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Assessment of climate change impact on water resources in the Pungwe river basin

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ABSTRACT

The Rossby Centre Regional Climate Model (RCA3) and the hydrological model HBV were linked to assess climate change impacts on water resources in the Pungwe basin until 2050. RCA3 was capable of simulating the most important aspects of the climate for a control period at the regional scale. At the subbasin scale, additional scaling was needed. Three climate change experiments using ECHAM4-A2, B2 and CCSM3-B2 as input to RCA3 were carried out. According to the simulations annual rainfall in 2050 would be reduced by approximately 10% with increasing interannual variability of rainfall and dry season river flow and later onset of the rainy season. The ECHAM4-A2 driven experiment did also indicate a slight increase of high flows. If the results indeed reflect the future, they will worsen the already critical situation for water resources, regarding both floods and droughts. Uncertainties, however in the downscaled scenarios make it difficult to prioritize adaptation options. This calls for inclusion of more climate change experiments, in an ensemble of climate scenarios possibly by using a combination of dynamical and statistical downscaling of general circulation models, as well as extending the simulations to 2100 to further ensure robustness of the signal.

1. Introduction

One of the major challenges with climate change is its impact on water resources and extreme hydrological events. Extreme precipitation is projected to increase significantly, especially in regions that are already relatively wet under present climate conditions, whereas dry spells are predicted to increase particularly in regions characterized by dry conditions in present-day climate (Christensen et al., 2007; Sillmann and Roeckner, 2008). Semi-arid regions of the developing world, which are already poor and face major water resource management and food security problems, are likely to be the most severely impacted.

Climate change is foreseen to increase water stress in some parts of the world and increase river discharge in others (Arnell, 2004). This emphasises the need to assess and take consideration to climate change impacts in the adaptive management of water resources. By using projected precipitation changes de Wit and Stankiewicz (2006) estimated that a decrease in perennial drainage will significantly affect present surface water across 25% of Africa by the end of this century. Southern Africa has also been pinpointed as one of the regions in the world whose food security will be negatively affected if sufficient adaptation measures towards the impacts of climate change are not taken

(Lobell et al., 2008). In spite of this, scenarios of climate change impacts are seldom explicitly considered in water resource management (Timmerman et al., 2008). As proposed by the United Nation Development Programme (UNDP), an essential step in the integration of climate change in water resources management is to assess the potential effects of climate change on water availability and extreme hydrological events in different regions in order to better understand the consequences on vulnerable sectors and societal groups and promote and implement appropriate response measures (Losjö et al., 2006). Against this background, UNDP, in collaboration with the Swedish Meteorological and Hydrological Institute (SMHI) and the Swedish International Development Cooperation Agency (Sida) initiated the project 'Climate change impacts on water resources in the Pungwe drainage basin'.

General circulation models (GCMs) are useful for providing climate change scenarios as a basis for estimating the impacts of climate change. To provide scenarios of water resources and extremes, results from GCMs can be applied in hydrological models to identify climate change impacts. However, GCMs do not usually provide sufficient spatial resolution for regional and local applications, that is, the scale usually needed to make effective decisions for adaptation strategies. Coastlines in GCMs are generally very roughly represented and topography is much smoother than in reality. This is especially an issue in applications where precipitation plays an important role since precipitation distribution is very sensitive to land/sea contrasts in

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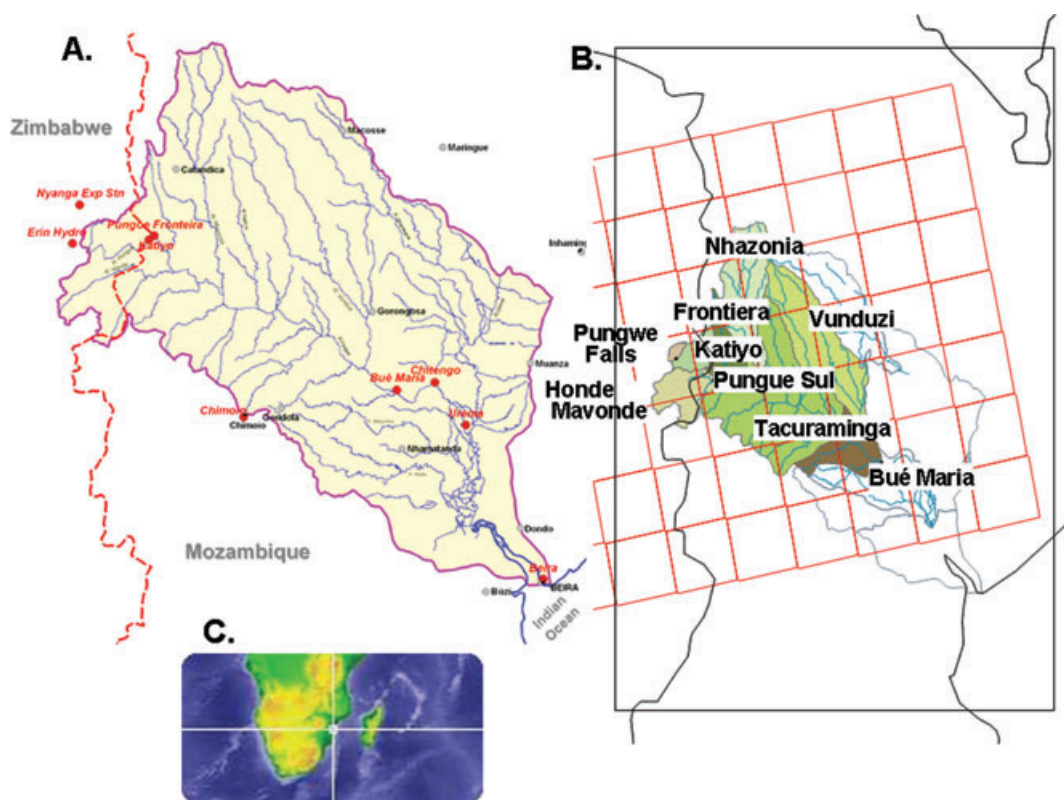


Fig. 1. (a) The Pungwe River basin. (b) Superimposing of RCA3 grids (50 km $\times$ 50 km) over the subbasins of the Pungwe basin included in the HBV model setup, i.e. the area upstream of Bué Maria (included subbasins shown in colour). (c) Map of Southern Africa with the location of the Pungwe basin indicated.

surface roughness and temperature and to complex topography where precipitation can be orographically forced or damped. Consequently, GCMs need to be regionalized in order to identify climate change impacts on water resources and extreme events, that is, in order to effectively support decision making (Fowler et al., 2007).

Simplified post-processing of global simulations and statistical downscaling are two methods of regionalization. A more advanced and computationally demanding method of regionalization, however, is dynamical downscaling with the use of regional climate models (RCMs). The main strengths of RCM downscaling are that it keeps the physical consistency between variables and takes into account feedback mechanisms in the system as the forcing from the GCM changes with time.

This paper presents integrations of the Rossby Centre Regional Climate Model (RCA3, Samuelsson et al., 2011; Jones et al., 2004; Kjellström et al., 2005) and the hydrological model HBV (Lindström et al., 1997), for assessment of possible consequences of global warming on the water resources in the Pungwe basin (Fig. 1) until 2050. The basin (31 151 km²) is shared between Mozambique and Zimbabwe. It has a mean annual runoff (MAR) of 3783 million m³, a river length of 400 km and a population of 1.2 million people. The selection of information on climate change impacts to be compiled was decided upon

during workshops with regional actors and was based on assessments of where it might be necessary to incorporate information about climate change in the Integrated Water Resources Management Strategy for the Pungwe basin. Results from the project were to be used for decision support on where to allocate funds from UNDP for water resource management, including a climate change component. The stakeholders expressed greatest concern in the time period up to 2020, and some interest in the period up to 2050. Consequently, funds for modelling were allocated to the period up to 2050.

The specific objectives of this paper are to:

1. Evaluate the merits and challenges of integrating a RCA3 with a river basin hydrological model (HBV) for an assessment of possible change in water availability and extreme hydrological events due to climate change in the coming 50 yr.
2. Make a preliminary assessment of how results from the integration of regional climate models and hydrological models can be useful in the preparation of precautionary actions to possible consequences of climate change on water resources and extreme hydrological events based on work from participatory workshops with regional actors.
3. Provide recommendations for further development of this study and for similar studies in other river basins.

2. Uncertainties of GCMs and of using RCMs with hydrological models

The primary rain-bearing systems over the majority of tropical land regions are of small-scaled convective nature. This coupled with the challenge of surface heterogeneity (Schulze, 2000) means that their simulation benefits from increased resolution. The coarse scale of GCMs and the regional scale of many climatic factors especially precipitation, motivates the use of regional modelling for Southern Africa. The conclusion that regional models, in spite of introducing new uncertainties, can add value over global simulations in regions with complex physiographical features as well as in terms of higher temporal resolution also has been found for other regions, for example, Europe by several authors (Rowell, 2006; Rummukainen, 2010).

Hudson and Jones (2002) concluded that their RCM (HadRM3H) did considerably better than forced GCMs in capturing the observed distribution of present-day rainfall and was able to resolve the tropical cyclones over Africa. Engelbrecht et al. (2002) concluded that their RCM (DARLAM) results for Southern Africa were both superior to those from the forcing GCM and compared favourably with a dense network of observations of precipitation and temperature. They also noted problems in simulating precipitation over regions of pronounced topography. However, although RCMs may better capture the observed distribution of regional rainfall and may have the potential to capture mesoscale non-linear effects of climate change, the RCM is only as good as the driving GCM, as it is the driving GCM that 'transmits' the broad climate change signal.

On a broad scale, different GCMs produce similar results for the future climate given the same emission scenarios. This involves a general warming that is stronger over continents than oceans, an increase in precipitation in a large part of the tropics and a decrease in precipitation in the subtropics (Christensen et al., 2007). However, the amplitudes of changes in precipitation and temperature, as well as the extent of the areas that are projected to be affected differ between the GCMs. Such differences have been illustrated for Southern Africa by Ruosteenoja et al. (2003) and discussed by Losj   et al. (2006). The difference between different GCMs implies that more than one GCM should be used to better capture some of the uncertainties in climate change at a regional scale. Apart from uncertainties in model formulation as well as in the emissions scenarios, internal variability in the climate system introduces an additional source of uncertainty in climate change scenarios. Examples of such variability can be decadal-scale fluctuations in sea surface temperatures (SST), long-term variability of the frequency of El Ni  o Southern Oscillation (ENSO) events, etc. A common way to deal with this kind of uncertainty is to use several ensemble members of climate change simulations, which differ in their initial conditions.

The use of RCMs linked to hydrological models is quite common for river basins in Europe and to a lesser extent for North

America. Few studies are, however available for Africa, Asia and South America (Teutschbein and Seibert, in press), which highlights the need for such studies in regions like Southern Africa. Available studies include Arnell et al. (2003) who applied the HadRM3H regional climate model across Southern Africa and a macroscale runoff model to simulate river flow. As shown by Teutschbein and Seibert (2010), among others, due to systematic errors in RCMs and the fact that the spatial scale needed for hydrological models does not always correspond to the scale of the RCMs, there is a need for scaling of RCMs before using them as input to hydrological models. The question of whether corrections are persistent for simulations of scenarios of future conditions is still open, and this adds to the cascade of uncertainties.

3. Methods

Regional climate change scenarios were generated for the Southern Africa region up to 2050, and fed into a hydrological model to assess impacts on the Pungwe River basin. This analysis was performed in close dialogue with regional actors. The modelling work was based on a chain of analyses from emission scenarios to assessment via GCMs, the RCM, additional bias correction and scaling to the subbasin level (i.e. the scale relevant for water resource management) and hydrological modelling. By using RCA the spatial gridding increased from less than one GCM cell to more than 12 RCM cells over the Pungwe basin (Fig. 1b). In order to ensure that results would be of interest for water resources management, the selection of analysed variables from the hydrological model (e.g. frequency analysis for high flow, frequency of days with insufficient water inflow to the city of Beira), as well as spatial scales for presentation of results and the time period for scenario experiments was decided upon during a meeting with the modellers and a reference stakeholder group, including representatives from water authorities in Mozambique and Zimbabwe. During a final workshop, the implications of the results on the Integrated Water Resources Management Strategy for the basin were discussed.

