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A model study of the energy and mass balance of Chhota Shigri glacier in the Western Himalaya, India

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Abstract

The impact of climate change on Himalaya mountain glaciers is increasingly subject of public and scientific debate. However, observational data are sparse and important knowledge gaps remain in the understanding of what drives changes in these glaciers' mass balances. The present study investigates the glacier regime on Chhota Shigri, a benchmark glacier for the observation of climate change in the monsoon-arid transition zone of Western Himalaya. Results of an energy-balance model driven by reanalysis data and the observed mass balances from three years on 50 m altitude intervals across the glacier display a correlation coefficient of 0.974. Contrary to prior assumptions, monsoon precipitation accounts for a quarter to a third of total accumulation. It has an additional importance because it lowers the surface albedo during the ablation season. Results confirm radiation as the main energy source for melt on Himalaya glaciers. Latent heat flux acts as an important energy sink in the pre-monsoon season. Mass balance is most sensitive to changes in atmospheric humidity, changing by 900 mm w.e. per 10% change in humidity. Temperature sensitivity is 220 mm w.e. K^{-1}. Model results using 21st century anomalies from a regional climate model based on the SRES A2 scenario suggest that a monsoon increase might offset the effect of warming.

1 Introduction

1.1 Himalaya mountain glaciers: current knowledge and open questions

The aggregate mass balance of Himalaya mountain glaciers has been negative during the last decades (Ren et al., 2006) with some exceptions in the higher Karakoram mountain range (Hewitt, 2005). This conforms to a global trend, in which Himalaya glaciers are in the medium range of glacier wastage. Despite the growing interest in Himalaya glaciers observations of glacier mass balance in the region are relatively

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sparse owing to the difficulties of field work in remote and politically unstable areas (IGOS, 2007; Inman, 2010). Remote sensing estimates have confirmed overall negative mass balances for the Western Himalaya and a recent acceleration of glacier wastage in the region (Berthier et al., 2007).

1.2 Global and regional climate change

In the Northwestern Himalaya, mean temperatures have risen faster than the global average. Bhutiyani et al. (2007) observe a rise of 1.6 °C between 1901 and 2002, Shekhar et al. (2010) report a 2 °C rise in mean temperature in Western Himalaya between 1984/85 and 2007/08, thus confirming the accelerated temperature rise in the late 20th century observed by Bhutiyani et al. (2007). Shekar et al. also report a decrease in winter snowfall by 50% and a decrease in cloud cover by 10% over the same period. Monsoon precipitation in the Himalaya has decreased over the last century (Bhutiyani et al., 2010).

While general circulation models unanimously suggest further 21st century warming, estimates of future monsoon precipitation differ considerably even for the same applied forcing. Using the Hadley center regional climate model PRECIS forced according to the IPCC SRES scenarios A2 and B2, Kumar et al. (2006) calculate a strong rise in monsoon precipitation and no changes in winter precipitation for Himachal Pradesh towards the end of the 21st century.

Conflicting results obtained by Ashfaq et al. (2009) using a regional climate model with higher horizontal resolution show a delayed monsoon onset and strong overall reductions of monsoon precipitation for the A2 scenario. While there is agreement on a projected future temperature rise, the sign or even magnitude of change for the Indian summer monsoon is thus still unclear and both scenarios should be considered for impact analysis.

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1.3 Characteristics of Western Himalaya glaciers

Since the Himalaya presents marked seasonal temperature changes, glaciers in the region are summer ablation glaciers. While glaciers on the Tibetan plateau and in Nepal receive almost all precipitation from the summer monsoon and are thus summer-accumulation glaciers, Chhota Shigri and other glaciers in Western Himalaya receive precipitation both from the summer monsoon and from mid-latitude westerlies in winter (Shekhar et al., 2010).

Thayyen and Gergan (2010) distinguish between "Alpine catchments", "Himalayan catchments", and a cold-arid regime in Northwestern Himalaya. The Chenab basin, where Chhota Shigri is located, is an "Alpine catchment" dominated by winter precipitation, while monsoon precipitation becomes predominant in the "Himalayan catchments" located further south-east.

1.3.1 Energy and mass balance

While most of the available literature focuses on mid- and high-latitude glaciers, energy balance of tropical glaciers has been studied far less extensively and the ablation regime of subtropical glaciers has received even fewer attention.

Energy balance has been studied on tropical glaciers in the Andes (Sicart et al., 2005) and Africa (Mölg and Hardy, 2004). In both cases, solar and longwave radiation have been found to be important components of the energy fluxes both in terms of their magnitude and control over seasonal variations. While variations in ablation on mid- and high-latitude mountain glaciers often correlate with respective changes of air temperatures as discussed by Ohmura (2001), low-latitude glaciers are often more vulnerable to changes in precipitation patterns affecting surface albedo (e.g. by enhanced or reduced snowfall events in the ablation season) or changes in atmospheric moisture (Kaser et al., 2005).

Energy balance studies carried out on glaciers on the Tibetan Plateau and in Nepal suggest that these glaciers in the subtropical Himalaya are sensitive to both changes

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in air temperature and the radiation balance, the latter being caused by changes in surface albedo or cloud cover (Bhakta Kayastha et al., 1999). These glaciers are classed as belonging to the "summer-accumulation type" (Ageta and Higuchi, 1984), since they receive accumulation almost exclusively in the monsoon season (June–September).

Similar studies on glaciers on the northern slope of the Himalayas, where precipitation is much lower due to the shading effect of the mountain range, have also pointed towards the importance of shortwave radiation as energy source and evaporation as energy sink that limits snow and ice melt (Aizen et al., 2002). Seasonal cloud cover also plays an important role in limiting radiation for those glaciers.

Existing studies on the climate sensitivity of Western Himalayan glaciers are either qualitative (Chaujar, 2009) or only explore statistical connections between meteorological variables and glacier response (Koul and Ganjoo, 2009). A deeper analysis of the energy balance yet remains to be undertaken for this region. The local glacier regime is likely to be shaped by the specific conditions of the monsoon-arid transition zone and may thus be quite different from the above-mentioned examples.

