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Assessing historical and future runoff modelled using rainfall from the analogue downscaling method

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Climate change impact on runoff studies require a much finer spatial resolution of climate inputs than global climate models (GCMs) can directly provide. Various methods have been used to obtain catchment-scale climate series, informed by GCM simulations for the future and current climates, to drive hydrological models. This study assesses the historical and future daily runoff over a large region modelled using rainfall from an analogue downscaling method developed by the Australian Bureau of Meteorology (BoM). The analogue method defines a daily weather type by relating large-scale drivers (predictors) to the climate variables (predictands) across a region of interest. The future climate is generated by choosing the observed historical climate on a day with the most similar daily weather type simulated by a GCM. This downscaling method has been used to downscale point and gridded rainfall across Australia and to study rainfall trends across southeast and southwest Australia.

In this study, two time slices of GCM daily rainfall – one historical (1961-2000) and one future (2046-2065) (IPCC AR4 A2 scenario), are downscaled from 11 GCMs to 0.05° (~5km) grid cells covering southeast Australia. The downscaled gridded rainfall is used to drive a widely used hydrological model and results are compared with the runoff, modelled using observed rainfall and rainfall scaled using a perturbation method (daily scaling) to reflect climate change. The results show that the analogue method underestimates rainfall and subsequently the modelled runoff. Therefore, it is necessary to use an inflation factor to scale the daily rainfalls to match the observed 1961-2000 seasonal means. Nevertheless, differences remain between daily analogues and observed rainfall distributions, and these translate to errors in the modelled daily and mean runoffs.

The percentage change in future runoff (for the period 2046-2065 relative to 1960-2000) modelled using rainfall from the analogue method and the daily scaling method are largely similar with the large majority of the results indicating a decrease in runoff particularly in the southern parts of the region. There are differences in some of the GCMs and the cause of the differences needs to be further investigated. The range in the modelled change in future runoff using the analogue method informed by the 11 GCMs is smaller than the range when using the daily scaling method.

The analogue method is a simple downscaling method and can therefore be relatively easily used with many GCMs to represent the range of uncertainty in the climate change projections. It has the potential to capture a fuller range of potential changes in future rainfall characteristics compared to simple perturbation or scaling methods. Like the scaling methods, analogues also ensure that the daily spatial correlation over large regions is preserved. However, the use of analogues based solely on observed historical data is a limitation. The modelling results here indicate that the analogue method can be useful for hydrological impact studies over large regions. More research is nevertheless required to continue to improve the analogue method (including posterior corrections of GCM predictor variables used to define the weather states and bias-adjusting the daily rainfall outputs from the analogue method) in order to produce daily rainfall that are sufficiently similar to the observed daily rainfall for direct use in hydrological models.

Keywords: *Analogue downscaling, Rainfall-runoff model, Climate change impact, Southeast Australia*

1. INTRODUCTION

General circulation models (GCMs) are arguably the best available tools for modelling future climate. However, GCMs provide information at a resolution that is too coarse to be used directly in hydrological modelling. Thus, downscaling techniques are required to transform the lower resolution GCM outputs to a finer scale suitable for local or regional impact assessment. In most of the climate change impact studies, the future climate projections from GCMs are downscaled to catchment scale using one of the available downscaling methods and the downscaled climate – mainly rainfall – is used to drive hydrological models to estimate future runoff.

There are two types of downscaling methods: statistical downscaling models and dynamic downscaling models. In addition, many impact studies also use simple empirical perturbations of the observations to obtain local climate change information (also referred to as 'delta-change' approach). This study focuses on the analogue downscaling method developed by the Australian Bureau of Meteorology (BoM). The analogue method defines a daily weather type by relating large-scale climate variables (predictors) to regional and local variables (predictands). The future climate is generated by choosing the observed historical climate on a day with the most similar daily weather type simulated by a GCM (Timbal et al., 2009). Compared to the widely used perturbation methods, it accounts for changes to a greater range of rainfall characteristics by considering the daily weather types and their sequencing as simulated by a GCM. It is also better suited to gridded hydrological applications compared to the multi-site statistical downscaling models and computationally effective compared to the dynamic downscaling models.

Although appealing, the analogue method has several limitations. It is a non-parametric method that re-samples the future climate from the historical climate data. It therefore cannot simulate a climate that has not been seen in the past, including rainfall events that are more extreme than those experienced in the past. The analogue method also requires bias correction of GCMs and inflation factors so that the generated rainfall show similar characteristics as the historical rainfall. It also relies on large training observations to identify suitable analogues for systems with large degrees of freedom. Like other statistical methods, it also assumes that the statistical relationship between predictors and predictands is stable and valid in a changing climate and that the chosen predictors encompass all the climate change signals.

