A Model Study of Dokriani Glacier, Garhwal Himalaya, India

Argha Banerjee and R. Shankar

Abstract One dimensional flowline models have been widely used to understand the past glaciations of various glaciers, and also to predict their future behaviour. We report results from a simplified flowline model simulation of Dokriani Glacier, Uttarakhand. The measured mass balance reported earlier for the period of 1991–2000, is used as input. The geometry of the glacier is also taken into account in a simple way. We assume that the glacier was close to a steady state around 1962 and that the equilibrium line altitude is moving up with a uniform rate since then. Our simulated glacier length data matches with available length record of this glacier for the period of 1962–2000 quite well. We discuss the model predictions for the future behaviour of this glacier for various possible warming rates.

Keywords Debris covered glacier · Glacier modelling · Flowline model · Glacier geometry · Dokriani glacier

1 Introduction

Understanding the future behaviour of various Himalayan glaciers is crucial because of their importance as hydrological resources. This necessitates modelling studies of these glacier systems. A general glaciological model can be tuned to describe a particular glacier using the measured values of a few basic field observables. This model can then be used to describe the past records, and to predict the future trends taking input from climate model predictions. This framework has been successfully employed to study various Himalayan glaciers, using various types of models (Naito et al. 2000; Adhikari and Huybrechts 2009). In this paper, we have used one dimensional flowline model (Oerlemans 1989, 2001) to study Dokriani glacier, Uttarakhand, India. Dokriani glacier is a partially debris covered glacier. A full

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description of this glacier thus requires a coupled flowline model of debris and ice (Naito et al. 2000). But we take an alternative approach, accounting for the effect of debris through an effective specific mass balance function in a simpler setting of a one dimensional flowline model for the ice flow. We use available geometrical data and mass balance data from the study of Dobhal et al. (2007) to calibrate this model. We assume a uniform warming rate during the period 1962–2002 that coincides with the warming rate observed during 1992–2002. Result from this model successfully describes the length variation of this glacier for the period of 1962–2002 (Dobhal et al. 2007). The model is also used to predict the future behaviour of this glacier under various possible uniform warming rates for the period of 2002–2042.

2 Study Area

The present study has been carried out on Dokriani glacier (30°49′–30°52′ N and 78°47′–78°51′ E) located in the Bhagirathi river basin in Garhwal Himalaya, of Uttarakhand. The glacier was originally mapped in 1962–1963 and was remapped in 1995 by the Survey of India. Dokriani glacier is one of the well-developed, medium sized (7.0 km^2) valley glaciers of Gangotri group of glaciers in the Garhwal Himalaya. It originates at an elevation of 6,000 m amsl and is formed by two cirque glaciers. The glacier follows NNW direction for about 2 km before it turns towards WSW and terminates at an altitude of 3,886 m (Fig. 1). The length

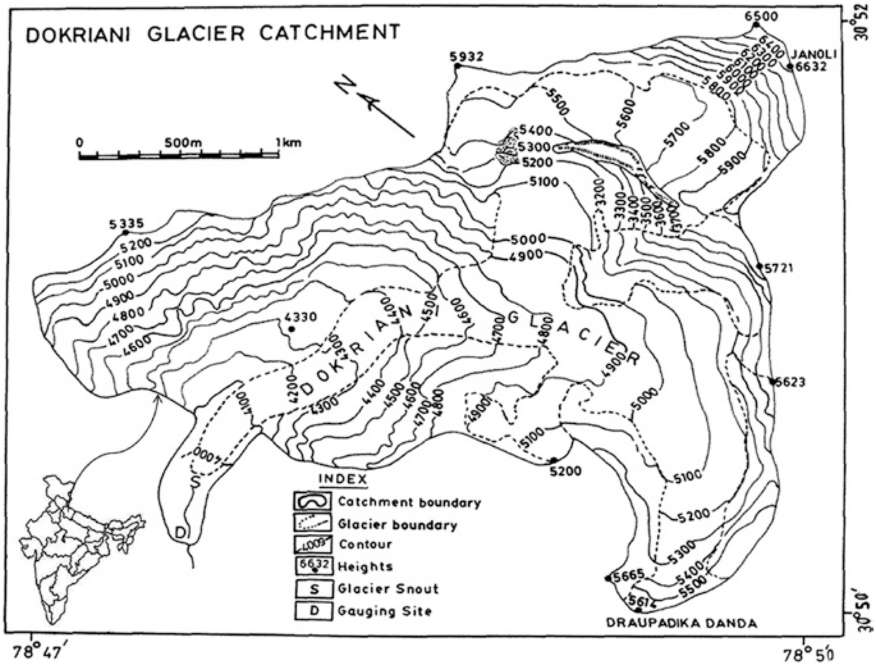


Fig. 1 Location map of Dokriani glacier (After: Thayyen et al. 1999)

