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The hydrologic impact of daily versus seasonal scaling of rainfall in climate change studies

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Abstract: There have been numerous recent studies examining the hydrologic consequences of climate change. One of the largest of these is the CSIRO Sustainable Yields project which is being carried out across four regions in Australia – the Murray-Darling Basin, South-west Western Australia, Northern Australia, and Tasmania (http://www.csiro.au/partnerships/SYP.html). The Sustainable Yields project has made an implicit assumption that the scaling of different daily rainfall amounts by a different factor has a significant impact on hydrologic response. This paper aims to test the hypothesis that this daily scaling of rainfall produces a measurable impact on hydrologic response.

To test this hypothesis, two different time series of rainfall are created. The first scales all of the daily rainfall amounts in a season by the same factor, for example, all of the daily rainfall in summer (DJF) may be scaled down by 15%. The second also has a 15% reduction in summer rainfall, but the individual daily amounts are scaled differently depending on the volume of daily rainfall; for example, the first percentile of rainfall may be scaled up by 5%, with consequently greater reductions in the remainder of the rainfall such that the overall total reduction in summer rainfall is 15%. These two time series are derived for 15 of the 23 IPCC GCMs (General Circulation Models) which have readily accessible daily rainfall data. For each of the 15 GCMs, these two time series of rainfall are then used as inputs into the SIMHYD rainfall-runoff model and the hydrologic impact of the daily scaling examined.

Results show that changes in the 1st percentile of rainfall (i.e. the most intense daily rainfall events) average between -4 and +8% across Tasmania for 15 of the GCMs in the 4th IPCC report, however these increases can be much greater over specific geographic areas. These average changes in 1st percentile rainfall result in a 0 to 8 mm increase in mean annual runoff (corresponding to 1.3%) as shown in Figure 1, although once again these increases can be much greater over specific areas. Note that increases in 1st percentile rainfall have a much greater impact on runoff than similar sized decreases.

Many GCMs indicate that the extreme rainfall will increase in the future, even in areas where mean annual rainfall is projected to decrease. As high rainfall events generate significant runoff, climate change impact on runoff studies that do not take this into account will underestimate changes in future runoff. The results from this study indicate that the modelled change in future mean annual runoff averaged over Tasmania can differ by 8 mm (1–2%), depending on whether or not daily rainfall amounts are scaled differently. This difference is comparable to the median and range of estimated changes in future runoff based on projected rainfall changes from 15 GCMs and may therefore be significant.

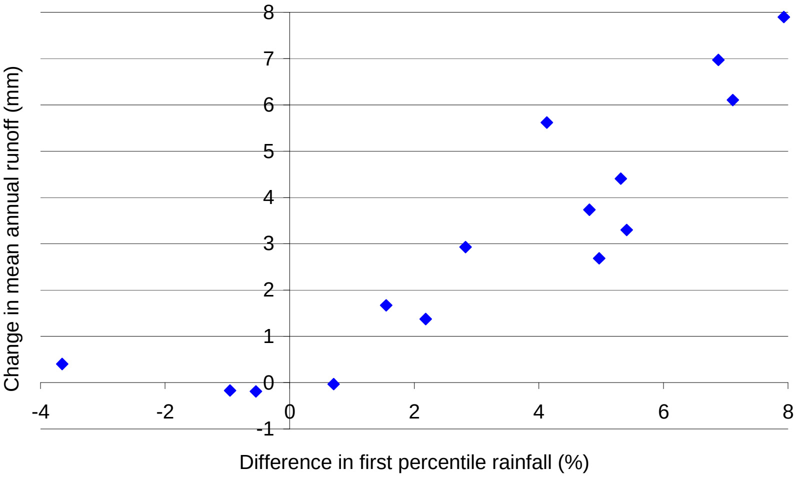

Figure 1. Relationship between change in 1st percentile of daily rainfall and mean annual runoff

Keywords: *Climate change, hydrologic response, daily scaling, seasonal scaling*

1. INTRODUCTION

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 twelve years rank among the twelve 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). 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.

