REGIONAL CLIMATE ENSEMBLE SIMULATIONS FOR IRELAND IMPACT OF CLIMATE CHANGE ON RIVER FLOODING

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ABSTRACT

In recent years, uncertainties in climate model projections have become of much interest because such a wide range of future projections have emerged from a combination of emissions scenarios and different general circulation models (GCMs). Decision-makers and scientists have the desire to know whether certain scenarios are more likely than others for different issues, such as river flooding. Through the ensemble approach the uncertainty in regional climate projections as well as in predicted impacts can be determined to estimate which predicted changes and impacts are robust features. To make a first step towards ensemble simulations for Ireland, different regional climate model (RCM) simulations have been performed to predict the climate of Ireland in a high horizontal resolution of 13 km for the time period 2021-2060. Two different GCM formulations as well as four different emissions scenarios have been used to drive the Rossby Centre Regional Atmospheric Model (RCA3) on a model domain including Ireland, the UK and parts of the North Atlantic. The precipitation output of all these different RCA3 simulations has been used as input for the HBV hydrological model, which has been run for the Suir river catchment as a test case. RCA3 and HBV have also been run for 1961-2000 to confirm the ability of the models to simulate present day conditions. Indeed the application of a high resolution RCM in connection with a conceptual hydrological model is shown to be capable of capturing the local variability of river discharge for present-day climate. Results suggest a moderate increase in temperature of 0.5 to 2 degrees Celsius in 2021-2060 compared to 1961-2000. Whereas in winter precipitation and runoff increases are predicted, in summer enhanced surface evaporation coincides with a precipitation decrease, which will have implications on water availability.

1 INTRODUCTION

The IPCC (Intergovernmental Panel on Climate Change) has stated that mean surface temperatures may rise 0.3-0.6° Celsius per decade in the 21st century (IPCC, 2001) as a result of anthropogenic influences. As increased temperatures will lead to greater amounts of water vapour in the atmosphere and an accelerated global water cycle, it can be expected that river catchment areas will be exposed to a greater risk of flooding.

To investigate the possible future development of the frequency and intensity of flooding events a hydrological model can be forced with the output from a climate model. However, because of the relatively coarse resolution of general circulation models (GCMs), it is difficult to capture the relatively inhomogeneous spatial distribution of precipitation due to an inadequate description of orography and land use. The high horizontal resolution of a regional climate model (RCM) is more appropriate for resolving the small scale features of orography and land use, that have a major influence on hydrological variables such as precipitation and runoff. Furthermore, significant efforts have been made to improve the representation of the land surface-atmosphere interaction, particularly for the hydrological component. The land surface parameterization scheme is an important component for the water cycle representation in a regional climate model. Because hydrological models need detailed precipitation information as an input, the high resolution of the RCM is ideal for capturing the variability of precipitation (Gutowski et al., 2003). If the horizontal resolution of the RCM is not fine enough, for example, the bias of the modelled precipitation will lead to an unrealistic hydrological control run if the unmodified output is used to drive a hydrological model (Graham, 2000).

The most important source of uncertainty in estimating the hydrological response comes from the GCM realisation including both the GCM formulation and the used emissions scenario with additional uncertainties linked to the local scale patterns in downscaling of temperature, precipitation and evapotranspiration in a specific drainage basin (Bergström et al., 2001; Gao et al., 2002). Therefore it is very important to estimate this uncertainty in future climate and climate impact projections in producing ensemble predictions and investigating which signals are robust. According to Giorgi and Mearns (2002) two criteria should be considered to assess the reliability of climate change simulations. First, the model performance for present day climate has to be investigated; the better the model performance the higher the reliability. Second, the convergence of future climate simulations by different models for a given emissions scenario has to be assessed; the closer the results are together the more reliable the projection.

Some impact studies of the climate change on flooding have been carried out in different countries and regions (Bergström et al., 2001; Pilling and Jones, 2002; Gao et al., 2002; Arnell, 2003). Depending on the spatial and temporal scales, and the aim of the study, different global and regional climate models have been used to translate the assumed climate change into a hydrological response. However, in all of these studies the horizontal resolution of the climate models was relatively coarse (50 km or more). None of the studies looked at extreme events on the base of daily precipitation and river discharge, both of which are crucial in terms of estimating possible impacts on society; the focus was on mean climate values.