3.1. The RCA3 setup

This study was based on a slightly modified version of RCA3 (Kjellstr  m et al., 2005; Samuelsson et al., 2011). RCA3 is considered to be a fast RCM primarily due to a fast radiation scheme, which to a large extent is based on empirical relationships (Savij  rvi, 1990). The drawback with such a scheme is that it may need adjustments if the environmental conditions are changed, like when moving the model domain between regions as from Europe to Southern Africa as in this case. Thus, applying RCA3 over Southern Africa called for some modifications in the atmospheric physics parameterisations. In addition, the default physiographic information in RCA3 did not satisfactorily represent land-surface conditions outside Europe. In order

to better reflect Southern African conditions, with regard to root depths, type of vegetation and vegetation coverage, etc., we introduced a globally consistent physiography based on ECOCLIMAP (Champeaux et al., 2005).

The model setup was the same for all simulations. RCA3 was run on a rotated latitude–longitude grid covering approximately 5°E–55°E and 0°S–40°S with a resolution of 0.4°, corresponding to 44 km. The model domain included 126×106 grid boxes of which the outermost eight on each side were used as boundary relaxation zones. The relaxation zone is excluded in all figures. Twenty-four levels were used in the vertical resolution and the time step for the calculations was 30 min. Each simulation included four months spinup prior to the starting date of the time period in question. These four months were excluded in the analyses. In terms of radiative forcing some parts were identical between the simulations. Aerosols and the solar constant were held constant. Apart from these common forcing agents and the changes in greenhouse gases and SST, as described separately for the different experiments below, no other types of external forcing were used in the simulations.

Initially, RCA3 was used to simulate the present-day climate for a control period (1961–1990) with lateral boundary data and SSTs taken from the European Centre for Medium Range Weather Forecasts (ECMWF) ERA40 reanalysis data set (Uppala et al., 2005). A complicating matter for this evaluation was the scarcity of high quality observations at a sufficient high temporal and spatial resolution. The results from this experiment were compared to observations in an effort to evaluate RCA3 for Southern Africa, using two different sources of observations. Those are gridded observations over land of temperature and precipitation from CRU (version TS2.1, Mitchell and Jones, 2005) and Willmott and Matsuura (2001), both at 0.5° resolution.

Second, three transient climate change experiments were performed with RCA3, using lateral boundary conditions and SST from two GCMs for the time period 1961–2050. Two of the simulations used boundary data from ECHAM4/OPYC3 (Roeckner et al., 1999) developed and run at DKRZ, the Deutsches Klimarechenzentrum GmbH and the Max-Planck Institute for Meteorology in Hamburg. The third simulation used boundary data from the Community Climate System Model (CCSM3, Collins et al., 2006) that has been developed under the auspices of the National Center of Atmospheric Research in Boulder (USA). The CCSM3 simulation was performed at the Rossby Centre. Both models are fully coupled atmosphere–ocean GCMs that are run at relatively coarse horizontal resolution (about 2.8° in ECHAM4/OPYC3 and 3.75° in CCSM3). The only forcing prescribed in the GCM simulations were variations in greenhouse gas concentrations and aerosols. For the control period (1961–1990) the observed forcing history (greenhouse gases, aerosols and solar constant) was used. For the scenario period (1991–2050) the forcing followed the SRES B2 (both models) and A2 (only ECHAM4/OPYC3) emission scenarios from the Intergovernmental Panel on Climate Change (Nakićenović and

Swart, 2000). In RCA3, these forcings are treated as equivalent carbon dioxide concentration changes as the model does not explicitly treat time variations in other greenhouse gases or aerosols. Leaf-area index was prescribed as an annual cycle with no interannual variability.

By looking at the transient evolution of climate change in the RCA3 downscalings the natural variability on decadal scales was estimated by comparing different time periods. This was done both in a continuous fashion, by looking at year-to-year changes, and by comparing two different time periods (1991–2020 and 2021–2050) to the control period. The results, both for present-day and future climates, were compiled as maps, representing mean values over four specific seasons (DJF, MAM, JJA and SON). The seasons DJF and JJA represent the wet and dry seasons in the Pungwe river basin and in the main parts of Southern Africa, while MAM and SON are transition seasons between the other two. In addition, annual cycles of area average values were compiled.

3.2. Use of a hydrological model to assess climate change impacts on water resources

The HBV model was applied to the upper Pungwe river basin, upstream of Bué Maria (Fig. 1b) to identify plausible changes to water availability and extreme events, with consideration to spatial variability at a subbasin scale, as well as to variability within and between years. The setup of the daily time step HBV model was made available from SWECO & Associates (2004). In this setup, the model was calibrated using data from a historical station network of hydroclimatological data (rainfall, evaporation, river discharge) (SWECO & Associates, 2004). Evaporation was collected with evaporation pans ('A' pans), that is, instruments used to hold water during observations for the determination of the quantity of evaporation. The HBV model was used to assess the possible consequences of climate change on water resources until 2050. In Fig. 2, the correspondence between modelled and observed river discharge at Bué Maria (Fig. 1b) is shown. In general, the model is able to capture monitored flow dynamics, which is well documented for low flows. For high flow, however, it is more difficult to evaluate against monitored river flow, as breaks in the monitored record often occurred (Fig. 2).

Due to limited availability of climatic databases with a daily time resolution in the lower parts of the basin, and due to oceanic water intrusions, it was not feasible to extend the HBV model setup to cover the entire basin. Within the project, assessments for the entire basin were carried out based on water-balance assessments (Andersson et al., 2006).

3.2.1. The HBV model. The HBV model was developed at SMHI. This work is based on the model version HBV-96 (Lindström et al., 1997). The HBV model is based on a geographical division in subbasins, which can be divided into elevation zones and different vegetation zones (mainly critical for

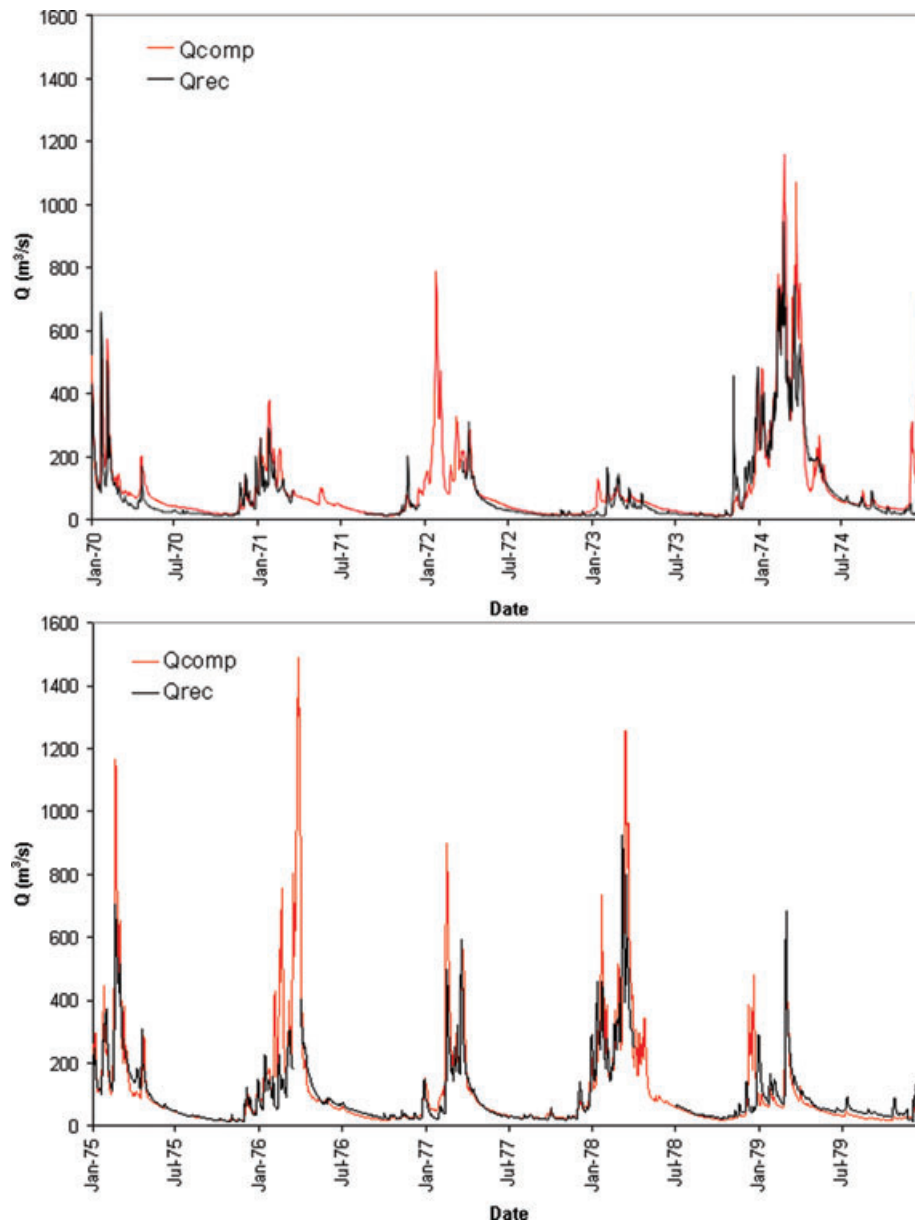


Fig. 2. Computed (HBV model) and recorded daily river discharge at Bué Maria for the 1970–1979 period. Black line represents recorded simulation. Red line represents HBV model simulation.

evapotranspiration and snow routines). It is usually (as in this application) run on a daily time step. The model is defined as conceptual, since it includes major hydrological processes, and depends on calibration of parameters, rather than estimation of their physical values. The model structure is rather simple, including subroutines for snow accumulation/melt, soil wetness, accumulation and flow of water through groundwater, water courses and lakes. The model also includes routines to handle flow regulations. In regions without snow, nine parameters are usually calibrated, using model optimization against observed streamflow.

3.2.2. Transferring climate change from RCMs to the hydrological models. The ability of RCMs to accurately describe the current climate has improved; however, when compared with observations, RCMs show biases. These biases are to a large degree inherited from the used GCM, but can also be a result of inadequacies in the parameterisations in the RCM (Graham et al., 2007). As a result, RCM simulations tend to have too many days with light precipitation and at the same time underestimate extreme precipitation. Using uncorrected RCM data in hydrological models may result in underestimated magnitudes of floods and droughts. Consequently, there is a need for

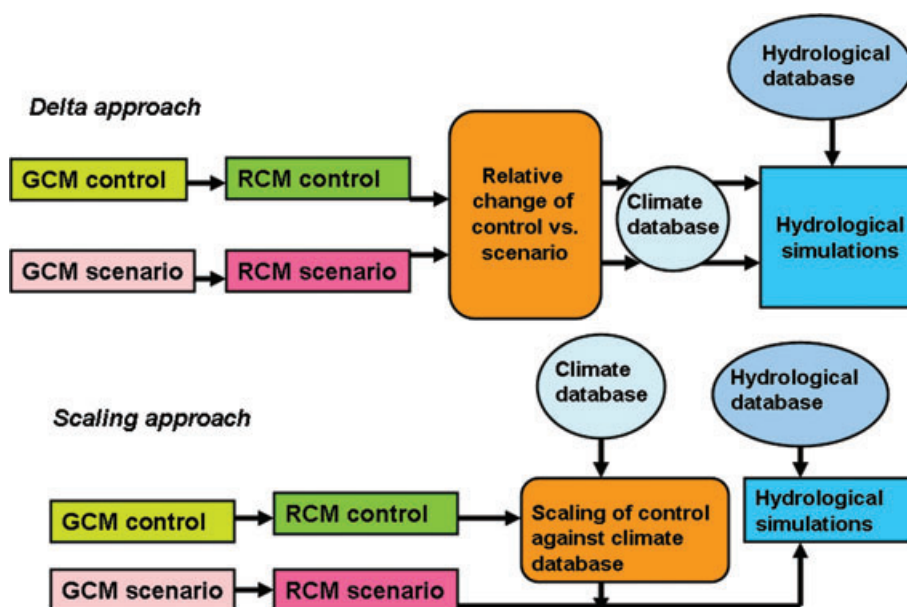


Fig. 3. Schematic presentation of the delta and scaling approaches for adjustment of RCM data to the subbasin scale.

adjustments of RCM data before using them as inputs to hydrological models. The objective of such adjustments is to provide a satisfactory agreement between statistical characteristics of observed and RCM generated precipitation and potential evaporation data at the subbasin scale for a historical period for which monitored data is available. In this study two different approaches to adjust RCM data were used; one based on delta change and the other on a scaling approach (Fig. 3). Both approaches are based on the assumption that bias correction parameters in the present-day climate remain invariate in future climate projections. This is a commonly used approach in climate change applications linked to hydrological modelling (Terink et al., 2010). However, it is not certain that this assumption is valid and in a study of future conditions in Europe it has been indicated that there can be significant limitations when temperatures in the warmest months exceed 4–6 °C above present day conditions (Christensen et al., 2008). Since projections of temperature increase in this study are significantly below this threshold, partly due to the focus only on the time period until 2050, we have assumed that it is justified to use bias correction parameters derived from the control period in our future climate projections. However, it needs to be considered that the threshold identified for European conditions, might be different in the Pungwe basin, with its warmer climate.