With all these known advantages and limitations, it is worth asking whether the analogue method is suitable in climate change impact on runoff studies and how the results compare with other commonly used methods. This study addresses this question by assessing the historical and future daily runoff modelled using rainfall from the analogue method. The results are compared with the results from a 'daily scaling' perturbation method to investigate (i) the suitability of the analogue method in climate change impact on runoff studies over a large region; and (ii) the difference between the two downscaling methods in modelling climate change impact on future runoff.

2. STUDY AREA AND DATA

The study area in southeast Australia is about 1.6 million km^2 and covers about 20% of continental Australia (Figure 1). It includes the whole of New South Wales, Victoria and the Australian Capital Territory, and parts of Queensland and South Australia. The entire Murray-Darling Basin and the Southeast Coast drainage divisions are in this region, with the Great Dividing Range separating the two drainage divisions.

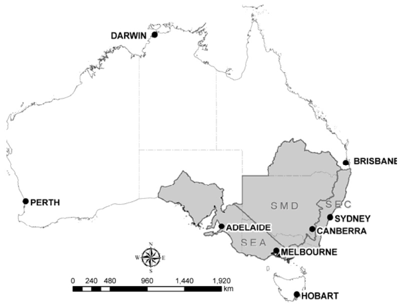

Figure 1. Study area in southeast Australia.

The baseline historical climate sequence is defined here as the observed climate from 1 January 1960 to 31 December 2000. It is derived on a 0.05° (~5 km) grids over southeast Australia (Figure 1), corresponding to 65,338 grid cells. The source of the climate data is the AWAP gridded climate datasets of the Australian Bureau of Meteorology (Jones et al., 2009). The AWAP gridded climate datasets provides surfaces of daily rainfall and other climate data interpolated from high quality point measurements. The gridded potential evapotranspiration (PET) used in the modelling experiments is the daily averages for each of the 12 months derived from long term daily PET calculated using Morton's wet environment algorithms (Morton 1983).

The daily GCM simulations used here are from 11 GCMs (cccma_cgcm3_1, cnrm_cm3, csiro_mk3_0, csiro_mk3_5, gfdl_cm2_0, gfdl_cm2_1, giss_e_r, ipsl_cm4, miroc3_2_medres, mpi_echam5, mri_cgcm2_3_2a) for the 20th century and the Special Report on Emissions Scenarios (SRES) A2 emissions scenario in the Fourth Asssessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC). The GCM outputs are obtained from the World Climate Research Programme's (WCRP's) phase 3 of the Coupled Model Intercomparison Project (CMIP3) archived at Program for Climate Model Diagnosis and Intercomparison (PCMDI) (http://www-pcmdi.llnl.gov). Only the 11 GCMs listed above have archived the daily climate variables required by the analogue approach and hence could be used in this study. Daily streamflow data (1960-2000) from 232 catchments in southeast Australia are used to calibrate the rainfall-runoff models. The catchments are largely unregulated and have less than 10% missing data from 1960 onwards. The streamflow data were obtained from the respective state water agencies and have been quality assessed as part of another project (Vaze et al., 2011).

3. METHOD

3.1. Analogue downscaling method

The analogue method derives the regional or local climate information by first determining a relationship between large-scale predictors to regional and local predictands. Once this relationship is established, the large-scale outputs from GCM simulations are used to estimate the corresponding local and regional climate characteristics using the same relationship. In this study, the NCEP/NCAR global re-analysis datasets (NNR), from 1958 to present, are used for the large-scale predictors. The analogues are determined by analysing/calibrating historical climate data. The choice of a single best analogue is based on a closest neighbour using a simple Euclidean metric. The metric is applied to a single vector which comprises daily normalised anomalies of point values within an optimised geographical area for the selected predictors. The choice of the optimal combination of predictors and the geographical area are two key steps in the optimisation of the analogue method. Three out of ten distinct climate regions defined over Australian continent are used in this study (Figure 1): the Southwest of Eastern Australia (SEA), the Southern half of the Murray-Darling Basin (SMD) and the South-East Coast (SEC). The predictors are chosen separately for each predictand (rainfall in this case), each region and each season. For the three regions, the most commonly used large-scale predictor is Mean Sea Level Pressure (MSLP, used in every region and every season) followed by Precipitation (PRCP, again used everywhere except autumn in SEA and summer in SEC), wind components (U_{850} and V_{850}) and specific humidity (Q_{850}) at 850hPa. The observed daily climate (AWAP 0.05° grid scale) from a day with the most similar analogue (based on re-analysis data) is used to generate daily rainfall for historical (NNR and GCMs) and future (GCMs) climatology. The analogue downscaling method and how the best combination of predictors was obtained is described in detail in Timbal et al. (2009).

