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Generation of rainfall scenarios using daily patterns of change from GCMs

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Abstract This paper proposes a modification of the perturbation approach to downscaling GCM rainfall. The proposed approach uses a daily pattern of change in ranked rainfalls from the GCM, and then scales the ranked point daily rainfall by this pattern of change. This new approach can produce sequences of "climate change impacted" point daily rainfall that are very different in magnitude to sequences that are produced by simpler perturbation methods, especially in terms of rainfall that will produce runoff. We argue that the proposed method is superior to simpler methods, because the method can produce sequences of "climate change impacted" point rainfall that are consistent with the changes in extreme daily rainfalls and changes in the frequency of wet days that occur in the GCM.

Key words downscaling; daily rainfall; global climate models; perturbation methods

INTRODUCTION

Rainfall is a driving variable for surface water hydrology. Climate change is likely to affect rainfall, altering the incidence and severity of floods and droughts. Such changes may have significant impacts on agriculture, water resources, infrastructure, and the environment. However, our best understanding of possible climate change is provided by Global climate models (GCMs) at a resolution that is too coarse to give results that are useful in hydrological studies. Downscaling of the GCM outputs is required (Giorgi *et al.*, 2001).

One of the simplest, and most widely used, techniques for generation of "climate change impacted" rainfall is to perturb observed records of point rainfall by the average change in GCM grid-square rainfall from current to future conditions, calculated on a monthly basis (see e.g. Prudhomme *et al.*, 2002). In this simple approach, all of the daily values occurring in a given month are scaled by the same percentage, regardless of the magnitude of the rainfall. This is despite the fact that the magnitude of extreme daily rainfalls is likely to increase with global warming (Stocker *et al.*, 2001). Using monthly GCM data in the perturbation method gives little indication of changes in daily extremes, which are of great interest in hydrological impact studies. The frequency of wet days may also change; applying the perturbation method with monthly GCM data gives no indication of this change.

An advantage of the perturbation method is that a number of GCMs can be sampled comparatively easily, allowing a range of possible changes in mean rainfall to be tested. Jones & Page (2001) used a climate scenario generator linked to a catchment model to process changes in mean monthly rainfall and potential evaporation from nine GCMs and scale historical daily climate records, and then explore a comprehensive range of changes in the catchment. This investigation was undertaken knowing that daily rainfall would not change uniformly, but it was not possible to sample such a large range of GCMs while producing more plausible changes in catchment daily rainfall. Most of the more plausible downscaling methods require daily data from each GCM to be used, and the application of sophisticated statistical and/or dynamic techniques. This is a resource intensive task, and limits the number of GCMs that can be sampled, increasing the precision of individual scenarios but limiting the range of uncertainty in the global-scale circulation that can be explored.

We commenced this investigation with the aim of diagnosing a method that could augment the perturbation method and produce more realistic changes in rainfall, without losing the ability to sample over a large range of GCMs. This paper presents the initial results of the investigation. A refinement of the perturbation method is presented here, which uses a pattern of change in GCM daily rainfall rather than the average percentage change. Transient GCM simulations are used to obtain patterns of change in ranked daily GCM rainfall from current (say 1961–1990) to future (say 2071–2100) conditions. The patterns of change are calculated separately for each calendar month. These patterns of change are then used to scale ranked historical point daily rainfall, thus obtaining a point rainfall scenario that is consistent with what the GCM is predicting about changes in daily, rather than just monthly, rainfall. In other words, the method is sensitive to the changes in extreme daily rainfalls and changes in the frequency of wet days that occur in the GCM, and produces a more realistic sequence of climate-change-impacted rainfall, compared to the commonly used approach of simply scaling all the historical rainfall values in each month by the same amount.

DAILY DATA FROM THE CSIRO MARK 2 GCM

Data were obtained from the CSIRO Mark 2 GCM for an ensemble of five transient runs for the A2 emissions scenario, and for an ensemble of five transient runs for the B2 emissions scenario (Watterson & Dix, 2002). The emissions scenarios provide plausible future projections of population growth, resource use, and hence greenhouse gas emission levels, which are input to the transient GCM runs. Scenario A2 can be thought of as a "high growth" scenario, and B2 can be thought of as a "moderate growth" scenario. The outputs of the transient Mark 2 GCM runs include daily temperature and precipitation over a grid with a resolution of approximately 400 km in each direction. The representation of Australia by the CSIRO Mark 2 GCM is shown in Fig. 1. We have analysed results for the eastern Victoria, central New South Wales, northern New South Wales, northeast New South Wales, southwest Western Australia, and northwest Northern Territory grid squares. These regions cover a range of climates, from alpine to semiarid to monsoonal. The eastern Victoria grid square is highlighted in Fig. 1.

