Generation of local-scale rainfall scenarios using changes in GCM rainfall: a refinement of the perturbation method

T.I. Harrold[a] **and R.N. Jones**[b]

[a]Research Institute for Humanity and Nature, Kyoto, Japan

[b]CSIRO Atmospheric Research, Melbourne, Australia

Abstract: Global Climate Models (GCMs) are the best tools from which future climate scenarios can be constructed. GCMs simulate important large-scale features of the Earth's climate system. However, it is changes in local-scale climate that will most affect rainfall. A popular approach for producing rainfall scenarios at scales relevant for hydrological impact studies is to calculate the average percentage change in GCM grid square rainfall from current to future conditions, with separate calculations for each month, and then to scale observed records of point daily rainfall by these percentage changes. This is termed the perturbation method. The main advantage of this method is that it is simple and easy to apply. However, the use of monthly GCM outputs ignores possible changes in daily extremes or the frequency of wet days, which are of great interest in hydrological impact studies. A refinement of the perturbation method is presented, which uses a daily pattern of change rather than the average percentage change. These patterns of change are then used to scale ranked historical point daily rainfall. This method is sensitive to the changes in extreme daily rainfalls and changes in the frequency of wet days simulated by the GCM, producing a more realistic sequence of changed daily rainfall, compared to the commonly used approach of simply scaling all the historical rainfall values in each month by the same amount.

Keywords: *GCMs; Rainfall scenarios; Daily rainfall*

1. 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. Rainfall scenarios at the local catchmetn scale are required (Giorgi and Hewitson, 2001; Mearns and Hulme, 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, for example, 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 very little indication of the changes in daily extremes, which are of great interest in hydrological impact studies. The frequency of wet days may also change with global warming; applying the perturbation method with monthly GCM data gives no indication of this.

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 and Page (2001) used a climate scenario generator linked to a catchment model to scale historical daily climate records by mean monthly changes rainfall and potential evaporation from nine GCMs, in order to explore a comprehensive range of change in the catchment. This investigation was undertaken knowing that daily rainfall would not change uniformly, but it was not possible to sample daily rainfall from such a large range of GCMs to produce more plausible scenarios. Most of the more plausible downscaling methods require daily data from each GCM to be used, and the application of sophisticated statistical and/or dynamical 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 the GCM simulations of daily rainfall. In other words, the method is sensitive to the changes in extreme daily rainfall and changes in the frequency of wet days that occur in the GCM, and produces a more realistic scenario, compared to the commonly used approach of perturbing all the historical rainfall values in each month by the same amount.

2. 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 and 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. 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 Mark2 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 Figure 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, varying from alpine to semi-arid, and from summer-rainfall dominated to winter-rainfall dominated to monsoonal. The eastern Victoria grid square is highlighted in Figure 1.

The global annual mean surface temperature modelled by the CSIRO Mark 2 GCM is shown in Figure 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 represent "current" conditions, and either 2021-2050 or 2071-2100 is selected to represent "future" conditions. The results presented here (Figures 3-5 and Figure 7) are for the A2 emissions scenario.

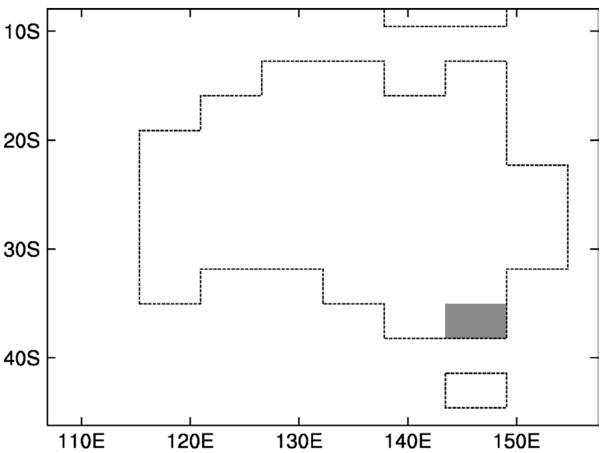

Figure 1. Australia as represented by the CSIRO Mark 2 GCM. The East Victoria grid square is highlighted.

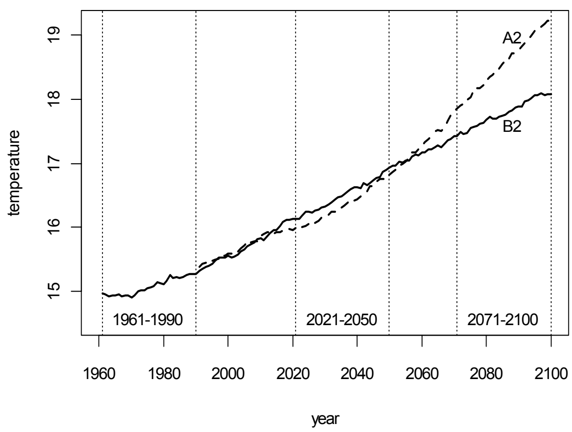

Figure 2. Global annual mean surface temperature for the CSIRO Mark 2 GCM.