1.4 Chhota Shigri glacier

Chhota Shigri is a valley glacier located in the Indian state Himachal Pradesh at 32.2° N 77.5° E (see Fig. 1). It has a surface of 15.7 km^2 and extends over a length of 9 km from an altitude of 4050 to 6263 m a.s.l. (Wagnon et al., 2007). A map of the glacier is shown in Fig. 2. Chhota Shigri discharges into Chandra river, which forms part of the Indus basin.

Indian and French researchers have initiated an ongoing monitoring of mass balance on the glacier that has been proclaimed a benchmark glacier for the observation of climate change (Wagnon et al., 2007). The monitoring programme has recently been extended to include meteorological observations, but the data have not yet been published, nor are they otherwise accessible (P.Wagnon, pers. comm.).

Wagnon et al. (2007) observe an average mass balance gradient of 0.69 m w.e. per 100 m, which is similar to glaciers in the European Alps but much less than on most tropical glaciers, which display mass balance gradients of up to 2 m w.e. per 100 m (Kaser, 2001).

Summer mass balance measurements confirm a pronounced ablation season between July and September, when most of the annual ablation takes place. Wagnon et. al suggest that the glacier receives most of its accumulation in winter, but might also gain some snowfall from the summer monsoon precipitation at higher altitudes.

The ongoing observation programme and the relatively large size and altitude extent make Chhota Shrigri a suitable object for the present study.

2 Model description

2.1 Surface energy balance

The basic equation for the surface energy balance as given by Greuell and Genthon (2003) is

$$Q_0 = S_{\mathrm{in}} \cdot (1-\alpha) + Lw_{\mathrm{in}} - Lw_{\mathrm{out}} + Q_{\mathrm{H}} + Q_{\mathrm{L}} + Q_{\mathrm{R}}, \tag{1}$$

where Q_0 is the resulting heat flux to the glacier surface, S_{in} incoming shortwave radiation, α the albedo of snow or ice, Lw_{in} and Lw_{out} incoming and outgoing shortwave radiation, Q_{H} and Q_{L} sensible and latent heat flux and Q_{R} the heat flux from rain. As suggested almost unanimously by the literature, the latter is assumed to be negligible.

Since no on-site measurements were available for the present study, incoming shortwave radiation had to be computed from other meteorological variables, following Greuell and Genthon (2003). The variation of the snow surface albedo is computed in the model by means of the parametrisation based on accumulated daily maximum temperatures since the last snowfall suggested by Brock et al. (2000). The albedo effect of a thin snow layer superimposed on ice is taken into account using the parametrisation developed by Bhakta Kayastha et al. (1999) from studies of a Tibetan glacier.

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The longwave radiation received by the glacier surface both from surrounding terrain and the atmosphere is computed depending on air temperature, cloud cover and atmospheric water vapour (Plüss and Ohmura, 1997). Outgoing longwave radiation is computed following the Stefan-Boltzmann-law of blackbody radiation.

Given the high elevation of Chhota Shigri, glacier ice and snowpack are likely to be too cold to apply the zero-degree-assumption. Surface temperatures are therefore computed from heat fluxes as described in the following section.

The sensible and latent heat fluxes are computed from air temperature and wind speed 2 m above the ground using the corresponding bulk equations given by Greuell and Genthon (2003):

$$Q_\mathrm{H} = \frac{\rho_\mathrm{air} C_{p\_\mathrm{air}} k^2 u (T_\mathrm{air} - T_\mathrm{surf})}{\left(\ln\frac{z}{z_0} + \frac{\alpha_\mathrm{m} z}{L_\mathrm{ob}}\right)\left(\ln\frac{z}{z_T} + \frac{\alpha_\mathrm{h} z}{L_\mathrm{ob}}\right)} \qquad (2)$$

and

$$Q_\mathrm{L} = \frac{\rho_\mathrm{air} L_\mathrm{s} k^2 u (q - q_\mathrm{s})}{\left(\ln\frac{z}{z_0} + \frac{\alpha_\mathrm{m} z}{L_\mathrm{ob}}\right)\left(\ln\frac{z}{z_q} + \frac{\alpha_\mathrm{h} z}{L_\mathrm{ob}}\right)}, \qquad (3)$$

where k is Karman's constant and T_air and q are air temperature and specific humidity at screen height z (2 m). α is an empirical constant usually taken to be 5 (Garratt, 1992). z_0, z_T and z_q are the surface roughness lengths for wind speed, temperature and humidity. C_{p_air} is the specific heat of air and L_s the latent heat of sublimation. T_surf and q_s are surface temperature and surface specific humidity.

2.2 Subsurface fluxes and temperatures

The one-dimensional subsurface model includes a representation of the snowpack and the underlying glacier ice. It models the diffusion of heat through both materials, with a no-flux condition at the lower boundary and the computed surface energy balance as boundary condition at the interface between the glacier and the atmosphere.

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When the temperature of snow or ice in the model exceeds the melting point, the excess heat is transferred to melt. Meltwater is retained in the snowpack by capillary forces. When a layer of snow is saturated with water or entirely melts, water percolates down into the next layer. Meltwater refreezes in snow layers that are colder than 0 °C. If meltwater reaches the ice surface or if there is no snowpack on the glacier and the ice is melting, it runs off.

Subsurface model structure

1. Surface fluxes are computed from last known surface temperatures
2. Snow and ice temperatures from diffusion processes are calculated
3. Melting and refreezing are derived from new temperatures and snow water content
4. Surface fluxes are recalculated using new surface temperatures
5. Steps 2–4 are repeated if necessary
6. Excess meltwater percolates down the snowpack
7. A new snow depth is computed and the grid adapted if necessary

Temperature changes are modelled using an implicit Crank-Nicolson scheme which has the advantages of being unconditionally stable and converging relatively quickly (Crank et al., 1947).

Capillary forces are assumed to be able to retain water in snow up to a volumetric content of 0.08 (Kattelmann, 1986). If this fraction is exceeded at the end of a timestep, the excess water is passed on to the next layer, or runs off at the snow-ice interface.