Global warming will lead to changes in regional climate. General Circulation Models (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 skill 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 (IPCC, 2007) are used in this study. These 15 models are chosen because they have readily available daily rainfall data which is essential for the daily scaling technique used in this study.

There have been numerous recent studies examining the hydrologic consequences of climate change. One of the largest of these is the CSIRO Sustainable Yields project which is being carried out across four regions in Australia – the Murray-Darling Basin, South-west Western Australia, Northern Australia, and Tasmania (http://www.csiro.au/partnerships/SYP.html). The Sustainable Yields project has made an implicit assumption that the scaling of different daily rainfall amounts by a different factor has a significant impact on hydrologic response. The reason for this is that the largest rainfalls produce most of the runoff, and therefore a change in the largest rainfalls should have a consequently larger impact on runoff. As many GCMs predict an increase in the largest daily rainfall amounts, even when they predict an overall decrease in rainfall, this effect could be significant in climate change studies. This paper aims to test the hypothesis that the daily scaling of rainfall produces a measurable impact on hydrologic response.

2. METHODS

All of the results shown here are based on the scaling of the historical daily rainfall sequence for the period 1924 to 2007 using one of two techniques – seasonal or daily scaling. For each of the 15 GCMs, mean annual runoff from a rainfall-runoff model driven with the historical rainfall series scaled using seasonal scaling is compared to mean annual runoff from a rainfall-runoff model driven with the historical rainfall series scaled using daily scaling.

2.1. Seasonal Scaling

For each of the 15 GCMs, and for each season (DJF, MAM, JJA, SON) and each GCM grid point, the simulated rainfall is plotted against simulated global average surface air temperature. A linear regression is fit through the data points and the slope of the linear regression gives the change in rainfall per degree of global warming. Figure 2 shows an example plot for one GCM, one grid cell and one season. In total, more than 300 of these regressions are derived (15 GCMs x between 4 and 12 GCM cells across Tasmania x 4 seasons). The slope of some of these lines are significant while others are not. Those that are significant are demonstrating a significant change in seasonal rainfall for that grid cell under global warming. Those that are not significant are retained in the analysis with the caveat that small changes in seasonal rainfall may not be statistically

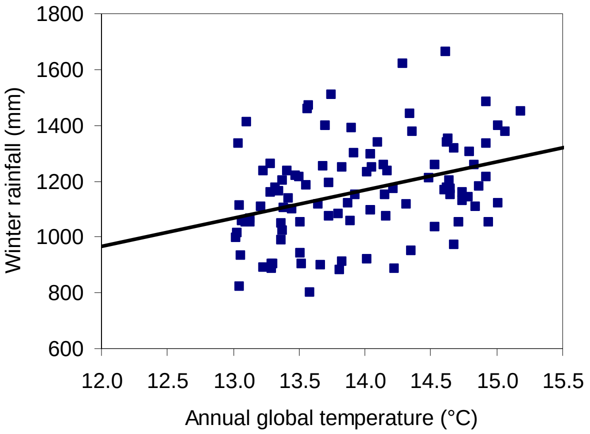

Figure 2. Example plot for one GCM, one grid cell and one season showing the method used to estimate change in rainfall for seasonal scaling.

significant.

The absolute change in rainfall per degree of global warming is converted to a percent change per degree of global warming relative to the model baseline climate of 1975 to 2004. This is done to reduce the effect of errors in the baseline rainfall on the magnitude of the simulated change (Whetton et al., 2005). The advantages of this method, also called the pattern scaling method, are that (i) because it decouples the GCM results from particular emissions scenarios, all available ensemble runs from the particular GCM can be used allowing the projections to be estimated from a large dataset, and (ii) by considering the trend in the simulated rainfall, it overcomes the problem of having to account for decadal variability when comparing simulations from two time slices/periods (Whetton et al., 2005; Suppiah et al., 2007). For this paper, a global warming of 1.0°C is used. This is equivalent to the IPCC (2007) median increase in global average surface air temperature by 2030 relative to 1990. For each GCM grid cell and for each season, the baseline 1924 to 2007 daily rainfall data is then scaled by the calculated seasonal scaling factors.