2 SETUP OF THE MODEL CHAIN

To create ensemble predictions of regional climate change for Ireland and its impact on river runoff several steps are necessary. Different GCM realisations have to be selected to serve as driving data for the RCM at its lateral boundaries; the RCM has to be run both for present day climate and for future climate using the different GCM boundary data; the high resolution RCM precipitation output of each realisation has to be used to drive the hydrological discharge model.

Four different GCM scenarios have been selected as boundary data for the investigation of future climate and river discharge: ECHAM4-B2, ECHAM5-B1, ECHAM5-A1B and ECHAM5-A2. This selection includes both different GCMs (ECHAM4 and ECHAM5) and different emissions scenarios (B1, B2, A1B and A2). The two GCMs are described in detail in Roeckner et al. (1996) (ECHAM4) and Roeckner et al. (2003) (ECHAM5). Main developments in ECHAM5 compared to ECHAM4 are a flux-form semi-Lagrangian transport scheme for positive definite variables such as water components, a new longwave radiation scheme, separate prognostic equations for cloud liquid water and cloud ice, a new cloud microphysical scheme and a prognostic-statistical cloud cover parameterisation. The four emissions scenarios chosen in this study cover the four main story lines as defined in the Special Report on Emissions Scenarios (SRES) (Nakicenovic et al., 2000): globalisation with an emphasis on environmental sustainability (B1), local and regional development with an emphasis on environmental sustainability (B2), globalisation combined with strong economic growth (A1B) and regional development with emphasis on economic growth (A2). Therefore a good range of possible developments of greenhouse gas concentrations in the future is considered in our ensemble.

The RCM used in this study is the Rossby Centre regional Atmospheric climate model version 3 (RCA3) (Kjellström et al., 2005; Jones et al., 2004), which has been developed from the High Resolution Limited Area Model (HIRLAM). Compared to the numerical weather prediction model HIRLAM several changes have been made to the radiation scheme, the turbulence scheme and the cloud parameterisation. A new land surface scheme has been developed and implemented in RCA3, which is described in detail in Samuelsson et al. (2006). Within a model grid cell several tiles with different surface properties such as type of vegetation, roughness length and albedo are considered. For all tiles water and energy balances are calculated separately and a weighted average over the grid cell is computed. The land surface scheme also includes soil moisture and runoff parameterisations.

For this study, the RCA3 model domain has been set up with a 0.12° (13 km) spherical, rotated latitude/longitude grid (Figure 1). For considering the effect of the North Atlantic ocean, the model domain includes good parts of this ocean north, west and south of Ireland. There is a large scale jump between the GCM and RCM spatial resolution. However, this model setup has been validated extensively. The results suggest, that the model configuration is well able to capture the characteristics of present day climate (Wang et al., 2006; McGrath et al., 2005).

For the river discharge simulation, the hydrological model HBV of the Swedish Meteorological and Hydrological Institute (SMHI) is used (Bergström, 1995; Lindström et al., 1997). This model is a semi-distributed, conceptual hydrological model using sub-basins as the primary hydrological units; it takes into account area-elevation distribution and basic land-use categories (forest, open areas and lakes). Sub-basins are considered in geographically or climatologically heterogeneous basins or catchment areas of large lakes.

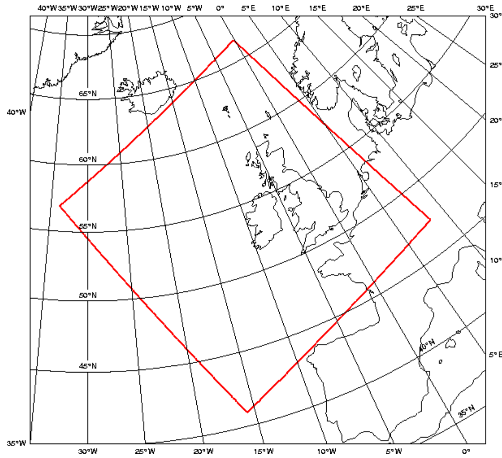

Figure 1: Model domain

The model consists of a precipitation routine representing rainfall, a soil moisture routine determining actual evapotranspiration and controlling runoff formation as well as a runoff routine defining the response function which transforms excess water from the soil moisture zone to runoff. This model has been evaluated as one of the most appropriate models for the assessment of climate change impacts on peak discharge and flood frequency analysis (Passchier, 1996); it has been widely used in Europe and other parts of the world in climate change studies (Liden and Harlin, 2000; Bergström et al., 2001; Menzel and Bürger, 2002).

In this study, the Suir river catchment located in the south-east of Ireland is investigated as a test case (Figure 2). This catchment covers 2173 km^2. Inside the catchment there is a hydrological observation station in Clonmel, which produces good quality discharge data. This enables us to do a careful calibration and validation of the hydrological model.