The delta change approach is based on superimposing changes in average values of climatic variables, as estimated from the RCM simulations, on available monitored time series of, for example, rainfall and potential evaporation from the control period (e.g. Arnell, 1998; Graham, 2004). The scaling approach uses the opposite strategy and superimposes deviations between observed time series and RCM simulations during the control

period on the RCM simulation based time series (e.g. Graham et al., 2007; Lenderink et al., 2007). As discussed by Graham et al. (2007) the two approaches have both advantages and disadvantages. As the delta approach uses observed climate as a baseline, the capability of the RCM to produce simulations that are comparable to observed climate is less crucial. It is stable and always gives results that can be related to present conditions. The main shortcoming, however is that the use of observed climate as a baseline implies that extreme precipitation and temperatures are modified by the same factor as all other events. Advantages of the scaling approach include a more direct representation of RCM results and thus climate variability more consistent with the RCM simulations whereas its main shortcoming is its sensitivity to the RCM used as input.

Since one of the objectives was to assess possible changes of the occurrence of extreme hydrological conditions, the scaling approach was applied to generate the daily time series used as input to the HBV model. The monthly time series, generated as input to the monthly water balance calculations, were calculated with a delta change approach, since the calculation of impacts on monthly water balance were less sensitive to possible changes of temporal distributions.

Delta factors, showing the relative change of averages from control vs. scenario time series, were estimated for rainfall and potential evaporation for the time series derived from the three climate change experiments. The period 1961–1990 was used as the control period, and delta factors were estimated for two 30 yr periods representing 1991–2020 and 2021–2050, respectively. The estimated delta factors were then multiplied with time series of subbasin monitored rainfall and potential evaporation (1961–1980).

In the initial analysis of the RCM output it was clearly seen that the model predicted too many days with small amounts of precipitation (drizzle). Also, the extremes during the control period were too far off from observations to be satisfactory. Scaling of precipitation was carried out in two steps in order to reflect the observed frequency of rainy days and to transform extreme precipitation to amounts that corresponded to the observed (Rosberg and Andreasson, 2006). In the first step, a cut-off value for precipitation was used to reduce the number of rainy days in order to remove the spurious drizzle generated by the RCA3 model. In order to identify these threshold cut-off values, observed and RCA3-generated precipitation time series were compared for the period 1961–1990 for individual subbasins. The second step aimed to transform the modelled precipitation to amounts that corresponded to monitored time series, based on an intensity dependent scaling. Days with precipitation from the RCA3 output during the control period and the observations were sorted into 20 percentiles, based on daily rainfall amounts. The relative difference in amounts of precipitation between each corresponding group was then derived. This created a lookup table for each sub basin that was used to scale the RCA3 outputs by multiplying all days with precipitation with the corresponding factor. In this way the frequency distribution in different rainfall classes was kept from the RCA3, but the total volume was adjusted. Evaporation was also scaled in a similar way as the described in the second step for precipitation scaling.

4. Results

Below the key results from the analyses are given. More details and figures related to the performed modelling results are provided in Andersson et al. (2006).

4.1. Climate modelling—the control period

The ability of RCA to correctly simulate the climate during the control period 1961–1990 depends not only on the model itself but also on input data at the lateral boundaries and at the sea surface. As noted by, for example, Balaz et al. (2003), intercomparison of precipitation datasets reveal significant differences, especially in regions with sparse rain gauge intensity, including large parts of Southern Africa. Consequently, differences between RCA results and observational data depend not only on the quality of the RCA but also on the quality of the observational data sets.

Here, the three control simulations have been analysed. Depending on which of the forcing global datasets that have been used, these are referred to as RCA3(ERA40), RCA3(ECHAM4) and RCA3(CCSM3). RCA3(ERA40) should be closer to observed climate as the boundary conditions represent a reanalysis data set while the two others can deviate more depending on the GCM performance in general and more specifically on their climate state for the specific period.

Generally the temperature in RCA3(ERA40) shows a somewhat cool bias with respect to CRU observations, in most areas within the range -2 to $+1$ °C as seen over the whole domain (Fig. 4). The cold bias is correlated with an overestimation of cloudiness of 10–20% (not shown). Along the west coast there is a narrow warm bias (Andersson et al., 2006), which is due to the difficulty of simulating the effect of cold sea water in combination with a sharp increase in altitude inland from the coast. Over the Pungwe river basin RCA3(ERA40) has a cold bias exceeding 2 °C in JJA (Fig. 5). Seen over the whole model domain RCA3(ECHAM4) gives a general warm bias, especially for the dry season July–October when it is also seen over the Pungwe area. This bias can partly be correlated with a warm bias in SST in ECHAM4 during May–October.

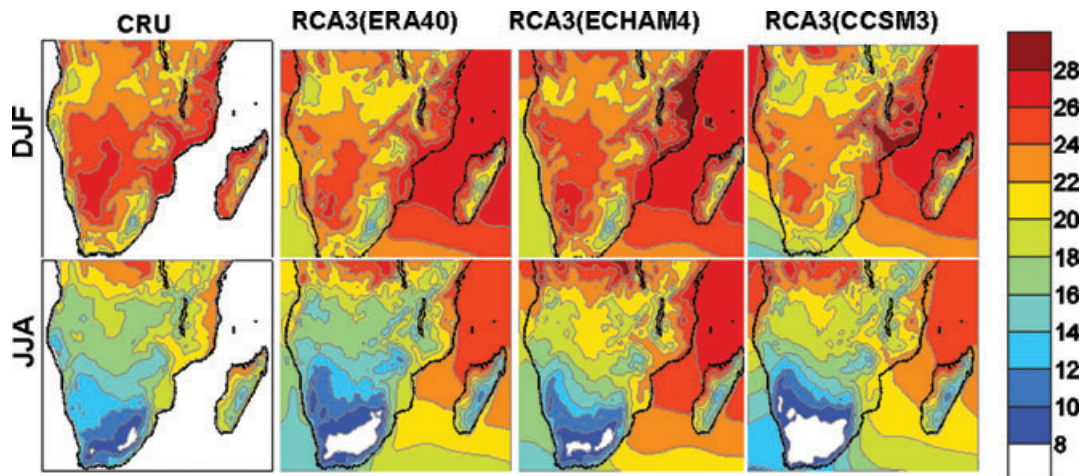


Fig. 4. DJF and JJA mean of 2 m air temperature (°C) for the period 1961–1990 according to CRU observations and as simulated by RCA3 with boundary conditions from ERA40, ECHAM4 and CCSM3, respectively.

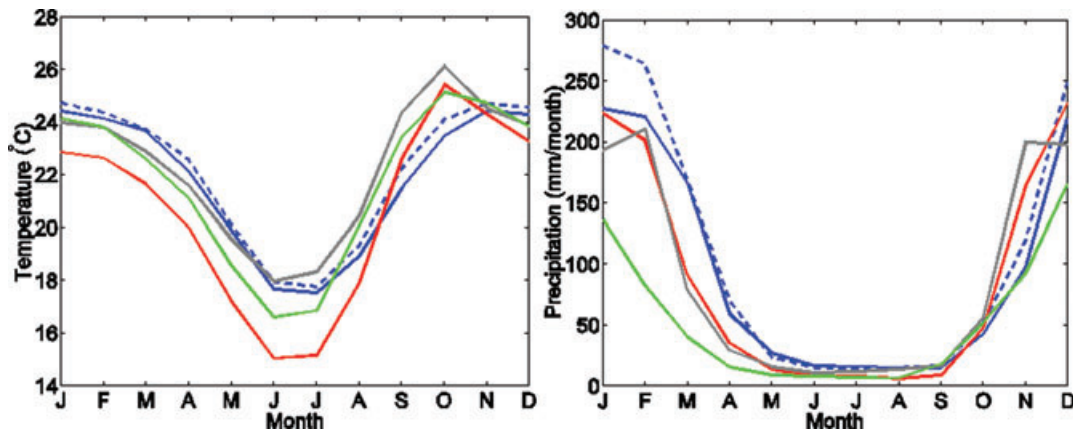


Fig. 5. Mean seasonal cycles (1961–1990) for area averaged 2 m air temperature ($^{\circ}\text{C}$) and precipitation (mm month^{-1}) over the Pungwe river basin. The lines represent observations from CRU (blue solid) and Willmott (blue dashed) and simulations by RCA3 with boundary conditions from ERA40 (red), ECHAM4 (grey) and CCSM3 (green), respectively.

RCA3(CCSM3) shows both negative and positive temperature biases over the continent, which is especially evident during JJA. A cold bias in the south is partly correlated with a cold bias in SST in the surrounding ocean. Similarly, a warm bias on the west coast is correlated with a warm bias in SST off that coast. The warm bias on the west coast of Africa is a general problem in upwelling areas with cold ocean currents in CCSM3 (Large and Danabasoglu, 2006) and not a result of the current horizontal model resolution. RCA3(ECHAM4 and CCSM3) are both warmer than RCA3(ERA40) over the Pungwe area which shows a better correspondence with observational data (Fig. 5).

RCA3(ERA40) captures the main features of the precipitation climate of Southern Africa (Figs. 5 and 6). This includes the pronounced wet and dry seasons and the main horizontal gradients during these seasons. Particularly it can be noted that all simulations show the winter maximum of precipitation in the Western Cape Province as produced by cyclonic activity over the mid latitudes reaching this region during austral winter. Regionally the

rainy area over land during summer extends a bit further south in RCA3 as compared to CRU observations. As for temperature this bias is correlated with the overestimation of cloud cover. At the continental scale, RCA3(CCSM3) generally gives too little precipitation during the wet season. Regionally, there is also an underestimation over parts of the eastern continent, including the Pungwe basin (Fig. 5).

4.2. Climate change experiments

The results of the downscaling experiments of today's climate, as compared to Willmott and CRU are considered to be a sufficient representation of the Southern African climate to allow the model system to be used for scenario simulations.

