Model Validation
7.1 Overview

In order to validate the DEB and Bare Snow-Ice models results, the glacier mass balance measurements using standard \textit{in-situ} glaciological method on the ablation zone were performed during the ablation period (May-October) for the two consequent glaciological years: i) 2011-2012 and ii) 2012-2013. The simulated melt and mass balance at point scale of K1 AWS (4270 m a.s.l.) was compared with the observed melt and mass balance at stake no. 21 near to the K1 AWS (Fig. 6.1 in Chapter 6). As the stake no. 21 is very near to the K1 AWS and having almost same debris thickness (~30 cm), it is assumed that the meteorological as well as surface conditions during the ablation period were mostly same. The melt energy computed at K1 AWS was spatially extrapolated over the entire ablation zone using extrapolated meteorological parameters (near-surface air and surface temperature, incoming longwave radiation and outgoing shortwave and longwave radiations) to compute the glacier-total mass loss and compared with the observed total melt. Further, validation of the DEB and Bare Snow-Ice models presented which is essential for its further use to study the mountain glaciers (especially for debris-covered glaciers) as well as to understand the impact of climate change on the glacierized regime. In view of the fact that the DEB and Bare Snow-Ice models incorporates all the energy fluxes to compute the glacier surface melt; these models are used to compute the effect of future climate change on glacier health by altering the near-surface meteorological conditions and surface characteristics.
7.2 Comparison of Simulated and Observed Melt Rate

Comparison of the simulated melt with observed melt rates at point as well as spatial scale was performed to identify the robustness of the DEB and Bare Snow-Ice models.

7.2.1 Glaciological Year: 2011-2012

Glacier Melt at Point Scale (4270 m a.s.l.)

The daily simulated melt (2.28 cm w.e. d⁻¹) through the DEB and Bare Snow-Ice modelling at K1 AWS site (4270 m a.s.l.) during the summer of 2012 was 1.10 times higher (10% more melt) than the measured one (2.07 cm w.e. d⁻¹) at stake No. 21 (Fig. 7.1 and Table 7.1). The correlation between daily simulated and observed melt was well matched with each other (Fig. 7.1).

Glacier Total-Melt at Ablation Zone

The studies of Rasmussen and Andreassen (2005) and Andreassen et al. (2008) suggested that point balance at a site near the middle of altitude range of a glacier correlates well with the glacier-total balance. However, the K1 AWS is located at 4270 m a.s.l. (Fig. 3.1; Chapter 3) which is nearly the mid of the altitude range of ablation zone (5000-3895 m a.s.l.). Therefore, this allows us to spatially extrapolate the modelled melt energy in the entire ablation zone. The simulated glacier-total ablation from the DEB and Bare Snow-Ice models approach was 1.97 m w.e.a⁻¹ which was 1.17 times higher than observed net ablation (1.69 m w.e., from stakes measurements) showing 17% more melt. The root mean square error (RMSE) between simulated and observed melt was 0.28, which was within the limit of the stake measurements and SEB calculations indicating the robustness of the DEB and Bare Snow-Ice models.
Table 7.1. Summary of simulated (DEB and Bare Snow-Ice models) and observed (glaciological method) surface mass (Ice) loss in the ablation zone and computed annual specific mass balance of the Chorabari Glacier during two consequent glaciological years (2011-2012 and 2012-2013).

<table>
<thead>
<tr>
<th>Approach</th>
<th>Mean Daily Melt at 4270 m a.s.l (cm w.e. d⁻¹)</th>
<th>Mean Daily Melt for Glacier Ablation Zone (cm w.e. d⁻¹)</th>
<th>Net Surface Mass Loss for Glacier Ablation Zone (10⁶ m³ w.e. a⁻¹)</th>
<th>Net Annual Specific Mass Balance † (m w.e. a⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2012*</td>
<td>2013*</td>
<td>2012*</td>
<td>2013*</td>
</tr>
<tr>
<td>DEB Model</td>
<td>2.28</td>
<td>2.31</td>
<td>1.06</td>
<td>1.10</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>6.6</td>
<td>6.8</td>
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<td></td>
<td></td>
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<td></td>
<td>- 1.96</td>
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<td>2011-12</td>
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<td>2012-13</td>
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<td></td>
</tr>
<tr>
<td>Glaciological Method</td>
<td>2.07</td>
<td>2.12</td>
<td>0.92</td>
<td>1.01</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>5.7</td>
<td>6.3</td>
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<td>2011-12</td>
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<tr>
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<td></td>
<td></td>
<td>2012-13</td>
</tr>
</tbody>
</table>

*For summer months (May-October) only.  †Specific Mass Balance is computed using Eqn (6.3).
Fig. 7.1. Comparison between daily simulated and observed net ablation at stake no. 21 (nearest to K1 AWS) during entire summer period (May-October 2012). The simulated ablation was 1.10 times higher than measured ablation showing a close correlation. N is number of observations. 1:1 line (dashed line) diagonal line is added to illustrate the tendency of the model to overestimate ablation.

