Modelling of meteorological parameters for the Chorabari Glacier valley, Central Himalaya, India

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In the present study, we have developed empirical relationships to estimate meteorological parameters at the glacier altitude from the data on non-glacier altitude. Meteorological data collected from automatic weather station at Chorabari Glacier from November 2011 to May 2013 are analysed and empirical equations for air temperature, relative humidity and incoming global radiation are proposed. The dataset of one year (November 2011–October 2012) is used in the calibration of models, while data for the next seven months (November 2012–May 2013) are employed to validate the models. Moreover, an analytical study is also conducted on incoming diffuse radiation (estimated through the established model for India). Further, a relationship is established to correlate the diffuse component of two sites. Variation trend of meteorological parameters with altitude is found to be different for each of the parameters, viz. quadratic for air temperature, logarithmic for relative humidity, and linear for global and diffuse radiation. Performance of the generated equations is tested through various statistical methods. The study reveals that developed correlations are able to give a good match with *in situ* measurements.

Keywords: Clearness index, empirical models, global and diffuse radiation, meteorology.

GLACIERS are widely recognized as a key icon of climate and global environment change[1]. Recent studies carried out on glacier recession indicate that there is a wide inconsistency in retreat rate caused by variability in climate[2–5] and terrain conditions. The change in meteorology at regional as well as global scale plays an important role in controlling the glacier health[6].

The major meteorological parameters, viz. air temperature, solar radiation, precipitation, wind and cloudiness greatly influence the mass and energy balance at the glacier surface[7,8]. Air temperature plays a major role in the context of radiation balance, turbulent heat exchange and precipitation[9]. It is responsible for the mass balance variability over distances of several hundred kilometres[10,11]. However, humidity has an inverse relation with air temperature. With increase in temperature, humidity decreases and vice versa. In addition, incoming global (solar) radiation (sum of beam and diffuse radiation) is the prime source for melting of valley glaciers and fluctuations in mass balance[12]. The amount of direct or beam radiation (radiation received without scattering by the atmosphere) and diffuse radiation (radiation received after the direction has been changed due to scattering by the atmosphere) depends on atmospheric constituents (notably aerosol). The incoming global radiation increases sharply with altitude because of decreased optical mass, including a reduction in constituents that absorb and scatter the radiation. Initially the glacierization of mountainous terrain depends critically on snow accumulation and distribution of solar radiation. Over lowlands and industrial areas, the diffuse radiation is much larger. However, in mountain regions, cloudiness mainly determines the variation of direct and diffuse component of radiation.

Though several studies on glacier melt/recession and climate change are available for the Himalayan glaciers[7,13–28], there is a necessity for comprehensive work on regional meteorology over the glaciers of Himalaya. In Himalaya, inaccessibility of region and harsh weather conditions lead to deficiency of the *in situ* continuous data collection which creates inadequacies of research work on regional meteorology.

In this study, we have analysed the meteorological data collected at two locations, viz. Rambara (2760 m amsl) and Base camp (3820 m amsl) from Automatic Weather Station (AWS) network installed at the Chorabari Glacier catchment. Further, meteorological parameters of a non-glacierized area (Rambara) are correlated with a site (Base camp) near to Chorabari Glacier using statistical method (Figure 1). Analysis is carried out for the daily values of three observed meteorological parameters – air temperature, relative humidity and incoming solar (global) radiation from November 2011 to May 2013. Further, empirical equations for each of the parameters are developed. An exercise for the estimation of diffuse radiation using an well established model[29], clearness index (fraction of global radiation in extraterrestrial radiation)

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and diffuse fraction (fractional amount of diffuse component in incident global radiation) is performed. The developed models are calibrated using observed data of Base camp site of one year (November 2011–October 2012). In order to evaluate the performance of the proposed models, they are further validated with the observed testing dataset of the other seven months (November 2012–May 2013).