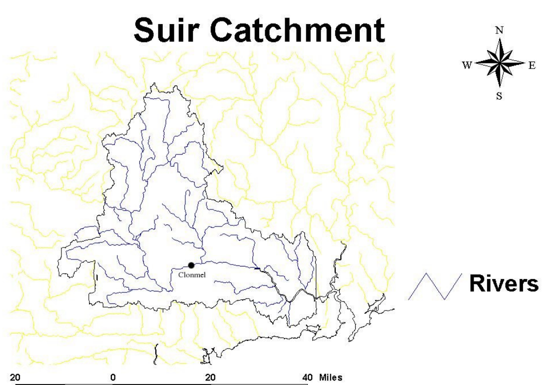

Figure 2: Suir catchment area and river network

Both RCA3 and HBV have been run for 2021-2060 using the four different ECHAM4 and ECHAM5 scenario datasets. This time period has been chosen rather than a time period towards the end of this century, because in terms of adaptation measures it is more relevant to know what the implications of climate change are in the nearer future. Two control simulations have been run for 1961-2000 in addition using the ECHAM4 and ECHAM5 control datasets. To determine the changes predicted by the different scenarios, differences between the ECHAM4-B2 scenario and the ECHAM4 control run driven simulations as well as between the different ECHAM5 scenario and the ECHAM5 control run driven simulations have been calculated. To remove biases occurring in present day climate simulations from future climate simulations, differences are calculated, investigated and discussed rather than considering the predicted values for the future as absolute values. This is a common approach in the climate and hydrological modelling community (Andréasson et al., 2004). It should be noted that due to nonlinearities in the climate system this approach can only be used if the present day climate simulations agree reasonably well with the observed climate.

Of course ideally also different regional climate models and different hydrological discharge models should be considered in an ensemble. Since it has been shown that the uncertainty stemming from different RCM and hydrological discharge formulations is small compared to the uncertainty stemming from the GCM realisation (Leckebusch et al., 2006; Jenkins and Lowe, 2003; Graham, 2000; Bergström, 2001), this has been abandoned due to constraints in computation time.

3 VALIDATION OF RCA3 AND HBV

In a model chain such as the one used in this study, uncertainties are added from one to the next member of the chain. Therefore it is important to assess the performance of RCA3 and HBV if these models are provided with observation based boundary values. Atmospheric data from the ECMWF 40-year reanalysis project (ERA-40) (Uppala et al., 2005) for 1961-2000 have been used for this purpose.