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2.3 Initial conditions and forcing

At the beginning of each year, snow and ice temperatures are set to the average air temperature of the corresponding altitude. Meteorological conditions are adapted from the IMD or NCEP datasets:

Relative humidity, cloud cover and wind are assumed to be constant. Pressure and temperature are adapted to the altitude. While a constant lapse rate is used to compute the temperature difference between the glacier and the respective data source (i.e. weather station or reanalysis data grid point), glacier wind is taken into account when computing temperatures on the glacier. Since field measurements of the stability of glacier winds or the thickness of the flow layer are unavailable, the glacier wind parametrisation developed by Greuell and Boehm (1998) on Pasterze glacier in Austria is adapted.

While air temperature over Pasterze was above the melting point during the entire observation period, air temperature over Chhota Shigri, especially at high elevations, can also be negative during the summer. It is thus unlikely that glacier wind will be a predominant feature over the whole glacier and ablation season. This is accounted for in the model by calculating all temperatures with a linear lapse rate in the first place and then replacing positive temperatures with the values calculated from an adapted glacier wind scheme.

Precipitation and cloud cover from the NCEP dataset are taken from the neighbouring grid point that provides the best match with maximum accumulation on the highest part of the glacier, where the annual mass balance is essentially equal to annual accumulation. Precipitation is tuned to obtain an agreement between modelled and measured mass balance at that point, but no further altitude-dependent tuning is carried out. Accumulation is likely to vary due to the terrain influence on precipitation and redistribution of snow through avalanches. However, in the absence of any field measurements such as seasonal mass balance data, further precipitation tuning would risk to mask weaknesses in the ablation model.

2.4 Grid resolutions and timesteps

The standard grid setting in this study was to compute shortwave and longwave radiation for each gridpoint of the DEM (about 30 m horizontal resolution) and average the results for all gridpoints within a 50 m altitude range. Extrapolation of meteorological data and the calculation of surface fluxes and subsurface processes are performed for one gridpoint in each of those altitude intervals. The standard depth of snow and ice layers is 0.1 m, ice temperatures are calculated to a depth of 5 m.

Solar radiation is computed every hour and averaged over six hours (reanalysis data) or one day (IMD) to match the timestep of the available meteorological data. Surface temperatures and subsurfaces fluxes, melt, runoff and refreezing are computed using a standard timestep of five minutes. The timestep is reduced if the iteration scheme does not converge.

3 Data used in the model

Input data used for running the model include meteorological data from a weather station in Manali provided by the Indian Meteorological Department (IMD), from the NCEP/NCAR reanalysis dataset (Kalnay et al., 1996) and model results from the regional climate model PRECIS (Kumar et al., 2006) as well as digital elevation model (DEM) data from the ASTER DEM. Meteorological measurements on the glacier have been taken recently but were not available for this study (P. Wagnon, pers. comm.).

3.1 Meteorological data

The IMD provided measurements of daily minimum and maximum temperatures, precipitation, cloud cover in different cloud categories (low, medium and high clouds) and relative humidity. Those measurements were taken at a weather station in Manali, located at 32.27° N 77.17° E at an elevation of 1950 m (see Fig. 1).

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NCEP/NCAR surface data include temperature, relative humidity, surface pressure and wind speed. These were taken from the nearest available gridpoint at 32.5° N 77.5° E. The elevation of this gridpoint in the model is 3953 m a.s.l. Precipitation and cloud cover are provided on a slightly different grid in the NCEP/NCAR datasets with closest gridpoints being located at 31.42/33.33° N and 76.88/77.75° E.

Output of the regional climate model PRECIS was provided in daily time series of temperature, precipitation, sea level pressure, relative humidity, cloud cover and wind speed. Time series covered the years 1961 to 1990 for the baseline scenario and 2071 to 2100 for the A2 scenario. The corresponding grid point in PRECIS is located at 77.57° E and 32.04° N at an altitude of 4254 m. Daily anomalies for each of the parameters were computed based on the mean values for each scenario and subsequently applied to the reanalysis data.

3.2 Terrain and mass balance data

The ASTER DEM is a digital elevation model covering the entire globe from 83° N to 83° S at a horizontal resolution of one arc-second (about 30 m) and an estimated vertical accuracy of 20 m at a 95% condence interval (NASA, 2006). The glacier extent was determined manually from a satellite photo published by Wagnon et al. (2007). Mass balance data for model tuning and the assessment of model performance were taken from the same publication and WGMS (2005).

4 Results and analysis

In the following section, modelled and observed mass balances are compared and the sensitivity of the model to changes in different parameters is discussed. Finally, results of the standard and climate change experiments are presented.

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4.1 Model performance

The good agreement between modelled and measured mass balances over a broad range of values (see Fig. 3) with a correlation coefficient of 0.974 for the debris-free part of the glacier suggests that the model correctly captures the sensitivity of the glacier to changes in the meteorological forcings.

4.2 Model sensitivity

The subsurface model and the glacier wind parametrisation are essential to obtain results close to the measured mass balance. Model runs employing the zero-degree-assumption (the surface is at the melting point, all heat flux towards the glacier translates into melt) or a linear lapse rate lead to a strong overestimation of ablation.

Model results are reasonably robust to surface roughness variations within the range of published observations. The lack of observational surface roughness data is therefore no mayor obstacle to the modelling project.

The model is thus most sensitive to the way forcings, especially air temperature, are being calculated for different points on the glacier. The second largest source of uncertainty is surface roughness, followed by the albedo of ice. Boundary and initial conditions or the threshold temperature for snowfall hardly affect the results.

The model results inspire enough confidence to use the model both for an analysis of the current glacier regime and its climate sensitivity.

4.3 Glacier regime

4.3.1 Accumulation

Wagnon et al. (2007) suggest that Chhota Shigri is a winter accumulation glacier, where accumulation and ablation happen in clearly distinguished seasons. They do, however, point out the possible role of some summer accumulation on the higher parts of the glacier. While the bulk of accumulation indeed occurs in winter, often concentrated in

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short, heavy snowfall events probably associated with westerly disturbances (Shekhar et al., 2010), Fig. 4 also shows an important role of monsoon accumulation (June–August).