The results from these climate change scenario simulations are representing the 30-yr periods 1991–2020 and 2021–2050, respectively, compared with their corresponding control period 1961–1990. In this way it is possible to compare the climate

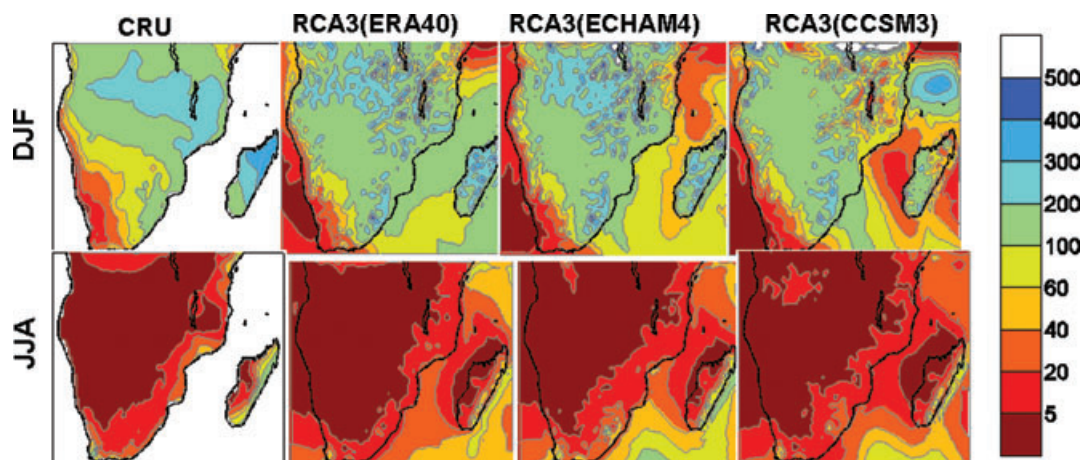


Fig. 6. DJF and JJA mean of precipitation (mm month^{-1}) for the period 1961–1990 according to CRU observations and as simulated by RCA3 with boundary conditions from ERA40, ECHAM4 and CCSM3, respectively.

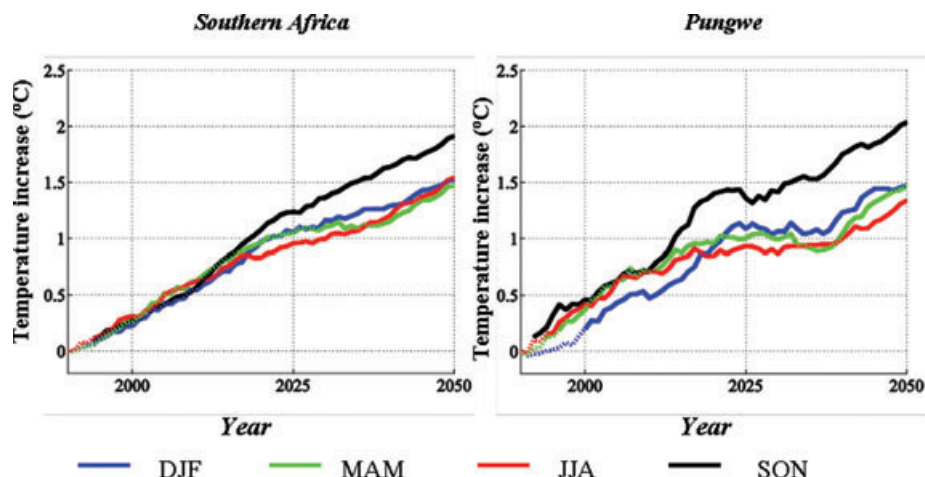


Fig. 7. 30-yr running means of area average 2 m temperature ($^{\circ}\text{C}$) in RCA3(ECHAM4-A2). Full (dashed) lines denotes 30-yr periods that are (are not) significantly different from the control period.

change signal of each scenario, regardless of the variations between the models in describing the present climate. More details can be found in Andersson et al. (2006). Here we discuss the climate change signals in temperature and precipitation with focus on the Pungwe river basin.

4.2.1. Changes in temperature. A general feature of the scenario simulations is a significant increase in temperature during all seasons (Fig. 7). The signal is larger over the continent than over the adjacent oceans, which is a widely observed feature in climate change simulations (Christensen et al., 2007). Regionally the patterns of increase may differ depending on which GCM that has been used as forcing. The strongest increase in temperature over the Pungwe area was simulated with RCA3(ECHAM4-A2, Fig. 7). At first glance the results may look strange as the A2 emission scenario leads to higher concentrations of greenhouse gases. However, the combined effect of changes in greenhouse gases and aerosol content, respectively, in the A2 and B2 scenarios leads to fairly small differences in their forcing on the climate system during the next few decades and it is not until the mid century that they start to diverge more substantially at a global scale. Further, since the sulphate emissions are larger in the A2 scenario there is a stronger local dampening in that scenario over Southern Africa in ECHAM4. This is also a general feature in several climate change experiments with different GCMs in this area for the early part of the century (Ruosteenoja et al., 2003).

For the period 2021–2150 the temperature increase for all seasons is statistically significant (in the sense that it exceeds the interannual variability during the control period) (Fig. 7). Taken as an areal average over Southern Africa, the increase (1990–2050) varies between 1.5 and 2.2 $^{\circ}\text{C}$ for all seasons and all scenarios [exemplified for RCA(ECHAM-A2 in Fig. 7). This corresponds to ranges presented by Ruosteenoja et al. (2003) for the time period 2010–2034 based on seven GCMs and four emission scenarios. The change is strongest at the end of the dry

season/start of wet season (September–November). The summer wet season (December–February) shows less warming than the other seasons for the first part of the period (1991–2020) but higher warming than for the autumn–winter seasons during the second part of the period.

4.2.2. Changes in precipitation. The pronounced seasonal cycle in Southern Africa, with one wet and one dry season, is seen in Fig. 8. None of the simulations give changes larger than $\pm 5\%$ in total precipitation amount integrated over the entire model domain during December–May while they give decreases of the order of 10–20% during June–November (not shown). These results lie in the ranges based on output from several climate models under different emission scenarios as presented by Ruosteenoja et al. (2003). For the Pungwe river basin it is clearly seen that there is a delay in the onset of the wet season in all three experiments (Fig. 8). In this region the delay is more pronounced than at the continental scale. The total precipitation amount decreases in these simulations compared to the control period during most parts of the year with the exception of the RCA3(ECHAM4) simulations that show an increase during December and January (Fig. 8). The largest drying is seen in the RCA3(CCSM3-B2), which is the driest one already in the control period. The climate change signal is in most cases stronger in the second period (2021–2050) compared to the first (1991–2020) although there are some exceptions to this, possibly related to natural variability in the system.

4.3. Subbasin downscaling and hydrological modelling

4.3.1. Changes in climatological variables, downscaled to the subbasin scale. The results indicate, compared to the period for which monitored records existed (1960–1980), a decrease of mean annual subbasin rainfall of 7–12% for the 1991–2020 and with 9–14% for the 2021–2050 period, with no significant indication of spatial variability of this reduction (Fig. 9).

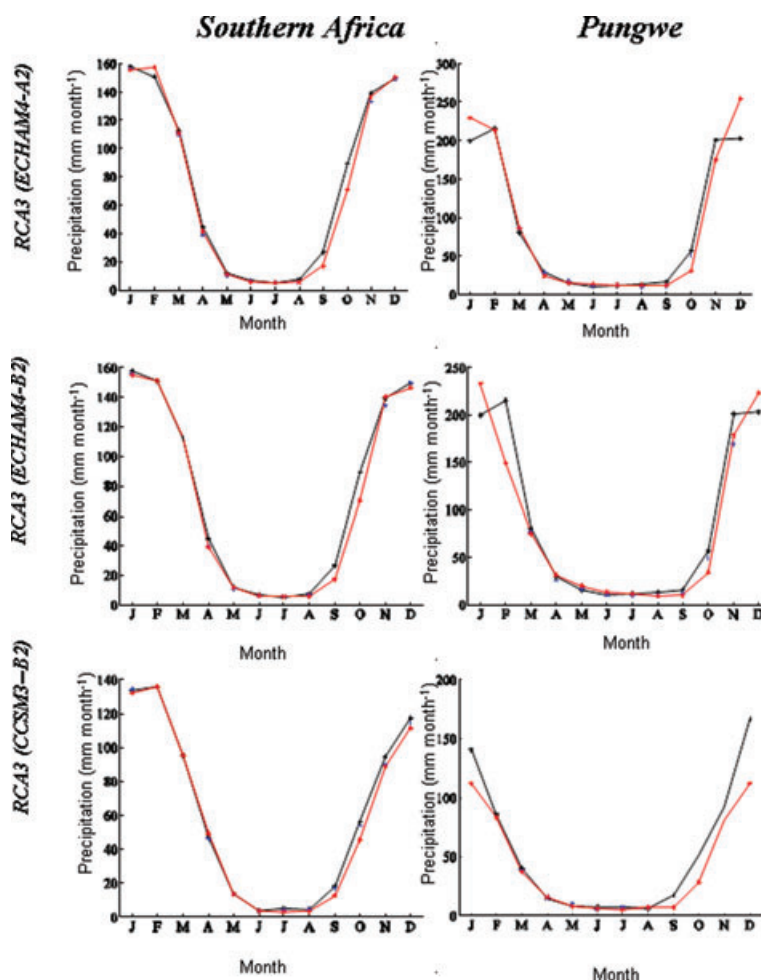


Fig. 8. Mean seasonal cycles of precipitation (mm month^{-1}) for the period 1961–1990 (black) and 2021–2050 (red) in the three transient climate change scenarios.

The temperature increase, indicated by the RCA3 simulations, would be expected to result in an increase of potential evapotranspiration. The HBV model results indicate (compared to the 1986–1980 period for which monitored data exists) a moderate increase of potential evapotranspiration for the period 1991–2020, with the most significant increase in the headwaters in the Zimbabwean upper part of the basin. For the 2021–2050 period, the potential evapotranspiration increases by approximately 20% in the headwater subbasins, and by 10% in the rest of the basin (Fig. 10). Analyses of the annual potential evapotranspiration cycle showed that the largest increase of potential evaporation occurred during the dry season (Fig. 11), providing even less water for actual evapotranspiration and growth. Since most of the increase of evaporation occurs during the dry season, with the most significant impact in the upper parts of the basin, increased potential evaporation might also have an impact on dry season water storage in dams.

4.3.2. Changes of water balance dynamics and of MAR. Soil moisture deficit assessments can be used as an indicator for the potential for agricultural production. However, the soil water accounting routine in the HBV model is not developed with the

aim to provide realistic soil moisture deficit estimates. Since participants requested information relevant to agriculture, it was decided to use water balance estimates primarily for assessments of climate change on rain-fed agriculture. For future work, the use of an agrohydrological model for more detailed assessments is recommended. The period with a positive water balance, which is favourable for rain-fed agricultural production, was reduced with approximately 0.5 months for the 1991–2020 period and 1 month for the 2021–2050 period (Fig. 11).

During the stakeholder workshops, it was pointed out that if MAR would be reduced during the coming decades; this would affect the issuing of water permits, environmental flows, sediment yields and concentrations of polluting agents. Concern was also shown for the increased risk of bush fires. Other recognised impacts included tourism, with emphasis on the Gorongosa national park, where the park infrastructure depends on water supply, as well as on hydropower production, with emphasis on the need to consider climate change experiments when calculating feasibility for future hydropower dams.