2.2. Daily Scaling

For daily scaling, to account for changes in the future daily rainfall distribution, the different daily rainfall amounts are scaled differently. The scaling factors for the different rainfall percentiles/amounts are determined by comparing daily rainfall simulations from the 15 GCMs over the periods 2046 to 2065 and 1981 to 2000. These time slices are chosen because they are the standard periods for which daily data are available for these 15 GCMs.

The method used is illustrated in Figure 3. The plot on the left compares the 2046 to 2065 and 1981 to 2000 daily rainfall distributions for one particular GCM grid cell in one season, and the plot on the right shows the percent change in 2046 to 2065 rainfall relative to 1981 to 2000 rainfall for the corresponding daily rainfall percentiles. To obtain a smooth transition in the daily scaling factors, the percent changes are estimated by averaging the rainfall amounts over percentile ranges: 1st percentile (all points smaller than 2nd percentile), 5th percentile (all points between 2.5th and 7.5th percentiles), 10th percentile (all points between 7.5th to 12.5th percentiles), and every five percentile range upwards to a highest category (see Figure 3), where all the smallest rainfall amounts are considered together. The highest category bound is defined by the percentile at which the observed rainfall is less than 1 mm, or the 30th percentile if the percentile at which the observed rainfall is less than 1 mm is above the 30th percentile. Therefore, if the highest category bound is the 30th percentile, all rainfall amounts above the 30th percentile are lumped together and used to determine the single value of percent change in rainfall amounts above the 30th percentile. The percent changes at the discrete percentile values are then interpolated to obtain the percent changes for all the rainfall percentiles/ranks (see Figure 3). Similarly to the seasonal scaling, more than 300 of these regressions are derived (15 GCMs x between 4 and 12 GCM cells across Tasmania x 4 seasons).

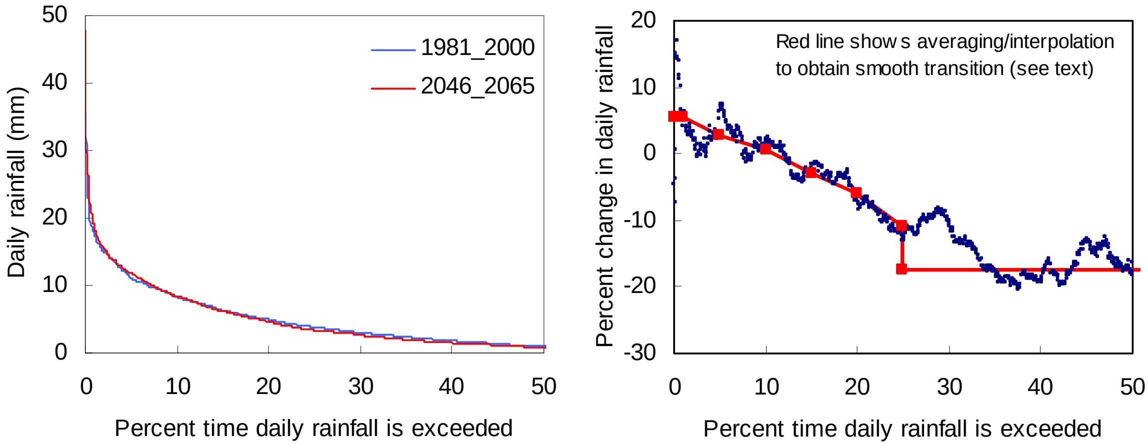

Figure 3. Example plot for one GCM, one grid cell and one season showing the method used to estimate change in rainfall for daily scaling.