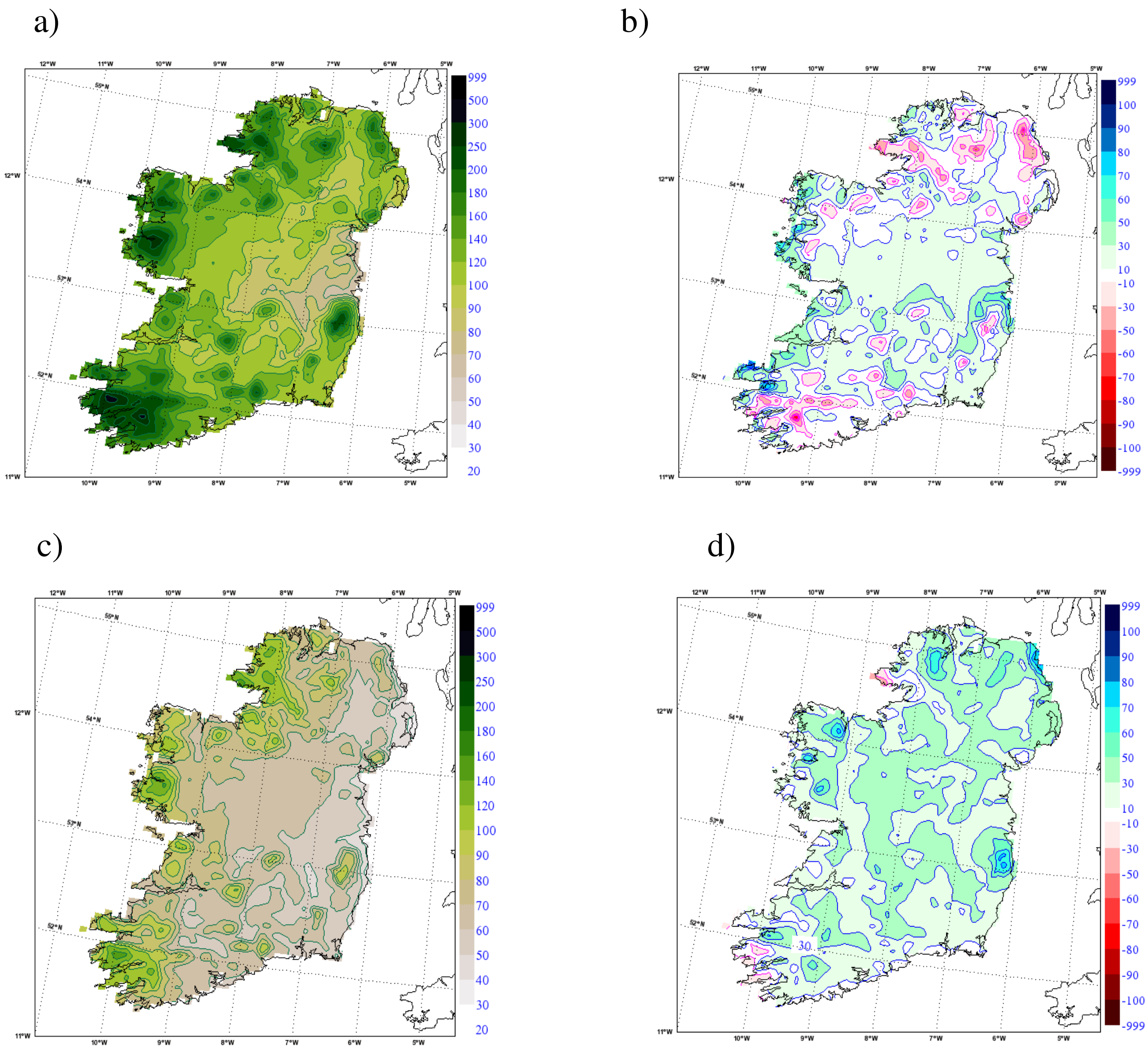

Figure 3: Mean monthly precipitation (1961-2000) from UKCIP data for January (a) and July (c) and differences of our ERA-40 driven RCA3 simulation relative to the UKCIP data ((b) and (d)) in mm/month. The UKCIP data are based on observed precipitation values interpolated to a 5-km grid.

Figure 3 shows gridded precipitation observations from UKCIP (Perry and Hollis, 2005) as well as differences between our ERA-40 driven RCA3 simulation and these observation data for January and July. The rainfall in the midlands is overestimated by about 20 to 30 mm/month or 20 to 40% in comparison with observational data with the stronger overestimation occurring in July. Two factors may have contributed to this: the observations generally underestimate rainfall amounts, particularly in windy conditions, and the model may produce too many light precipitation events. In contrast, there is too little rainfall in mountainous areas in January, where the model underestimates rainfall by up to 80 mm/month or 25%. This could be attributed to a lack of detail in the representation of the surface features at the 0.12° resolution of the model. In July agreement in mountainous areas is much better, suggesting that only the heavy winter rainfall in these areas is difficult to simulate.

Agreement for 2 m temperature is much better (not shown). In January our simulation shows a slight cold bias of 0.5 °C in most regions of the country, whereas biases are usually below 0.25 °C in July. It should be noted that the results for both precipitation and 2 m temperature for the two selected months are representative for winter and summer. In spring and autumn biases are usually between the ones discussed for January and July.

Before the validation of the hydrological model, the observed precipitation data for the period January 1960 to December 1964, which includes relatively dry and wet years, and monthly mean climate potential evapotransipiration values are firstly used to drive the HBV model for the calibration. Although insufficient observation data coverage limited the duration of the calibration to 5 years, the minimum requirement according to the model documentation of SMHI (SMHI, 2004), which recommends the use of 5-10 years of calibration data, is still met. In order to assess the performance of the model, the Nash-Sutcliffe efficiency coefficient R^2 (Nash and Sutcliffe, 1970) and the relative error RE are calculated. For the calibration of the Suir catchment, R^2 reached 0.787, which implies that the model has a good performance in this area (Figure 4). Except for the peak values, which are slightly underestimated, the variation of the simulated discharge coincides with the observed discharge fairly well from visual inspection. This is also confirmed by the smaller RE value, which is only 0.24.

