Influence of Rainfall Scenario Construction Methods on Runoff Projections
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ABSTRACT
The future rainfall series used to drive hydrological models in most climate change impact studies is informed by global climate models (GCMs). This paper compares future runoff projections in 11 000 0.25° grid cells across Australia from a daily rainfall–runoff model driven with future daily rainfall series obtained using three simple scaling methods, informed by 14 GCMs. In the constant scaling and daily scaling methods, the historical daily rainfall series is scaled by the relative difference between GCM simulations for the future and historical climates. The constant scaling method scales all the daily rainfall by the same factor, and the daily scaling method takes into account changes in the daily rainfall distribution by scaling the different daily rainfall amounts differently. In the daily translation method, the GCM future daily rainfall series is translated to a 0.25° gridcell rainfall series using the relationship established between the historical GCM-scale rainfall and 0.25° gridcell rainfall data. The daily scaling and daily translation methods generally give higher extreme and annual runoff than the constant scaling method because they take into account the increase in extreme daily rainfall (which generates significant runoff) simulated by the large majority of the GCMs. However, the difference between the mean annual runoff simulated with future daily rainfall series obtained using the constant versus daily scaling methods is generally less than 5%, which is relatively smaller than the range of runoff results from the different GCMs of 30%–40%.

1. Introduction
Changes in spatial and temporal patterns of climate variables associated with global warming will have an effect on regional- and catchment-scale hydrological processes. In particular, changes in the extreme rainfall because of intensified hydrological cycle will be amplified in the runoff response (Chiew 2006). The change in runoff will have significant implications on water resources, and for this reason there have been literally thousands of studies on the effect of climate change on runoff.

Global climate models (GCMs) are the best tools available for simulating global and regional climate systems, particularly with the rapid improvements in climate modeling over the last few decades. However, the representation of hydrological fluxes in GCMs is generally too simplistic (Kuhl and Miller 1992; Miller and Russell 1992; Kite et al. 1994) to estimate runoff realistically. Therefore, most climate change impact studies involve the use of hydrological models, in which a model is first developed to represent current conditions and then a future climate series is used to drive the model to estimate the effect of climate change on runoff. The future climate information is usually obtained from GCMs. However, GCMs provide climate information at a resolution that is too coarse to be used directly in hydrological modeling. For example, the spatial resolution of runoff impact assessment is generally of the order of 10 km compared to a typical GCM spatial resolution of more than 200 km.

The catchment-scale future climate series data (particularly daily rainfall) required to drive hydrological models in impact studies come from either (i) empirically scaling the historical data informed by GCM simulations, (ii) statistically downscaling GCM-scale atmospheric predictors to catchment-scale climate, or (iii) dynamic downscaling to provide higher-resolution climate projections. This paper focuses on the empirical scaling methods.

The statistical downscaling methods relate large synoptic-scale atmospheric predictors to catchment-scale rainfall (Perica and Foufoula-Georgiou 1996; Wilby and Wigley 2000; Mpeelasoka et al. 2001; Chandler and Wheater 2002; Charles et al. 2004; Mehrotra et al. 2004).
The dynamic downscaling methods generally use high-resolution regional climate models nested in a GCM, with the GCM time-dependently driving the regional model at its boundaries (Giorgi 1990; Renwick et al. 1998; Gordon and O'Farrell 1997; Nunez and McGregor 2007). The statistical and dynamic downscaling methods are better than the empirical scaling methods that scale the historical climate series because (i) they directly consider the spatial- and temporal-scale differences between GCM atmospheric predictors and catchment-scale rainfall; (ii) they take into account changes in the characteristics and relative frequency of synoptic patterns in a future climate; and (iii) GCM simulations of large-scale atmospheric circulation are better than GCM simulations of rainfall. For these reasons, statistical and dynamic downscaling methods are increasingly used in hydrological impact studies (Xu 1999; Diaz-Nieto and Wilby 2005; Fowler et al. 2007). Nevertheless, the application and calibration of the statistical downscaling methods can be fairly laborious and require expert judgment, and the use of the dynamic downscaling method is also constrained by the spatial resolution and computation expenses (von Storch et al. 1993; Cubasch et al. 1996; Wilby and Wigley 1997). The focus of this paper is on the simple empirical scaling methods; the statistical and dynamic downscaling methods are not addressed in this paper.