For the basin upstream of Bué Maria (cf. Fig. 1) the scenarios of changes in MAR indicated that for the 1991–2020

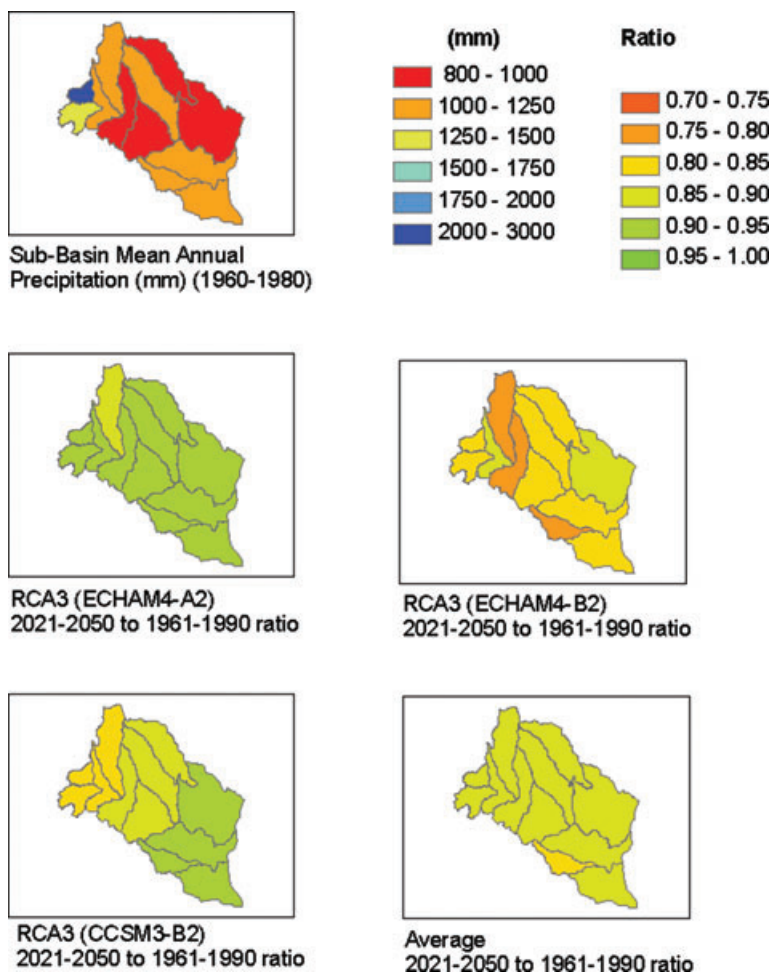


Fig. 9. Monitored annual subbasin precipitation (1960–1980) and mean ratio of simulated subbasin precipitation for 2021–2050, compared to that simulated for 1961–1990 in RCA3(ECHAM4-A2), RCA3(ECHAM4-B2) and RCA3(CCSM3-B2), respectively.

period, runoff in the drier parts of the basin will decrease to about 55–75% of the MAR compared to the control period (1961–1990). In the wetter parts the runoff is estimated to be approximately 90% of the control period MAR. For the 2021–2050 period, RCA3(ECHAM4-B2) and RCA3(CCSM3-B2) show a decrease in MAR to a value corresponding to 30–65% of the control period MAR in the drier subbasins and 50–95% in the wetter subbasins. RCA3(ECHAM4-A2) does not indicate any significant change, and even an increase of runoff in some subbasins (Fig. 12).

4.3.3. Seasonal mean and variability changes in precipitation and streamflow. During the workshops, participating stakeholders stated that indications of decreased flow in rivers would augment the need for water storage and accelerate the planning of new dams. When making assessments of climate change impacts on water resources to prepare effective adaptation strategies, it is often information on seasonal variability and changes, rather than annual, that is required. It is also vital to obtain assessments of how the variability between years will change in the future. Arnell et al. (2003) used climate change scenarios from regional models to estimate changes of streamflow in Southern Africa.

Their results indicated that extreme flows were predicted to increase more than mean flows and even to increase in areas where the mean flow decreases. This demonstrates the importance of considering not only changes in mean climate but also changes of climate variability. The scaling approach used in this project made it possible to capture seasonal changes at basin and sub-basin scale, which are discussed in this section (Table 1), as well as flow duration and return periods, which are discussed in the next section.

For analyses in this section ‘significant’ is defined as a change of more than 10% on 30 yr medians.

A robust signal of decreased median rainfall was detected for the SON period. For the JJA period no significant change of medians of rainfall was detected, with exception of an increase in RCA3(ECHAM4-A2) for 2021–2050. When it comes to river discharge, however, decreases in DJF were also significant in all three scenario experiments, demonstrating the impact of not only decreased rainfall but also of increased temperature (Table 1).

The coefficient of variation (CV) is a statistical measure of the dispersion of data around the mean in a time series (eq. 1). A

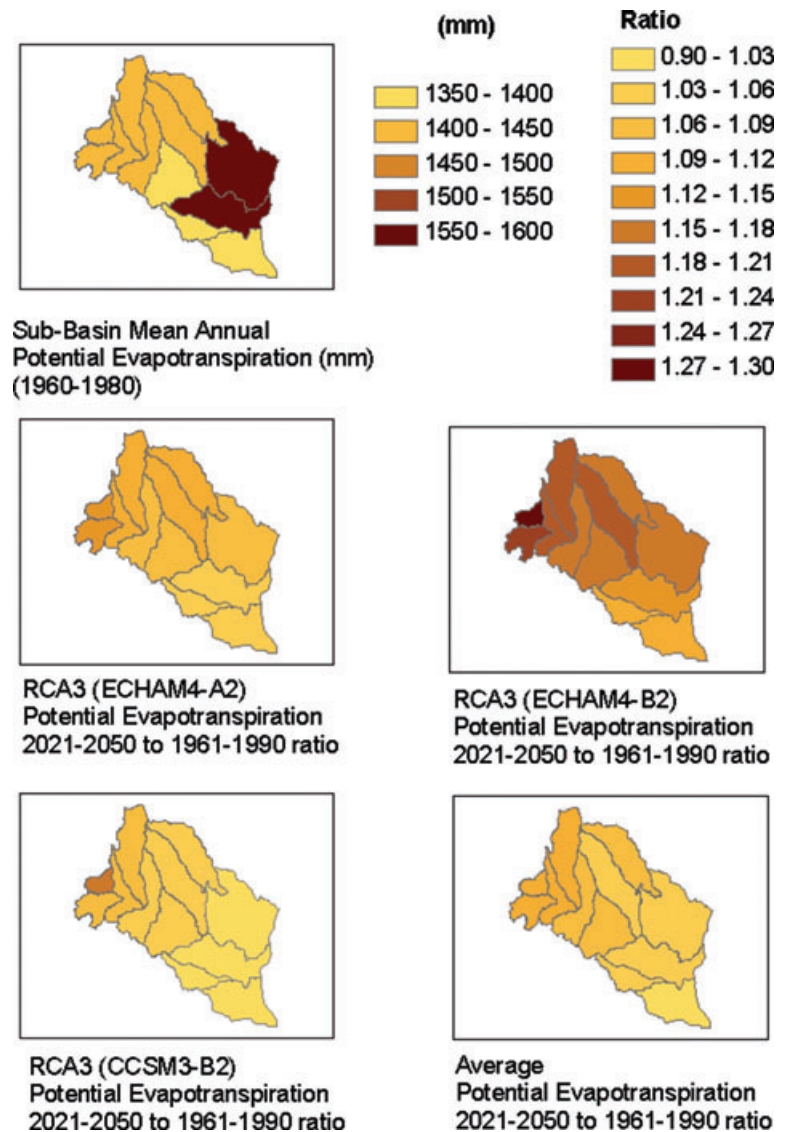


Fig. 10. Mean annual potential evapotranspiration (1961–1990) and ratio of future (2021–2050) to 1961–1990 mean annual evapotranspiration in the Pungwe basin. A ratio above one indicates increased potential evapotranspiration.

high CV indicates higher occurrence of extreme years (i.e. both wet and dry years).

$$CV = \frac{\text{standard deviation}}{\text{mean}} \times 100. \quad (1)$$

Assessments of interannual CV for precipitation revealed that interannual variability of rainfall might increase significantly (10–50%), especially in the drier parts of the basin, where the interannual variability is already high for the reference period. It should be noted that the CV only expresses the variability between years, and that frequency or duration analyses are needed in order to assess how an increased CV is related to increased frequency of dry or wet conditions.

Interannual variability of streamflow (upstream of Bué Maria, Fig. 1b) was estimated both for the MAR and for the dry season flow (April–September), by estimations of the CV. For the control period (1961–1990) there was a pattern of higher in-

terannual variability in the drier subbasins, and lower variability in the wetter headwater subbasins. With the exception of RCA3(ECHAM4-B2) for the period 1991–2020 which showed a significant increase of the CV, the interannual variability of the MAR for the 1991–2020 and the 2021–2050 periods was unchanged or decreased when compared to the control period. For dry-season flow, the CV was for the 2021–2050 period significantly increased in both RCA3(ECHAM4-B2) and RCA3(CCSM3-B2).

4.3.4. Changes of flow duration and return periods for high flows. A flow duration curve is a graph, representing the time during which the water discharge is equal or exceeded during a certain period of time. Based on the HBV simulations, driven by the three climate change experiments, flow duration curves were computed for all subbasins upstream of Bué Maria. The flow duration curves were divided into:

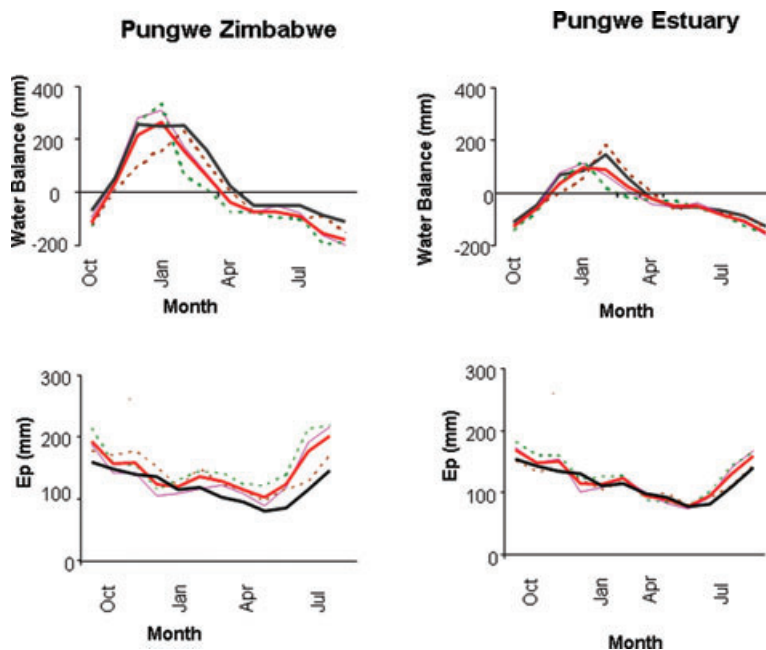


Fig. 11. Mean monthly potential evaporation (Ep) and water balance in headwaters (Pungwe Zimbabwe) and in the Pungwe estuary for the 1960–1980 and the 2020–2050 period. A negative water balance indicates that the monthly rainfall is smaller than the monthly atmospheric demand of moisture. The control period is based on monitored rainfall and potential evaporation (1961–1980) and scenario estimates (2020–2050) are based on RCA3 output with bias corrections with the delta change method. Black line represents control period; purple line represents RCA3(ECHAM-A2), green line represents RCA3(ECHAM-B2), brown line represents RCA3(CCSM-B2) and red line represents average of the three climate change experiments.

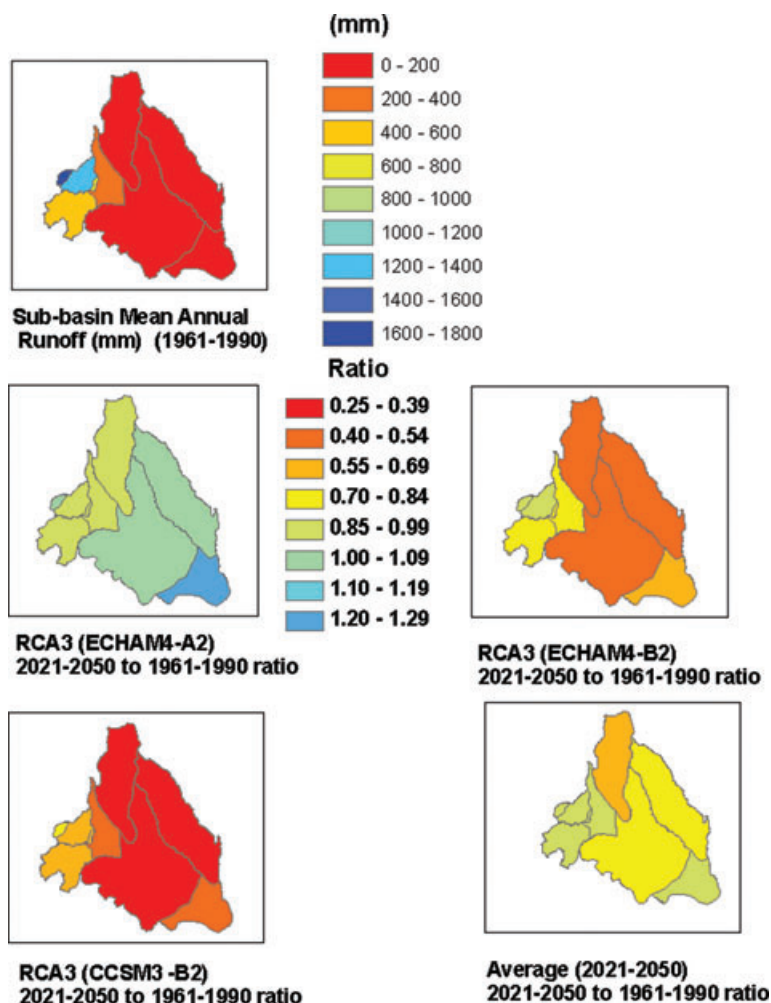


Fig. 12. Mean annual runoff (mm) (1961–1990) and ratio of future (2021–2050) to present mean annual runoff in the Pungwe basin, upstream Bué Maria. A ratio above one indicates increased MAR whereas a ratio below one indicates decreased MAR.