The global annual mean surface temperature modelled by the CSIRO Mark 2 GCM is shown in Fig. 2, as an average of the five transient runs for each of the A2 and B2 scenarios. The transient runs were for the period from 1871 to 2100. In this paper, the daily GCM rainfall for two 30-year periods is compared: 1961–1990 is selected to

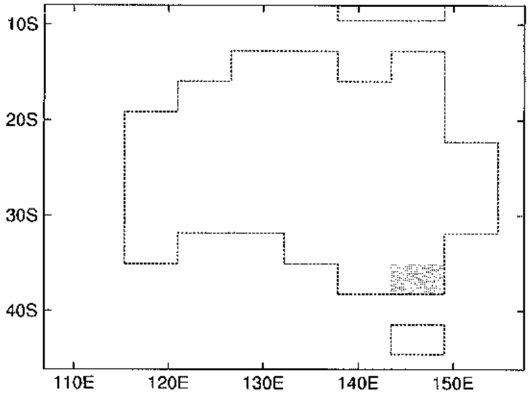

Fig. 1 Australia as represented by the CSIRO Mark 2 GCM. The eastern Victoria grid square is highlighted.

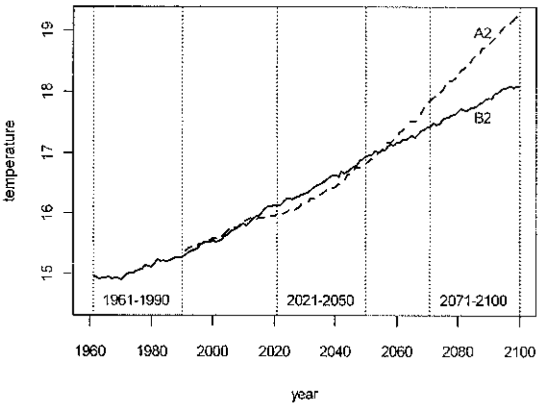

Fig. 2 Global annual mean surface temperature for the CSIRO Mark 2 GCM.

represent "current" conditions, and either 2021–2050 or 2071–2100 is selected to represent "future" conditions. The results presented here (Figs 3–5 and Fig. 7) are for the A2 emissions scenario.

Figure 3 shows the GCM rainfall for the eastern Victoria grid square for current conditions. The rainfalls are ranked from highest to lowest; 40% of the days are wet, and the average January rainfall is 52.0 mm per month. Figure 4 shows the GCM rainfall for future conditions; 32% of the days are wet, and the average January rainfall is 49.6 mm per month. Figure 5 is constructed by subtracting Fig. 4 from Fig. 3, and expressing the resulting pattern of change as a proportion of the current condition's amounts in Fig. 3. The reduction in wet day frequency from 40% to 32% is shown by the flat line. The most extreme rainfall has increased by 54%. The rest of the curve shows how the intermediate rainfalls have changed. The change in average rainfall from 52.0 mm to 49.6 mm represents a reduction in rainfall of 4.6%.

The proposed method for producing scenarios of point rainfall is to apply a smoothed version of the pattern of change of Fig. 5 to an observed point rainfall record from within the eastern Victoria grid square. For example, the historical rainfall record

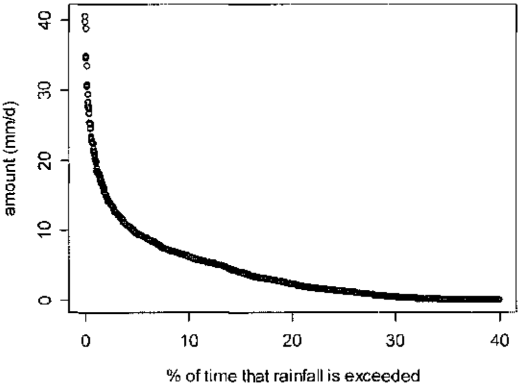

Fig. 3 Eastern Victoria: GCM daily rainfall for all Januarys 1961–1990. Combined results from an ensemble of five transient runs are shown.

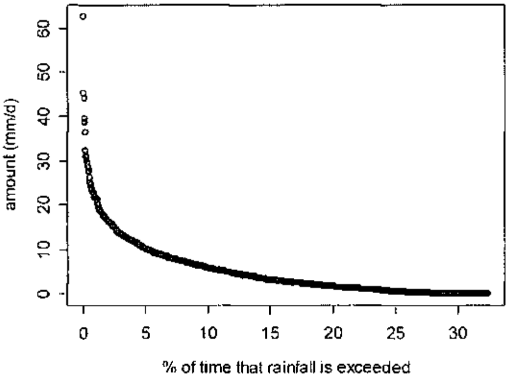

Fig. 4 Eastern Victoria: GCM daily rainfall for all Januarys 2071–2100. Combined results from an ensemble of five transient runs are shown.