3.2. Daily scaling method

A perturbation method – daily scaling method is also used here to obtain the climate change impact on runoff estimates. The daily scaling method is described in details in Chiew et al. (2009) and it has been widely used in Australia for large scale climate change impact on runoff studies such as CSIRO Sustainable Yields projects (http://www.csiro.au/partnerships/SYP.html), NSW future climate and runoff projections (Vaze and Teng, 2011) and SEACI (http://www.seaci.org). The observed daily rainfall series are scaled to obtain a future rainfall series based on the difference between the control (1960-2000) and future (2046-2065 under SRES A2 emission scenario) GCM simulations. This approach takes into account the changes in daily distribution as well as the changes in seasonal means. This is important for rainfall because many GCMs indicate that future extreme rainfall is likely to be more intense, even in some regions where projections indicate a decrease in mean seasonal or annual rainfall. As the high rainfall events generate large runoff, only considering changes in seasonal means would lead to an underestimation of the extreme runoff as well as the mean annual runoff.

3.3. Rainfall-runoff modelling

The Sacramento lumped conceptual daily rainfall–runoff model (Burnash et al., 1973) is used in this study. The input data to the model are daily rainfall and PET, and the model simulates daily streamflow. The Sacramento model is widely used by water agencies, research organisations and consultants for local and regional water resources assessments across southeast Australia.

The model is first calibrated against observed streamflow data and then driven with historical and future climate data respectively with the same optimised parameter values to obtain modelled historical and future runoff. The model is used to estimate daily runoff for the 65,338 grid cells across the study area. The modelling at 0.05° grid cells allows a better representation of the spatial patterns and gradients in the rainfall. The optimised parameter values are used for all the grid cells within each of the calibration sub-catchments.

The runoff for a non-calibration sub-catchment is modelled using optimised parameter values from the geographically closest calibration sub-catchment.

3.4. Modelling experiments

Three sets of modelling experiments are carried out where the analogue method is applied without any ‘inflation factors’, with ‘variance-corrected’ inflation factors and with ‘match-mean’ inflation factors. The analogue technique has a tendency to underestimate the observed variance. This is a known problem for regression based statistical downscaling methods (Von Storch, 1999) including the analogue approach. In the case of rainfall, the reproduction of the mean is dependent on the ability of the technique to reproduce the observed variance and results in a dry bias. For this reason, Timbal et al. (2006) introduced a correction/inflation factor to adjust the reconstructed rainfall series and enhance the variance and improve the reproduction of the mean. The rationale for applying correction/inflation is that the analogue reconstructed rainfall is affected by the size of the pool of analogues which becomes smaller in the case of rare large rainfall events. Therefore, the error in finding the best matching analogue increases and the chances are that the best analogue found would describe more frequent but less intense rainfall events thus underestimating the rainfall in the reconstructed series. A very simple factor based on the observed ratio of dry versus wet days was first developed to limit some of the risks linked to artificially inflating the variance when using downscaling techniques (Timbal et al., 2006). For the application across the entire Australian continent and across all seasons, the original factor was adjusted to depend on a correction of the shape and scale parameters of a fitted gamma distribution applied to the observations (Evans et al., 2011).

The inflation factors were developed using the high quality network of rainfall observations across the Australian continent but applied to the gridded observations (AWAP) in this study. Two sets of inflation factors are derived for each of the 0.05° grid cells based on the comparison between the analogue downscaled rainfall from the re-analysis datasets (NNR) and AWAP observed rainfall, for the historical period (1961-2000). One set of inflation factors are calculated to obtain a perfect match for the variance of daily rainfall (‘variance-corrected’) for a season whereas the other set are determined to match the seasonal mean of rainfall series (‘match-mean’). The same set of inflation factors which are determined based on the pool of available observations are applied without further adjustment to the daily rainfall downscaled from NNR and 11 GCMs for two time periods, one historical (1961-2000) and one future (2046-2065). The analogue and observed climate data are used to drive the Sacramento model to estimate runoff across southeast Australia. The simulated runoff for the historical period using analogue downscaled rainfall is compared with the runoff simulated using the observed rainfall. The future runoff simulated using the analogue method is compared with the historical runoff to estimate climate change impact on runoff. These results are also compared with the climate change impact on runoff results obtained using the daily scaling method.