Study area

Chorabari Glacier valley lies in the Mandakini River basin between 30°41′–30°48′N lat. and 79°1′–79°6′E long. (Figure 1). It has a total catchment area of ~63.8 sq. km (from Rambara town to Kedarnath Peak), ~25% of which (~16 sq. km) is covered with snow, ice and glaciers (Table 1). The Chorabari, Companion and four unnamed small glaciers, including ice apron, hanging glaciers, glacieret and cirque glacier are mapped in the valley. Distribution of these glaciers (generally found >3800 m amsl) is maximum in the southwest and southeast aspects of the valley. Chorabari (area ~6.66 sq. km; length 7.5 km) is the largest glacier of this valley and is a major source of the Mandakini River which eventually joins the Alaknanda River near Rudraprayag, Uttarakhand[4]. Climate of the valley is influenced by two main processes – (i) above 3895 up to 6420 m amsl, the glacier processes, and (ii) below 3895 m amsl, the glacio-fluvial processes. This valley receives maximum precipitation due to the Indian summer monsoon and by the western disturbances during summer and winter respectively[4,6,23]. The general climate of the area is dry–cold in winter (November–April) and humid–temperate in summer (May–October). Geologically, the area is situated north of Pindari Thrust comprising calc silicate, augen and granitic gneisses, schist and granite pegmatite apatite veins belonging to the Pindari Formation[30].

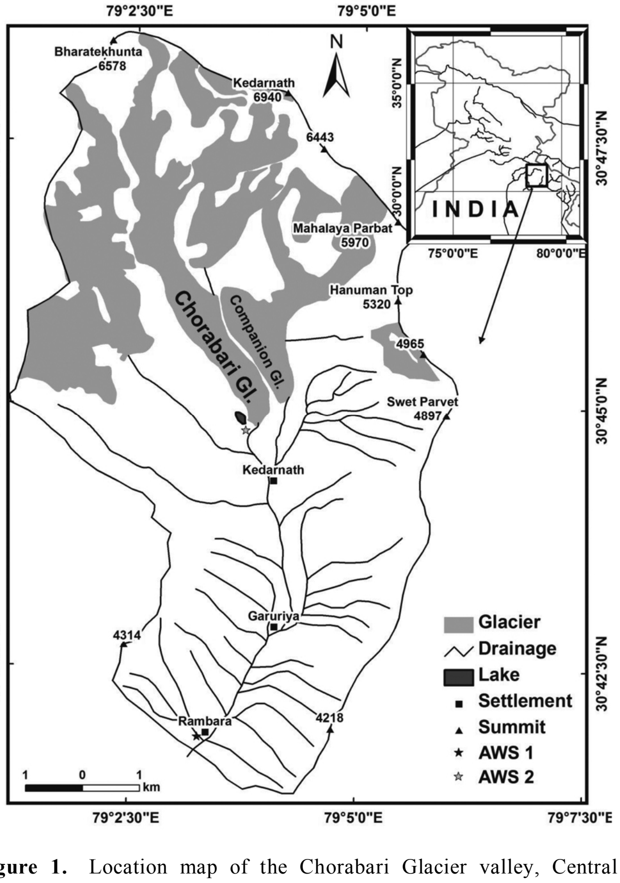

Figure 1. Location map of the Chorabari Glacier valley, Central Himalaya, India and automatic weather stations (AWS) installed at Ramabara (AWS 1, 2760 m amsl) and Base camp (AWS 2, 3820 m amsl) sites.

Methodology

In the Chorabari Glacier valley, a network of two AWS at: (i) Rambara (AWS 1; 2760 m amsl) ~4.66 km below the snout (30°41′50.007″N, 79°03′21.23″E) of glacier and (2) Base camp (AWS 2; 3820 m amsl) situated near the snout (30°44′42.8″N, 79°03′48.4″E) was installed in October 2011 to collect the meteorological data (Figure 1). Detailed description of the meteorological sensors used in AWS is given in Table 2. Data of air temperature (T), relative humidity (R_h) and incoming global solar radiation (H) were analysed from November 2011 to May 2013. To identify the altitudinal change in meteorological parameters, correlations for temperature (between T_1 and T_2), relative humidity (between R_{h1} and R_{h2}), global radiation (between H_1 and H_2) and diffuse radiation (between H_{d1} and H_{d2}) were generated for these sites. Detailed description of abbreviations used in the text is given in Table 3. The meteorological data from November 2011 to October 2012 were applied for calibration of equations, while the dataset from November 2012 to May 2013 was used for validation of established correlations. As diffuse component of solar radiation was not measured directly, it was estimated by employing the available data of air temperature and relative humidity for both locations of Chorabari Glacier valley using the equation[29]

$$\frac{H_\mathrm{d}}{H_\mathrm{o}} = 0.0051 + 0.0033T + 0.002R_\mathrm{h}. \qquad (1)$$