Table 1. Seasonal (SON, DJF, MAM and JJA) medians of scaled precipitation (P) and river discharge (Q) for the Pungwe basin upstream of Bué Maria for 1961–1990, 1991–2020 and 2021–2050 from RCA3(ECHAM4-A2), RCA3(ECHAM4-B2) and RCA3(CCSM3-B2), respectively. Both total volumes (mm month^{-1} for P and $\text{m}^3 \text{s}^{-1}$ for Q) and the change (%) when compared to 1961–1990 are shown. Decrease of more than 10% is shaded in brown; increase of more than 10% is shaded in blue

P (mm) SON	ECHAM4 A2	ECHAM4 B2	CCSM3 B2	Q ($\text{m}^3 \text{s}^{-1}$) SON	ECHAM4 A2	ECHAM4 B2	CCSM3 B2
1961–1990	286	286	274	1961–1990	103	103	85
1991–2020	227 (–21%)	199 (–30%)	236 (–14%)	1991–2020	71 (–31%)	60 (–42%)	76 (–10%)
2021–2050	192 (–33%)	206 (–28%)	194 (–29%)	2021–2050	66 (–66%)	49 (–53%)	64 (–48%)
P (mm) DJF	ECHAM4 A2	ECHAM4 B2	CCSM3 B2	Q ($\text{m}^3 \text{s}^{-1}$) DJF	ECHAM4 A2	ECHAM4 B2	CCSM3 B2
1961–1990	607	607	624	1961–1990	604	604	569
1991–2020	567 (–7%)	570 (–6%)	561 (–10%)	1991–2020	489 (–19%)	412 (–32%)	415 (–27%)
2021–2050	648 (+7%)	553 (–9%)	505 (–19%)	2021–2050	500 (–17%)	365 (–40%)	259 (–54%)
P (mm) MAM	ECHAM4 A2	ECHAM4 B2	CCSM3 B2	Q ($\text{m}^3 \text{s}^{-1}$) MAM	ECHAM4 A2	ECHAM4 B2	CCSM3 B2
1961–1990	122	122	128	1961–1990	271	271	236
1991–2020	135 (+10%)	123 (+1%)	127 (–1%)	1991–2020	265 (–2%)	234 (–14%)	212 (–9%)
2021–2050	133 (+9%)	128 (+4%)	129 (+1%)	2021–2050	287 (+6%)	190 (–30%)	178 (–31%)
P (mm) JJA	ECHAM4 A2	ECHAM4 B2	CCSM3 B2	Q ($\text{m}^3 \text{s}^{-1}$) JJA	ECHAM4 A2	ECHAM4 B2	CCSM3 B2
1961–1990	42	42	40	1961–1990	104	104	94
1991–2020	42 (+1%)	41	38 (–3%)	1991–2020	99 (–5%)	88 (–15%)	86 (–9%)
2021–2050	54 (+29%)	40 (–5%)	42 (+6%)	2021–2050	102 (–2%)	74 (–29%)	65 (–31%)

- the highest flows, exceeded not more than 1% of the time
- flows exceeded between 1% and 30% of the time
- low flows, exceeded between 30% and 100% of the time.

For the highest flows, there is a general trend towards *decrease*. The only exception is RCA3(ECHAM4-A2) for 2021–2050 and RCA3(ECHAM4-B2) for 1991–2020, for which *increased* high flows are indicated. For low flows, all scenarios indicate a reduction (Fig. 13).

Frequency analyses were performed for various sites in the basin, using annual maximum daily river discharge as inputs to assess possible changes in occurrence of high flows (Andersson et al., 2006). In this paper results from the downstream site Bué Maria (15 046 km^2) and Frontiera (687 km^2) in the upper part of the basin (Fig. 1) are shown, based on modelled daily river discharge from the scaled RCA3 precipitation and temperature outputs from the three scenarios (Table 2). The results were derived using the Gumbel distribution. Since the HBV model uses a daily time step, the frequency analysis represents daily mean flow. A design flow should, however, be based on the instantaneous peak. The relation between daily and instantaneous peak is related to the size of a basin. Based on SWECO and Associates (2004), a correction factor of 1.1 was used for Bué Maria, and a factor of 1.5 for Frontiera.

For the headwater site at Frontiera, both frequency analyses from HBV outputs from model runs based on scaled rainfall and evaporation from RCA3(ECHAM4-B2) and RCA3(CCSM3-B2) indicated a *decrease* of flow peaks for the 2021–2050

period compared to the control period (1961–1990), whereas the RCA3(ECHAM4-A2) indicated an *increase* of flow peaks. At the downstream site (Bué Maria), peakflows were also lower during the 2021–2050 period. However, at Bué Maria, the two ECHAM4 driven experiments did not give results that were consistent over time (Table 2). In summary, signs of *decreased* peak flow were indicated for the downstream station Bué Maria, whereas at the headwater station Frontiera, RCA3(ECHAM4-A2/B2) the results indicated *increased* peaks.

4.3.5. *Intake of freshwater to the city of Beira.* Low stream-flow in Pungwe at Bué Maria is of concern to the intake of freshwater to the city of Beira (Fig. 1a), the second largest city in Mozambique, with about one million inhabitants. The possibility of an increase of days with insufficient water inflow to Beira was thus a major concern for the reference group of stakeholders. During the workshops, it was pinpointed that a decrease of the MAR (discussed above) but especially of dry season flow would alert the need of a salt water intrusion barrier downstream of the freshwater intake to the city of Beira, in order to prevent salinization.

The flow to safeguard the intake of freshwater for Beira has been estimated as $10 \text{ m}^3 \text{s}^{-1}$ (Chamuco, 1997). An assessment of the number of days per year when water flow was below this limit showed that RCA3(ECHAM4-B2) and RCA3(CCSM3-B2) indicated an increased number of days, with a highly significant upward trend from about 2020 and forward for RCA3(CCSM3-B2), see Fig. 14.

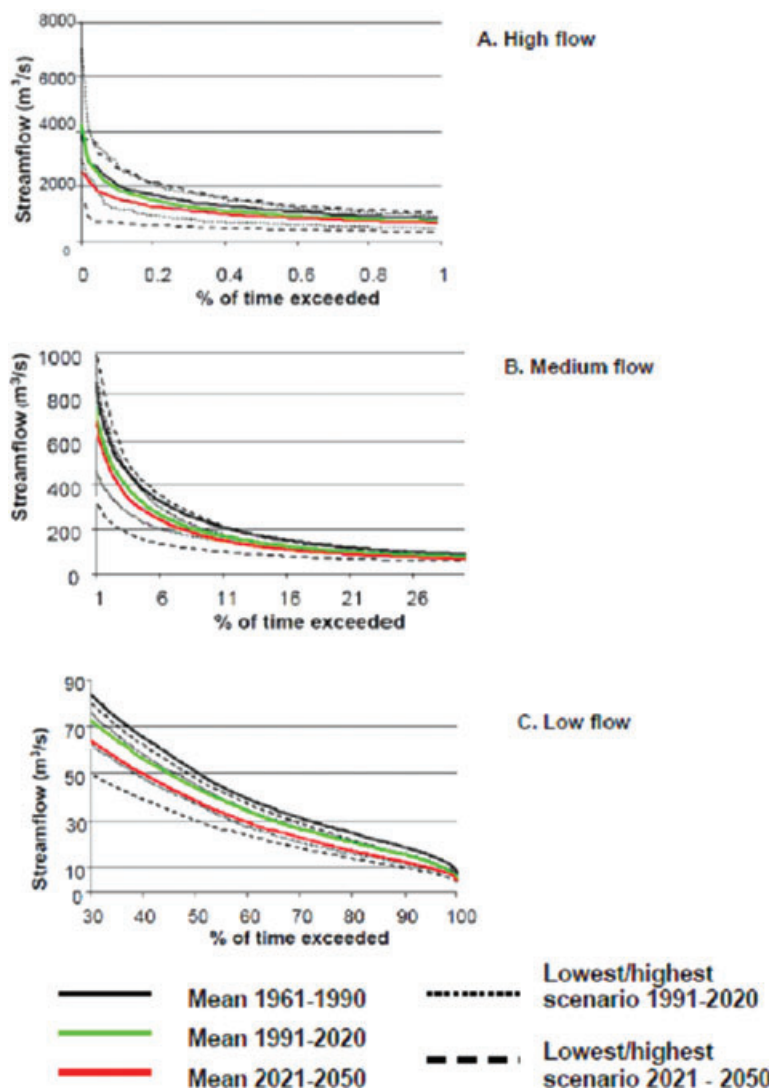


Fig. 13. Flow duration curves, shown percentage of time when daily streamflow of various magnitudes are exceeded at Bué Maria. The black, green and red lines show the average from the simulations, based on the three climate change experiments. The grey lines show the lowest and highest scenarios with the three climate change experiments for 1991–2020 (filled) and 2021–2050 (dotted): (a) 1% highest daily flows; (b) below 1% highest, but above 30% lowest daily flows; (c) 30% lowest daily flows.

5. Discussion—lessons learned and consequences for water resources management

In general the signal to noise ratio in climate change scenarios increases the further into the future we look. Many changes are significant at the end of the 21st century while for the next decades the climate change signal is often of the same order of magnitude as the natural variability. As a consequence, an impact study with a 100 yr perspective can be based on only a few scenarios while a study focusing on the nearest future would require a larger ensemble of scenarios. The IPCC Fourth Assessment Report (AR4) Working group I concludes that there is a robust signal from global models of decreased rainfall over Southern Africa in JJA and SON by 2080–2099 (A1B scenario) and state that the time required for the emergence of a clearly discernable signal, defined as when the 20 yr average with a 95% confidence differs from the 1980–1999 mean is 70–90 yr (Christensen et al., 2007). Strictly this result would mean that

studies focusing on a time period closer than 70 yr in time are questionable from a statistical point of view. However, society still needs to take decisions based on indications of risk in this time period even though the background information is less certain. From this aspect it is motivated to perform impact studies on the near future as long as the uncertainties are addressed. In this specific project the end-users had their focus on the time period up till 2050. We conclude that some robust signals can be detected for this period. The decrease in river discharge, due to a combination of decreased precipitation and increased air temperature and potential evapotranspiration was especially significant. A robust signal was also found for decreased median rainfall for the SON period which corresponds to the statement by the IPCC AR4 Working Group 1 (Christensen et al., 2007). In contrast to the IPCC reporting for Southern Africa, however, no significant decrease of rainfall was detected in Pungwe for the JJA period.