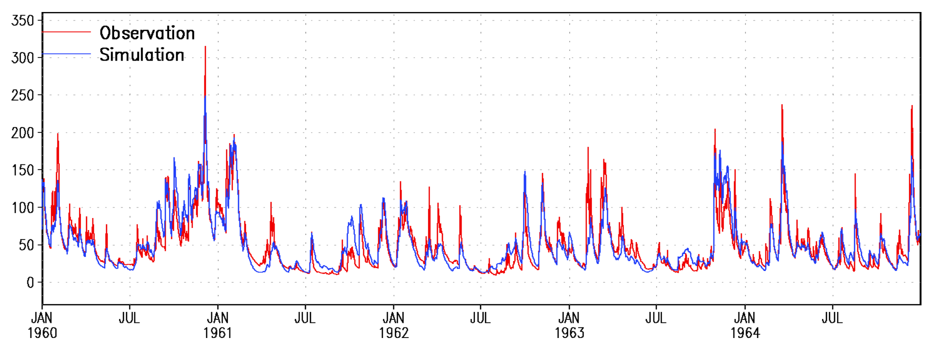

Figure 4: Observed and simulated (using observed precipitation as the input) discharge [m^3/s]

After the successful calibration of the HBV model using the observed climate variables, the dynamically downscaled precipitation is used to drive the HBV model. As an example Figure 5 shows 10 years of the ERA-40 driven RCA3 simulation time series of discharge in the Suir catchment between 1981 and 1990 compared to the observations. Generally, the evolution of the simulated discharge shows good agreement with the observed discharge. This is also true for the other three decades of the 40-year period. However, there are some discrepancies in the timing of the flood events, which lead to large differences between the observed and simulated discharge at specific times. Moreover, peak values are often underestimated, which causes a higher relative error of 0.4. The underestimation of the heavy precipitation intensities from RCA3 causes the underestimation of the discharge peaks. On the whole, the simulation is a little worse compared to the calibration; R^2 only reaches 0.545, while the correlation coefficient reaches 0.79. This confirms that the model simulates the evolution of the discharge reasonably well, whereas the underestimated peak values caused the R^2 value to be relatively low. Figure 6 gives return values of the maximum daily discharge of the observation and ERA-40 driven simulation calculated by generalized extreme value (GEV) method. The distribution of return values for the different return periods show a fair agreement, although they are systematically underestimated by about 15-20% in the simulation.

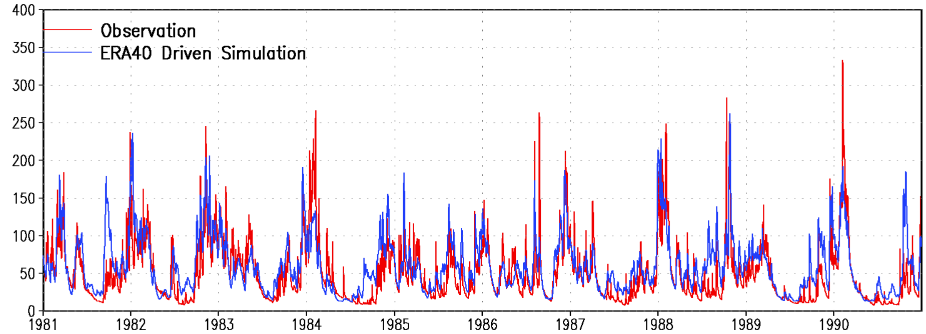

Figure 5: Observed and simulated (ERA-40 driven simulation) discharge [m^3/s]

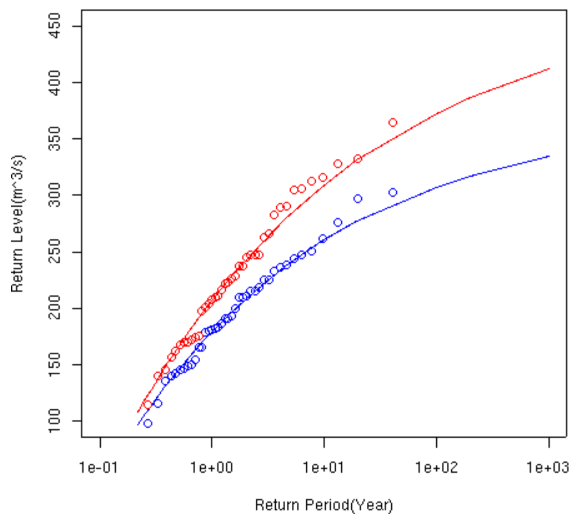

Figure 6: Return values of observed (red) and simulated (blue) (ERA-40 driven simulation) maximum annual discharge (Circles: Values of maximum daily discharge per year, lines: Fit using generalized extreme value distribution)