Apart from its positive contribution to the mass balance, summer snowfall increases the surface albedo. When all accumulation is set to occur in winter, the glacier-wide specific mass balance is reduced by up to 1000 mm w.e. per year. The effect of summer accumulation is especially remarkable around the equilibrium line, which is shifted upwards by several hundred meters in the winter accumulation experiment. Ablation of up to 2000 mm w.e. occurs on parts of the glacier that virtually do not experience melt in the standard model run.

While winter accumulation accounts for the bigger part of the annual accumulation, summer accumulation does have a share of 25–30%. Its effect on mass balances is higher than that of winter accumulation because it increases the surface albedo during the ablation season.

4.3.2 Ablation

The beginning of the ablation period occurs gradually from the lower towards the upper end of the glacier, while the ablation season ends at all altitudes simultaneously (see Fig. 5). Ablation begins before the onset of monsoon precipitation (cf. Fig. 4) and is slowed down when the first summer snow falls on the glacier. On the lowest parts of the glacier (not shown), ablation begins in late April. This results in an ablation season of more than four months (May–August), the last three thereof being the monsoon season, where accumulation and melt occur simultaneously.

Ablation displays a marked diurnal cycle, but can also happen at night in the core ablation period.

With two distinct accumulation seasons (winter and monsoon accumulation) and an ablation season that partly falls into the second accumulation period, Chhota Shigri does not fall into any of the categories that are commonly used to classify glaciers according to the seasonality of ablation and accumulation.

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4.3.3 Internal accumulation

Internal accumulation is the refreezing of meltwater in a cold snowpack. Model results suggest that less than 10% of all meltwater refreezes in the ablation zone of Chhota Shigri. Around the equilibrium line, almost half of the meltwater refreezes within the snowpack. Around 5500 m, all meltwater refreezes in the snowpack and no runoff occurs. Averaged over the whole glacier, refreezing corresponds to 5–10% of all meltwater for the modelled years. A maximum of refreezing above the equilibrium line has also been observed on polar and mid-latitude glaciers (Braithwaite et al., 1994).

Other than for the overall mass balances, no data such as seasonal snow depth or snow and ice temperature profiles were available to verify the accuracy of specific results of the modelled subsurface processes. The above results should thus be interpreted with caution. However, since the subsurface model makes it possible to obtain accurate overall mass balances, there is reason for some confidence in the results.

4.3.4 Energy balance components

The modelling results confirm that radiation is the biggest contributor to melt, with shortwave radiation accounting for more than half of the total energy flux in melt periods. Net longwave radiation (the difference between received and emitted longwave radiation) accounts for a slightly smaller part. Sensible heat flux ranges at about 20 to 25% of the total flux, whereas latent heat flux is mostly negative and reduces the energy flux towards the glacier by about 20%. An overview of heat fluxes averaged over a year and the entire glacier area is given in Table 1, whereas the average seasonal cycle of energy fluxes in the ablation zone is shown in Fig. 6.

4.3.5 Shortwave radiation

Regarding the seasonal cycle, shortwave radiation is remarkably reduced by the enhanced cloud cover in the monsoon season (June–August) compared to the potential

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clear-sky radiation for this period of the year. Figure 7 shows that the beginning of the melt period (around day 250) happens mostly under clear-sky conditions, whereas cloud cover reduces the incoming shortwave radiation by about 50 W m^{-2} during most of the monsoon season. Potential clear-sky radiation reaches its maximum just at the beginning of the monsoon season. Cloud cover is thus a further way how the summer monsoon affects mass balance and asserts control over the glacier regime in North-western Himalaya. Even though clouds also enhance incoming longwave radiation, under the present climate the seasonal variation of shortwave radiation is clearly higher than that of net longwave radiation (see Fig. 6).

In the seasonal cycle, repeated snowfall events during the monsoon season increase the surface albedo of the glacier also at lower altitudes: The high albedo of snow persists longer at higher altitudes and throughout the whole ablation season above 5550 m in the accumulation zone. The surface albedo declines to the albedo of bare ice earlier at 4550 than at 5050 m, but repeatedly rises to higher values during the ablation season for both altitudes. It should be noted that these results are not constrained by albedo observations. They do, however, gain some credibility since the albedo parametrisation scheme leads to the previously described agreement of modelled and measured mass balances. Ignoring summer snowfall effects on the surface albedo leads to a much lower correlation.

Important variations of the surface albedo over time due to melt and summer snowfall have also been observed on mid-latitude glaciers (Strasser et al., 2004).

4.3.6 Longwave radiation

Seasonal variations in net longwave radiation are relatively low, with a maximum value being reached during the monsoon season, when relatively high air temperatures coincide with high humidities and cloud covers. Even though the annual average given in Table 1 is higher than that of shortwave radiation, its actual contribution to melt energy is smaller, since melt mainly occurs in times of high incoming shortwave radiation.

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With longwave-radiation being higher in zones with a high sky-view factor, the observed profile of incoming longwave radiation seems to be in conflict with observations by Strasser et al. (2004) in the Alps, where longwave radiation from slopes is higher than from the atmosphere. Since no field measurements of longwave radiation on Chhota Shigri are available to support modelling results and the profile of modelled longwave radiation is rather irregular, these results should be treated with caution. A stronger atmospheric source for longwave radiation compared to the Alps would, however, be explainable from the higher humidity in the warm monsoon season.

4.3.7 Latent heat flux

Latent heat flux on aggregate makes a negative contribution to the energy balance, which means that evaporation at low humidity values is a heat sink limiting ablation. This heat sink becomes most important in the pre-monsoon season, when air temperatures have risen and solar radiation is high but humidity is low. The latent heat flux then goes to almost zero or even takes positive values in the monsoon season, when condensation from the very moist air may become a heat source.