Here, H_d and H_o are in kWh/m^2-day, T in °C and R_h is in %. Daily value of H_o was worked out using the relation[31]

$$H_\mathrm{o} = \frac{24}{\pi} I_\mathrm{sc} E_\mathrm{o} \cos\phi \cos\delta \left[\sin\omega_s - \left(\frac{\pi}{180}\right)\omega_s \cos\omega_s \right]. \qquad (2)$$

The clearness index K_t and diffuse fraction K_d were computed using the following equations utilizing the observed data of global radiation and estimated data of H_o and H_d (ref. 31)

$$K_t = \frac{H}{H_\mathrm{o}}, \qquad (3)$$

Table 1. Characteristic features of the Chorabari Glacier valley, Central Himalaya, India

Parameters	Description
Basin	Mandakini River Basin, upper Ganga catchment, Garhwal Himalaya
Location/landmark	Kedarnath Town, Rudraprayag District, Uttarakhand
Area	~63.8 sq. km
Elevation extension	6420–2760 m amsl (up to Rambara)
Orientation	South
River	Mandakini (major), Madhuganga, Dudhganga and Saraswati (tributaries)
Geology (rock type)	Crystalline rocks; mainly augen and granitic gneisses
Glacier regime	
Glacierized area	16 sq. km (~25% of total area)
No. of glaciers	Chorabari Glacier (7.5 km; largest glacier), Companion Glacier and four unnamed small glaciers, including ice apron, hanging glaciers, glacierete and cirque glacier
General climate	
Winter (November–April)	Dry–cold influenced by western disturbances
Summer (May–October)	Humid–temperate influenced by Indian summer monsoon
Rainfall*	~800–1600 mm
Processes	The valley is influenced by two main processes: (i) Above 3895 upto 6420 m amsl, the glacier processes are dominant (ii) Below 3895 m amsl the glacio-fluvial processes are dominant.

*Source: Dobhal *et al.*[23].

Table 2. Sensors used in AWS for the measurement of meteorological parameters

Parameter	Sensor	Range	Manufacturer (model)	Height from surface (m)
Air temperature	Temperature probe	–50°C to +50°C	Campbell Scientific (HMP45C212)	2
Relative humidity	Relative humidity probe	0–100%	Campbell Scientific (HMP45C212)	2
Incoming global (solar) radiation	Pyranometer	2000 W/m^2	Kipp and Zonnen (CMP 3)	6

Table 3. Details of abbreviations used in text

Element	Symbol	Unit
Air temperature	T (T_1/T_2)*	°C
Relative humidity	R_h (R_{h1}/R_{h2})*	%
Incoming global (solar) radiation	H (H_1/H_2)*	kWh/m^2-day
Extraterrestrial radiation (radiation outside the Earth's atmosphere)	H_o (H_{o1}/H_{o2})*	kWh/m^2-day
Latitude of site	ϕ	Degree
Eccentricity correction factor	E_o	
Solar declination angle	δ	Degree
Sunrise or sunset hour angle	ω_s	Degree
Solar constant (1.367 kW/m^2)	I_{sc}	kW/m^2
Day of the year	n	
Correlation coefficient or coefficient of determination	R^2	Non-dimensional
Clearness index (fraction of global radiation in extraterrestrial radiation)	K_t	Non-dimensional
Diffuse fraction (fractional of diffuse component in incident global radiation)	K_d	Non-dimensional

*1 represents meteorological parameter for Rambara AWS and 2 for Base camp AWS.

$$K_d = \frac{H_d}{H}. \tag{4}$$

The performance of the developed models was statistically evaluated using six different statistical predictors – (i) coefficient of determination (R^2); (ii) adjusted R^2; (iii) mean percentage error (MPE); (iv) root mean square error (RMSE); (v) mean bias error (MBE) and (vi) t-test (Table 4).