Despite the limitations of the empirical scaling methods, they are simple and offer a practical solution to constructing future climate scenarios in numerous studies on the effect of climate change on runoff (Chiew and McMahon 2002; Singh and Bengtsson 2004; Wurbs et al. 2005; Salathe 2005; Fowler et al. 2007). Because the empirical scaling methods are simple to use, they can be easily applied across large regions and can be used with ensemble runs from different GCMs and for various greenhouse-gas emission scenarios, therefore taking into account the large uncertainties associated with global warming and local climate change projections.

The aim of this paper is to compare the runoff modeled using a daily rainfall–runoff model driven with scenarios of future daily rainfall series obtained using three simple empirical scaling methods—constant scaling (CS), daily scaling (DS), and daily translation (DT)—informed by GCM simulations. In the constant scaling and daily scaling methods, the historical daily rainfall series is scaled by the relative difference between GCM simulations for the future and historical climates. The constant scaling method scales all the daily rainfall by the same factor, and the daily scaling method takes into account changes in the daily rainfall distribution by scaling the different daily rainfall amounts differently. In the daily translation method, the GCM future daily rainfall series is translated to a 0.25° gridcell rainfall series using the relationship established between the historical GCM-scale rainfall and 0.25° gridcell rainfall data. The implications of the results and scaling methods are discussed. The rainfall–runoff model is applied to 11,000 0.25° grid cells across Australia. The historical simulations are carried using daily rainfall and potential evapotranspiration data from 1981 to 2000. The future simulations are carried out using future daily rainfall time series scenarios, obtained by comparing 2046–65 and 1981–2000 simulations from 14 GCMs.

2. Rainfall–runoff modeling and historical climate data

a. Rainfall–runoff modeling

Daily runoff is modeled using a simple lumped conceptual daily rainfall–runoff model (SIMHYD) for 11,000 0.25° × 0.25° (~25 km × 25 km) grid cells across Australia. The structure of SIMHYD and the algorithms describing the processes modeled by SIMHYD are shown in Fig. 1. SIMHYD has been used successfully in Australia for...
various applications, including climate change impact on runoff (Chiew and McMahon 2002) and regionalization studies (Chiew and Siriwardena 2005; Reichl et al. 2006). The model parameter values used here come from Chiew et al. (2002), who calibrated and validated SIMHYD using observed streamflow data from 331 catchments across Australia. Runoff for each 0.25° × 0.25° grid cell in this study is modeled using optimized parameter values from the geographically closest “calibration catchment.” In general, the runoff estimates are relatively good in regions with good coverage of streamflow data (mainly, the southeast and eastern regions, and the southwest corner of Australia) but relatively poor elsewhere; however, the runoff estimates are sufficiently reasonable for the purpose of this study where only the relative change in future runoff values are used.

b. Historical climate data

The daily rainfall and areal potential evapotranspiration (APET) data from 1981 to 2000 come from the Agro-Meteorological Datasets for Geo-Spatial Modelers (SILO) of the Queensland Department of Natural Resources and Water (Jeffrey et al. 2001). The SILO data provide surfaces of daily rainfall and other climate data at 0.05° × 0.05° grids for all of Australia, interpolated from point measurements made by the Australian Bureau of Meteorology. The daily APET is calculated from the SILO daily data for solar irradiance, near-surface air temperature, and vapor pressure using Morton’s wet environment evapotranspiration algorithm (Morton 1983; Chiew and McMahon 1991).

3. Future climate data

a. Global climate models

The future climate series is obtained by analyzing daily rainfall simulations from 14 GCMs for 1981–2000 and 2046–65, for the global warming associated with the midrange greenhouse-gases emission scenario [Special Report on Emissions Scenarios (SRES) A1B; Solomon et al. 2007]. The 14 GCMs are listed in Table 1. The simulations are obtained from the World Climate Research Programme’s (WCRP) phase 3 of the Coupled Model Intercomparison Project (CMIP3; available online at https://esg.llnl.gov:8443/).

b. Simple methods used to obtain future climate series

The three empirical scaling methods are illustrated using common datasets for a 0.25° grid cell in southeast Australia (37°S, 145°E); observed 0.25° gridcell historical winter (June–August) daily rainfall series for 1981–2000 (Cell_His); GCM (mk3.0) modeled historical winter daily rainfall series (at the GCM resolution of more than 2°) for 1981–2000 (GCM_His); and GCM modeled future winter daily rainfall series for 2046–65 (GCM_Fut). The three scaling methods use the previously mentioned data to obtain a future (2046–65) winter daily rainfall series for the 0.25° grid cell (Cell_Fut) to drive the rainfall–runoff model.