Heat loss through evaporation is lower at lower altitudes, especially during ablation periods, when its average contribution to the energy balance is zero, while it averages about $-100\,\mathrm{W\,m^{-2}}$ around 5000 m, both over the whole year and during the ablation season. This is in stark contrast with the energy budget of mid-latitude glaciers, where latent heat flux is negligible (Vincent, 2002), whereas a strong negative latent heat flux has also been reported from tropical glaciers in the Andes for the dry season (Vuille et al., 2008).

While the albedo effect of summer accumulation and the enhanced cloud cover are mechanisms by which the monsoon limits melt on Chhota Shigri, the advection of moist air masses that limits the latent heat flux or even makes it positive towards the glacier surface contributes to ablation. This opposed effect will probably reduce the glacier's vulnerability to possible monsoon reductions, since increased radiation and lower albedos will be counteracted by the stronger heat loss through evaporation.

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Energy and mass balance model of a Himalaya glacier

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4.4 Mass balance sensitivity to climate change

The results of various experiments to explore the sensitivity of the mass balance to changes in different meteorological parameters will be presented and discussed in the following section. Table 2 gives on overview of the conducted sensitivity experiments. All experiments are based on the reanalysis data for 2002–2006. Unless stated otherwise, mass balance changes refer to the average of the specific annual mass balance of the glacier for those years.

4.4.1 Atmospheric temperatures

As is to be expected, the mass balance of Chhota Shigri depends on atmospheric temperatures. The glacier-wide annual mass balance is reduced by 220 mm w.e. per degree of atmospheric warming for a range of –2 to +6 K compared to present temperatures. The effect of warming on mass balances on different parts of the glacier is non-linear for individual years, however, the average trend based on four years of glacier-wide mass balances is linear.

Oerlemans and Fortuin (1992) report a range of mass balance sensitivities from 120 to 1150 mm K^{-1} for a sample of glaciers representative of global conditions. The results obtained in this study would place Chhota Shigri within the lower part of that range, which agrees with their observation that mass-balance sensitivity correlates with annual precipitation. Chhota Shigri lies in a relatively dry climate and would thus be expected to display a relatively low mass balance sensitivity to warming.

Various studies on the climate sensitivity of glaciers in the European Alps agree that mass balance sensitivity is higher at low elevations (Vincent, 2002; Gerbaux et al., 2005). In the present study, highest overall changes in mass balances were also computed for the lowest part of the glacier, where debris cover makes those results unrealistic. In the absence of debris cover, Chhota Shigri would present a similar profile of high mass balance sensitivities on the lower part and lower sensitivities at higher altitudes. Debris cover of glacier tongues is widespread on Himalaya glaciers (Nicholson, 2004) and it remains an important task to study its effects on climate sensitivity.

For a warming of 6 °C, which is on the upper end of 21st century projections for India from GCM results, strong melt and negative mass balances occur at altitudes above 5500 m. The accumulation area is reduced to the small steep slopes on the highest part of the glacier and most of the present accumulation area is below the equilibrium line.

4.4.2 Relative humidity

Model results suggest that the mass balance of Chhota Shigri is most sensitive to changes in relative humidity, with a mass balance reduction of 900 mm w.e. per 10% increase in relative humidity. This could stabilise the glacier in the case of a future monsoon reduction, which would also cause a decrease in humidity.

A strong mass balance sensitivity to changes in atmospheric moisture is typical of tropical glaciers (Vuille et al., 2008). The moisture sensitivity of glaciers in the European Alps is only a fraction of the value found on Chhota Shigri (Gerbaux et al., 2005).

4.4.3 Cloud cover

The effect of reduced cloud cover is smaller than that of temperature, but still distinguishable: A ten percent reduction in cloud cover causes a reduction of the annual glacier-wide mass balance by 80 mm. The absolute change in mass balances is stronger on the lower part of the glacier, whereas the accumulation area is not affected.

A reduction by ten percent corresponds to the observations of climate change in the region reported by Shekhar et al. (2010). Since this figure comes without any seasonality analysis, the change has been applied equally through the whole year. If the actual change occurred predominantly in the monsoon season, the effect on glacier mass balances would be stronger. Reduced cloud-cover in winter would not affect mass balances at all.

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4.4.4 Snowfall

On average, a ten percent change in annual snowfall corresponds to a 140 mm change in the annual glacier-wide mass balance. The loss in accumulation is increased by about 30% due to increased ablation at lower albedos. Reduced snowfall has its strongest effects around the equilibrium line.

The effect of precipitation changes on the mass balance is much stronger than found by Jiang et al. (2010) for a modelling study of a glacier on the Tibetan plateau. Jiang et al. only modelled a time series from July to October, which makes comparisons with their results somewhat difficult. As the Tibetean plateau receives accumulation almost exclusively in the monsoon season, they should still capture the main effects of precipitation changes.

4.4.5 Observed climate change

The observed trends described for the region by Shekar et al. include a 2 °C warming over the last decades, a 30% decrease in snowfall and a 10% decrease in cloud cover. When the meteorological data is modified to represent the climate state before those changes occurred, the average glacier-wide annual mass balance rises by 1100 mm w.e. This shows that the observed climate change has already strongly affected mass balances on Chhota Shigri. The negative overall mass balances and corresponding low accumulation area ratios observed by Wagnon et al. (2007) for the years 2002/03, 2003/04 and 2005/06 represent the present state of Chhota Shigri. The glacier is currently losing mass due to the climate change that has already occurred in the region.

4.4.6 Monsoon changes and temperature sensitivity

A change in monsoon precipitation by 10% leads to a mass balance change of about 40 mm w.e. under present temperatures. As explained above, this is not only due to the accumulation effect but also to the important reduction of the surface albedo from summer snowfall.

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However, the future change in monsoon precipitation will not only change the mass balance of Chhota Shigri directly, it also influences the sensitivity of the glacier to warming. If monsoon precipitation is reduced by 40% (Ashfaq et al., 2009), one degree of warming translates to an average mass balance loss of 200 mm w.e. If precipitation in the monsoon season increases by a similar amount (Kumar et al., 2006) this sensitivity is reduced to 170 mm w.e. per degree of warming. The difference to the overall temperature sensitivity given above is due to a smaller range of changes tested for the different monsoon scenarios.