Results and discussion

Analysis of meteorological data

The meteorological data from November 2011 to May 2013 (Figure 2) were analysed for Rambara and Base camp sites of Chorabari Glacier valley. Table 5 lists the calculated daily average of meteorological parameters.

Average temperature during November 2011–October 2012 for Rambara was 8.4°C and for Base camp site, it was

Table 4. Description of statistical tests applied for performance evaluation of the proposed models

Statistical predictors	Physical significance
Coefficient of determination (R^2)	Closeness between predicted and observed values
Adjusted R^2	Modification of coefficient of determination
Mean percentage errror (MPE)	Percentage deviation in estimated values from measured values
Mean bias error (MBE)	Long-term performance of the model
Root mean square error (RMSE)	Information on short-term performance of the model
t-test	To determine whether or not the equation estimates are statistically significant

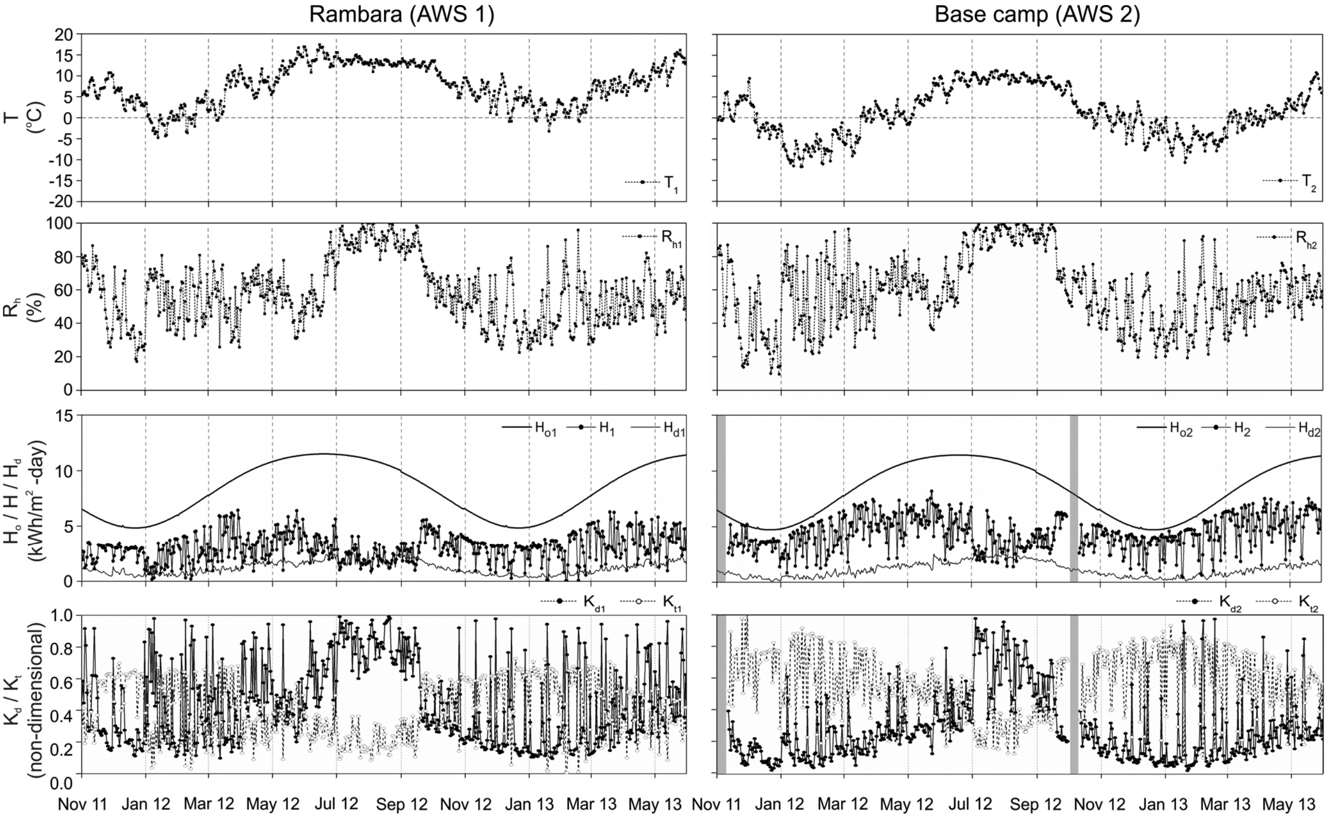

Figure 2. Daily observed average temperature (T), relative humidity (R_h), incoming global (solar) radiation (H) and calculated extraterrestrial radiation (H_o), diffuse radiation (H_d), diffuse fraction (K_d) and clearness index (K_t) for Ramabara (AWS 1, 2760 m amsl) and Base camp (AWS 2, 3820 m amsl) sites during November 2011–May 2013. A data gap (marked in grey colour) in H_2 of AWS 2 during 1–11 November 2011 and 1–11 October 2012 exists and therefore, K_{d2} and K_{t2} could not be computed.

2.3°C. During the testing data period (November 2012–May 2013), average temperature was 6.3°C and –0.9°C in Rambara and Base camp respectively. Relative humidity for calibration dataset (November 2011–October 2012) was 63% for Rambara and 64% for Base camp, whereas for testing dataset, it was 49% for Rambara and 50% for Base camp. Global solar radiation showed an average value of 2.94 kWh/m^2-day in Rambara and 4.31 kWh/m^2-day in Base camp during November 2011–October 2012. On the other hand, for the validation