1) CONSTANT SCALING

In the constant scaling method (also called the delta or perturbation method), the entire gridcell observed historical daily rainfall series is scaled by a constant factor, determined as the ratio of the mean future GCM rainfall divided by the mean historical GCM rainfall, to obtain the future gridcell daily rainfall series. The constant scaling method is illustrated in Fig. 2.

The method was first proposed by Santer et al. (1990) and used in the Intergovernmental Panel on Climate Change (IPCC) First Assessment Report to generate future climate scenarios (Mitchell et al. 1990) using change fields from 2 × CO₂ GCM experiments. It has subsequently been widely adopted in climate scenario generators and has been used with results from coupled ocean–atmosphere global models [e.g., in the Model to Assess the Greenhouse Effect (IMAGE 2) (Rotmans et al. 1994), the project of Evaluation of Strategies to address Climate Change by Adapting to and Preventing Emissions (ESCAPE) (Alcamo et al. 1994a,b), scenario generator (SCENGEN) (Hulme et al. 1995a,b; Hulme and Carter 2000), and the Climate Variations and Land Use programme (CLIMPACTS) (Kenny et al. 2000)]. The constant scaling method is used in most hydrological impact modeling studies because of its simplicity. Lettenmaier and Gan (1990), Miller and Russell (1992), and Chiew et al. (1995), among others, were the first

<table>
<thead>
<tr>
<th>GCM</th>
<th>Horizontal resolution</th>
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<tbody>
<tr>
<td>CCCma (Canada)</td>
<td>3.8° × 3.8°</td>
</tr>
<tr>
<td>CNRM (France)</td>
<td>3.5° × 2.8°</td>
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<tr>
<td>ECHAM5 (Germany)</td>
<td>2.0° × 1.875°</td>
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<tr>
<td>GFDL (United States)</td>
<td>2.5° × 2.0°</td>
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<tr>
<td>GISS-AOM (United States)</td>
<td>3.0° × 3.0°</td>
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<tr>
<td>INMCM3 (Russia)</td>
<td>4.0° × 5.0°</td>
</tr>
<tr>
<td>IPSL CM4 (France)</td>
<td>2.5° × 3.75°</td>
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<tr>
<td>MIROC-m (Japan)</td>
<td>2.8° × 2.8°</td>
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<tr>
<td>MIROC-h (Japan)</td>
<td>2.8° × 2.8°</td>
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<tr>
<td>MIUB (Germany)</td>
<td>4.0° × 3.75°</td>
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<tr>
<td>CSIRO mk3.0 (Australia)</td>
<td>1.9° × 1.9°</td>
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<tr>
<td>CSIRO mk3.5 (Australia)</td>
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<td>NCAR (United States)</td>
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users of the constant scaling method in the assessment of runoff sensitivity to climate change.

2) DAILY SCALING

Like the constant scaling method, the daily scaling method (also called quantile–quantile mapping) scales the gridcell observed historical daily rainfall series to obtain a gridcell future daily rainfall series. However, the different daily rainfall amounts are scaled differently in the daily scaling method, as indicated by the different changes to different rainfall ranks/percentiles in the GCM future daily rainfall series relative to the GCM historical daily rainfall series. The daily scaling method is illustrated in Fig. 3.

The consideration of different changes to the different parts of the daily rainfall distribution is important in hydrological impact studies because more runoff is generated in the bigger events. This consideration is also necessary in assessing the climate change effect on hydrological extremes. Examples of the use of the daily scaling method to provide future rainfall series to drive hydrological models include studies by Harrold and Jones (2003), Vaze et al. (2008), Chiew et al. (2008), and Mpelasoka and Chiew (2008).

3) DAILY TRANSLATION

In the daily translation method (also called bias correction), a distribution mapping technique is used to establish a relationship between the observed gridcell historical daily rainfall and the GCM historical daily rainfall (at the different rainfall ranks/percentiles). This relationship is then used to translate the GCM future daily historical rainfall series to obtain a gridcell future daily rainfall series. The daily translation method is illustrated in Fig. 4.