### 7.2.2 Glaciological Year: 2012-2013

#### Glacier Melt at Point Scale (4270 m a.s.l.)

The daily simulated melt (2.31 cm w.e. d$^{-1}$) through the DEB and Bare Snow-Ice models at K1 AWS site during the summer of 2013, was 1.09 times higher (9% more melt) than the observed one (2.12 cm w.e. d$^{-1}$) at stake No. 21 (Fig. 7.2 and Table 7.1). The correlation between daily simulated and observed melt corresponds well to each other (Fig. 7.2).
Glacier Melt at Ablation Zone

The simulated glacier-total ablation from the DEB and Bare Snow-Ice models was 2.03 m w.e. a⁻¹ which is 1.09 times higher than calculated one (1.86 m w.e., from stakes measurements) showing 9% more melt. The root mean square error between the simulated and observed melt was 0.17, which was within the limit of the stake measurements and SEB calculations indicating robustness of these models. The results specify a good correlation between the simulated and glacier-total ablation in the ablation zone.

![Graph](image)

**Fig. 7.2.** Comparison between daily simulated and observed net ablation at stake no. 21 (nearest to K1 AWS) during entire summer period (May-October 2013). The simulated ablation was 1.09 times higher than measured one showing a close correlation. N is number of observations. 1:1 line (dashed line) diagonal line is added to illustrate the tendency of the model to overestimate ablation.
7.3 Discussion

7.3.1 Validation of DEB and Bare Snow-Ice Models

To run the DEB and Bare Snow-Ice models, a set of daily observed meteorological data at K1 site and the summer precipitation collected at K2 site (2012) and TRMM rainfall records for two complete consequent glaciological years i.e. (i) from 01 November 2011 to 31 October 2012 and (ii) from 01 November 2012 to 31 October 2013 were used as input data. In these models, calculated fresh snow density ($\rho_s$) during the end of October, 2011 ($\rho_s = 85$ kg m$^{-3}$) at 4800 m a.s.l. was used as initial input. The linearly interpolated meteorological parameters for the data gap at K1 AWS using K2 AWS data was almost similar to the observed values (see Chapter 4). However, the simulated data creates small discrepancies between the observed and simulated values but generally acceptable.

To validate these models results, the simulated ablation was compared with the observed ablation from stakes measurements between the observation dates in May to October (for the ablation zone only). The simulated ablation was 1.17 times higher (~17% more melt) than observed ablation in 2011-2012 and 1.09 times higher (~9% more melt) than observed ablation in 2012-2013 which represents results are generally good and can be acceptable. The possible reasons for this difference are i) during the summer use of the modelled $T_s$, ii) use of constant snow density during the winter and summer and (iii) use of average supraglacial debris thickness while on the glacier surface it is highly variable. The simulated melt during 2012-2013 glaciological year was found very near to the observed melt as compared to the 2011-2012 glaciological year. The possible reason for this uncertainty may be possibly due to more snow accumulation (25.7 m in 2012-2013 and 23.7 m in 2011-2012) and more summer rainfall (1489 mm in 2013 and 933 mm in 2012) in the area, and availability of continuous meteorological data. More the precipitation creates less the difference between near-surface air temperature and surface temperature that result in good correlation between the observed and simulated surface ablation. Since, the validation presented here suggested that the DEB and Bare Snow-Ice models are enough reliable to estimate the surface mass fluctuation of Chorabari Glacier.
therefore, the sensitivity of glacier mass balance response to change in meteorological variable and surface conditions can be identified.