For each of the 15 GCMs, the above daily scaling factors are used to scale the different daily rainfall amounts in the 1924 to 2007 daily rainfall series. This entire series is then scaled using the seasonal scaling factors derived in Section 2.1 to ensure that the mean rainfalls in the four seasons are the same as those in Section 2.1.

3. RESULTS

3.1. Rainfall

For the seasonally-scaled rainfall, the entire historical daily rainfall sequence for the period 1924 to 2007 is scaled by the same factor in each season. However, for the daily-scaled rainfall, the daily rainfall sequence is scaled by a different factor depending on the magnitude of the daily rainfall.

As an example of this, Figure 4 compares the percent change in the future 1st percentile rainfall determined using the seasonal scaling and daily scaling methods for the rainfall projections from the GFDL GCM (note that the percent changes to all the daily rainfall amounts are the same in the seasonal scaling method). The differences in the future 1st percentile rainfall between the seasonal scaling and daily scaling methods (right hand side plot in Figure 4) from all 15 GCMs are shown in Figure 6. This figure shows that in general the daily scaling produces an increase in 1st percentile rainfall for most of the 15 GCMs compared to seasonal scaling. Only the NCAR-PCM1, INMCM, and CNRM models predict a decrease in 1st percentile rainfall averaged over the whole State.

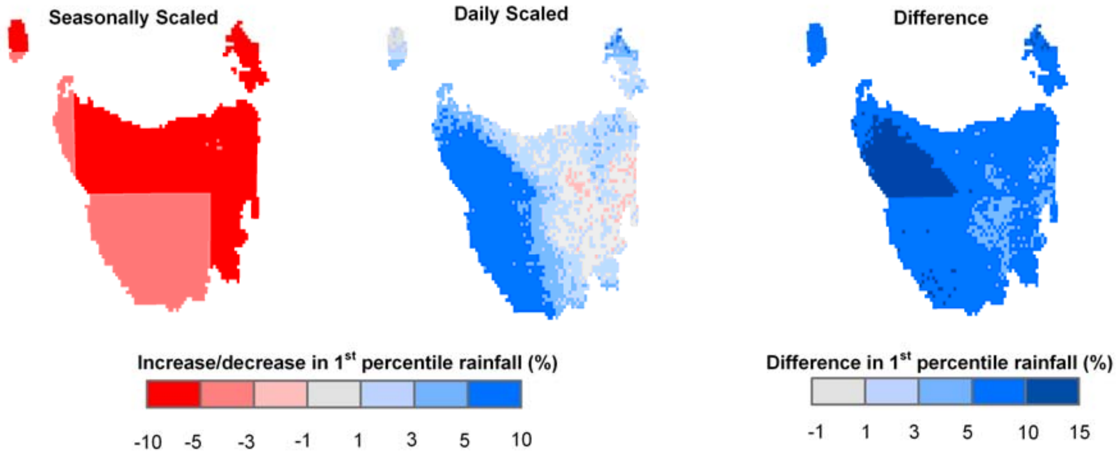

Figure 4. Comparison of daily 1st percentile rainfall for seasonal and daily scaling techniques for the GFDL model.

3.2. Runoff

To evaluate the impact of these changes in 1st percentile rainfall on total runoff, the two future daily rainfall time series determined using the seasonal scaling and daily scaling methods are run through the SIMHYD rainfall-runoff model. This model has been calibrated using observed rainfall and runoff from 89 stream gauges across Tasmania along with a regionalisation technique where the parameters of ungauged grid cells are taken from the nearest calibration grid cell [see Viney et al. (2009a,b) for details]. The differences in runoff between the seasonal scaling and daily scaling daily time series are examined. As an example of this, Figure 5 compares the percent change in the future mean annual runoff determined using the seasonal scaling and daily scaling methods for the rainfall projections from the GFDL GCM. The differences in the future mean annual runoff between the seasonal scaling and daily scaling methods (right hand side plot in Figure 5), from all 15 GCMs are shown in Figure 7. Comparison of Figure 6 with Figure 7 shows that areas that have a higher 1st percentile rainfall under the daily scaling technique also have a higher mean annual runoff. However, reductions in the 1st percentile of rainfall do not necessarily produce reductions in mean annual runoff.

