Assessment of climate change impacts on floods in an Alpine watershed

Christian Dobler

Abstract

The present study assesses possible effects of climate change on floods in an Alpine watershed. A three-step modelling approach consisting of i) downscaling of global climate data, ii) hydrological modelling and iii) statistical analysis constitutes the basis of this investigation. The first results indicate that the projections of heavy precipitation events are subjected by large variability. This makes a detection of climate change signals difficult. Floods with a return period up to ~10 years are expected to decrease in the future scenarios, whereas no clear signals were obtained for floods with higher return periods.

Keywords: Alps, climate change, downscaling, hydrological modelling

1 Introduction

Global climate change is expected to significantly modify the hydrological cycle in mountain regions. Dobler et al. (2010) assessed climate change impacts on runoff regime of the Lech river in the northern Alps and found a considerable shift in the runoff regime with a redistribution of runoff from summer to winter months in the future scenarios. Numerous other studies have obtained similar results (e.g. Horton et al. 2006). However, beside climate change impacts on the hydrological cycle, shifts in extreme events like floods are of high social and economic interest. In order to anticipate possible changes in advance, assessments of climate change impacts on floods are necessary.

The societal need to respond to global climate change requires climate data of the future. The most common tools to produce climate data constitute the General Circulation Models (GCMs). However, the representation of topography and climate processes in these models is too coarse to investigate regional aspects. There are two approaches to overcome this scaling-problem: process-based techniques (dynamical downscaling) and statistical techniques (statistical downscaling) (e.g. Hewitson & Crane 1996).

Dynamical downscaling uses highly resolved numerical computer models (RCM – Regional Climate Models), nested in a global climate model. But even such RCMs of a significantly higher resolution are currently not able to realistically illustrate the meteorological conditions of a topographically complex terrain like the Alps. Biases of up to 2 K for mean annual 2 m temperature and of more than 50% for precipitation (Kotlarski et al. 2005) are still too large for a direct coupling to hydrological models.

Statistical downscaling, in contrast, basically comprises the development of empirical relationships between the large-scale GCM output and the local-scale variables (e.g. Prudhomme et al. 2002), or in short:

$$y = f(x)$$

for a small-scale variable y, not adequately represented in a GCM, and a large-scale variable x (von Storch 1999). The various statistical downscaling techniques can be categorized as 'weather classification', 'regression models', and 'weather generators'. A detailed overview is given by Wilby et al. (2004). However, most statistical downscaling techniques perform well in reproducing mean climate variables and only few models realistically simulate extreme events.

Expanded Downscaling (EDS), developed by Bürger (1996), was designed to solve this deficiency. EDS is an advancement of the concept of multiple linear regression (MLR). In contrast to MLR, EDS better simulates local climate variability. EDS has been applied in a variety of studies around the world (e.g. Dehn et al. 2000; Bürger & Chen 2005).

The objective of the present study is to assess possible impacts of climate change on floods in an Alpine watershed. The statistical downscaling technique Expanded Downscaling (EDS) was selected to downscale the coarse GCM output to a local scale. Finally, the hydrological model HQsim was used to perform runoff simulations for present and future conditions.

2 Study area

In the present investigation the watershed of the river Lech up to the water gauge in Lechaschau, near Reutte, was studied. The basin covers ~1,000 km² and contains around one quarter of the whole Lech watershed up to Marxheim in Germany. Figure 1 shows the location of the study area.

The catchment is marked by extreme differences in height within short distances. The distribution of height reaches from ~800 to ~3,000 m a.s.l. For a detailed description of the watershed see Dobler et al. (2010).

3 Methodology

A three-step approach to evaluate the impacts of climate change on floods is used in the present investigation: i) downscaling of climate scenario data by applying EDS, ii) simulating discharges with the hydrological model HQsim and iii) applying flood frequency analysis. Figure 2 gives an overview of the methodological steps.