4 FUTURE CHANGES IN PRECIPITATION AND 2 M TEMPERATURE

Figure 7 shows the predicted changes in precipitation for January and July for the ECHAM4-B2 and ECHAM5-A1B scenarios. According to both predictions increases in precipitation of about 20 mm/month corresponding to 15% on average are simulated in January while the regions of the strongest increases are different between both scenarios. For July not much change is simulated according to the ECHAM4-B2 scenario, whereas quite substantial decreases of about 30 mm/month corresponding to 20% on average are simulated according to the ECHAM5-A1B scenario. The spatial distribution of changes from the ECHAM5-B1 and ECHAM5-A2 scenarios is generally similar to the one from the ECHAM5-A1B scenario with smaller magnitudes of changes in the ECHAM5-B1 scenario and comparable magnitudes of changes in the ECHAM5-A2 scenario. This shows that the GCM formulation has even more influence on the predicted changes than the emissions scenario. It also shows that there still is a considerable uncertainty stemming from the GCM formulation. The main reasons for these different change patterns are different large scale circulations in atmosphere and ocean and different vertical structures of the atmosphere over the North Atlantic. The predicted changes in the 2 m temperature (not shown) are similarly affected by the GCM formulation: they are generally stronger in the ECHAM4-B2 scenario (between 1 and 2 °C with the lower values occurring in spring and the higher values in winter and summer) compared to all ECHAM5 scenarios (between 0 and 1.5 °C with the lowest values occurring in spring in the ECHAM5-B1 scenario and the highest values in summer in the ECHAM5-A1B scenario).