4. DISCUSSION

The impact of an increase (or decrease) in 1st percentile rainfall on mean annual runoff can be seen in Figure 1 which shows that an increase in the magnitude of 1st percentile rainfall of approximately 7% leads to around an extra 8 mm of mean annual runoff (corresponding to around 1.3%). While this is relatively small compared to the total volume of runoff averaged across the whole of Tasmania, it can be significantly higher than this in certain geographic regions as shown in Figure 7 where changes in mean annual runoff of up to 30 mm can be seen (driven by increases of up to 15% in the magnitude of 1st percentile daily rainfall events). Additionally, it can be seen that increases in 1st percentile rainfall have a much greater impact on runoff than similar sized decreases.

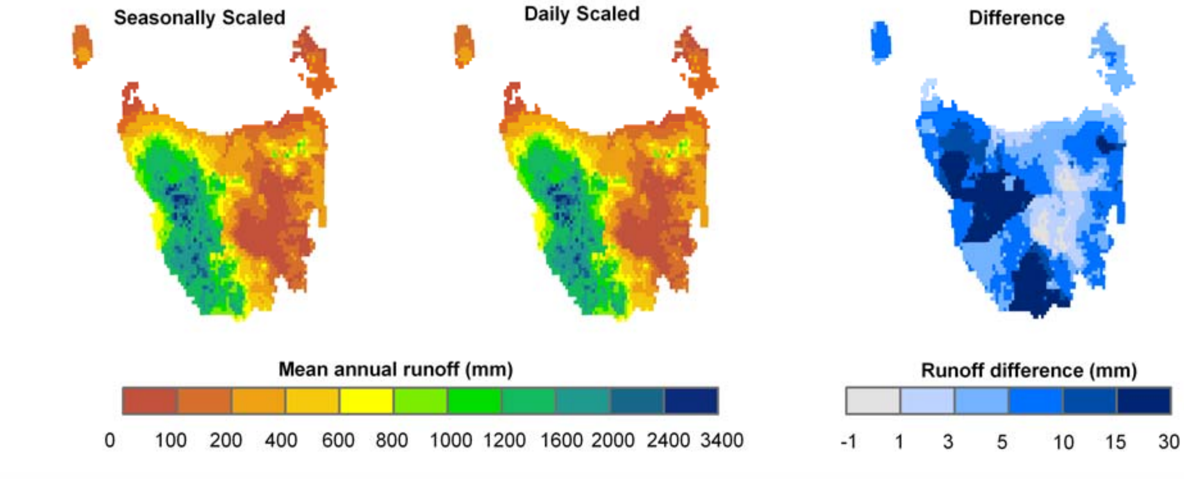

Figure 5. Comparison of mean annual runoff for seasonal and daily scaling techniques for the GFDL model.

5. CONCLUSIONS

Many GCMs indicate that the extreme rainfall will increase in the future, even in areas where mean annual rainfall is projected to decrease. As high rainfall events generate significant runoff, studies which examine climate change impacts on runoff that do not take this into account will underestimate changes in future runoff. The results from this study indicate that the modelled change in future mean annual runoff averaged over Tasmania using the SIMHYD daily rainfall-runoff driven with future daily rainfall determined using a seasonal scaling method (that does not consider changes in the daily rainfall distribution) and a daily scaling method (which considers changes in the daily rainfall distribution) can differ by up to 8 mm (or 1.3%) averaged across the whole State. This difference is comparable to the median and range of estimated changes in future runoff based on projected rainfall changes from 15 GCMs. These differences can also be much greater over specific geographic regions.

