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Non-linearity of the runoff response across southeastern Australia to increases in global average temperature

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Abstract Many studies examining the impact of climate change on runoff use a technique whereby the changes in rainfall for a particular region are derived per degree of global warming. These changes in rainfall are then used to drive a rainfall–runoff model to produce a change in runoff, which can also be interpreted per degree of global warming. The technique assumes that the change in rainfall scales linearly with global average temperature. That is, a two degree increase in global average temperature will produce twice the change in rainfall as a one degree increase in global average temperature. This paper uses the CCCMA_T47, CCCMA_T63, CNRM and IAP global climate models (GCMs) to examine the nature of the relationship between runoff and global average temperature across a range of scales in southeastern Australia for projected temperature increases of 1.0, 1.3, 2.0 and 3.3 degrees, representing medium and high global warming scenarios for 2030 and 2060, respectively. Results indicate that for individual GCM grid cells (~40 000 km^2) and most small catchments, the vast majority of runoff responses to increases in global average temperature up to 3.3 degrees are reasonably linear. This is particularly the case for large changes in runoff (>5% per degree global warming), and more so when the projected changes in rainfall are consistent across all seasons. However, small projected changes in rainfall may display a non-linear runoff response to increases in global average temperature, particularly when the seasonal response shows increases in rainfall in one season and decreases in another. In the vast majority of cases, this non-linearity takes the form of more runoff than expected for higher levels of global warming. At larger scales, when averaging across a number of GCM grid cells, differences in response between grid cells mean that the overall regional runoff response to increases in global average temperature can be non-linear. The implications of this finding are that regional-scale analyses of changes in runoff due to projected climate change require rainfall–runoff models to be run for each projected increase in global average temperature – simple linear approximations can only be used with prior knowledge of the nature of the relationship.

Key words runoff; rainfall; climate change; southeastern Australia

BACKGROUND

There have been many studies examining the impact of climate change on water availability in Australia. Recent examples include the CSIRO Sustainable Yields projects (http://www.csiro.au/partnerships/SYP.html) and the South Eastern Australian Climate Initiative (http://www.seaci.org). The outputs of these (CSIRO, 2010) and similar projects (Vaze *et al.*, 2008) are being used to guide Federal and State government water policy and must therefore demonstrate the use of best available science.

These studies consider future climate change projections, and how changes in climate are transformed into changes in runoff and water availability. Typically, global climate model (GCM) projections of future climate are used to drive hydrological models that have been calibrated using historical rainfall–runoff data. The method used to derive the future climate sequences varies from study to study, and may involve statistical or dynamic downscaling of GCM outputs, or simple scaling of historical rainfall and climate sequences. There is considerable research currently being carried out on downscaling techniques (Fowler *et al.*, 2007); however, downscaling GCM outputs typically involves long computer run times. As a result, many studies produce future climate time series by scaling the historical time series. Many of these studies also express the change in rainfall and other climate variables (typically evaporation) per degree global warming (pattern scaling), therefore assuming a linear response between the change in the climate variable and global average surface air temperature. This simple approach is also used here.

This paper uses pattern scaling of rainfall and potential evaporation on a seasonal basis across southeastern Australia for four different levels of global warming using outputs from four GCMs. These projections of future climate were then used to drive a rainfall–runoff model, and projections of runoff for the four levels of global warming produced. These projections of runoff were then analysed at a range of scales in order to determine whether they scale linearly with global average temperature. A linear relationship would allow runoff projections to be scaled easily for a range of global warming projections. A non-linear response would make this type of simple scaling of runoff more difficult.

METHODS

In this study, four levels of global warming were considered: 1.0, 1.3, 2.0 and 3.3°C increases in global average surface air temperature. These represent medium and high global warming scenarios from the IPCC Fourth Assessment Report for 2030 and 2060, respectively (IPCC, 2007).

The baseline historical climate sequence was defined as the observed climate from 1 January 1895 to 31 December 2008. It was derived on a 0.05° (~5 km) grid over southeastern Australia (Fig. 1), corresponding to 53 447 grid cells. The source of the climate data is the SILO Data Drill of the Queensland Department of Environment and Resource Management (Jeffrey *et al*., 2001). The SILO Data Drill provides surfaces of daily rainfall and other climate data interpolated from point measurements made by the Australian Bureau of Meteorology.