Unlike the constant scaling and daily scaling methods in which the gridcell future daily rainfall sequence is the same as the historical daily rainfall sequence (but with different amounts), the gridcell daily rainfall sequence in the daily translation method is the same as the GCM future daily rainfall sequence (but with GCM-scale values translated to finer gridcell scale values).

The concept of bias correction in the daily translation method has been shown to be skillful in different settings. For example, Wood et al. (2004), Dettinger et al. (2004), VanRheenen et al. (2004), and Maurer and Hidalgo (2008) applied bias correction by performing the quantile mapping at the resolution of the GCM for rainfall and temperature, and applied spatial disaggregation of the
bias-corrected values on subGCM grid scale (0.125° grid) by interpolation. Payne et al. (2004) used probability mapping methods for spatial downscaling and bias correction of both global and regional climate model outputs in their investigation of the effects of water resources on climate change in the Columbia River basin. Similarly, Christensen et al. (2004) studied the effects of climate change on the hydrology and water resources of the Colorado River basin using model bias-corrected rainfall for the Colorado River. Sharma et al. (2007) used a bias-correction method based on gamma–gamma transformation to improve the frequency and amount of raw GCM rainfall at GCM grid nodes for modeling basin-level observed runoff for the upper Ping River basin (Thailand).

In this study, the three scaling methods are applied separately to each of the four seasons (summer, autumn, winter, and spring). In addition, the future gridcell rainfall series in the daily scaling and daily translation methods are rescaled such that the mean future gridcell rainfalls in the four seasons relative to the mean historical gridcell rainfalls are the same as the future GCM mean rainfalls relative to the historical GCM mean rainfalls. The mean future gridcell rainfalls in each of the four seasons are therefore the same in all three methods. This rescaling is done because there is more confidence in the GCM simulations of mean conditions and because the application of the three methods can be easily compared.

4. Results

a. Changes in rainfall

The 1981–2000 time series of observed daily rainfall (at 0.25°, about 25 km) and simulations of 14 GCMs (at 200–400-km spatial resolution) are used to obtain a
2046–65 rainfall time series for each of the ~11 000 0.25° × 0.25° grid cells across Australia, using the three scaling methods.

The plots in Fig. 5 show the spatial distributions of percentage changes in mean annual rainfall over Australia for 2046–65 relative to 1981–2000, simulated by the 14 GCMs. The results for three large regions are also summarized in Table 2: 1) southeast Australia (SEA) which covers the Murray–Darling, southeast coast, and Tasmania drainage basins (Table 2a); 2) northern Australia (NA), which covers the northeast coast, Gulf of Carpentaria, and Timor Sea drainage basins (Table 2b); and 3) southwest western Australia (SWWA), which covers the southwest coast drainage basin (Table 2c). These three key regions of Australia have very different climates, broadly classified as “temperate” and “semiarid” in SEA, “tropical” in NA, and “temperate Mediterranean” in SWWA; the rainfall and runoff results for these regions will be discussed subsequently. The plots in Fig. 5 indicate that the large majority of the GCMs simulates a wetter future in northern Australia (11 of the 14 GCMs for NA; see Tables 2a–2c); and the large majority of GCMs simulates a drier future in southern Australia (10 of the 14 GCMs for SEA and 13 of the 14 GCMs for SWWA).

The whisker plots in Figs. 6a–6c summarize the distributions of changes to the mean annual rainfall and the high extreme daily rainfall (99th percentile daily rainfall or daily rainfall that is exceeded 1% of the time) over the 0.25° grid cells in the three regions for the three scaling methods for the 14 GCMs. For a given GCM, the three methods give exactly the same change in mean annual rainfall because of the common rescaling used (see section 3). However, a comparison of the constant and daily scaling results in Figs. 6a–6c indicates that the
FIG. 5. Percentage changes in mean annual rainfall for 2046–65 relative to 1981–2000 derived from 14 GCMs for (bottom right) 12 major Australian drainage basins: Northeast Coast (I), Southeast Coast (II), Tasmania (III), Murray–Darling (IV), South Australian Gulf (V), Southwest Coast (VI), Indian Ocean (VII), Timor Sea (VIII), Gulf of Carpentaria (IX), Lake Eyre (X), Bulloo Bancannia (XI), and Western Plateau (XII).
large majority of GCMs shows either a bigger increase in high extreme daily rainfall compared to the increase in mean annual rainfall or a smaller decrease in high extreme daily rainfall compared to the decrease in mean annual rainfall. This is particularly clear in SEA and SWWA, where some GCMs show an increase in the extremely high daily rainfall despite a decrease in mean annual rainfall in some of the grid cells.