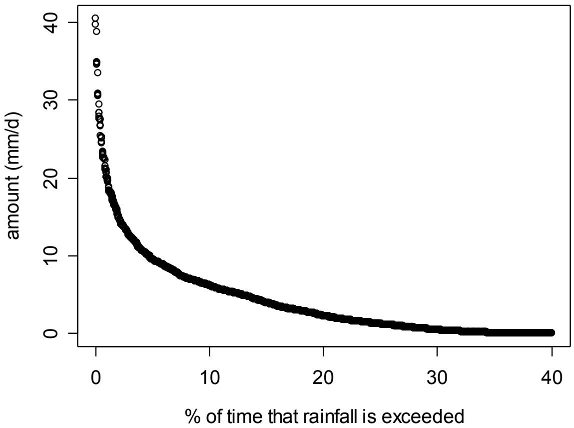

Figure 3. East Victoria: GCM daily rainfall for all Januarys 1961-1990. Combined results from an ensemble of five transient runs are shown.

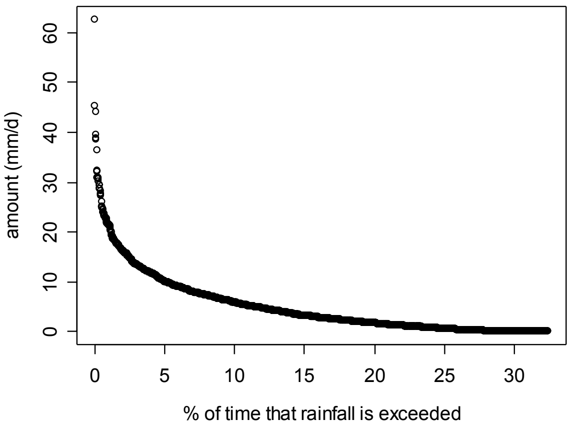

Figure 4. East Victoria: GCM daily rainfall for all Januarys 2071-2100. Combined results from an ensemble of five transient runs are shown.

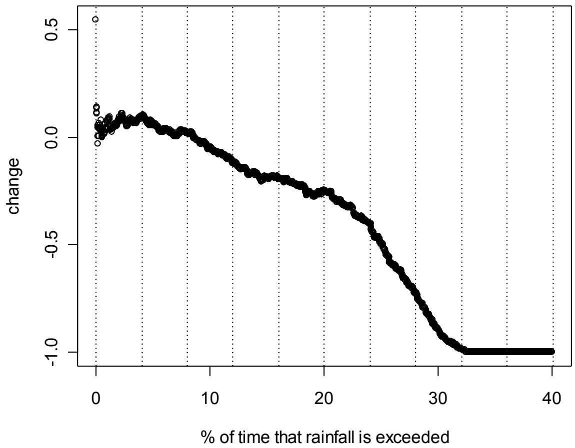

Figure 5. East Victoria: Pattern of change.

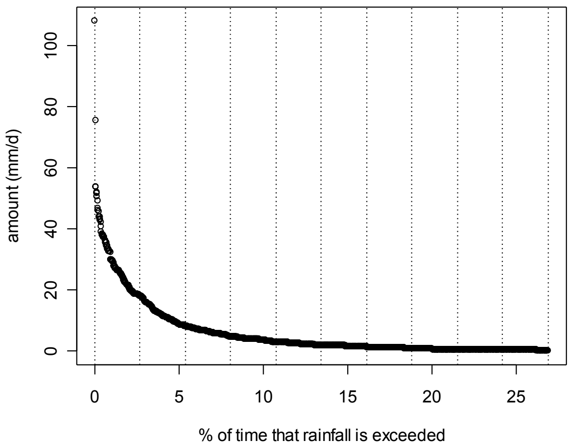

Figure 6. Melbourne point rainfall 1856-1998.