It should be noted that these results only take into account the relative change in monsoon precipitation, whereas a change in monsoon patterns would also affect cloud cover, the seasonality of precipitation (e.g. a delayed onset of the monsoon) and atmospheric humidity. In order to make a realistic assessment of the combined impact of all changes associated with different scenarios of monsoon development, the glacier model should be run with model output from the respective regional climate models.

4.4.7 PRECIS A2 scenario

Regional climate model results from PRECIS indicate a 5.7 °C warming, an increase in precipitation by 11% and small decreases in humidity and cloud cover for the end of the 21st century under the SRES A2 scenario compared to a 20th century baseline run (Kumar et al., 2006). The increase in precipitation takes places in the monsoon season (monsoon precipitation increases by 22%), whereas temperatures in the monsoon season only increase by 4.5 °C.

Superimposing those anomalies on the 2002–2006 reanalysis data did not lead to a substantial change in mass balances. This suggests that the projected monsoon increase could offset the projected warming on Chhota Shigri. Unfortunately it was not possible to obtain model results from the group that projected a decrease in monsoon precipitation (Ashfaq et al., 2009) within the timeframe available for this study to compare the impact on mass balances.

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5 Conclusions

5.1 Model performance

The mass balance of Chhota Shigri has been modelled successfully from reanalysis meteorological data using the surface energy budget approach. Modelled and measured mass balances at different altitudes over the glacier for three years show a good agreement with a correlation coefficient of 0.974. Both the vertical gradients of mass balance and the climate sensitivity of the glacier are well captured in the model.

5.2 Glacier regime

Results show that monsoon precipitation (June–August) accounts for 25 to 30% of the total accumulation. It also reduces ablation by up to 1000 mm w.e. compared to the same amount of precipitation in winter due to the stronger effect of summer snowfall on the surface albedo. Chhota Shigri can thus neither be considered a typical winter nor summer accumulation glacier, but displays two distinct accumulation seasons.

Model results suggest that on average, 5–10% of all meltwater refreezes within the snowpack. Most refreezing occurs around the equilibrium line, which is similar to observations on polar and mid-latitude glaciers. Ignoring subsurface heat fluxes leads to an overestimation of ablation by 37%, which is considerably more than has been found for mid-latitude glaciers.

Shortwave radiation provides the biggest part of melt energy in the lower part of the ablation zone, and almost all melt energy towards its upper end. Topographical shading may explain some specific local features of the mass balance gradient, but the average albedo gradient caused by melt and the exposition of ice is much more important on the glacier scale. Cloud cover in the monsoon season strongly reduces incoming shortwave radiation.

The sensible heat flux towards the glacier is around 100 W m^{-2} in melt periods at the lower end of the glacier and only 5 W m^{-2} towards the upper end of the ablation

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zone, which is similar to the profile observed on mid-latitude glaciers. Latent heat flux is negative during most of the year and a very important heat sink in the pre-monsoon season, when it reaches up to $-300\,\mathrm{W\,m^{-2}}$. It goes towards zero or even low positive values during the monsoon season. Such an important role of latent heat flux has also been reported from tropical glaciers, however with different seasonal characteristics.

In spite of some similarities with mid-latitude or Northern Himalaya glaciers, glaciers in the monsoon-arid transition zone in Western Himalaya have a different glacier regime, which is governed by two accumulation seasons.

5.3 Climate sensitivity

Mass balance on Chhota Shigri is most sensitive to changes in atmospheric humidity. While mass balance is also sensitive to changes in both air temperature and precipitation, its sensitivity to rising temperatures depends on the trend in monsoon precipitation. Temperature sensitivity is higher if monsoon precipitation is assumed to decrease. As would be expected for a glacier in a relatively arid region with low mass turnover rates, mass balance sensitivity to warming is relatively low compared to other glaciers on a global scale. The current state of Chhota Shigri is already a result of the climate change that has been observed in the region throughout the last decades. Annual glacier-wide mass balances would on average be about 1100 mm w.e. higher without those changes in air temperature, cloud cover and precipitation.

Model results following the PRECIS regional climate model data suggest that a projected 22% increase in monsoon precipitation might offset the 5.7 °C warming and keep mass balances on Chhota Shigri within their current range in the 21st century. A comparison to the impact of a possible monsoon suppression yet remains to be undertaken.

The dependence of the temperature-sensitivity of mass balances on the trend in monsoon precipitation questions the validity of studies using a constant degree-day factor derived from present-day observations to model 21st century melt processes in the Himalaya region. It also emphasises the need for a better understanding of the future of monsoon precipitation.

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To further increase the accuracy and reliability of the model, it would be beneficial to use meteorological field data from the glacier itself, both to get a better general forcing and to improve the glacier wind scheme. Since melt on high altitudes is mostly driven by radiation, the temperature-dependent albedo parametrisation developed in the Alps should also be verified against Himalaya measurements. It would be interesting to conduct a similar modelling study on one of the advancing glaciers in the Karakoram mountain range to compare results and investigate the drivers of the Karakoram anomaly.

