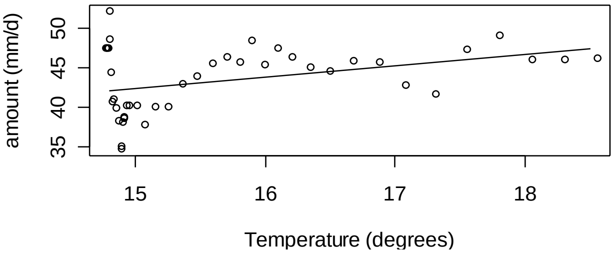

Figure 5. GCM maximum daily rainfall in January (mm/day) for the east Victoria grid square, plotted against global average temperature.

Note that the global average temperatures for 1975, 2035, and 2085 are 15.1°C, 16.4°C and 18.6°C respectively. Reading the amount (mm/day) for these temperatures from the regression line in Figure 5 gives smoothed estimates for the maximum daily rainfall that are more robust than the unsmoothed estimates (circles).

By repeating the regressions for other parameters of the distribution of ranked daily rainfall, we are able to define a smoothed daily pattern of change for any given global warming. We have done this for 21 parameters that can be used to define a summarised version of the daily pattern of change shown in Figure 2c. These parameters are the amounts at each of the first ten percentile points of the curve, at the decile points, and the future conditions wet day frequency (to standardise across all years, the percentile and decile points are defined by setting 100% equal to the wet day frequency for 1975). As a guide, the locations of the 10 deciles are shown as vertical lines on Figure 2c. At each of the x-locations, the y-value is defined as (F-C)/C, where F refers to the parameter value in the future climate, and C refers to the parameter value in the current climate (1975), and F and C are read from regression lines similar to the one shown in Figure 5. Each of the (F-C)/C values represents a “change ratio” for scaling catchment rainfall. When scaling catchment rainfall, 100% is set equal to the wet day frequency for the catchment (Figure 2d). Linear interpolation is used between the points.

Selected points from the resulting pattern of change for the east Victoria GCM grid square for January for 2035 and 2085 are shown in Table 1. 12 sets of these patterns of change were constructed, one for each month, and then used to scale catchment rainfall. This procedure was repeated for the six locations shown in Figure 1 and Table 2. Note that, following Harrold et al. (2005), we define a wet day as 0.1 mm or more of rainfall at the GCM scale. This avoids problems with GCM drizzle.

All except the last two columns in Table 1 are change ratios that were used to scale the catchment rainfall. The last two columns are wet day frequencies. Note that 1%, 5%, 10% and 50% in this table are not exceedance probabilities. The 1975 wet day frequency defines the 100% x-ordinate, and also defines exceedance probability; for example, the exceedance probability for the "1% rainfall" is (.01 × the wet day frequency).

Table 1 shows that the change in maximum rainfall (and other low percentile rainfalls) for East Victoria in January is much greater than the change in average rainfall. This is consistent with the findings of Harrold et al. (2005), and was found to be the case across locations and across seasons. Maximum rainfalls and low percentile rainfalls often increase even when average rainfalls decrease. This is very important because it significantly affects runoff, as shown in the results presented in the next section.

4. RESULTS AND DISCUSSION

Table 2 shows the percentage changes to the mean annual rainfall and runoff and to the extreme and high daily rainfall and runoff (0.1%, 1% and 5% exceedance probabilities) simulated by the hydrological model for 2035 and 2085, relative to the historical climate (1901-1998). The 1% daily rainfall is about the third or fourth highest daily rainfall in a year, and the 0.1% rainfall is the highest daily rainfall in about two to three years. The table shows percentage changes for model runs using rainfall data obtained from the daily scaling and constant scaling methods. The percentage changes in the extreme and high daily rainfall are not shown for the constant scaling method because the changes are similar to the changes in the mean annual rainfall.

Mean annual rainfall reduces with global warming at five of the six locations/GCM grid squares, with the largest reduction in south-west Australia. In the Northern Territory location/grid square, mean annual rainfall increases with global warming. These estimates are consistent with the –15% to +5% change in average rainfall for most of eastern Australia and a rainfall decrease of up to 20% in south-west Australia in the climate change projections for 2030 published by CSIRO (2001).

The 0.1% daily rainfall increases with global warming at all locations except Northeast New South Wales, where there is little change. The percentage change values for 1% and 5% rainfalls are not as high as the 0.1% values, and in some cases they are neutral or slightly negative. The changes in rainfall are magnified in runoff. Comparing mean rainfall and runoff changes for 2085, for East Victoria a 5% decrease in rainfall translates to a 10% decrease in runoff for daily scaling (13% for constant scaling). For the Northern Territory a 4% increase in rainfall translates to a 16% increase in runoff for daily scaling (13% for constant scaling).