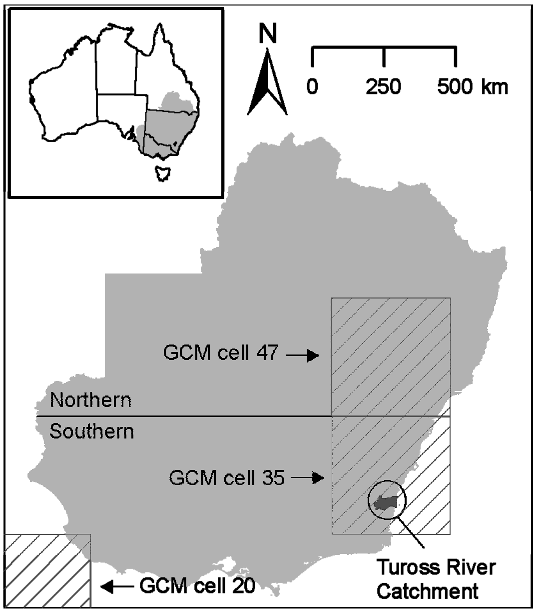

Fig. 1 The southeastern Australia study region, and associated CCCMA_T47 GCM grid cells and other locations referred to in the text.

Archived monthly simulations from the CCCMA_T47, CCCMA_T63, CNRM and IAP GCMs were analysed to estimate the change in rainfall and potential evaporation per degree of global warming. The CCCMA_T63 GCM projects a wetter future climate for this region, while the other three GCMs project a drier future. Data from each of the four seasons were analysed separately. Figure 2 shows an example of this for one grid cell and one variable (rainfall) in one season (summer). The percent changes in rainfall and potential evaporation per degree of global warming were then multiplied by the four levels of global warming to obtain seasonal scaling factors. The seasonal scaling factors were then used to scale the historical daily climate data for each 0.05° grid cell from 1895 to 2008 to obtain 114-year rainfall sequences for each GCM and each level of global warming.

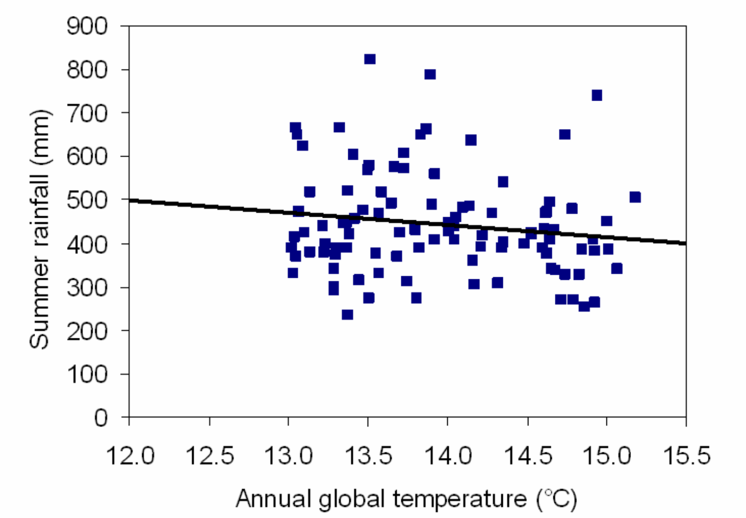

Fig. 2 Example of the seasonal scaling technique. The regression line gives the change in summer rainfall per degree global warming for one GCM grid cell.

The GCM projections of changes in daily rainfall amounts were also taken into account by scaling different daily rainfall amounts by different factors. In general, this led to projected increases in large daily rainfalls and decreases in small and medium daily rainfalls for the projected future climate (see Post *et al.*, 2009a, for more detail). Accounting for the changes in the magnitude of daily rainfall events has been shown to have a measurable impact on runoff generation (Post *et al.*, 2009b), with increases in the magnitude of large daily rainfall events (while keeping mean annual rainfall constant) leading to increases in mean annual runoff.