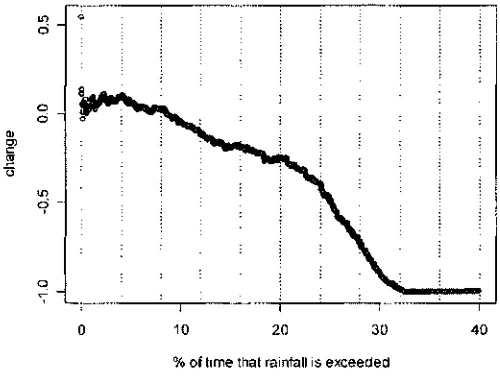

Fig. 5 Eastern Victoria: pattern of change.

for Melbourne is shown in Fig. 6; 27% of the days in this record are wet. If the unsmoothed pattern of change of Fig. 5 is applied to this point record, the most

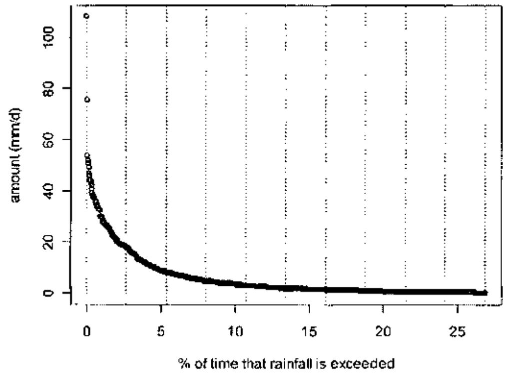

Fig. 6 Melbourne point rainfall 1856–1998.

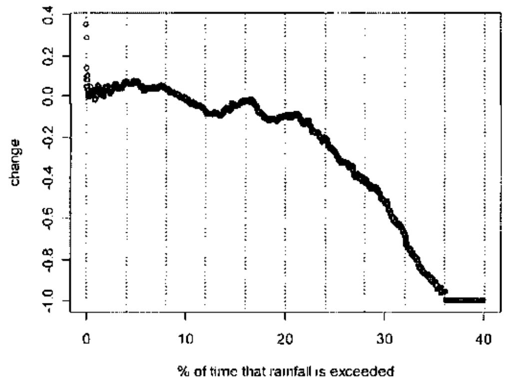

Fig. 7 Eastern Victoria: Pattern of change for 2021–2050.

extreme amount would be increased by 54%. The wet day frequency would be reduced from 27% to 22% by changing the 19% of raindays with the lowest rainfalls, to dry days. And the intermediate rainfall amounts would be increased or decreased by the change ratio from the appropriate position in Fig. 5 (note that if the x-axis in both Figs 5 and 6 is changed to 0–100, this new range is an exceedance frequency for the subset of the data that consists solely of wet days; the deciles of this range are shown by the vertical lines on each plot). A final step in this procedure is to adjust the resulting global warming scenario of point rainfall, to ensure that mass balance is maintained. For this example, the average change at the GCM resolution is a 4.6% reduction in January rainfall; all days in the scenario are scaled by a ratio which ensures that the total January rainfall in the scenario is 4.6% lower than the total January rainfall in the original point record.

It must be noted that the pattern of change in Fig. 5 is very sensitive to sampling variability. For example, when patterns of change are calculated from single ensemble runs instead of from the full ensemble of five that were used to produce Fig. 5, the patterns can vary from one ensemble run to another. Also note that the extreme left-hand part of the change curve is constructed from a small number of extreme rainfalls, and hence is most sensitive to sampling variability. One proposal to reduce the effect of this sampling variability is to construct a smoothed version of the pattern of change by using a moving average, at least for the most extreme part of the curve. Another is to average the results from adjacent grid squares. Strategies for smoothing the change curve are being investigated.

Variations in the patterns of change across months and across regions were investigated, for both the A2 and B2 emissions scenarios. The pattern of change shown in Fig. 5 is typical of the shapes that were obtained. Most months and most locations showed a decrease in the number of wet days, and therefore had a flat tail, and most showed increases in the extreme rainfalls, even when the average rainfall per month decreased. We found that extreme rainfalls often increased by around 20%. This agrees with results that have been reported for a different GCM from the UK, and it agrees with theoretical results based on the increase of the moisture-holding capacity of the atmosphere with global warming (Allen & Ingram, 2002).