The daily scaling results for runoff present a picture that is different to that for constant scaling, and arguably more valid (because daily scaling considers changes in extreme rainfall that are different from the average rainfall, and most of the runoff is generated during high rainfall events). For example, for Central New South Wales the constant scaling and daily scaling results for mean runoff are of opposite sign, and for Central North New South Wales the reduction in mean runoff for daily scaling is less than half that estimated by constant scaling. There are also very significant differences between the results for daily and constant scaling for 0.1%, 1%, and 5% runoff.

Because most locations show an increase in extreme rainfall, even when there is a decrease in mean annual rainfall, constant scaling overestimates decreases in runoff where there is a decrease in mean annual rainfall, and underestimates increases in runoff where there is an increase in mean annual rainfall.

The results presented in Table 2 are an improvement on the results presented in Chiew et al. (2003) because the rainfall changes are now based on regression through 41 data points, not just two data points. The SIMHYD rainfall-runoff models, and evaporation inputs to SIMHYD, were also revised based on recent research, as noted in section 2.

Figure 6 shows frequency plots of daily rainfall and runoff for all six catchments for historical, 2035, and 2085 conditions. Results are shown for two seasons, namely November-April and May-October. In every catchment, the changes in rainfall (shown in the first and third columns) are fed into the SIMHYD rainfall-runoff model along with increases in APET of 4% (for 2035) and 11% (for 2085). It can be seen from the figures that there are significant seasonal differences in the rainfall and runoff changes, and that these differences vary from catchment to catchment.

Table 1. Daily Pattern of Change in GCM grid-square rainfall for East Victoria in January for 2035 and 2085. All values shown (except the wet day frequencies in the last two columns) are relative changes calculated as (F-C)/C, where F is the value in 2035 or 2085, and C is the value in 1975. In this table, the exceedance probability for the "x% rainfall" is (x% × the 1975 wet day frequency).

	average rainfall	max rainfall	1% rainfall	5% rainfall	10% rainfall	50% rainfall	1975 wet day freq. (defines 100%)	2035/ 2085 wet day freq.
2035	0.003	0.045	0.026	0.020	0.034	-0.026	34.2%	32.6%
2085	0.009	0.120	0.071	0.054	0.092	-0.070	34.2%	29.9%

Table 2. Percentage changes to the mean annual rainfall and runoff and to the 0.1%, 1% and 5% daily rainfall and runoff in 2035 and 2085 relative to historical climate (1901-1998). Results from simulations with rainfall scenarios derived using both the daily scaling and the constant scaling methods are shown. In this table, 0.1%, 1% and 5% are exceedance probabilities. Rainfall and runoff are reported in mm.

		Rainfall			Runoff				
		1901-1998 mm	2035 % change (daily)	2085 % change (daily)	1901-1998 mm	2035 % change (daily)	2035 % change (const)	2085 % change (daily)	2085 % change (const)
North-East New South Wales (206014 Wollomombi River at Coninside)	Mean	794	-1%	-4%	95	-3%	-6%	-10%	-13%
	0.1 %	58	1%	-1%	26	-3%	-5%	-16%	-8%
	1 %	28	-2%	-6%	3	-5%	-6%	-14%	-15%
	5 %	12	0%	-2%	1	-2%	-6%	-8%	-16%
Central-North New South Wales (420010 Wallumburrawang Creek at Bearbug)	Mean	635	-2%	-4%	18	-3%	-9%	-9%	-22%
	0.1 %	63	2%	6%	3	-5%	-6%	-3%	-11%
	1 %	29	0%	1%	1	-2%	-7%	-8%	-14%
	5 %	11	-2%	-4%	0	-6%	-8%	-18%	-20%
Central New South Wales (421048 Little River at Obley No 2)	Mean	626	-0%	-1%	43	1%	-2%	3%	-4%
	0.1 %	53	4%	10%	7	6%	1%	18%	6%
	1 %	26	3%	5%	2	-1%	-4%	2%	-4%
	5 %	10	0%	0%	1	-2%	-5%	-4%	-9%
East Victoria (403217 Rose River at Matong North)	Mean	1283	-2%	-5%	441	-4%	-5%	-11%	-13%
	0.1 %	77	2%	9%	26	9%	-10%	12%	-13%
	1 %	43	2%	5%	12	0%	-2%	0%	-6%
	5 %	21	0%	0%	6	-4%	-5%	-8%	-10%
South-West Western Australia (611111 Thomson Brook at Woodperry Homestead)	Mean	932	-3%	-9%	160	-6%	-9%	-16%	-21%
	0.1 %	53	6%	15%	10	-4%	-9%	0%	-13%
	1 %	31	2%	5%	5	0%	-4%	-4%	-12%
	5 %	16	-2%	-6%	2	-7%	-9%	-16%	-21%
North-West Northern Territory (814159 Seventeen Mile Creek at Waterfall View)	Mean	1056	2%	4%	149	6%	4%	16%	13%
	0.1 %	97	3%	8%	20	8%	8%	22%	23%
	1 %	48	3%	9%	7	6%	4%	17%	14%
	5 %	19	1%	3%	2	5%	4%	12%	12%