In a first step, the output of GCMs was statistically downscaled by applying the EDS technique. The downscaled data, in turn, were used to force the hydrological model HQsim, which produced runoff series for present and future climate conditions. Finally, a statistical analysis between both runoff series was carried out.

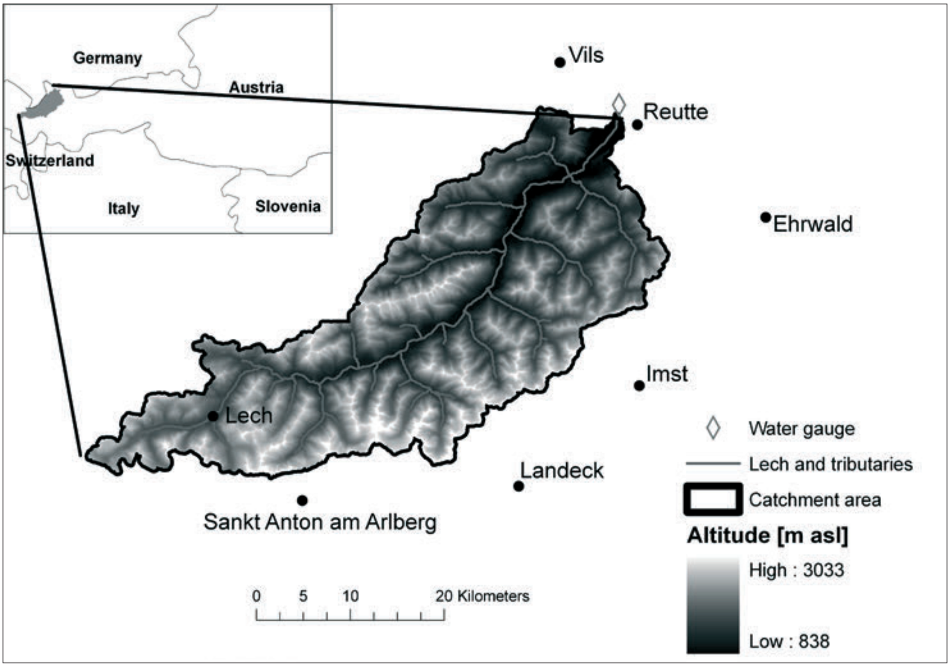

Figure 1: Map of the Lech watershed.

Each of the applied models was calibrated according to the observed data from 1989 to 2000, and, in a further step, validated by data of the periods 1971 to 1988 and 2001 to 2005. The used models (EDS, HQsim) are known to provide realistic results when driven by observed data. The main assumption when using the models in climate impact researches is that the parameters of the calibrated models will also be valid for a changed climate. Secondary effects like shifts in land use or settlement development were not covered by this research.

3.1 Statistical downscaling of GCM output

In the present investigation, the ECHAM5 model (Roeckner et al. 2003) from the Max Planck Institute of Meteorology, and the HadGEM2 (Collins et al. 2008) model from the Met Office Hadley Centre for Climate Prediction were used. The period of 1971 to 2000 was selected as baseline that represents the current conditions, while the period of 2071 to 2100 served as future scenario. For the ECHAM5 model, the emission scenarios A1B and A2 were considered, whereas for the HadGEM2 model the A1B emission scenario was used. For both models three ensemble runs were considered.

The output of the two GCMs was downscaled by developing a statistical relationship between large scale atmospheric variables and local scale variables (e.g. Zorita & von Storch 1999). In this research the Expanded Downscaling (EDS) technique was applied to bridge this scaling gap.