Having derived rainfall and potential evaporation sequences for each of the future projections for each GCM, these climate sequences were then used as inputs into the SIMHYD rainfall–runoff model to produce future runoff. Details of the calibration and regionalisation of the SIMHYD rainfall–runoff model across southeastern Australia can be found in Chiew *et al.* (2009).

RESULTS AND DISCUSSION

Grid cell scale

As changes in seasonal rainfall were derived from the GCMs, they are identical within each GCM grid cell (~30 000–60 000 km^2). Within each of these GCM grid cells there are around one to two thousand 0.05° grid cells for which the SIMHYD rainfall–runoff model was run. The runoff response is similar across most 0.05° grid cells within each GCM grid cell, both annually and for each of the four seasons. Generally, large increases or large decreases in rainfall produce essentially linear responses in terms of runoff, particularly when the change in rainfall is reasonably evenly distributed throughout the year (i.e. there are increases or decreases in all four seasons). As an example, Fig. 3 shows the annual runoff response to a 4.7% decrease in annual rainfall per degree global warming for CCCMA_T47 grid cell #20. The four points represent percent change in rainfall and runoff for each of the four global warmings of 1.0, 1.3, 2.0 and 3.3 °C. It should be noted that while the response is essentially linear, the runoff response is much greater than the change in rainfall. Thus a 16% reduction in rainfall leads to a 40% reduction in runoff. This is in agreement with the concept of runoff elasticity (Chiew, 2006).

In contrast to the linear changes in runoff seen in Fig. 3, when changes in rainfall per degree global warming are smaller, runoff responses can be highly non-linear, particularly if they are of a different sign in different seasons. For example, Fig. 4 shows the runoff response to a small increase (1.2%) in annual rainfall per degree global warming for CCCMA_T47 grid cell #47. In this case, there is a reduction in rainfall in spring (10.8%) accompanied by an increase in rainfall in

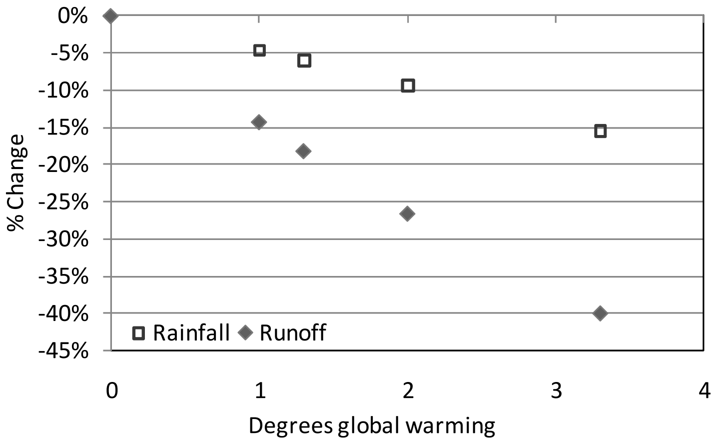

Fig. 3 Runoff response to a 4.7% decrease in mean annual rainfall per degree global warming distributed reasonably evenly throughout the year for CCCMA_T47 GCM grid cell #20.

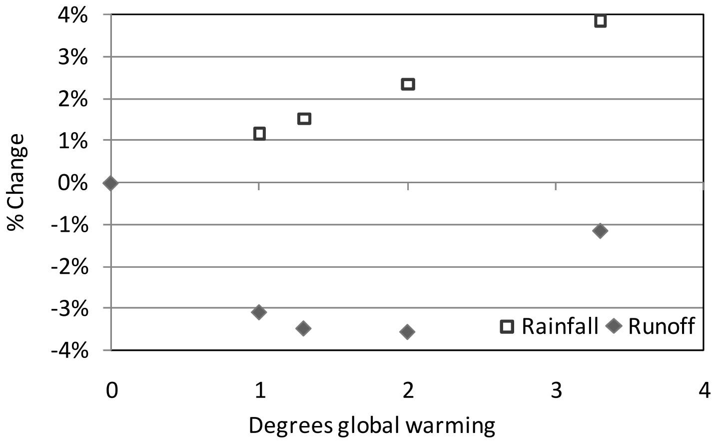

Fig. 4 Runoff response to a 1.2% increase in mean annual rainfall per degree global warming including a 10.8% decrease in spring rainfall for CCCMA_T47 GCM grid cell #47.