of the glacier is 5.5 km with a width varying from 0.08 to 2.5 km. The total catchment area is 15.7 km^2, with the glacier ice covering an area of 7.0 km^2 whereas thickness of glacier ice varies from 25 to 120 m between snout and accumulation zone. Lower reaches of the ablation zone are covered by debris, while the lateral moraines exist all the way along the glacier up to the accumulation zone (Gergan et al. 1999).

3 Methodology

3.1 Flowline Model

One-dimensional flowline model (Oerlemans 1989, 2001) provides a simple way to describe a valley glacier (Oerlemans 1997; Wallinga and Van der Wal 1998; Adhikari and Huybrechts 2009). The model dynamics is determined by local conservation of ice,

$$\partial tH = 1/w\, \partial x(HUw) + B \tag{1}$$

where, H is the thickness of ice, w is the cross-sectional area, U is the cross-section averaged ice velocity along the flowline, B is mass balance function, x is the longitudinal coordinate, and t denotes time. The mean flow velocity can be parameterised by the following relation,

$$U = fd(gH\, \partial x(H + z))^3 H + fs(gH\, \partial x(H + z))^3 / H \tag{2}$$

here fd and fs are two parameters controlling contributions of ice deformation and sliding to the ice ow, and z(x) defines the bedrock geometry. Given z(x) and B(x; t), Eq. (1) provides a complete description of any particular glacier.

3.2 A Simple Model of Dokriani Glacier

Dokriani glacier is a partially debris covered Himalayan valley glacier, situated in the Bhagirathi basin and is about 5.5 km long. Dobhal et al. (2007) have measured its specific mass balance curve as a function of altitude and the snout retreat for the period of 1992–2000. The extent of this glacier in 1962 is also known from maps published by Survey of India. We model this glacier using a simplified mass balance function (Fig. 2a) that approximates the measured specific balance rates for the period 1992–2000 (Fig. 2). Compared to the mass balance curve of a typical debris free glacier, where melting increases monotonically at lower elevations, the mass balance curve of Dokriani glacier nearly saturates to a constant ablation rate in the lower part of the ablation zone. This is a typical feature of the mass balance function of debris covered glaciers where insulation provided by a thick debris layer inhibits melting in the lower ablation zone.

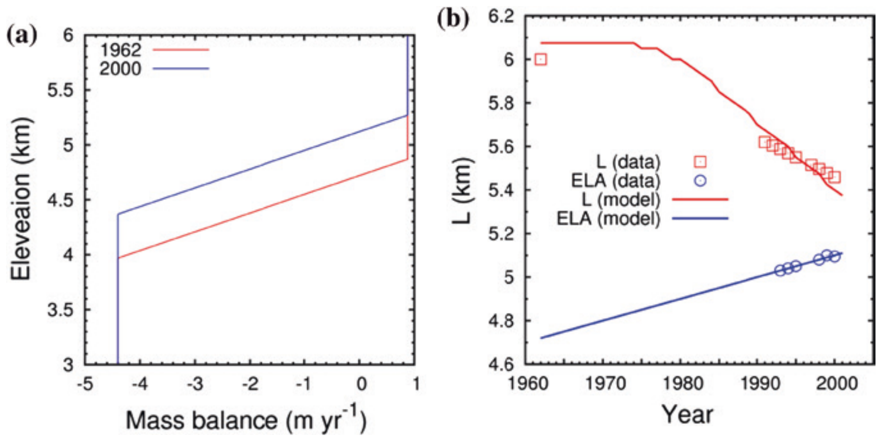
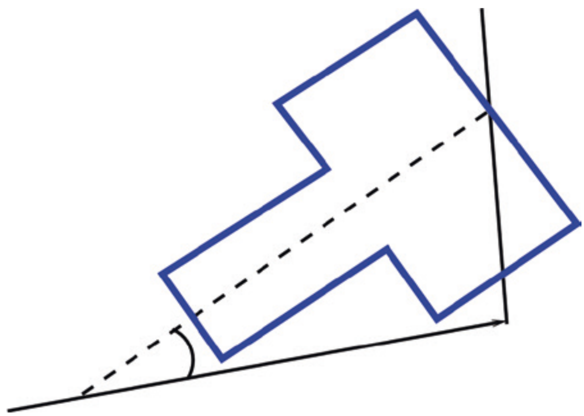


