Hydrological and cryospheric modeling in the Qugaqie catchment on the Tibetan plateau: theoretical approach

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Abstract

More than one-sixth of the global population rely on glacier and snow melt for their water supply. Changes in temperature and precipitation are expected to significantly affect the cryospheric balances and the hydrology of headwater catchments in the Himalayas and on the Tibetan Plateau. Accurate modeling of the hydrological response to climate change in these catchments is complicated due to the large climatic heterogeneity and the lack of data in mountain catchments. In this study we developed a combined cryospheric hydrological model for the glaciated Qugaqie catchment on the Tibetan plateau. The model explicitly simulates glacier movement in combination with major hydrological processes such as evapotranspiration, surface runoff, ablation and groundwater base flow at a high spatial resolution with a daily time step. An innovative two stage calibration procedure is used. First the historical evolution of glaciers is calibrated using the recent location of glacier tongues and secondly the hydrological processes are optimized using discharge observations and mass balance measurements on the glacier. From our preliminary results we conclude that the combination of hydrological processes and glacier movement in a high resolution raster based model has the potential to accurately simulate both glacier evolution and river flow in a high altitude glaciated catchment. More work is required to further optimize model performance and to assess the impact of climate change.

Introduction

More than one-sixth of the global population rely on glacier and snow melt for their water supply (Barnett et al. 2005). Changes in temperature and precipitation are expected to significantly affect the cryospheric balances and the hydrology of headwater catchments in the Himalayas and on the Tibetan Plateau (Cruz et al. 2007; Immerzeel et al. 2009). Accurate modeling of the hydrological response to climate change in these catchments is complicated due to the large climatic heterogeneity and the lack of data in mountain catchments. Traditionally, glacier dynamics are not linked to other hydrological processes such as evapotranspiration, surface runoff and base flow in a single model (Sharp et al. 1998). Most hydrological impact studies on the contrary deploy simple degree day methods (Hock 2005) and assume hypothetical reduction in future glacier areas (Singh & Bengtsson 2004; Hock 2005; Rees & Collins 2006; Immerzeel et al. 2009). Although these studies provide valuable insights into the possible range of future options, they suffer from large uncertainty about the plausibility of the future evolution of snow and ice.

Recently there has been a strong debate about the melt rate of Himalayan and Tibetan glaciers. The claim that all glaciers in the Himalayas could disappear by 2035 in the AR4 of the IPCC (Cruz et al. 2007) has been the source of great controversy and has been admitted to stem from a wrong quotation of grey literature (Schiermeier 2010). Obviously, there is large uncertainty and variability in the retreat rates of glaciers and to settle the debate in a rational manner there is a strong need for reference studies that reliably model the transient evolution of glaciers and hydrology.

In this study we developed a combined cryospheric hydrological model for the glaciated Qugaqie catchment on the Tibetan plateau. The model explicitly simulates glacier movement in combination with major hydrological processes such as evapotranspiration, surface runoff, ablation and groundwater base flow at a high spatial resolution with a daily time step. An innovative two stage calibration procedure is used. First the historical evolution of glaciers is calibrated using the recent location of glacier tongues and secondly the hydrological processes are optimized using discharge observations and mass balance measurements on the glacier.

Study area

The Qugaqie catchment (60.7 km^2) is located on the shores of Lake Nam Co on the northeastern slope of the Nyainqêntanglha mountain range on the southern part of the Tibetan plateau (Figure 1). The elevation in the catchment ranges from 4714 m.a.s.l. near the outlet into the lake to 6082 m.a.s.l. The Zhadang glacier is the largest glacier in the catchment (2.0 km^2) and is located in the southwestern part of the catchment. The Zhadang glacier spans the elevation range 5515-6090 m.a.s.l. and it is a debris free glacier with a fan-shaped terminus (Kang et al., 2009). The climate in the catchment is characterized by monsoon dominated precipitation, with 90% of the annual precipitation concentrated in the months May to September. The average annual precipitation is around 400 mm. Due to the large elevation differences the air temperature is highly variable, but near the glacier terminus (5400 m.a.s.l.) the temperature ranges from -15 °C in winter to 7 °C in summer. The average annual reference evapotranspiration is 500 mm. Hydro-meteorological data for 2007 and 2008 were used to force and calibrate the model. There are two automated weather stations (AWS) available in the catchment (5400 m.a.s.l. and 5800 m.a.s.l) and two hydrological stations 4782 m.a.s.l. and 5365 m.a.s.l.).