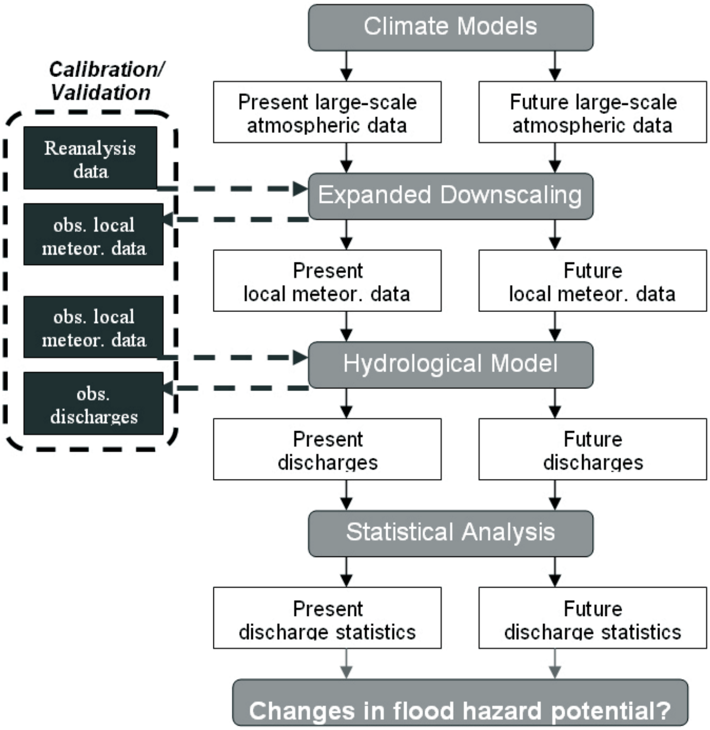

Figure 2: Methodological steps.

EDS represents an advancement of multiple linear regression and is particularly suited to the simulation of extreme events like floods (Bürger 1996; Bürger & Chen 2005). EDS is based on minimizing the least square error under the constraining side condition that the local covariance is preserved. This result in a local climate variability that is much more realistic simulated than in other regression models. A detailed description of the EDS technique is given by Bürger (1996).

EDS was calibrated by establishing a statistical relationship between observed atmospheric fields, taken from the reanalysed dataset of the NCEP (National Centers for Environmental Prediction, Kalnay et al. 1996) and the observed local climate data. The years of 1989 to 2000 were used as calibration period. The large-scale fields vorticity, divergence, temperature, and specific humidity at the 700 and 850 hPa level and precipitation at the surface were selected from the GCMs output, whereas temperature and precipitation data were used at the local scale. The process was carried out on a daily basis. The quality of the process was validated for the periods of 1971 to 1988 and 2001 to 2005. In a final step, EDS is derived from the large-scale GCMs output.

3.2 Hydrological modelling

In this study, the hydrological model HQsim (Kleindienst 1996) was selected to perform runoff simulations. The model is based on the water balance model BROOK (Federer & Lash 1978) and was further modified by Kleindienst (1996).

HQsim is a semi-distributive model which divides the catchment area into hydrological response units (HRUs). HRUs have been created by intersecting soil, vegetation and topographical data. Daily temperature and precipitation data from 14 meteorological stations were used as forcing for the HQsim model. The model was calibrated on the basis of runoff data from the period of 1989 to 2000 and validated with data from the years 1971 to 1988 and 2001 to 2005. First results of the application of the model can be found in Dobler et al. (2010).

4 Results

4.1 Performance of the EDS models

Before examining climate change impacts on flood events, the performance of the EDS model in downscaling precipitation from large-scale atmospheric data is tested. Figure 3 shows a comparison of the cumulative distribution functions (cdfs) of observed and downscaled data exemplary for one representative precipitation station (station 101220; see Figure 1) within the catchment. The results show that the cdfs of both series agree fairly well, indicating that EDS produces long-term statistics similar to observations.