summer (8.7%), autumn (1.9%), and winter (2.6%). For lower levels of global warming, the reduction in spring rainfall dominates and the net effect is a reduction in mean annual runoff. However, for higher levels of global warming, the increase in rainfall at other times of the year (particularly summer) begins to offset the reductions in rainfall in spring, and the net effect of a 3.3 degree global warming is a much smaller reduction in overall runoff than the effect of lower levels of global warming. In other GCM grid cells where the seasonal changes in rainfall are even more markedly different, lower levels of global warming can cause a reduction in overall runoff, while higher levels of global warming can cause an increase in overall runoff.

For this grid cell, the assumption that runoff scales linearly for higher levels of global warming would lead to a significant underestimation of runoff. A linear assumption based on the 3.1% reduction in runoff seen for a 1.0°C increase in global average temperature leads to a projected reduction in runoff of 10.2% for 3.3°C of global warming. However, running the rainfall–runoff model for 3.3°C of global warming provides a projected decrease in runoff of just 1.1%.

Catchment and basin scale

At the GCM grid cell scale, the non-linear responses seen in Fig. 4 are only observed for quite small changes in overall annual rainfall, where the seasonality of the changes (increases in some seasons and decreases in others) and the impacts of the scaling of large daily events can become important. For example, between 76% (CCCMA_T47) and 99% (IAP) of 0.05° grid cells show a virtually linear response of runoff to changes in rainfall caused by increases in global average temperature. That is, a linear relationship fit through the changes in runoff for the four levels of global warming in these grid cells has an r^2 greater than 0.9. To illustrate, the relationship shown in Fig. 3 has an r^2 of 0.99 (essentially linear), while that shown in Fig. 4 has an r^2 of 0.03 (highly non-linear).

Although the vast majority of individual 0.05° and GCM grid cells show an essentially linear response to global warming, overall catchment and basin-scale responses can be non-linear. When catchments are relatively small, and are therefore limited to one or two GCM grid cells where the projected changes in rainfall are relatively large and very similar across seasons, responses tend to be linear. For example, Fig. 5 shows the response for the 2000 km^2 Tuross River catchment. Here, as the catchment is completely contained in CCCMA_T47 cell #35, which shows a relatively large increase in rainfall (2.75%) per degree global warming, the runoff response per degree global warming for the catchment is essentially linear.

At larger scales, however, the runoff response per degree global warming may become quite non-linear. For example, Fig. 6 shows the runoff response averaged across northern, southern, and the whole of southeastern Australia based on outputs from the CCCMA_T63 GCM. While rainfall is projected to increase by 1.4% across the north, 0.2% across the south, and 0.9% overall, the runoff response to these changes in rainfall can be very non-linear.

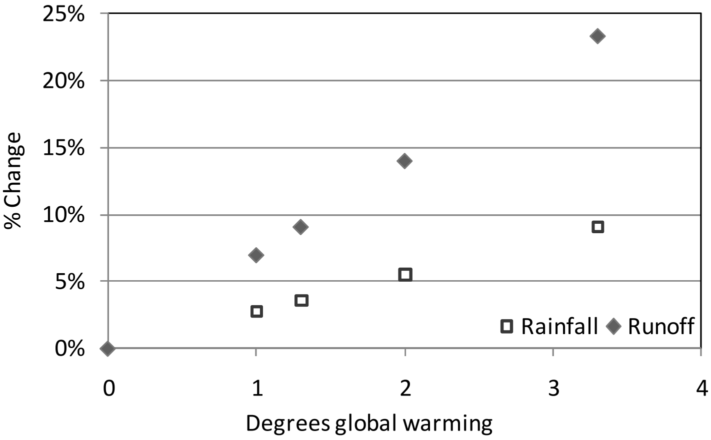

Fig. 5 Runoff response in the Tuross River catchment to a rainfall increase of 2.75% per degree global warming averaged over the catchment area from the CCCMA_T47 GCM.