4. RESULTS AND DISCUSSION

4.1. Historical rainfall and runoff

The analogue method underestimates the variance and mean in rainfall. Since rainfall is the main driver of runoff, this underestimation will be amplified in runoff. This is why the inflation factors are used to correct the analogue downscaled rainfall so that it can provide more reliable runoff estimates. Figure 2 illustrates the impact of different inflation factors on analogue downscaled daily rainfall and simulated runoff for a 0.05° grid cell in Melbourne. The plots in Figure 2 show the distribution of daily rainfall and runoff for two seasons (Dec-Jan-Feb and Jun-Jul-Aug). The numbers shown in the legends are seasonal means.

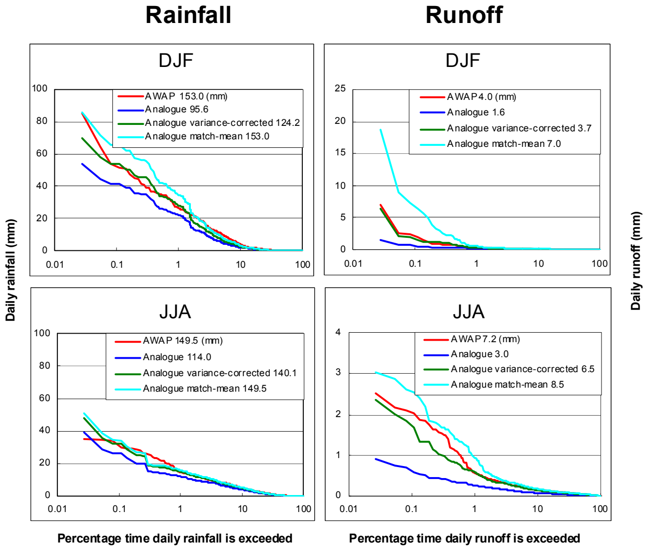

Figure 2. Daily rainfall and runoff distribution for one 0.05° grid cell in Melbourne (1961–2000).

The plots show that the analogue downscaling without any correction underestimates the rainfall. The rainfall distributions are significantly improved after applying the ‘variance-corrected’ inflation factors. The underestimation in seasonal means are also reduced from 38% to 19% in summer and from 24% to 6% in winter for the example provided in Figure 2. The seasonal means of 'match-mean' analogue rainfall perfectly match the observed ones but it comes at the cost of the high rainfall events being overestimated. This difference is amplified in the runoff estimates due to the non-linearity between rainfall and runoff and the importance of high rainfall events. The runoff modelled using analogue rainfall without correction is underestimated by ~60% (for seasonal means); this bias is strongly reduced when the 'variance-corrected' analogue rainfall is used (i.e. the underestimation is reduced to ~10%). The runoff modelled using 'match-mean' analogue rainfall is overestimated by 75% and 18% for the two seasons respectively due to the overestimated high runoff events.

The Sacramento model is driven with the three sets of analogue downscaled rainfall along with observed rainfall at 0.05 grids. The runoff modelled using analogue downscaled rainfall without any correction and the 'variance-corrected' analogue rainfall are both consistently underestimated everywhere across the study area. Hence the results from these two sets of downscaled rainfall are not discussed further in this paper.

The comparison between the runoff simulated using the analogue 'match-mean' rainfall (downscaled from NNR) and the runoff simulated using observed rainfall for all the grid cells across the region is shown in Figure 3. The runoff characteristics compared here are mean seasonal (Dec-Jan-Feb, Mar-Apr-May, Jun-Jul-Aug and Sep-Oct-Nov) runoff, mean annual runoff, high runoff characteristic (Q1, daily runoff that is exceeded 1% of the time) and low flow characteristic (Low Flow Days, number of days per year when runoff is less than 0.1 mm). When plotting the 65,338 grid cells together, the mean annual runoff, and to a lesser extent mean seasonal runoff, modelled using the 'match-mean' analogue rainfall, is in good agreement with the runoff modelled using the observed rainfall. However, the high runoff and low flows are not as well captured. The use of a more complex inflation/correction, such as quantile-quantile mapping, may be able to better reproduce the historical rainfall characteristics. Nevertheless, the benefit of this kind of corrections can be overweighed by having to rely too much on the observations.