In a next step, a focus on the simulation of extreme precipitation events is established. Figure 4 illustrates the 35 most extreme heavy precipitation events of the observed and downscaled time series from 1971 to 2005. In general, downscaling extreme events like heavy precipitation is a difficult task, because such events occur comparatively seldom within selected time intervals. However, the results indicate

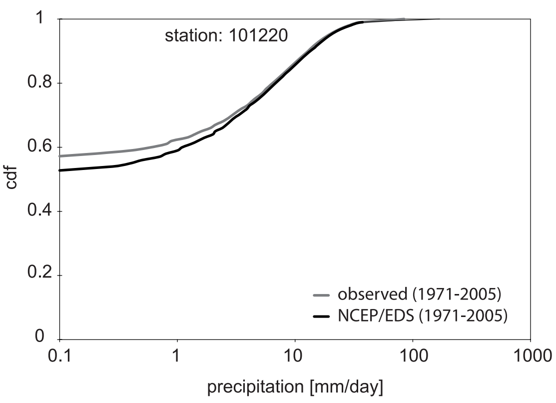

Figure 3: Comparison of observed and downscaled reanalysis data for the period of 1971 to 2005 for one selected precipitation station within the catchment (station 101220: Höfen-Oberhornberg).

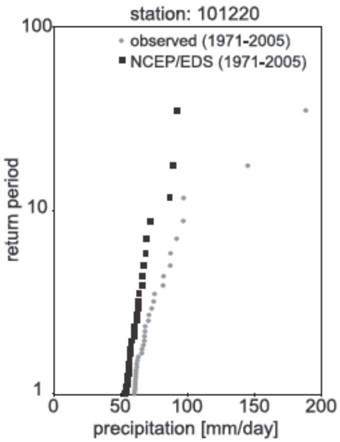

Figure 4: Observed and downscaled heavy precipitation events for the period of 1971 to 2005 (station 101220: Höfen-Oberhornberg).

that the EDS model performs well in reproducing extreme precipitation events. Except for the two most extreme events, only little deviations between observed and simulated precipitation events were detected.

4.2 Performance of the HQsim model

Figure 5 gives an example of the performance of the HQsim model. In general, the simulated runoff series matches observations fairly well. The Nash-Sutcliffe (Nash & Sutcliffe 1970) coefficient for daily runoff simulations is 0.86, based on the period from 1971 to 2005. The model simulates both short flood periods and long-term conditions very well.

4.3 Climate change impacts

The calibrated and validated EDS model was then used to downscale the GCM output. Figure 6 shows that the control runs of the GCMs produce heavy precipitation events similar to observations. Except the most extreme event, which was significantly underestimated, a good agreement between observed and downscaled GCM data was obtained. However, the figure shows that the projections are subjected by large variability. The range between the ensemble members of each GCM provides an estimation of natural variability. Thus, the variability in the projections results from both natural variability and differences between the two climate models. This large uncertainty makes a detection of climate change signals difficult.

When comparing the control simulations (1971 to 2000) with the future scenario (2071 to 2100), only little deviations were found. As can be seen, the uncertainty is by far larger than the weak climate change signal. This is especially true for the most extreme events, for which no clear signals were obtained.

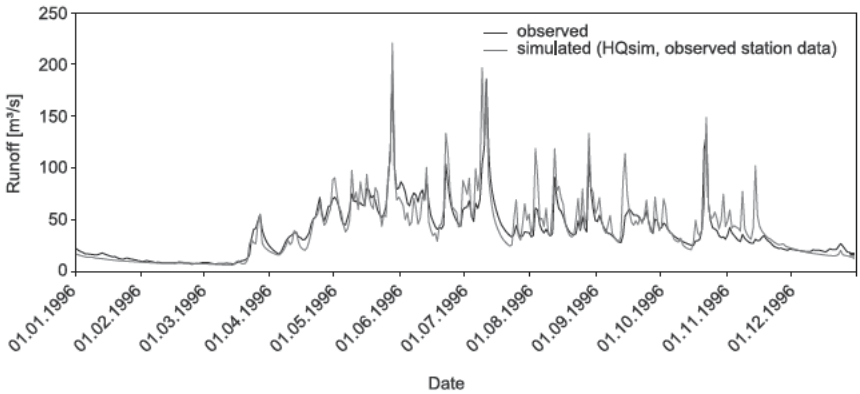

Figure 5: Observed and simulated hydrograph for the year 1996 (water gauge Lechaschau).