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Table 1. Heat fluxes averaged over the glacier.

flux	sw radiation	net lw radiation	latent heat	turbulent heat
$W\ m^{-2}$	48.2	67.1	−95.8	20.3

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Table 2. Sensitivity of the surface mass balance to changes in different meteorological parameters.

changed parameter	tested range	mass balance change
Temperature	−2 to +6 K	$-220\,\mathrm{mm\,w.e.\,K^{-1}}$
Relative humidity	−20 to +20%	$-900\,\mathrm{mm\,w.e.}\,(10\%)^{-1}$
Cloud cover	−15 to +15%	$80\,\mathrm{mm\,w.e.}\,(10\%)^{-1}$
Snowfall	−50 to +50%	$140\,\mathrm{mm\,w.e.}\,(10\%)^{-1}$
Monsoon precipitation	−40 to +40%	$40\,\mathrm{mm\,w.e.}\,(10\%)^{-1}$

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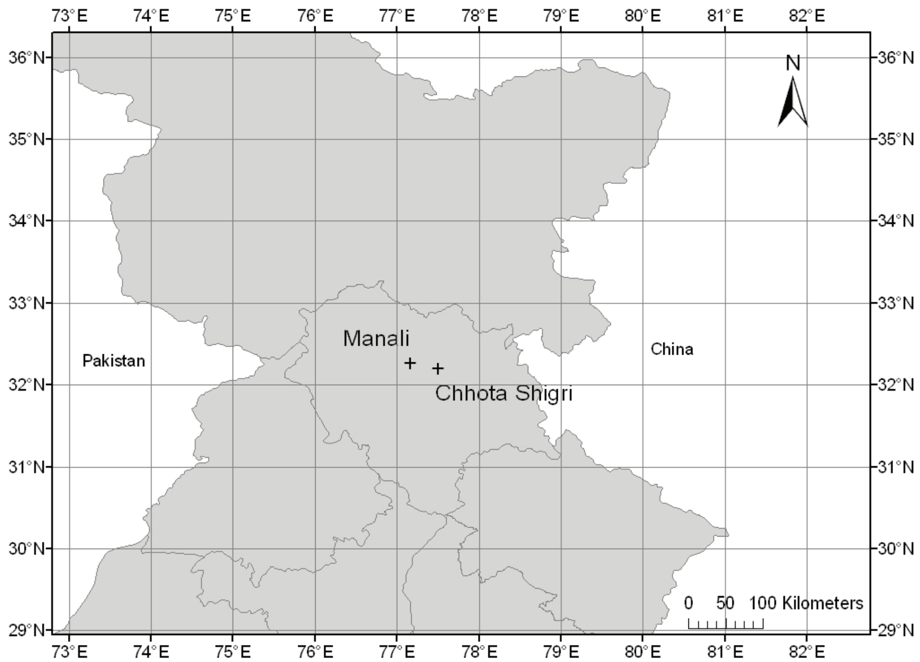

Fig. 1. Location of Chhota Shigri glacier and Manali within the Indian State Himachal Pradesh.

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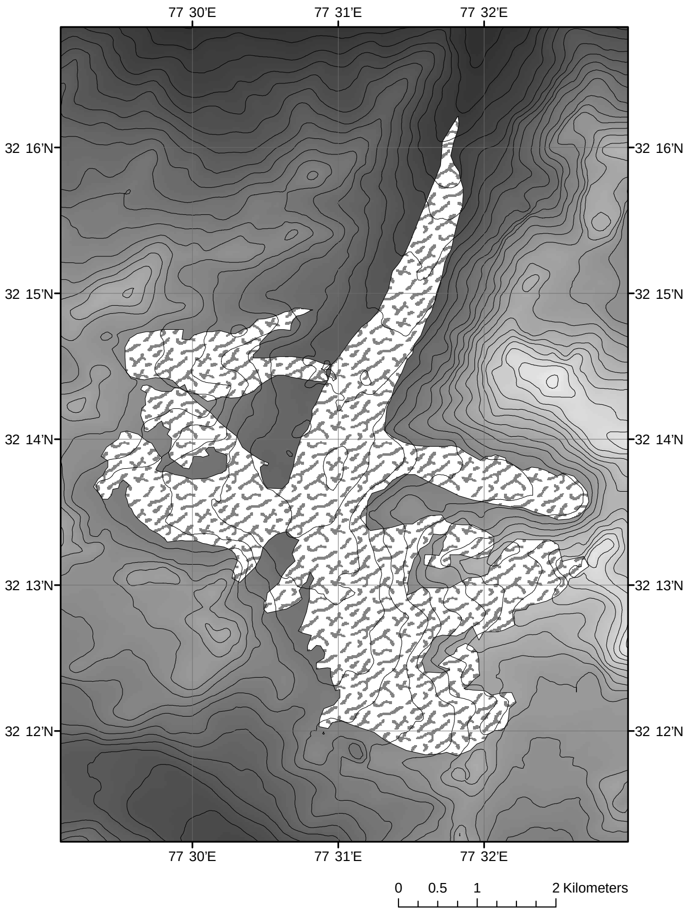

Fig. 2. Chhota Shigri glacier, contour lines (100 m intervals) derived from ASTER DEM, glacier extent from a satellite photo published by Wagnon et al. (2007).

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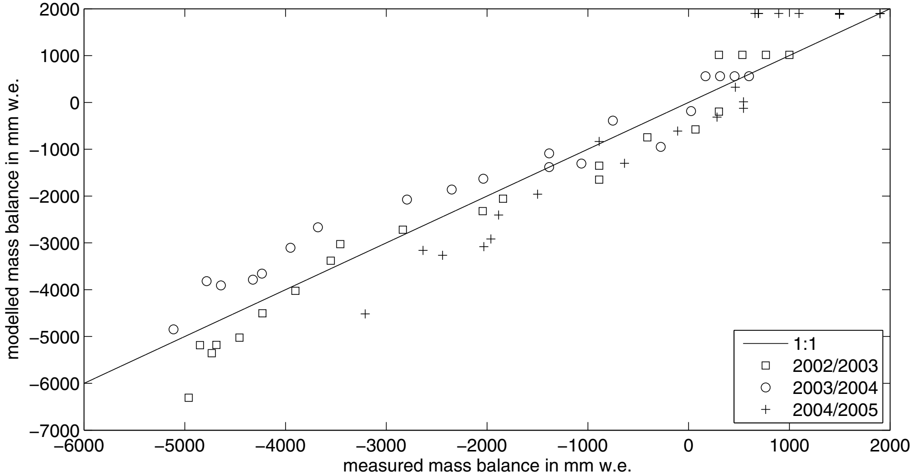

Fig. 3. Modelled vs. measured mass balances, $r=0.974$.