When using rainfall downscaled from the 11 GCMs (1960-2000), the runoff results are in less agreement with the runoff modelled using the observed rainfall (not shown here due to space limitations) than when downscaled NNR rainfall was used. In particular, the mean annual runoff for ipsl_cm4 is underestimated due to the underestimation of MAM rainfall and high rainfall events. While the inflation factors developed aim at correcting the analogue downscaling inherent dry bias, these factors do not attempt to correct GCM biases. Instead, GCM biases are dealt with by the analogue technique by mean of using normalised anomalies for the predictors. While this approach maps back the daily meteorological situations generated by the GCM on the space provided by the reanalyses, it does not provide a framework to obtain a realistic distribution of these meteorological situation. Highly order errors are therefore uncorrected and appear to introduce additional bias when the downscaling technique and subsequently the Sacramento model are applied.

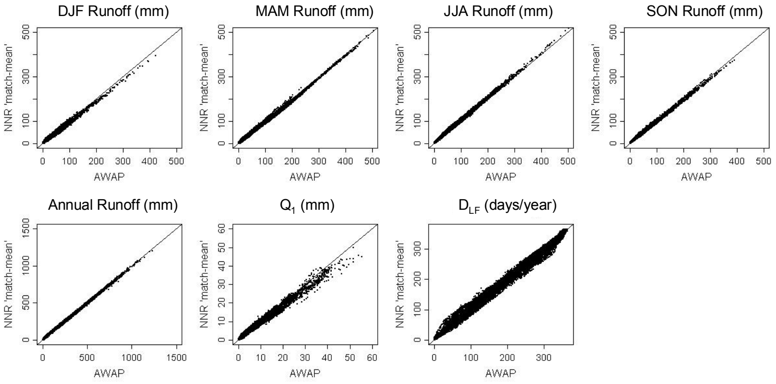

Figure 3. The runoff modelled using the analogue 'match-mean' rainfall (downscaled from NNR) versus the runoff modelled using AWAP observed rainfall for 65,338 0.05° grid cells in southeast Australia (1961–2000).

4.2. Future runoff

The climate change impact on runoff is estimated by comparing the historical and future modelled runoff using analogue rainfall with the 'match-mean' inflation factors. The percentage change in runoff for each of the 11 GCMs are compared with the results obtained from the daily scaling using the same GCM inputs (except giss_e_r for which the result from the daily scaling is absent).

The percentage changes in mean annual runoff across the study area estimated using rainfall from the two downscaling methods for the period 2046-2065 relative to 1960-2000 are compared side by side in Figure 4.

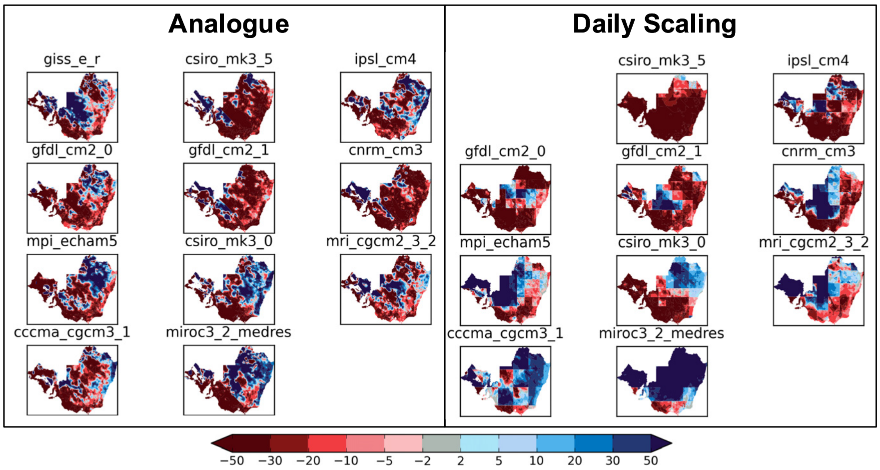

Figure 4. Percentage change in future mean annual runoff for the period 2046-2065 relative to 1960-2000 modelled using the analogue method and the daily scaling method informed by the 11 GCMs.