Figure 3 shows the GCM rainfall for the East 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 Figure 4 from Figure 3, and expressing the results as a percentage change from the current amounts in Figure 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 from Figure 5 to an observed point rainfall record from within the East Victoria grid square. For example, the historical rainfall record for Melbourne is shown in Figure 6. 27% of the days in this record are wet. If the raw pattern of change of Figure 5 is applied to this point record, the most extreme amount would increase by 54%. The wet day frequency would reduce 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 Figure 5 (note that if the x-axis on both Figure 5 and Figure 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 of point rainfall 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 Figure 5 is very sensitive to sampling variability. For example, when patterns of change are calculated from a single model run instead of from the full ensemble of five, the patterns can vary from one ensemble member 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 way to reduce the effect of this sampling variability is to construct a smoothed version of the pattern of change by using a moving average based on five raw values, at least for the most extreme part of the curve. Another is to average the results from adjacent grid squares. Strategies for producing smoothed versions of the change curve, especially those for extreme values, 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 Figure 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 and Ingram, 2002).

We have also investigated whether the GCM pattern of change is a function of global warming, by analysing data from the five transient A2 runs for 2021-2050 compared to the results for 2071-2100. Figure 2 shows that the global warming for the A2 scenario increases substantially between these two periods. This investigation confirmed that the pattern of change does appear to be a function of global warming. Figure 7 shows the pattern of change for January for East Victoria when 2021-2050 is used as “future conditions”, and the data from Figure 3 is used as “current conditions”. Figure 7 can be directly compared with Figure 5. The slope of the pattern of change in Figure 7 is not as steep as that in Figure 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 global mean temperature increases. Similar results were obtained for other months and other locations. We also compared the results for A2 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 in Figure 2. We are investigating ways to scale the patterns of change by the magnitude of global warming, so that the perturbation method can be used in a wider range of scenarios and not be restricted to representing the model simulation that provided the source data. We are also interested in a plausible method of scaling daily rainfall knowing global warming and the change in average rainfall per degree of global warming as utilised by Page and Jones (2001).

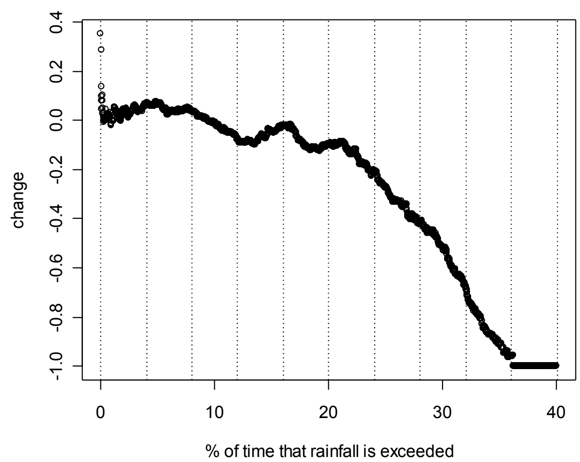

Figure 7. East Victoria: Pattern of change for 2021-2050.

3. DAILY DATA FROM THE CSIRO MARK3 GCM

Daily change patterns for the CSIRO Mark3 GCM were also analysed. 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, we encountered problems in our analysis of the daily change patterns from this GCM. These problems were:

1. Interdecadal variability (and variability in general) affected the results.

2. The data used was discretised to the nearest 0.1mm. This affected the tail end of the change curves. This is a minor problem, however, compared to (1). Non-discretised data will be obtained for any further analysis.

An important conclusion from the work with Mark 3 data is that the shape of the daily change curve (cf. Figure 5) is much more stable when an ensemble of at least five runs is used. Even though the results for the Mark 3 model were promising, and the method seems valid for this data, the method cannot be reliably implemented unless an ensemble of runs is available.

4. 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 (for example, Charles et al. (1999), Fowler et al. (2000), and Wilby et al. (2002)) consider synoptic patterns in their formulation. However these more complicated approaches take a long time to formulate and calibrate for a particular location.

Osborn (1997) presents theory which suggests that, if the relative frequency of synoptic patterns is unchanged at both the GCM scale and the local scale, then relative changes in mean rainfall at the GCM scale correspond to relative changes in mean rainfall at the local scale. That is, if changes in synoptic patterns are ignored, then changes in mean rainfall can be treated as being scale invariant. This is the basic premise of perturbation methods. Here, we assume that the relative pattern of change in daily rainfall 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.

5. FUTURE WORK

This scaling method has been applied to area-averaged daily rainfall (1901-1998) for catchments in each of the six GCM grid squares analysed here, and the scaled rainfall has been used in hydrological modelling runs (Chiew et al. 2003). The proposed methodology results in significantly different runoff to a perturbation method using monthly averages. Further studies are also planned for the upper Macquarie catchment in New South Wales, and for other catchments in Australia. In these studies, the scaling methodology will be used to generate rainfall scenarios that consist of several spatially correlated point records. This work will include analysis of whether the scaling method adequately preserves spatial correlations.