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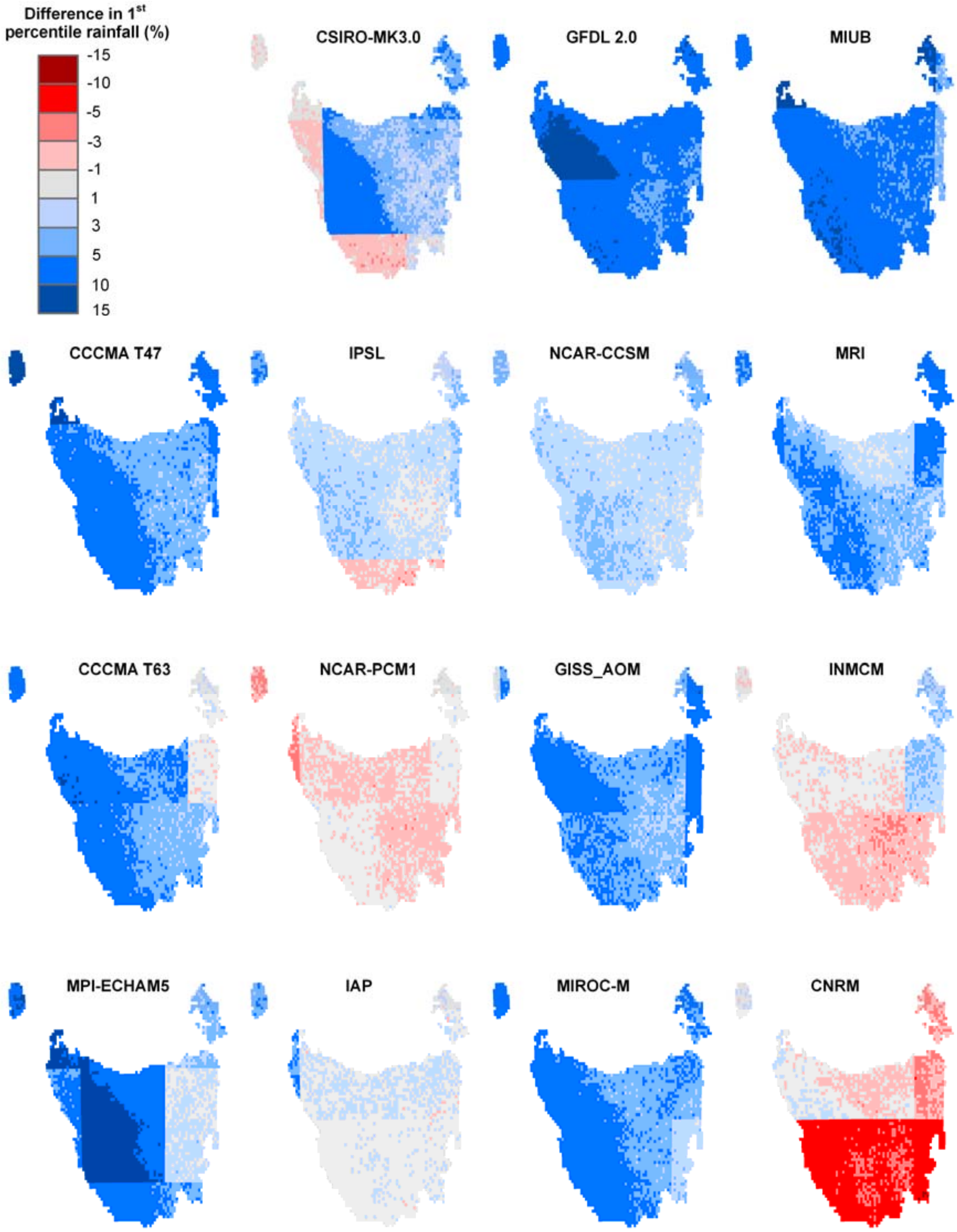

Figure 6. Difference in daily 1st percentile rainfall between daily scaling and seasonal scaling techniques. Positive numbers (blue) indicate where daily scaled rainfall is larger than seasonally scaled rainfall.