Table 2. Flood frequency analysis (Gumbel) based on HBV-simulation driven by RCA3(ECHAM4-A2), RCA3(ECHAM4-B2) and RCA3(CCSM3-B2) for return periods of 2, 10, 100 and 1000 yr. Both total volumes ($\text{m}^3 \text{s}^{-1}$) and the change when compared to 1961–1990 are shown. Decrease of more than 10% is shaded in brown, increase of more than 10% is shaded in blue

Station	Return period (yr)	Peak flow ECHAM4 (control) ($\text{m}^3 \text{s}^{-1}$)	Peak flow CCSM3 ($\text{m}^3 \text{s}^{-1}$)	Peak flow ECHAM4 A2 ($\text{m}^3 \text{s}^{-1}$)	Peak flow ECHAM4 B2 ($\text{m}^3 \text{s}^{-1}$)	Peak flow CCSM3 B2 ($\text{m}^3 \text{s}^{-1}$)	Peak flow ECHAM4 A2 ($\text{m}^3 \text{s}^{-1}$)	Peak flow ECHAM4 B2 ($\text{m}^3 \text{s}^{-1}$)	Peak flow CCSM3 B2 ($\text{m}^3 \text{s}^{-1}$)
		1961–1990		1991–2020		2021–2050			
Frontiera (head-water)	2	245	239	246 (0%)	232 (−5%)	197 (−18%)	266 (+9%)	220 (−9%)	157 (−34%)
	10	454	418	465 (+2%)	466 (+3%)	381 (−9%)	501 (+10%)	412 (−9%)	288 (−31%)
	100	715	640	739 (+3%)	758 (+6%)	609 (−5%)	794 (+11%)	644> (−10%)	451 (−30%)
	1000	971	858	1007 (+4%)	1044 (+8%)	834 (−3%)	1081 (+11%)	872 (−10%)	611 (−29%)
Bué Maria (down-stream)	2	1043	881	836 (−20%)	945 (−8%)	654 (−26%)	1122 (+8%)	683 (−35%)	369 (−58%)
	10	2157	2031	1762 (−18%)	3093 (+44%)	1553 (−24%)	2547 (+18%)	1429 (−34%)	813 (−60%)
	100	4355	3465	2918 (−33%)	5773 (+33%)	2674 (−39%)	4325 (−1%)	2359 (−46%)	1367 (−61%)
	1000	6160	4874	4053 (−34%)	8404 (+34%)	3775 (−23%)	6071 (−1%)	3272 (−47%)	1911 (−61%)

All three scenarios indicated that water availability might decrease due to less annual rainfall, a later start to the rainy season and less rainfall in the early part of the rainy season, as well as an increased potential evapotranspiration, especially in the dry season. There was also consistency between the three experiments that the annual water balance will shift towards increased water deficits and that the period with a positive water balance will be shortened. There did also seem to be a robust signal with regard to a decrease of river flow for dry years. Such consistency did, however, not exist when it comes to scenarios of the risk for flooding where RCA3(ECHAM4-A2), in contrast to the other two experiments, indicated a need, at least in the headwaters of the basin, to also be prepared for increased risks for high flows and flooding in the future.

Also the choice of hydrological model might have an impact on the robustness of the results. Although the HBV model setup provided acceptable correspondence to monitored streamflow (Fig. 2), previous studies (Lidén and Harlin, 2000) have shown that the model performance of the HBV model deteriorates in more arid climates, probably due to that it was initially developed for humid temperate climates. In our case, the choice of the HBV model was pragmatic as a model setup was available from previous studies. Otherwise, a recommendation is to use mod-

els that are developed to capture the dominating hydrological processes in the region where it is applied.

From discussion with the stakeholders in the reference group, the general response to the presented results was that if they reflect changes that will occur in the coming decades, they will worsen the already critical situation regarding water availability, and even possibly introduce an increased risk for flooding. However, do the three climate change experiments performed provide sufficient robustness so that they can be used by decision makers and other stakeholders in their formulation of an Integrated Water Resource Management strategy? The fact that no consistency was found with regard to trends of high flows makes the simple answer no. This finding underscores the need for reducing and understanding the uncertainties of the modelling chain. Large uncertainties are associated with all the steps of the chain (from emission scenarios through GCMs, RCMs, bias corrections and scaling to subbasins to the hydrological modelling) and increasing the spatial resolution though regional downscaling can magnify inherent weaknesses of the used GCM (Schiermeier, 2010). Although the RCA3 simulations on the Southern African scale showed satisfactory results both for temperature and precipitation as compared to available observations it is obvious that when a smaller region as the Pungwe basin is

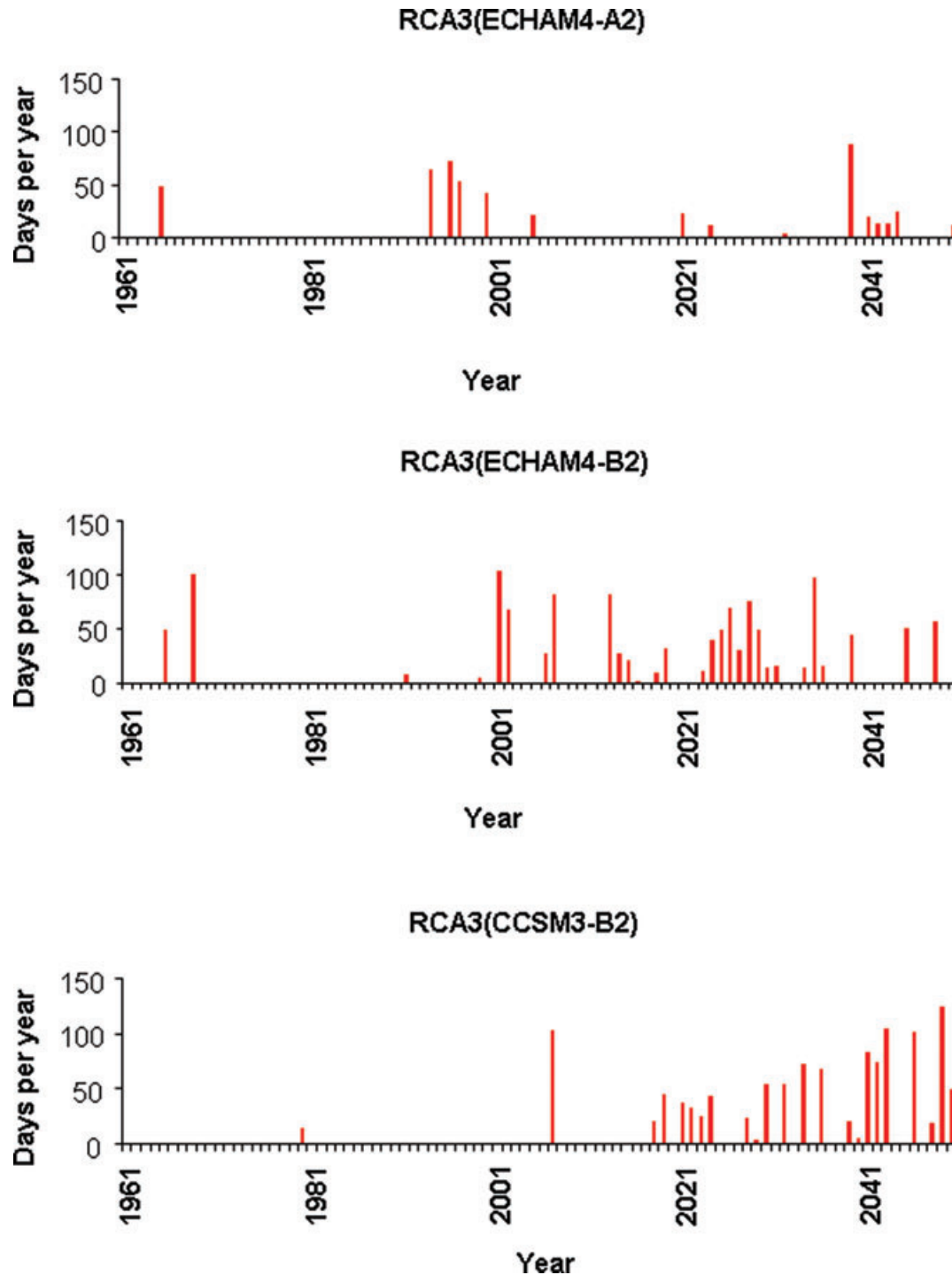


Fig. 14. Number of days per year when water flow in Pungwe at Bué Maria, simulated with the three climate change experiments, is below $10 \text{ m}^3 \text{ s}^{-1}$, which is considered as the minimum flow to safeguard the intake of freshwater for Beira (Chamuco, 1997).

considered, simulations and observations show larger discrepancies. The reason is that the local climate to a large extent depends on local feedback mechanisms, which means that the model gets large freedom to create the local climate given to-

pographic, vegetation and SST conditions in the area. Some of these differences would be expected to be reduced with additional model development, smaller model domain and/or higher resolution.

The rather low correlation between RCA3(ERA40) and ERA40 over the Pungwe region indicates that the regional precipitation depends on local conditions and feedback mechanisms and not so much on the forcing model, although the overall available moisture is given by the lateral boundary conditions and SSTs. The scaling of RCA3 data at subbasin level is used as a tool to better reflect local climatic variability. Merging dynamic and statistical downscaling might be a way to further sophisticate downscaling to the basin level.

In spite of the revealed uncertainties, the regional simulations give an indication of a need to prepare for drier conditions. It can be argued that investing in measures to improve the ability to cope with drier conditions and an increased risk for flooding (based on the not so robust signals from this study) in the Pungwe basin is valuable, since exposure and vulnerability are high and while the coping strategies to deal with current climate conditions are low. Identified adaptation measures to these conditions can therefore be considered to be 'no-regret' options which will strengthen resilience even if the predicted climatic change would be slightly erroneous. Even non-robust signals can be used as a good argument to increase adaptive capacity among vulnerable groups and sectors. However, due to economic constraints, a cost-benefit analysis of where to allocate the limited amount of financial resources especially designed for coping with climate change calls for more robust signals from climate change experiments.

This leads us to the question of how the scientific community can best contribute to providing decision-makers and other stakeholders with information that facilitates decisions regarding adaptation strategies linked to climate change. Evidently, researchers also need to decide where to focus limited financial, as well as human resources. As stated by IPCC AR4 Working Group II (Kundzewicz et al. 2007), even in large river basins, climate change scenarios from different climate models may result in very different future projections of future runoff. Results are to a large degree determined by the choice of GCM, emission scenario, initial conditions and downscaling techniques, as well as of the choice of hydrological model. Results based on only three scenario experiments can, by pointing in the same direction give a false impression of a certain future. If the aim of a project is to provide information that is to be used for decisions related to adaptation, it is essential that the uncertainty is estimated. Consequently, if a choice has to be made between performing a few high-resolution simulations or to perform several coarser simulations, we would recommend the latter. As stated by Blöschl and Montanari (2010) depending on single climate change experiments instead of ensembles of experiments in climate change assessments related to water resource management can turn hydrological impact studies into gambling. For regions with limited availability of downscaled climate change scenarios, including the Pungwe basin, there is still need to provide more RCMs before ensembles of combinations of regional climate and hydrological models can be performed. This project

is one contribution to future ensembles. The ensembles need to capture uncertainty and this is probably best realised through the use of a combination of available dynamical and statistical downscaling of GCMs. Such recommendations have also, based on comparison of outputs, been suggested by, for example Busuioac et al. (2006).

To contribute to good water resources management, information needs to be relevant to end-users. As shown, for example, by Andersson et al. (2008), the potential for model-derived environmental information to have a real impact on planning depends on regional/local identification of problem areas, as well as definitions of what type of information that is relevant. Impacts on water resources management at the local/regional level, for example, where adaptation measures are implemented, depends on a close cooperation between various interest groups, with water resource/climate experts acting as information providers/facilitators. Although this project was initiated with such ambitions, this goal was only partly fulfilled. The reference group consisted of national high level experts and decision makers with limited knowledge of conditions within the Pungwe basin. A high-level reference group is beneficial for decisions on a national and transnational level, but less so for assessing impacts and suggest adaptation strategies for the respective river basins. Stakeholders with specific knowledge of conditions in each basin need to be involved and active in the dialogue with climate and water experts.