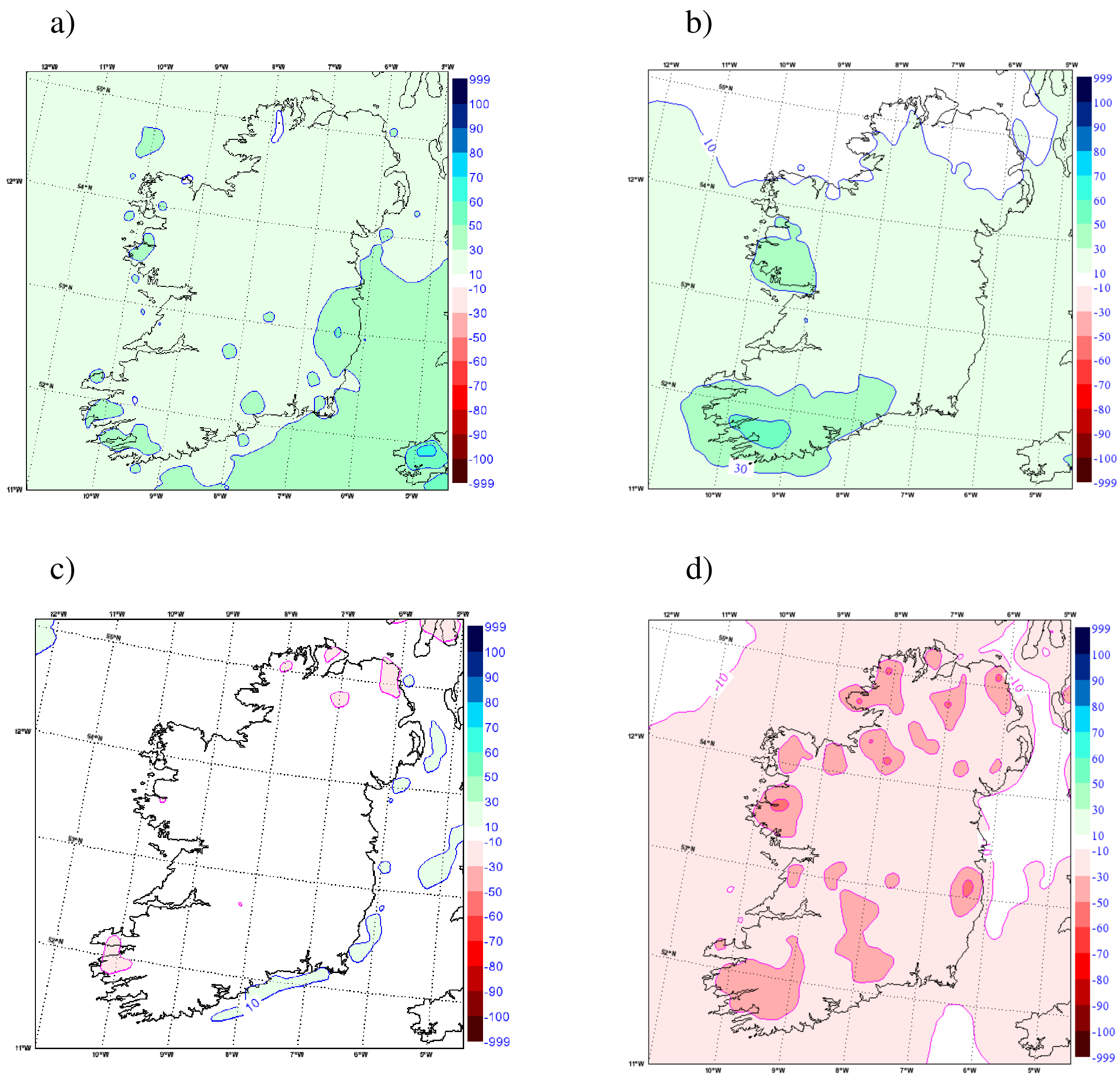

Figure 7: Predicted precipitation changes in mm/month in January according to (a) the ECHAM4-B2 scenario and (b) the ECHAM5-A1B scenario and in July according to (c) the ECHAM4-B2 scenario and (d) the ECHAM5-A1B scenario.

5 FUTURE CHANGES IN RIVER RUNOFF

To investigate the effect of the climate change under different climate scenarios, the control climate is firstly evaluated. Figure 8 shows the 40 year monthly mean discharge from all simulations compared to observations. The ECHAM4 driven simulation indicates slightly overpredicted discharge. The biggest difference between the ERA-40 and ECHAM4 driven simulation is in the winter season; there are only minor differences in the summer season. The ECHAM5 driven simulation shows an even stronger discharge overprediction than the ECHAM4 driven simulation. Whereas there are not much differences between ECHAM4 and ECHAM5 in winter, the overprediction gets particularly strong in the summer season in ECHAM5. This is also reflected by the mean precipitation; the ECHAM5 driven simulation tends to have higher mean precipitation.

For the future projection, the biggest difference between ECHAM4-B2 scenario and its control run is in the winter season, where the discharge increases by up to 20% in December and January while the summer discharge remains nearly unchanged. The ECHAM5-A2 scenario also shows increased discharge in the winter season, but an obvious decrease in the summer season. As from the analysis of precipitation, the ECHAM5-A1B and B1 scenarios show a change similar to the ECHAM5-A2 scenario.

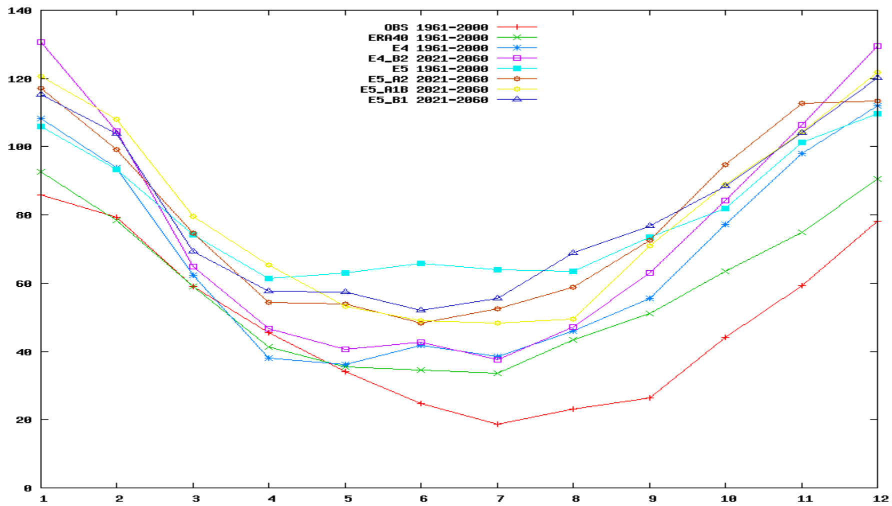

Figure 8: Annual cycle of observed and simulated (driven by ERA-40, ECHAM4 and ECHAM5 data) discharge, 1961-2000, compared with the simulated discharge for 2021-2060 driven by ECHAM4 and ECHAM5 data [m^3/s]

The return value analysis (Figure 9) shows, that the intensity and frequency of heavy discharge events clearly increases according to the ECHAM4-B2 scenario, whereas a weak decrease can be seen in the ECHAM5-A2 scenario. Again trends similar to the ECHAM5-A2 scenario are found in the other two scenarios (not shown).