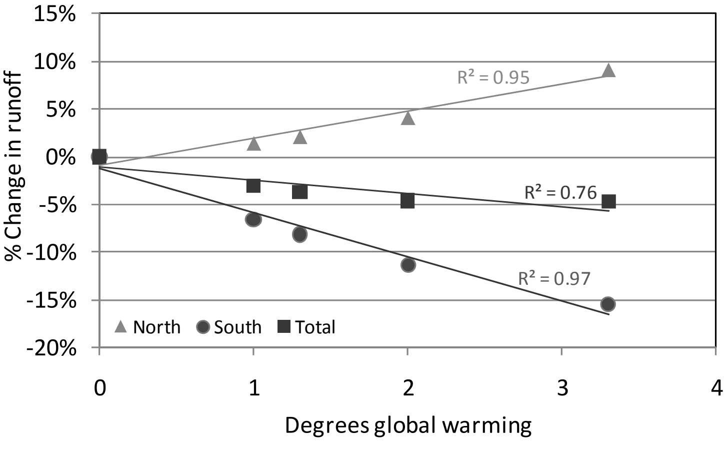

Fig. 6 Runoff response across northern, southern, and the whole of south-eastern Australia to rainfall increases of 1.4%, 0.2% and 0.9% per degree global warming, respectively, from the CCCMA_T63 GCM.

Across the northern part of the region, the result is much as expected, with a relatively linear increase in runoff in response to the increase in rainfall. However, across the southern part of the region, the 0.2% increase in rainfall per degree of global warming actually leads to a decrease in runoff. This occurs because the increases in rainfall mostly occur in summer and autumn, which do not generate much runoff across the southern part of the region. Conversely, there are large *decreases* in rainfall in winter and spring, which is when much of the runoff is generated. Thus, while rainfall over the south increases by 0.2% overall, in the key runoff generating season of spring, rainfall actually decreases by 4.2%.

Averaged across the whole region, runoff decreases slightly for low levels of global warming but this decrease levels out for 3.3°C of global warming, leading to a non-linear response overall (Fig. 6). This is because for low levels of global warming, the runoff response is dominated by the decreases in runoff across the southern part of the region. However, at higher levels of global warming, the overall response is dominated by the increases in runoff in the north of the region. As above, a linear assumption based on the 3.0% reduction in runoff seen for a 1.0°C increase in global average temperature leads to a projected reduction in runoff of 9.9% for 3.3°C of global warming. Running the rainfall–runoff model for 3.3°C of global warming, however, provides a projected decrease in runoff of just 4.7%.

CONCLUSIONS

This paper has examined the nature of the runoff response across southeastern Australia to various levels of global warming, as modelled by the CCCMA_T47, CCCMA_T63, CNRM and IAP GCMs. The technique used modifies rainfall per degree of global warming, ensuring that the rainfall response to increased global average temperature is linear. At catchment scale (within a single GCM grid cell), the runoff response to global warming is essentially linear for between 76% and 99% of 0.05° grid cells, as well as the vast majority of catchments which fall entirely within one GCM grid cell. However, within GCM grid cells that show only a small change in rainfall per degree global warming, the runoff response can be quite non-linear due to a combination of the seasonality of rainfall changes, along with differences in the scaling of large daily rainfall events. At larger scales encompassing multiple GCM grid cells, differences between rainfall projections for different GCM grid cells can produce a runoff response which is also quite non-linear.

The behaviour seen in Fig. 6, whereby runoff across southeastern Australia decreases for small increases in global average temperature, but then begins to level out for higher levels of global warming is only seen in results from the CCCMA_T63 GCM. This GCM projects drier conditions across the southern part of southeastern Australia, and wetter conditions across the northern part of southeastern Australia. Conversely, the CCCMA_T47, CNRM and IAP GCMs show an essentially linear response of runoff to global warming averaged across the northern, southern, and whole of southeastern Australia. These models project drying over the whole region, and also in most seasons. As the majority of GCMs also project drier conditions across the whole region (Chiew *et al*., 2009), the non-linearity of runoff responses to increases in global average temperature at the whole-of-region scale may be the exception rather than the rule for southeastern Australia. Future work will investigate the nature of this relationship for these other GCMs.

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