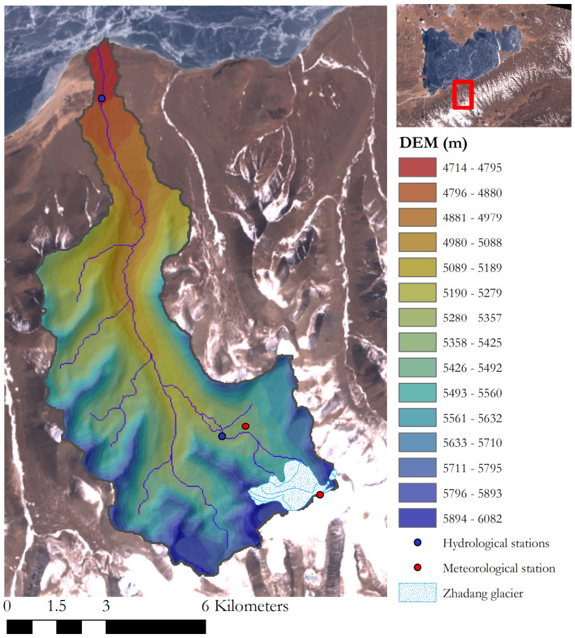

Figure 1 Location of the Qugaqie catchment, digital elevation model, hydrological and meteorological stations and the Zhadang glacier.

Methods and results

The entire model is developed using the PCRaster environment for numerical modeling in environment science (Karssenberg et al. 2001). The model is setup at a spatial resolution of 30 meter (305 x 542 cells). For each cell the following model concepts are simulated at a daily time step.

Glacier bottom motion is modeled as slow, viscous flow using Weertman's sliding law (Weertman 1957). It is assumed that the basal ice is at the melting point, such that a film of water is conceived to exist between the ice and the underlying bedrock. Two mechanisms are considered. The first is slow viscous deformation and the second is regelation. Regelation occurs because as the ice flows over a bedrock obstacle, the higher upstream pressure causes the ice to melt at the interface, because the melting temperature depends on pressure. The water which is thus formed squirts around the rock and correspondently refreezes on the downstream side. Weertman combines these two processes and derives the Weertman sliding law

$$\tau_b \approx v^2 R u^{\frac{2}{n+1}} \qquad \text{(Eq. 1)}$$

here τ_b is the basal shear stress (Pa), v (-) is a measure of the roughness of the bedrock, R is a material roughness coefficient (Pa $s^{1/3}$), u is the sliding speed (m s^{-1}) and n (-) is the creep constant of Glenn's flow law (~3 in most cases) (Glen, 1952). The driving force of glacial movement is gravity and τ_b is defined as

$$\tau_b = \rho g H \sin(\beta) \qquad \text{(Eq. 2)}$$

Where ρ (kg m^{-3}) is the ice density, g is the gravitational acceleration (m s^{-2}), H (m) is the ice thickness and β (°) is the surface slope. By combining Eq. 1 and Eq. 2 under the assumption that glaciers only move when the basal shear stress exceeds the equilibrium shear stress (τ_0 (N m^{-2})) the sliding speed can be derived

$$u^{\frac{2}{n+1}} = \frac{\rho g H \sin(\beta) - \tau_0}{v^2 R} \qquad \text{(Eq. 3)}$$

This equation is used to model glacial movement as function of slope, ice thickness and bedrock properties for each daily time step for each cell. Snow accumulates in the upstream parts of the catchment and each time step the sliding speed is calculated for each cell. Based on the sliding speed the ice is transported down the digital elevation model. As the snow and ice is progressively moving downstream, the temperature increases and snow and ice ablation (Q_a) occurs using a degree day factor (*ddf*). A fraction (α) of the total ablation leaves the catchment as runoff while, the remainder of the ablation ($1-\alpha$) is stored in the glacier/snow pack and is released as base flow. The initial ice depth is calculated based on the known extent of the glaciers derived from remote sensing and the depth is estimated by:

$$H = \frac{\tau_0}{\rho g \sin(\beta)} \qquad \text{(Eq. 4)}$$

The model is forced by daily precipitation and temperature data from the automatic weather stations. Temperature is spatially differentiated using a vertical lapse (λ_t) rate, which is a calibration parameter. For precipitation a vertical lapse rate is applied. Precipitation is partitioned in either snow (S) or rain (P) using these daily fields, the lapsed temperature fields and a threshold temperature (0 °C).