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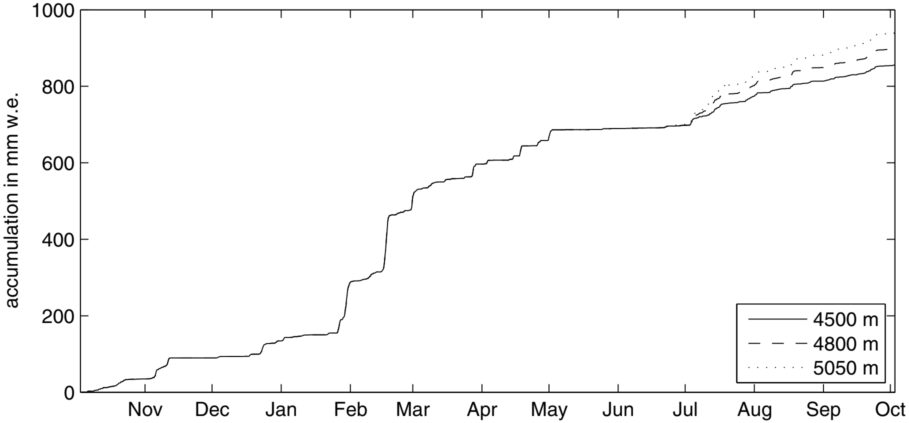

Fig. 4. Accumulated snowfall at different altitudes for September 2002–September 2003, based on NCEP data.

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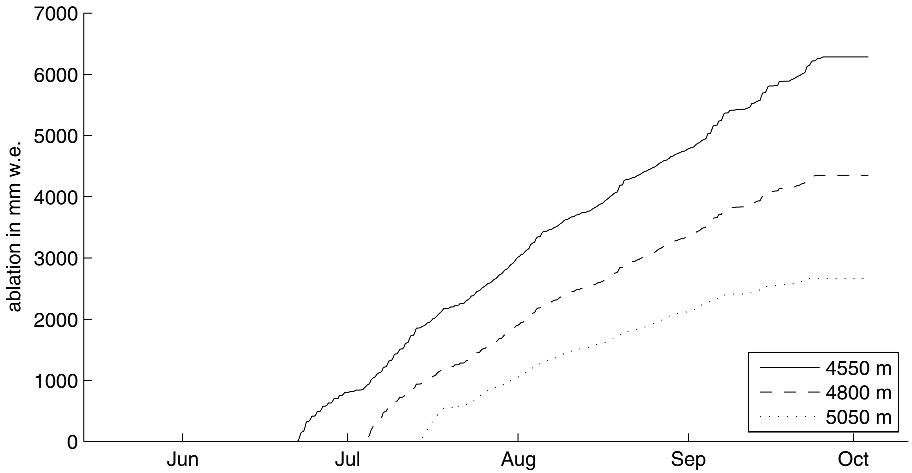

Fig. 5. Accumulated ablation at different altitudes in the hydrological year September 2002–September 2003.

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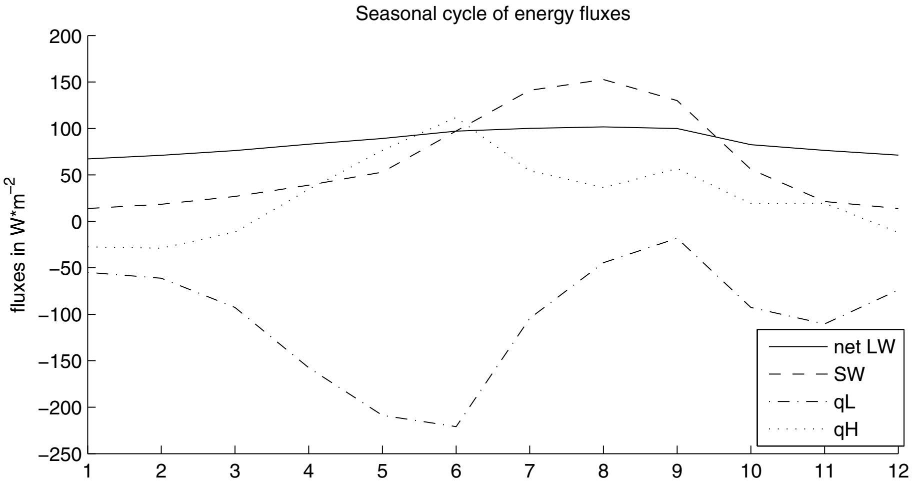

Fig. 6. Average seasonal cycle (monthly means January–December) of different energy fluxes in the ablation zone at 4550 m.

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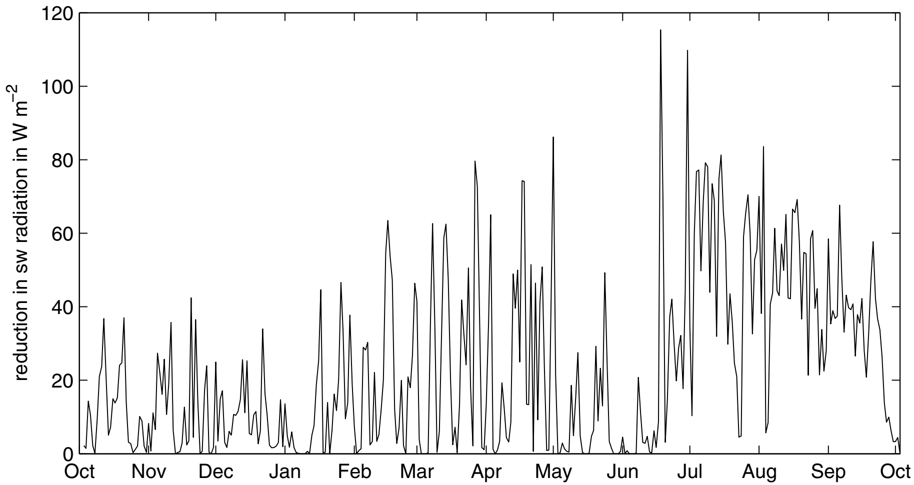

Fig. 7. Reduction of the clear-sky radiation due to cloud cover in 2002/03.

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