period, it was 3.23 kWh/m^2-day for Rambara and 4.50 kWh/m^2-day in Base camp. The computed average diffuse radiation (eq. (1)) for the calibration period was 1.34 kWh/m^2-day at Rambara and 1.27 kWh/m^2-day at Base camp site of the glacier valley. For testing dataset, diffuse radiation was 0.94 kWh/m^2-day at Rambara and 0.82 kWh/m^2-day at Base camp.

Equations for temperature and relative humidity

Air temperature being an important meteorological parameter is one of the vital factors in the melting of glaciers. It is obvious from Figure 3 *a* that variation in air temperature between two sites (Rambara and Base camp) of the Chorabari Glacier valley is a second-order polynomial. In Rambara area, the valley is narrow (creating shadow effect) covered with dense forest resulting in high moisture content (humidity) in the area, which controls rapid change in temperature (T_1). However, in the Base camp area, the valley is wide with less vegetation (less moisture content), causing sudden change of temperature (T_2) in the area. The mathematical interpretation of this variation of temperature between the two sites can be described by a second-order polynomial (Table 6).

Table 5. Average of observed and modelled meteorological parameters for 2011–12 and 2012–13 glaciological year (November–October)

Meteorological parameter (units)	2011–2012 (November–October)	2012–2013 (November–May)	2012–2013$^{\delta}$ (November–May)
T (°C)	8.4*/2.3†	6.3*/–0.9†	–0.3
R_h (%)	63*/64†	49*/50†	52
H (kWh/m^2-day)	2.94*/4.31$^{\dagger¥}$	3.23*/4.50†	4.5
H_o (kWh/m^2-day)	8.58*/8.54†	7.58*/7.54†	–
H_d (kWh/m^2-day)	1.34*/1.27†	0.94*/0.82$^{\dagger\#}$	0.75$^{\#}$
K_d	0.51*/0.33$^{\dagger¥}$	0.35*/ 0.22†	–
K_t	0.37*/0.53$^{\dagger¥}$	0.45*/0.62†	–

*Rambara, †Base camp. $^{\delta}$Modelled data for Base camp; ¥Data gap in H of Base camp AWS during 1–11 November 2011 and 1–11 October 2012 exists and therefore average is computed based on the available data. #Average value is based on available data (1 November 2012–17 May 2013).