Fig. 2 **a** Approximate mass balance function used to model Dokriani glacier (Based on field data from Dobhal et al. 2007). Between 1962 and 2000, the whole curve is assumed to be moving up at an uniform rate. **b** Comparison of available length data and model result for the period 1962–2000. The assumed variation of ELA and corresponding available data are also shown

Fig. 3 simplified geometry used to model Dokriani glacier



To model the effect of a warming climate, the equilibrium line altitude (ELA) is moved up uniformly with time, keeping the shape of the mass balance curve the same. We assume that the glacier was in a steady state around 1962 with ELA at 4,870 m and that the ELA has been moving up with a constant rate of 10 m/year. These values are obtained from the best fit linear extrapolation of the ELA data (Dobhal et al. 2007) for the period of 1992–2000. A uniform bedrock slope with 0.4 is used and the area above the elevation of 5,000 m is taken to be 3.3 times larger than that below this elevation. This simplified geometry is shown in Fig. 3.

We have used fd and fs values that are smaller than those used by Oerlemans (2001) by a factor of 1/4. This has been done to match the observed average ice thickness values of 50 m (Gergan et al. 1999) for this glacier following Adhikari and Huybrechts (2009). Also note that we follow the numerical scheme described by Oerlemans (2001) to solve the flowline equation and our temporal and spatial discretization steps are 0.00025 year and 25 m respectively.

4 Model Results

4.1 The Past Data

As shown in Fig. 2b, our simple model does very well in reproducing the length variation data for the period of 1962–2002. This shows that despite our simplifying assumptions the model does capture the behaviour of the real glacier reasonably well. One interesting feature of the modelled response is that while the warming has been assumed to start in 1962 in our model, the glacier length has remained remarkably steady for a period of about 15 years after that subsequently the glacier has undergone steady retreat. This surprising behaviour is related to the presence of debris cover in the lower ablation zone of this glacier. Here, the insulating effects of thickening debris layer causes ablation to saturate to a minimum value, which otherwise would have increased towards lower elevations. As a result, the initial response of a debris covered glacier to warming is thinning of the glacier while the length remains steady. After this initial delay the length also starts shrinking.

4.2 Future Trends

Using the same model we have explored the future behaviour of this glacier under various possible warming rates as shown in Fig. 4. As expected higher warming rates leads to faster retreat and smaller warming rates slows the rate of length retreat. Notably, even as the warming rate is assumed to change after 2002, it takes about 20 years for this change to affect the steady retreat rate. This is true even in the case where temperature becomes steady after 2002. This, again, can be related to the presence of the debris cover which modifies the nature of the response properties of the glaciers because of its insulating effects.

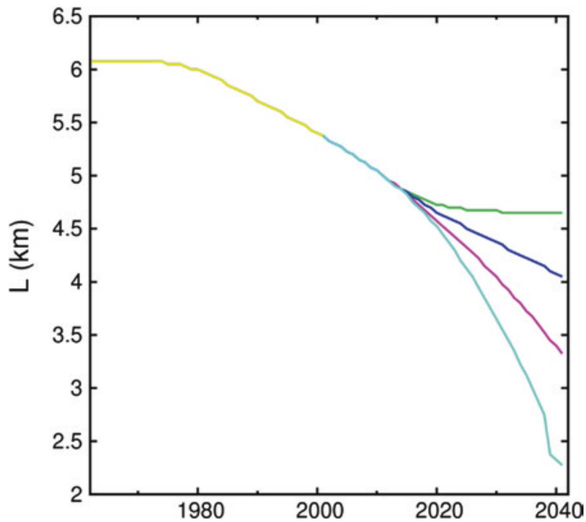


Fig. 4 Model prediction for retreat of Dokriani glacier for an assumed ELA movement rate of 0 m/year (*green*), 5 m/year (*dark blue*), 10 m/year (*purple*) and 15 m/year (*sky blue*) during the period of 2002–2042

5 Conclusion

We have performed a flowline line model simulation of Dokriani glacier using a simpled geometry and an eective mass balance function. Our model results describe the retreat data for this glacier for the period of 1962–2002 reasonably well. We also simulate the future behaviour of this glacier under various climatic conditions for the period of 2002–2042. Interestingly the response of this glacier to change in prevailing steady climatic condition is characterised by a time scale of about 15 years during which the length remains unaffected by the change. This is typical of a debris covered glacier where initial climatic response is through thinning and the shrinking of the glacier length starts after a characteristic delay.

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