1. Introduction

Physically-oriented modeling of glacio-hydrological processes in the Himalaya is affected by uncertainties due to the complexity of the process spatial variations and low data availability. We use the glacio-hydrological model TOPKAPI-ETH to simulate glacier mass balances and runoff from the Hunza River Basin, Karakorum, Northern Areas of Pakistan. Three key sources of model uncertainty in future runoff projections are compared: modeled parameters, climate projections and natural climate variability. The model performance is discussed by comparing model output to recent observations about glacier mass balances in the area.

2. Project aims

- Identify the sources of uncertainty that affect the reliability of projections about future water availability in high-mountain Asia.
- Assess how these model uncertainties vary in space and in time.
- Identify individual model parameters and variables that mostly affect uncertainty in simulated streamflow.
- Use these insights to answer questions where models should be allocated for observational network design and how field experiments should be designed, in order to efficiently reduce model uncertainty.

3. Study area

- The 5 sub-basins (Gasherbrum, Hunza, Satpara, Herich and Shigar) and 3 sub-regions (Kunjerab, Naltar and Ziarat).
- Both topographically and climatically heterogeneous.
- Land cover: about 60% deserts, 30% alpine tundra and 10% temperate forest.

4. Model and model calibration

TOPKAPI-ETH is a physically-oriented, distributed glacio-hydrological model. It has been successfully applied to simulate streamflow from high-elevation catchments (e.g. Ragettli & Pellicciotti, 2012).

5.1 Parametric uncertainty

1. Generating 20%-parameter uncertainty, we generate 1000 random parameter sets using Sobol's quasi-random number generator.
2. We run TOPKAPI-ETH for 50 years, using the 1000 parameter sets and one time series of stochastically simulated precipitation and temperature.
3. We explore the capacity of individual parameters to explain the modeling uncertainty in simulated runoff using a regional sensitivity analysis approach (Fig. 3).

5.2 Climate model uncertainty

1. Three GCMs are used: CGCM3, CM2 and MIROC3, considering the IAM emissions scenario and monthly outputs.
2. GCM outputs are downscaled to daily temporal resolution at the station locations using a stochastic approach, providing an ensemble of future scenarios.
3. For each GCM we generate 100 stochastic series of precipitation and temperature data of 10-year length each, for each decade until 2050.
4. We run TOPKAPI-ETH for 50 years, using each of the 100 stochastic series of input data and the calibrated parameter set.

5.3 Natural climate variability

The stochastic downsampling approach accounts for the natural variability of climate by preserving the observed statistical properties of precipitation and monthly outputs. In turn, to the effect of the stochastic nature of these variables can be taken into account when simulating the hydrological response of a catchment.

6. Model performance

The model performance is discussed by comparing model outputs to recent observations about glacier mass balances in the area by geodetic mass balance observations, satellite images and direct measurement. In order to take into account the uncertainty due to the lack of adequate locally observed climate data, model performance is analyzed for each sub-region (Fig. 5).

7. Discussion and Conclusions

- The main effects of the three sources of uncertainty (sections 5.1-5.3) on simulated runoff can be comparatively quantified. Fig. 7 shows that the effect of different sources is subject to strong variability in time and in space.
- The effect of ±30% parameter uncertainty often exceeds the effect of other sources of uncertainty. Since there is no evidence that parameters are stable in time and in space, parametric uncertainty has to be taken into account in future projections.
- The effect of the climate model uncertainty increases with time. For recent projections of future runoff and glacier response, GCMs outputs should be used in an ensemble manner.
- The effect of stochasticity in meteorological input cannot be neglected and is especially important for sub-regions with a high proportion of observational data: total precipitation falling as rain (especially Naltar; see Table 1).

- Total mass of glaciers in the Hunza River Basin is more or less stationary during the control period (Table 1). This is in accordance with recent studies (Hewitt & Schoeller al, 2011, Guzzetti et al., 2012, Kuh R al, 2012) and it is an indication that the model climate input might represent adequately the local climate. Likely, precipitation in the Himalayan basin is overestimated.
- The approach does not yet take into account interactions between sources of uncertainty and thus provides only estimates about the main effects of individual sources.
- In order to reduce most efficiently uncertainty in simulated runoff, the temperature distribution should be monitored in the field (Fig. 4). The analysis of information content (IC) is an efficient tool to screen model parameters for model components that are disproportionately affected by parameter uncertainty. The method can also be applied to calculate IC of intermediate model output at grid-cell level, and thus to estimate the distribution of IC both in time and in space.