The spatial maps for the 11 GCMs on the left side present the results from the analogue method with 'match-mean' correction. The maps for the 10 GCMs (same 11 GCMs less giss_e_r) on the right side are the results from the daily scaling. Generally the spatial patterns of the percentage change in runoff from the two downscaling methods look similar but there are large differences locally. It is interesting to notice that unlike the daily scaling which displays the GCM grid resolution, the results obtained with the analogue technique have more realistic spatial patterns (due to the same historical day chosen for all the grid cells within a climatic region). Although in this study the analogue technique divided the study area into three climate regions for which different analogue models were set up, the transition between these regions does not appear unrealistic.

Averaged across southeast Australia, the percentage change in mean annual runoff for both the downscaling methods for each GCM are plotted in Figure 5. The majority of the results show a reduction in future runoff with 7 out of 11 GCMs from the analogue method and 8 out of 10 GCMs from the daily scaling suggesting a drier future. There is a high correlation between the two sets of results. The difference between the percentage changes in mean annual runoff when using downscaled rainfall from the two downscaling methods varies from 1% to 39% with a median difference of ~10%. This is consistent with the findings from the previous study (Chiew et al., 2010) which suggests that the differences in results from different downscaling methods are generally smaller than the range of the future projections from the GCMs. While largely similar, there are large differences (> 15%) between the two methods for some of the GCMs. In particular, the results from ipsl_cm4 and csiro_mk3_0 disagree in the direction of the change. This is surprising because GCM rainfall, as the input for the daily scaling, is often used as a large-scale predictor by the analogue method. One of the possible reasons might be that, for these GCMs, the analogue method is capable of capturing a strong positive response along the east coast (where most of the runoff is generated) whereas the daily scaling can not produce the same signature from the GCM simulations. The issues associated with the analogue method in reproducing historical rainfall characteristics (see section 4.1) can also affect the future runoff projections as ipsl_cm4 happens to perform poorest in reproducing historical mean annual runoff. Further investigation is needed to determine the cause of the difference for these GCMs between the two downscaling methods. The range (10th -90th percentile) of the results from the 11 GCMs for percentage change in mean annual runoff when using analogue downscaled rainfall is ~38%. This is smaller than the range of ~49% when using the daily scaling. This is expected because: (i) the analogue method uses large-scale atmospheric variables as predictors which is supposedly better than using GCM rainfall only; and (ii) the analogue method normalises anomalies of the predictor fields from long-term climatology (either using monthly or seasonal means) and perform analogue search on the anomalies whereas the daily scaling uses the changes directly by comparing two periods of GCM daily outputs.

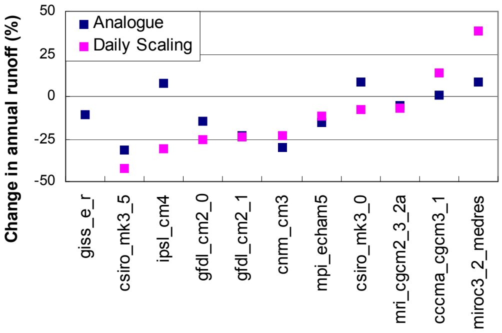

Figure 5. Change in mean annual runoff (%) averaged across the study region.

5. CONCLUSIONS

This study assesses the analogue downscaling method for climate change impact on runoff modelling across southeast Australia. The results show that daily rainfall from the analogue method scaled to match the observed historical seasonal means can be used with hydrological models to simulate the long-term runoff averages over large regions reasonably well. However, the analogue method does not reproduce the observed daily rainfall distribution sufficiently to consistently model the range of runoff characteristics.

The percentage change in future runoff (for the period 2046-2065 relative to 1960-2000) modelled using rainfall from the analogue method and the daily scaling method are largely similar with the large majority of the results indicating a decrease in runoff particularly in the southern parts of the region. There are differences for some of the GCMs and the cause of the differences needs to be further investigated. The range in the modelled change in future runoff using the analogue method informed by the 11 GCMs is smaller than the range when using the daily scaling.

The analogue method is a simple downscaling method and can therefore be relatively easily used with many GCMs to represent the range of uncertainty in the climate change projections. It has the potential to capture a fuller range of potential changes in future rainfall characteristics compared to simple perturbation or scaling methods. Like the scaling methods, analogues also ensure that the daily spatial correlation over large regions is preserved. However, the use of analogues based solely on observed historical data is a limitation. The modelling results here suggest that the analogue method can be useful for hydrological impact studies over large regions. More research is nevertheless required to continue to improve the analogue method (including posterior corrections of GCM predictor variables used to define the weather states and bias-adjusting the daily rainfall outputs from the analogue method) in order to produce daily rainfall that are sufficiently similar to the observed daily rainfall for direct use in hydrological models.

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