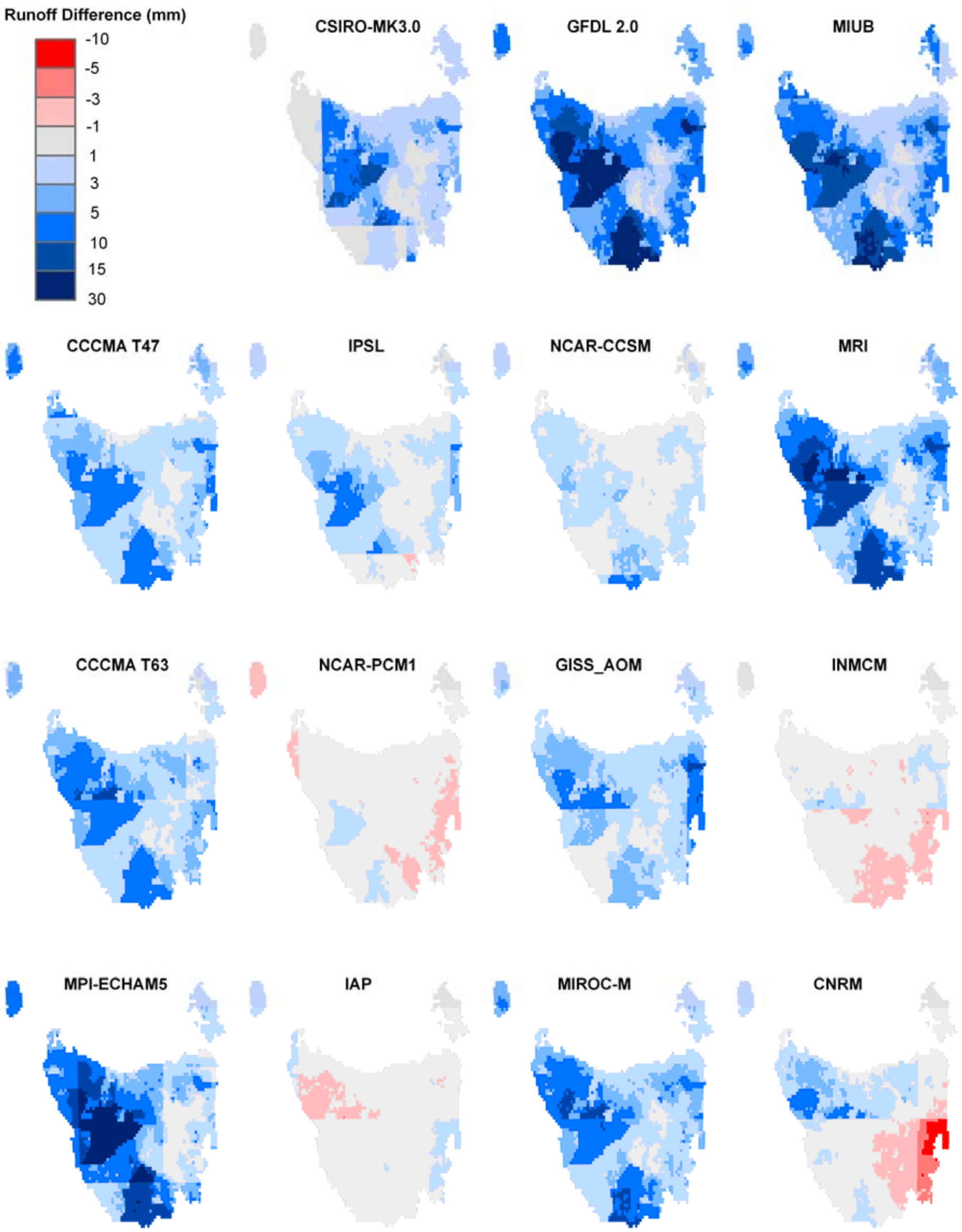

Figure 7. Difference in mean annual runoff between daily scaling and seasonal scaling techniques. Positive numbers (blue) indicate where runoff derived from a daily scaling technique is larger than runoff derived from a seasonal scaling technique