When detailed adaptation strategies toward the potential impacts of climate change are outlined by regional planners in the Pungwe basin, the climatological and hydrological information from this project will not be specific enough for their requirements. In order to ensure that project results are operationally used at the regional level, it is necessary that a research-driven project like this is followed up by implementation orientated projects, including components that assure regional access to databases related to climate change, as well as a sustainable support of the use of hydrological models and interface tools that link climate and hydrological models.

6. Conclusions

The evaluation of the RCA3 model in Southern Africa shows that, given appropriate boundary conditions, it was capable of simulating the most important aspects of the climate on a regional scale. When used at a subbasin scale, additional scaling was needed to capture the prevailing spatial and temporal variability.

For the Pungwe basin, the three scenario experiments were consistent in indications of the following changes when comparing the control period (1961–1990) with the 2021–2050 period.

- Increased air temperature with approximately 1.5 °C for all seasons except the end of the dry season (SON), when the increase is around 2 °C.

- Reduction of annual rainfall by approximately 10%, with no significant variability between subbasins.
- Delay of the start of the rainy season by approximately one month
- Decreased river flow and available water for the entire Pungwe River basin due to a decrease in precipitation and an increase in evaporation. River flow is particularly reduced during the end of the dry/start of the wet season (50–60% reduction) which could imply severe consequences for agricultural production.
- Reduction of the annual period favourable for agricultural production by approximately one month.
- Increased interannual variability of rainfall, as well as of dry season streamflow, whereas the interannual variability of MAR seems to be less affected.
- Increased number of days with critically low flow for the freshwater intake to the city of Beira.

In contrast to the generally consistent results that ‘dry conditions get drier’, RCA3(ECHAM4-A2) indicated a slight increase of precipitation and river flow for some of the wet months, and in some subbasins an increase of occurrence of very high floods. Perceived robustness from using only three climate change experiments can be questioned. However, if these scenarios indeed reflect the future, they indicate that already critical situation regarding water availability might be worsened, and affect many aspects of daily life in the region, as well as during extreme situations. As concluded by national actors from Mozambique and Zimbabwe during the final project workshop, although only three scenarios were provided, the available information needs to be considered, together with other aspects of Integrated Water Resource Management, since building adaptive capacity takes time and consequences might be severe if actions are delayed until the impacts are more certain. The most beneficial adaptive strategies to begin with are those that will help to cope with existing climate variability. A need for prioritizing does however exist, for example, between actions to prevent impacts of water deficit and actions to prevent flooding. The need to reduce uncertainty, calls for inclusion of more climate change experiments in ensemble climate scenarios, for example, by using a combination of available dynamic and statistical downscaling of GCMs.

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References

- Andersson, L., Hellström, S. S., Kjellström, E., Losjö, K., Rummukainen, M. and co-authors. 2006. Climate change impacts on water resources in the Pungwe drainage basin. SMHI Report 2006-24. Norrköping, Sweden, 86 pp.
- Andersson, L., Alkan Olsson, J., Arheimer, B. and Jonsson, A. 2008. Use of participatory scenario modelling as a platform in stakeholder dialogues. *Water SA* **34**(3) HELP Special Edition, 439–447.
- Arnell, N. W. 1998. Climate change and water resources in Britain. *Clim Change* **39**, 83–110.
- Arnell, N. W. 2004. Climate change and global water resources: SRES emission and socio-economic scenarios. *Global Environ. Change* **14**, 31–52.
- Arnell, N. W., Hudson, D. A. and Jones, R.G. 2003. Climate change scenarios from a regional climate model: estimating change of runoff in Southern Africa. *J. Geophys. Res.* **108**, 4519–4535.
- Balaz, S., Fekete, M., Vörösmarty, J., Roads, J. O. and Willmott, C. J. 2003. Uncertainties in precipitation and their impacts on runoff estimates. *J. Clim.* **17**, 294–304.
- Blöschl, G. and Montanari, A. 2010. Climate change impacts – throwing the dice? *Hydrol. Process.* **24**, 374–381.
- Busuioc, A., Giorgi, F., Bi, X. and Ionita, M. 2006. Comparison of regional climate model and statistical downscaling simulations over different winter precipitation change scenarios over Romania. *Theor. Appl. Climatol.* **86**, 101–123.
- Chamuco, A. L. 1997. *Bué Maria dam, Mozambique: multipurpose reservoir operation using genetic algorithm techniques*. MSc Thesis. IHE, Delft.
- Champeaux, J. L., Masson, V. and Chauvin, F. 2005. ECOCLIMAP: a global database of land surface parameters at 1 km resolution. *Meteorol. Appl.* **12**, 29–32.
- Christensen, J. H., Boberg, F., Christensen, O. B. and Lucas-Picher, P. 2008. On the need for bias correction of regional climate change projections of temperature and precipitation. *Geophys. Res. Lett.* **35**, L20709, 6 pp., doi:10.1029/2008GL035694.
- Christensen, J. H., Hewitson, B., Busuioc, A., Chen, A., Gao, X. and co-authors. 2007. Regional climate projections. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (eds S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis and co-editors). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- Collins, W. D., Bitz, C. M., Blackmon, M. L., Bonan, G. B., Bretherton, C. S. and co-authors. 2006. The community climate system model: CCSM3. *J. Clim.* **19**, 2122–2143.

- de Wit, M. and Stankiewicz, J. 2006. Changes in surface water supply across Africa with predicted climate change. *Science* **31**, 1917–1921.
- Engelbrecht, F., Rautenbach, C., McGregor, J. and Katzfey, J. 2002. January and July climate simulations over the SADAC region using the limited-area model DARLAM. *Water SA* **28**, 361–374.
- Fowler, H. J., Blenkinsop, S. and Tebaldi, C. 2007. Linking climate change modelling to impacts studies: recent advances in down-scaling techniques for hydrological modeling. *Int. J. Climatol.* **27**, 1547–1578.
- Graham, L. P. 2004. Climate change effects on river flow to the Baltic Sea. *Ambio* **33**, 235–241.
- Graham, P., Andreasson, J. and Carlsson, B. 2007. Assessing climate change impacts on hydrology from an ensemble of regional climate models, model scales and linking methods—a case study on the Lule River basin. *Clim. Change* **81**, 293–307.
- Hudson, D. A. and Jones, R. G. 2002. Regional climate model simulations of present-day and future climates in Southern Africa. Hadley Centre technical note 39. Met. Office, Hadley Centre, Bracknell, UK, 41 pp.
- Jones, C. G., Willén, U., Ullerstig, A. and Hansson, U. 2004. The Rossby Centre Regional Atmospheric Climate Model Part I: model climatology and performance for the present climate over Europe. *Ambio* **33**, 199–210.
- Kjellström, E., Bärring, L., Gollvik, S., Hansson, U., Jones, C. and co-authors. 2005. A 140-year simulation of European climate with the new version of the Rossby Centre regional atmospheric climate model (RCA3). Reports Meteorology and Climatology, 108, SMHI, Sweden, 54 pp.
- Kundzewicz, Z. W., Mata, L. J., Arnell, N. W., Döll, P., Kabat, P. and co-authors. 2007. Freshwater resources and their management. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (eds M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden and C. E. Hanson). Cambridge University Press, Cambridge, UK, 173–210.
- Large W. G. and Danabasoglu, G. 2006. Attribution and impacts of upper-ocean biases in CCSM3. *J. Climate* **19**, 2347–2365.
- Lenderink G., Buishand A. and van Deursen, W. 2007. Estimates of future discharges of the river Rhine using two scenario methodologies: direct versus delta approach. *Hydrol. Earth Syst. Sci.* **11**, 1145–1159.
- Lidén, R. and Harlin, J. 2000. Analysis of conceptual rainfall-runoff modelling performance in different climates. *J. Hydrol.* **238**, 231–247.
- Lindström, G., Johansson, B., Persson, M., Gardelin M. and Bergström, S. 1997. Development and test of the distributed HBV-96 hydrological model. *J. Hydrol.* **201**, 272–288.
- Lobell, D. B., Marshall, B. B., Tebaldi, C., Mastrandrea M. D., Falcon W. P. and co-authors. 2008. Prioritizing climate change adaptation needs for food security in 2030. *Science* **319**, 607–610.
- Losjö K., Andersson, L. and Samuelsson, P. 2006. Climate change impacts on water resources in the Pungwe drainage basin. SMHI Report 2006-45. Norrköping, Sweden.
- Mitchell, T. D. and Jones, P. D. 2005. An improved method of constructing a database of monthly climate observations and associated high-resolution grids. *Int. J. Climatol.* **25**, 693–712.
- Nakićenović, N. and Swart, R. (Eds) 2000. *Emission Scenarios: A Special Report of Working Group II of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, UK, 599 pp.
- Roeckner, E., Bengtsson, L., Feichter, J., Lelieveld, J. and Rodhe, H. 1999. Transient climate change simulations with a coupled atmospheric-ocean GCM including the troposphere sulphur cycle. *J. Clim.* **12**, 3004–3032.
- Rosberg, J. and Andreasson, J. 2006. From delta change to scaling and direct use of RCM output. In: *European Conference on Impacts of Climate Change on Renewable Energy Sources*, Reykjavik, Iceland, June 5–9, 2006.
- Rowell, D. P. 2006. A demonstration of the uncertainty in projections of UK climate change resulting from regional model formulation. *Clim. Change* **79**, 243–257.
- Rummukainen, M. 2010. State-of-the-art with regional climate models. *WIREs Clim. Change* **1**, 82–96. doi:10.1002/wcc.008.
- Ruosteenoja, K., Carter, T. R., Jylhä, K. and Tuomenvirta, H. 2003. Future climate in world regions: an intercomparison of model-based projections for the new IPCC emission scenarios. The Finnish Environment 644, Finnish Environment Institute, 83 pp.
- Savijärvi, H. 1990. A fast radiation scheme for mesoscale model and short-range forecast models. *J. Appl. Met.* **29**, 437–447.
- Samuelsson, P., Jones, C., Willén, U., Gollvik, S., Hansson, U. and co-authors. 2011. The Rossby Centre Regional Climate Model RCA3: model description and performance. *Tellus* **63A**, 4–23.
- Schiermeier, Q. 2010. The real wholes in climate science. *Nature* **463**, 284–287.
- Schulze, R. E. 2000. Modelling hydrological response to land uses and climate change. A Southern African perspective. *Ambio* **29**, 12–22.
- Sillmann, J. and Roeckner, E. 2008. Indices for extreme events in projections of anthropogenic climate change. *Clim. Change* **86**, 83–104.
- SWECO and Associates. 2004. Development of the Pungwe River basin joint integrated water resources management strategy. The Pungwe River Monograph, Main report, 67 pp.
- Terink, W., Hurkmans, R. T.W.L., Torfs, P. J. J. F. and Uijlenhoet, R. (2010). Evaluation of a bias correction method applied to downscaled precipitation and temperature reanalysis data for the Rhine basin. *Hydrol. Earth Syst. Sci. Discuss.* **7**, 221–267.
- Teutschbein, C. and Seibert, J. 2010. Regional climate models for hydrological impact studies at the catchment-scale: a review of recent modeling strategies. *Geography Compass* **4**, 834–860.
- Timmerman, J. G., Pahl-Wostl, C. and Moltgen, C. (Eds) 2008. *The Adaptiveness of IWRM: Analysing European IWRM Research*. IWA Publishing, London, UK.
- Uppala, S. M., Kållberg, P. W., Simmons, A. J., Andrae, U., da Costa Bechtold, V. and co-authors. 2005. The ERA-40 Re-analysis. *A.J. Roy. Meteorol. Soc.* **131**, 2961–3012.
- Willmott, C. J. and Matsuura, K. 2001. *Terrestrial Air Temperature and Precipitation: Monthly and Annual Time Series (1950–1999)* Version 1.02. Available at: http://climate.geog.udel.edu/~climate/html_pages/README.ghcn_ts2.html (Accessed in April 22, 2010).