Reference evapotranspiration (ET_0) is calculated based on minimum, maximum and average temperature according to the Hargreaves equation (Hargreaves et al. 1985). By limiting potential evapotranspiration with the actual soil water content actual evapotranspiration is calculated.

On snow and ice free cells surface runoff (Q_s) is calculated according to the curve number method (SCS USDA 1972). The curve number (CN) parameter is a calibration parameter and kept constant for the entire catchment. The sum of P-ET_a-Q_s is then added to the soil water storage and if the maximum soil water storage (θ_m), which is calibrated, is exceeded recharge to the groundwater occurs. Groundwater base flow (Q_b) is modeled similar to the SWAT model (Neitsch et al. 2005) that is based on the work of Smedema & Rycroft (1983) to quantify the non-steady response of groundwater flow to recharge. Finally, for each cell the total runoff (Q) is calculated as the sum of $Q_a+Q_s+Q_b$ and routed to the catchment outlet following a recession equation.

The model is calibrated using the Parameter ESTimation (PEST) software. PEST is able to run a model as many times as it needs to while adjusting its parameters until the discrepancies between selected model outputs and a set of observations is reduced to a minimum. The PEST algorithm method is based on the non-linear parameter estimation theory (Doherty 2005).

The calibration procedure follows a two step approach. First the parameters related to the glacier modeling are manually calibrated as glacier evolution is a much slower process than the hydrological processes such as evapotranspiration, surface runoff, ablation and base flow. Two parameters that influence glacier evolution are calibrated (*R, ddf*). A bias corrected time series of precipitation and temperature from 1957-2002, based on the ERA40 dataset (Uppala et al. 2005), is used to force the model with the aim to reproduce the location of glaciers and permanent snow in the year 2000 based on remote sensing. In the second step PEST is used and hydrological parameters are calibrated by simulating the period 2007-2008 for which both discharge and meteorological measurements are available.

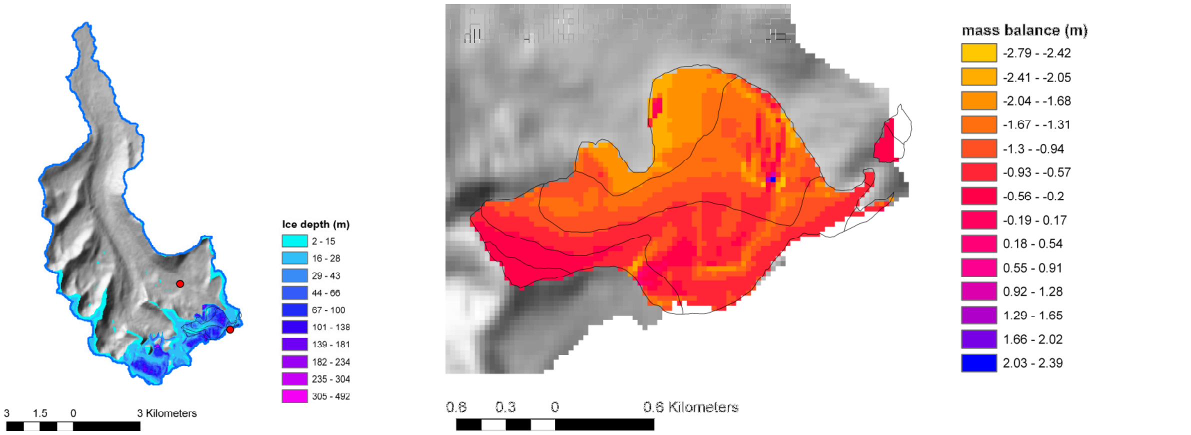

Figure 2 Preliminary calibration results. Simulated ice depth after 1957-2002 simulation (left) and mass balance in 2007 for the Zhadang glacier (right).

Figure 2 shows some initial results. In the left figure the simulated ice depth and extent after the 1957-2002 simulation is shown. The ice extent after 45 years of simulation matches well with the observed outline of the Zhadang glacier. The right figure shows the mass balance in 2007. The average mass balance based on the model results equals -1100 mm w.e. which is in reasonable agreement with observed point values on the glaciers (-783 mm w.e.). From this preliminary analysis we concluded that the combination of hydrological processes and glacier movement in a high resolution raster based model has the potential to accurately simulate both glacier evolution and river flow in a high altitude glaciated catchment. More work is currently undertaken to further optimize model performance and to assess the impact of climate change.

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