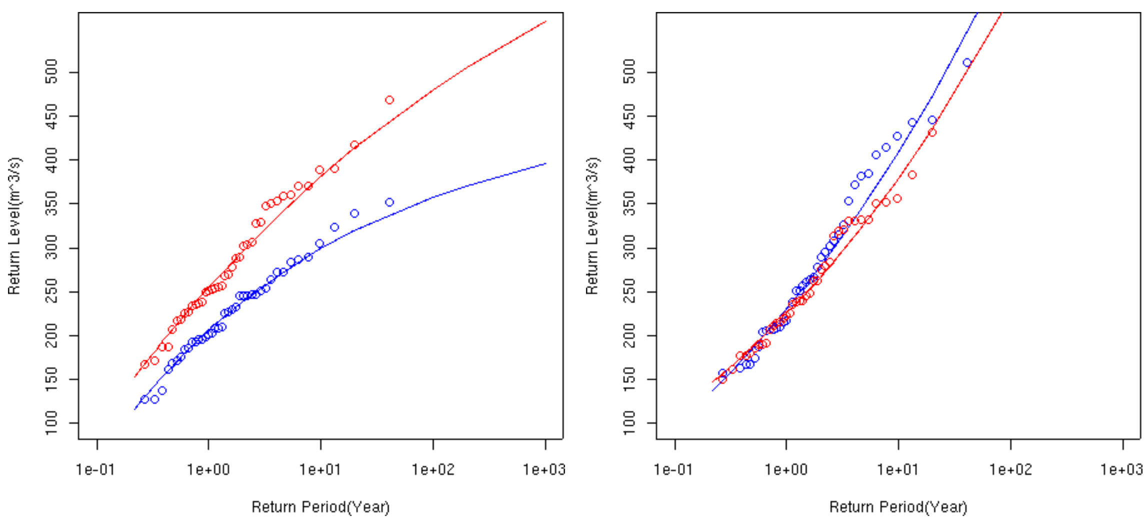

Figure 9: Return values of the simulated maximum annual discharge using the ECHAM4-B2 (a) and ECHAM5-A2 (b) driven RCA3 simulation for the present-day (blue) and future climate (red)

6 CONCLUSIONS

In this study, RCA3 and HBV have been applied to study the effect of climate change on river discharge under different climate scenarios. The input data are taken from a high resolution regional climate model driven by different data sets. Concerning the performance of the precipitation simulation, a present day RCA3 simulation driven by data from the ERA-40 reanalysis project is firstly investigated (see also Wang et al., 2006). The local precipitation distribution is captured fairly well. The calibration and validation results of our ERA-40 driven present day simulation show that the HBV model can reproduce the discharge reasonably well. There is, however, a small overestimation of the discharge in the summer season and an underestimation of the intensity of extreme discharge events in the winter season, which can be explained by the biases of the precipitation simulation. Because further biases are introduced if using present day data from the global climate models ECHAM4 and ECHAM5 instead of the ERA-40 data, for estimating the changes for future climate differences between the ECHAM4 and ECHAM5 future climate simulations and the respective present day climate simulations have been calculated. Results, which are common to all of the four realisations for the future and can therefore be considered as robust results, include a general warming of 0.5 to 2 °C in 2021-2060 compared to 1961-2000 with the lower values occurring in spring and the higher values occurring in summer and winter. Also the increase of winter precipitation by 15% on average is a robust result, whereas predictions for summer precipitation vary from no change to a substantial decrease by 20%, which together with higher temperatures and connected stronger evaporation could have implications on water availability and water quality. The differences in the precipitation projections are also resulting in considerable differences in the mean annual cycle of discharge: the ECHAM5 scenarios show a smaller discharge increase in the winter season than the ECHAM4 scenario. In summer, the ECHAM5 scenarios show a decrease in the discharge, whereas there is no change according to the ECHAM4 scenario. For the extreme events, the projection of the future climate shows a strong increase in the return levels of daily discharge values in the ECHAM4 scenario but a slight decrease in the ECHAM5 scenarios. In the investigated Suir catchment, the 10-year return value of the maximum river discharge increases by more than 20% when using the ECHAM4-B2 emission scenario for 2021-2060 compared to 1961-2000, whereas in the ECHAM5 scenarios, the future extreme discharge slightly decreases.

Our analysis suggests that there still is a large uncertainty in the global climate projections, which are probably mainly connected with the GCM formulation and not so much with the chosen emission scenario.

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