The increase in high-rainfall intensity in a warmer climate is consistent with atmospheric theory and is simulated in the majority of GCMs (Gordon et al. 1992). A warmer atmosphere is capable of holding larger amounts of moisture, which potentially fuels rises in high-rainfall events to a given increase in precipitable water (Allen and Ingram 2002; Trenberth et al. 2003; Held and Soden 2006, Allan and Soden 2008).

Like the daily scaling method, the daily translation method also generally gives higher extreme daily rainfall amounts compared to the constant scaling method. However, the relative difference between the daily translation and constant scaling methods is bigger than the relative difference between the daily and constant scaling methods. This is likely due to both the constant and daily scaling methods scaling the historical 0.25° gridcell rainfall directly, whereas the daily translation method uses the GCM future rainfall series and bias corrects it to 0.25° gridcell rainfall based on the relationship between historical GCM and 0.25° gridcell rainfalls.

### b. Changes in runoff characteristics

The changes in 2046–65 mean annual runoffs relative to 1981–2000 runoffs, obtained by running the rainfall–runoff model with 2046–65 rainfall obtained using the three scaling methods, for the 14 GCMs for the three regions are shown in Tables 2a–2c. The plots in Figs. 7a–7c show the cumulative number of 0.25° grid cells (percent of cells in a region), showing a change in mean annual runoff greater than a specified value for the three regions. For the constant scaling and daily scaling methods, the simulated 0.25° gridcell 2046–65 runoff is compared directly against the 0.25° gridcell 1981–2000 runoff driven with the 0.25° observed gridcell daily rainfall series. However, in the daily translation method, where the future runoff is modeled using future GCM daily rainfall sequence (with bias correction to 0.25° gridcell rainfall amount), to ensure consistency in the GCM daily rainfall structure, the simulated 0.25° gridcell 2046–2065 runoff is compared against the 0.25° gridcell 1981–2000 runoff driven with the 0.25° observed gridcell daily rainfall series.

The results indicate that the percent change in mean annual rainfall is generally amplified as a 2%–3% change in mean annual runoff, which is consistent with other Australian studies (Chiew 2006). The most obvious difference in the runoff modeling results is the generally higher runoff estimated by the daily scaling method compared to the constant scaling method. This
is particularly clear for SWWA, where the mean annual runoff modeled with future rainfall obtained using the daily scaling method is higher than that modeled with future rainfall obtained using the constant scaling method for all the 14 GCMs, with the percent change in future mean annual runoff for the two scaling methods differing by up to 7% (Table 2c; Figs. 7a–7c). The daily scaling method also gives higher future runoff compared...
to the constant scaling method for SEA for the large majority of GCMs, with the percent change in future mean annual runoff for the two scaling methods differing by up to 5% (Table 2a).

The higher mean annual runoff from the daily scaling method compared to the constant scaling method is because most GCMs indicate that the increase (or decrease) in extreme rainfall intensity will be bigger (or smaller) than the increase (or decrease) in mean annual rainfall. High-rainfall events generate significant runoff and by considering the different changes to different parts of the daily rainfall distribution, the daily scaling method takes this into account and therefore gives higher future mean annual runoff than the constant scaling method. This result is clearly observed in SWWA and SEA, where the large majority of GCMs simulates either a bigger increase in high extreme daily rainfall compared to the increase in mean annual rainfall or a smaller decrease in high extreme daily rainfall compared to the decrease in mean annual rainfall, and less clear in NA, where there is less difference between the change in extreme and mean annual rainfalls (see section 4a and Figs. 6a–6c).

The daily translation method also appears to adequately take into account the different changes to the different parts of the daily rainfall distribution, with future mean annual runoff simulated with future rainfall obtained using

![Figure 6](http://journals.ametsoc.org/jhm/article-pdf/10/5/1168/4103671/2009jhm1045_1.pdf)
the daily translation method being generally higher than that simulated with future rainfall obtained using the constant scaling method. However, this result is less clear for the daily translation method than for the daily scaling method, and the relative difference between the daily translation and constant scaling methods (changes in future mean annual runoff differing by up to 10%) is larger than the relative difference between the daily scaling and constant scaling methods. This is because 1) the daily translation method considers both the change in different parts of the daily rainfall distribution as well as the change in the time series (and therefore other daily and longer-period rainfall characteristics) and 2) the future runoff series is compared against the historical runoff series driven with historical GCM daily rainfall series (with bias correction to 0.25° gridcell rainfall amount).