This method is in the early stages of development. The results presented here are for the CSIRO Mark2 GCM. We recognise the finding of McAvaney et al. (2001), that due to the many uncertainties involved in climate modelling, it is important to utilise results from a range of climate models. It is this aim, after all, that has led to the desire to investigate methods suitable for use in a climate scenario generator. 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. However, that the method described in this paper works best when an ensemble of runs from the same model is available, limiting this method to ensemble simulations.

As noted in the introduction, our goal is to develop a scaling method that produces realistic changes in daily rainfall while being able to sample 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 number 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, and not daily, outputs are available.

6. ACKNOWLEDGEMENTS

Much of this work was carried out while the first author was at CSIRO Atmospheric Research, Australia. The support of CSIRO and the Japan Society for the Promotion of Science is gratefully acknowledged. The authors thank Ian Watterson, Ramasamay Suppiah and Bob Cechet for constructive comments. GCM data was provided by CSIRO, and the Melbourne point rainfall record was obtained from the Australian Bureau of Meteorology. Ian Watterson produced Figure 1 and assisted in processing the GCM data.

7. REFERENCES

Allen, M.R. and W.J. Ingram, Constraints on future changes in climate and the hydrologic cycle, *Nature* 419, 224-232, 2002.

Charles, S.P., B.C. Bates, P.H. Whetton and J.P. Hughes, Validation of downscaling models for changed climate conditions: case study of southwestern Australia, *Climate Research* 12(1), 1-14, 1999.

Chiew, F.H.S., T.I. Harrold, L. Siriwardena, R.N. Jones, and R. Srikanthan, Simulation of climate change impact on runoff using rainfall scenarios that consider daily patterns of change in GCMs, MODSIM 2003 International Congress on Modelling and Simulation, Modelling and Simulation Society of Australia and New Zealand, Townsville, 14-17 July, 2003.

Fowler, H.J., C.G. Kilsby and P.E. O'Connell, A stochastic rainfall model for the assessment of regional water resource systems under changed climatic conditions, *Hydrology and Earth System Sciences*, 4(2), 263-282, 2000.

Giorgi, F. and B. Hewitson, et al., Regional Climate Information – evaluation and projections, In Houghton, J.T., Y. Ding, D.J. Griggs, M. Noguer, P. Van Der Linden and D. Xiaosu, (eds.) *Climate Change 2001: The Scientific Basis*, Cambridge University Press, Cambridge, 583-638, 2001.

Jones, R.N. and C.M. Page, Assessing the risk of climate change on the water resources of the Macquarie River Catchment, MODSIM 2001 International Congress on Modelling and Simulation, Modelling and Simulation Society of Australia and New Zealand, Canberra, 2, 673–678, 2001.

McAvaney B.J., et al., Model evaluation, In Houghton, J.T., Y. Ding, D.J. Griggs, M. Noguer, P. Van Der Linden and D Xiaosu, (eds.) *Climate Change 2001: The Scientific Basis*, Cambridge University Press, Cambridge, 471-523, 2001.

Mearns L.O. and M. Hulme, et al., Climate Scenario Development, In Houghton, J.T., Y. Ding, D.J. Griggs, M. Noguer, P. Van Der Linden and D Xiaosu, (eds.) *Climate Change 2001: The Scientific Basis*, Cambridge University Press, Cambridge, 739-768, 2001.

Osborn, T.J., Areal and point precipitation intensity changes: Implications for the application of climate models, *Geophysical Research Letters* 24(22), 2829-2832, 1997.

Page, C.M., and R.N. Jones, OzClim: The development of a climate scenario generator for Australia, MODSIM 2001 International Congress on Modelling and Simulation, Modelling and Simulation Society of Australia and New Zealand, Canberra, 2, 667-670, 2001.

Prudhomme, C., N. Reynard, and S. Crooks, Downscaling of global climate models for flood frequency analysis: where are we now? *Hydrological Processes*, 16, 1137-1150, 2002.

Stocker T.F., et al., Physical climate processes and feedbacks, In Houghton, J.T., Y. Ding, D.J. Griggs, M. Noguer, P. Van Der Linden and D Xiaosu, (eds.) *Climate Change 2001: The Scientific Basis*, Cambridge University Press, Cambridge, 417-470, 2001.

Watterson, I.G. and M.R. Dix, Simulated changes due to global warming in daily precipitation means and extremes and their interpretation using the gamma distribution, *Journal of Climate*, submitted, 2002.

Wilby R.L., D. Conway and P.D. Jones, Prospects for downscaling seasonal precipitation variability using conditioned weather generator parameters, *Hydrological Processes* 16, 1215-1234, 2002.