We have also investigated whether the GCM pattern of change is a function of global warming, by analysing data from 2021–2050 compared to the results for 2071–2100. It can be seen from Fig. 2 that the global warming increases substantially between these two periods. The results of this investigation show that the pattern of change does appear to be a function of global warming. Figure 7 shows the pattern of change for January for eastern Victoria when 2021–2050 is used as "future conditions", and the data from Fig. 3 are used as "current conditions". Figure 7 can be directly compared with Fig. 5. The slope of the pattern of change in Fig. 7 is not as steep as that in Fig. 5, and the flat tail of the change pattern is shorter. In other words, the change pattern for 2021–2050 is not as well developed as that for 2071–2100, and the change pattern becomes more intense as the global warming intensifies. Similar results were obtained for other months and other locations. We also compared the results for the A2 scenario for 2071–2100 with results for the B2 emissions scenario for 2071–2100. Figure 2 shows that the A2 scenario is substantially warmer at that time, and, as expected, the change curves for the B2 emissions scenario were generally not as well developed as those for the A2 emissions scenario. We are working on ways to scale the patterns of change by the amount of global warming, in much the same way as the climate scenario generator developed by Page & Jones (2001) uses change in average rainfall per degree of global warming.

DAILY DATA FROM THE CSIRO MARK3 GCM

We also analysed daily change patterns for the CSIRO Mark 3 GCM. This is a new model that has a better representation of interdecadal variability than the Mark 2 GCM. The Mark 3 results were similar to the Mark 2 results. We found that extreme daily rainfalls often increased by around 20%, and that the change curves usually had flat tails. However, the interdecadal variability (and variability in general) affected the results. A conclusion from this work is that the shape of the daily change curve (cf. Fig. 5) is much more stable when an ensemble of runs is used.

LIMITATIONS OF THE METHODOLOGY

The synoptic patterns that produce rainfall are important. For example, the evolution over time of a frontal system is different to that of a thunderstorm. The characteristics and the relative frequency of these synoptic patterns may be affected by climate change. Perturbation methods ignore this. More complicated downscaling methods (Charles *et al.*, 1999; Fowler *et al.*, 2000; Wilby *et al.*, 2002) consider synoptic patterns in their formulation. However, these more complicated approaches take time to calibrate for a particular location.

An assumption made here is that the relative pattern of change is scale invariant, i.e. the relative pattern of change at the GCM scale can be applied to point rainfall. This assumption will be verified with area averages of observed data. The comments of Osborn (1997) may be of relevance here, however these comments apply to absolute rather than relative changes.

FUTURE WORK

Plans are in place to apply the downscaling method that has been developed to area-averaged daily rainfall (1901–1998) for 12 catchments, two for each of the GCM grid squares analysed here, and then do hydrological modelling runs to see whether the use of the proposed methodology results in significantly different runoff to a perturbation method using monthly averages. Further studies are also planned for the Macquarie catchment, and for other catchments in Australia. In these studies, the downscaling methodology will be used to generate rainfall scenarios that consist of spatially correlated point records. This work will include analysis of whether the downscaling method adequately preserves spatial correlations.

The proposed method is in the early stages of development. The results presented here are for the CSIRO Mark 2 GCM. We recognise the finding of McAvaney *et al.* (2001), that due to the many uncertainties involved in climate modelling, it is important to use results from a range of climate models when analysing potential changes in the global-scale circulation. Also note that changes in extreme rainfall are related to both the magnitude of global warming and the changes in mean rainfall that exist in a GCM, so the results obtained here should be replicated for several emission scenarios. The A2 and B2 emission scenarios are a popular choice as a minimum set of scenarios for global warming studies. Future work will involve obtaining data and then analysing the daily change patterns from GCMs from the UK, Canada, Germany, USA, and Japan. It is noted, however, that the method described in this paper works best when an ensemble of runs from the same model is available, so that the number of GCMs to which the method can be applied may be limited by data availability.

As noted in the introduction, our goal is to develop a downscaling method that produces realistic changes in daily rainfall without losing the ability to sample over a large range of GCMs. The authors feel that the first part of this goal is achievable, and that the methodology proposed here is robust for the six Australian regions where it has been tested. However, the need for ensembles of daily GCM outputs does limit the range of GCMs to which the methodology can be applied. Further work on the methodology will concentrate on reducing the effect of variability on the pattern of change, and on identifying typical and stable GCM daily patterns of change across broad regions. If broad-scale patterns can be identified, these patterns could be used to disaggregate monthly data, thus increasing our ability to produce realistic changes in daily rainfall using GCMs where only monthly outputs are available.

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