7.3.2 Glacier Sensitivity to Future Climate Change

Glacier Response to Meteorological Parameters

In order to test the sensitivity of the DEB model and Bare Snow-Ice models, these models were run using altered the contrasting meteorological parameters (near-surface air temperature ($T_a$) by ± 1°C, surface temperature ($T_s$) by ± 1°C, relative humidity (RH) by ± 20%, precipitation (P) by ± 20%) and surface characteristic (debris thickness (h_d) by ± 20 cm) during the ablation period. Based on the perturbation of each variable and its respective influence to the other parameters, sensitivity of these models was determined by computing the relative change in specific mass-balance for each variation (Fig. 7.3). Results indicate that if $T_a$ is increased by 1°C, 0.21 m w.e. more meltwater (an increase of 5%) would run off. While in reverse if $T_a$ was decreased by 1°C, the surface melting will be reduced by 0.20 m w.e. (a decrease of 5%) (Fig. 7.3). Similarly, if surface temperature ($T_s$) is increased by 1°C, the surface melting will be increased by 0.21 m w.e. (an increase of 5%). However, if $T_s$ is decreased by 1°C, 0.20 m w.e. less ice (a decrease of 5%) would melt (Fig. 7.3). Changes in the specific mass-balance for perturbations of RH are $-0.06$ m w.e. (2%) and 0.05 m w.e. (1%) for + 20% and − 20% humidity perturbations, respectively. An increase of 20% in P directly influences the amount of accumulation, but simultaneously changes the albedo and consequently reduces the net energy of the system which leads to less surface melting of glacier. The changes in specific mass-balance for perturbations of P are $-0.11$ m w.e. (3%) and 0.05 m w.e. (1%) for −20% and + 20%, respectively (Fig. 7.3) which indicates that the sensitivity of change in summer precipitation is lower than the other meteorological parameters. Overall, the sensitivity of the DEB and Bare Snow-Ice models suggest that the specific mass-balance is more sensitive for the perturbation of air temperature ($T_a$) and surface temperature ($T_s$) than any other parameters especially in the ablation area of the glacier during the summer.
Fig. 7.3. The sensitivity of glacier specific mass balance was examined by perturbations of $T_a$ (± 1°C), $T_s$ (± 1°C), $R_H$ (± 20%), $P$ (± 20%) and $h_d$ (± 20 cm) in the DEB and Bare Snow-Ice models. Symbols are representing the near-surface air temperature ($T_a$), surface temperature ($T_s$), relative humidity ($R_H$), precipitation ($P$) and debris thickness ($h_d$), respectively. Blue coloured line is showing the reference annual specific mass balance of a debris-covered glacier. Condition coloured with grey is showing the surface condition while rest are showing the meteorological conditions.
Glacier Response to Surface Characteristic

It is well established fact that the response of glaciers is majorly controlled by both climatic and non-climatic factors. Therefore, study of effect of perturbation of surface characteristic to the DEB model was carried out using altered supraglacial debris thickness ($h_d$) of ± 20 cm during the ablation season. Results indicate that if $h_d$ is increased by 20 cm, deficiency of 0.37 m w.e. (a decrease of 9%) in ice melt would occur but if $h_d$ is reduced by 20 cm, the ice melt would be increased by 1.04 m w.e. (an increase of 25%) (Fig. 7.3). The results indicate that the DEB model is nearly two times more sensitive to a decrease of $h_d$ by 20 cm which suggest that sub-debris ice melt rates depend more strongly on debris thickness than air temperature. The study also supports the previous studies (Østrem, 1959; Loomis, 1970; Nakawo and Young, 1981; Mattson et al., 1993; Kayastha et al., 2000; Nicholson and Benn, 2006; Brock et al., 2010, Reid and Brock, 2010; Lejeune et al., 2013) which indicates that under thin debris, the ablation rates are higher and under thicker debris, the ablation rates progressively decline.

7.4 Summary

This chapter summarize the simulated glacier surface melt at point as well as spatial scale. The daily and seasonal surface melt of Chorabari Glacier was computed using the net energy for melting the glacier surface (computed from DEB and Bare Snow-Ice models) during the summer period (ablation season) of 2011-2012 and 2012-2013 and compared with the observed melt on same scale. Even though, the simulated ablation was 1.17 times higher (~17% more melt) in the 2011-2012 and 1.09 times higher (~9% more melt) in the 2012-2013 than the observed ablation, this represents that the obtained results are more or less good and can be acceptable to run the model. The comparison between simulated and observed melt presented here is the final outcome of present investigation. The characteristics of these models have been discussed extensively in Chapter 5, where these models were developed. As with respect to time, these models are able to correctly simulate the melt rates during the different seasons of a year. The spatial variability of melt rate that is typical to calculate for the mountain glaciers and which can only be very roughly reproduced.
through the temperature-index approach, is modelled here effectively with the high accuracy. Another key issue is that the work has addressed the spatial extrapolation and modelling of the meteorological input from point measurements to the glacier-wide scale. While this is a crucial aspect of distributed modelling in general, it plays a particular role in modelling of glacier catchment because of the high heterogeneity of the hydrological environment.

In addition, the performance of the DEB and Bare Snow-Ice models were checked with respect to the future climate change. These models were run by altering of the meteorological parameters (such as air and surface temperature, relative humidity, precipitation) and glacier surface characteristics (debris thickness). The results suggested that for the debris covered mountain glaciers, the specific mass balance is highly sensitive for the perturbation of surface characteristics followed by meteorological conditions.