5. Summary and conclusions
The future rainfall series used to drive hydrological models in many climate change impact studies is informed by GCM rainfall simulations. This paper compares rainfall–runoff modeling results from a daily rainfall–runoff model driven with future rainfall series obtained using three simple scaling methods informed by relative GCM simulations for the future and historical climates. The rainfall–runoff modeling is carried out for ~11 000 0.25° grid cells across Australia, and the results and implications are presented mainly for three key regions in Australia. Here 14 GCMs are considered, using the 1981–2000 daily rainfall simulations and the 2046–65 daily rainfall simulations for the midrange IPCC SRES A1B scenario.

In the constant scaling and daily scaling methods, the 0.25° gridcell 1981–2000 historical daily rainfall series are scaled by the change in the 2046–65 (future) rainfall relative to the 1981–2000 (historical) rainfall simulated by the GCMs to obtain the 0.25° gridcell future daily rainfall series. In the constant scaling method, the entire daily rainfall series (in each of the four seasons) is scaled by the same factor. In the daily scaling method, the different daily rainfall amounts are scaled differently, as
indicated by the different changes at the different rainfall ranks/percentiles simulated by the GCMs. In the daily translation method, the future GCM daily rainfall series is used as the 2046–65 0.25° gridcell daily rainfall series but bias corrected to gridcell rainfall amounts using the relationship established between the 1981–2000 gridcell and GCM daily rainfalls.

The results show that the large majority of the GCMs simulate a wetter future in northern Australia and a drier future in southern Australia. The change in rainfall is amplified in runoff, with a 1% change in mean annual rainfall generally amplified as a 2%-3% change in mean annual runoff. The mean annual runoff from the daily scaling method is generally higher than the mean annual runoff from the constant scaling method. This is because a large majority of the GCMs shows either a bigger increase in high extreme daily rainfall compared to the increase in mean annual rainfall or a smaller decrease in high extreme daily rainfall compared to the decrease in mean annual rainfall, particularly in southern Australia. High-rainfall events generate significant runoff, and by considering the different changes to different parts of the

Fig. 7. Cumulative number of 0.25° grid cells across SEA, NA, and SWWA regions (percent of the area of a region) showing change in mean annual runoff less than a specified value modeled using future rainfall obtained using the CS (blue), DS (green), and DT (pink) methods for (a) CCCma, CNRM, ECHAM5, GFDL, and GISS-AOM GCMs; (b) INMCM, IPSL CM4, MIROC-h, MIROC-m, and MIUB GCMs; and (c) CSIRO mk3.0, CSIRO mk3.5, MRI, and NCAR GCMs.

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daily rainfall distribution, the daily scaling methods take this into account and therefore simulates higher runoff compared to the constant scaling method. This advantage that the daily scaling method has over the constant scaling method can be important, particularly in studies on changes in extreme runoff. However, the difference between the mean annual runoff simulated with future daily rainfall series obtained using the constant scaling and daily scaling methods generally differ by less than 5%, which is relatively smaller than the range of runoff results from the different GCMs of 30%–40%.

The daily translation method also appears to adequately take into account the different changes to the different parts of the daily rainfall distribution, with the daily translation method generally giving higher runoff than the constant scaling method. However, this result is less clear for the daily translation method than for the daily scaling method, and the relative difference between the daily translation and constant scaling methods is larger than the relative difference between the daily scaling and constant scaling methods. This is because the daily translation method not only considers the change in the different parts of the daily rainfall distribution but also the change in the daily rainfall sequence and therefore other daily and longer-period rainfall characteristics. The daily translation method therefore has the potential to offer more realistic future rainfall projections, but its use is limited today by the limited number

![Fig. 7](Continued)
of readily available archived GCM daily rainfall simulations. The constant scaling method only considers the relative change in monthly or seasonal rainfall and can therefore be used with the more readily available monthly GCM simulations for different ensemble runs for different emissions scenarios to take into account the large uncertainty associated with global warming scenarios and the GCM simulation of local rainfall.

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REFERENCES


——, M. C. Peel, and A. W. Western, 2002: Application and testing of the simple rainfall-runoff model SIMHYD. Mathematical Models of Small Watershed Hydrology and Applications,