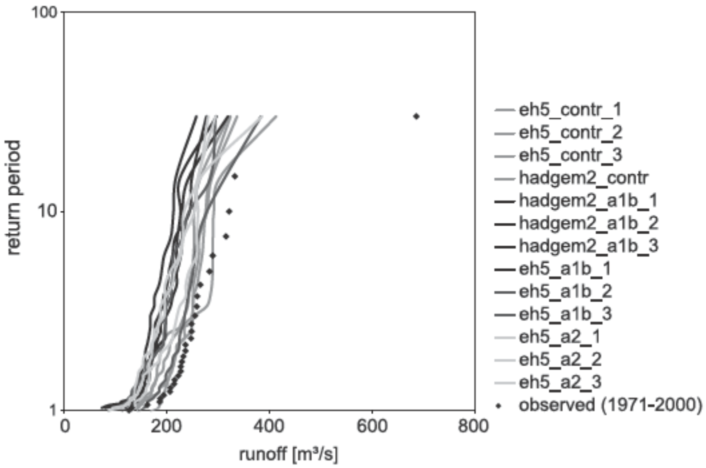

Figure 6: Climate change impacts on heavy precipitation events (control simulations are denoted by contr; the last number indicates the number of the ensemble run).

Finally, the impacts of climate change on flood events are investigated. Figure 7 shows the return period of flood events based on i) the observed time series, ii) the control simulations, and iii) the scenario simulations. It can be seen, that the control simulations matches observations fairly well, except the outlier (flood 1999) which was significantly underestimated. Floods with a return period of up to ~10 years are expected to decrease in the future scenarios. For the most extreme floods, instead, no clear signals were obtained as these projections are highly uncertain.

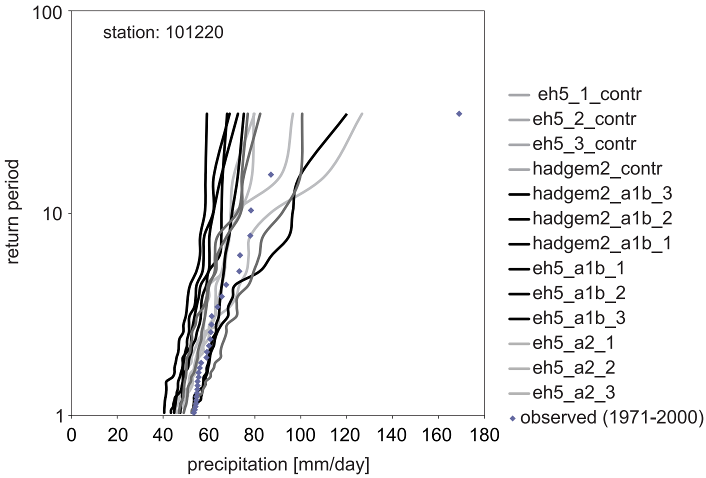

Figure 7: Climate change impacts on flood events (control simulations are denoted by contr; the last number indicates the number of the ensemble run).

5 Conclusion

Global climate change is expected to significantly modify the hydrological cycle in Alpine watersheds. Although a lot of studies have assessed the effects on mean climate variables, only few attempts have been made so far to investigate extreme events.

In this study, the effects of climate change on floods in the Alpine watershed Lech Valley were assessed. The output of two GCMs was statistically downscaled by applying the EDS model. The downscaled data, in turn, was used to force the hydrological model HQsim.

The results of downscaling large-scale atmospheric data from NCEP reanalysis and two GCMs were presented. The EDS model was able to simulate both long-term statistics and single extreme events fairly well. The downscaled GCM output generated heavy precipitation events similar to observations. The results show large uncertainty in the projections of heavy precipitation events. The use of ensemble members and different GCMs were useful to assess this range of uncertainty. For the most extreme precipitation events, this uncertainty is by far larger than the climate change signal.

Floods with a return period up to ~10 years are projected to decrease in the future. Simulations of floods with higher return periods are subjected by large uncertainty and thus, no clear climate signals were obtained. Further investigations will follow to analyse the effects of climate change on floods in more detail.

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