Table 6. Derived empirical models for correlating the meteorological parameters at Rambara and Base camp sites of Chorabari Glacier valley

Model no.	Meteorological parameter	Empirical model*
1	Air temperature (T)	$T_2 = 0.008T_1^2 + 1.058T_1 - 7.358$
2	Relative humidity (R_h)	$R_{h2} = 47.47\ln(R_{h1}) - 130.9$
3	Incoming global radiation (H)	$H_2 = 0.932H_1 + 1.507$
4	Diffuse radiation (H_d)	$H_{d2} = 0.962H_{d1} - 0.153$

*1 – Rambara (2760 m amsl); 2 – Base camp site (3820 m amsl).

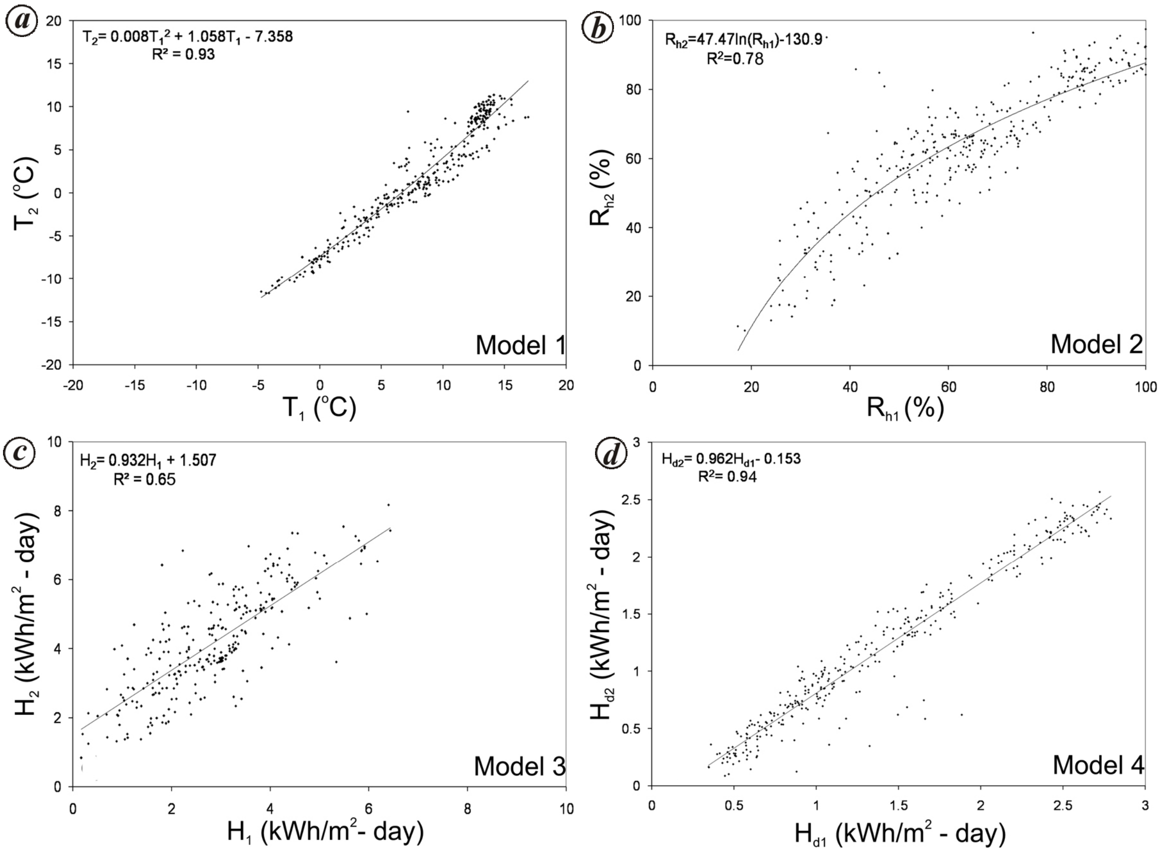

Figure 3. Trends of variation in (***a***) temperature (quadratic–model 1), (***b***) relative humidity (logarithmic – model 2), (***c***) global (solar) radiation (linear – model 3) and (***d***) diffuse radiation (linear – model 4).

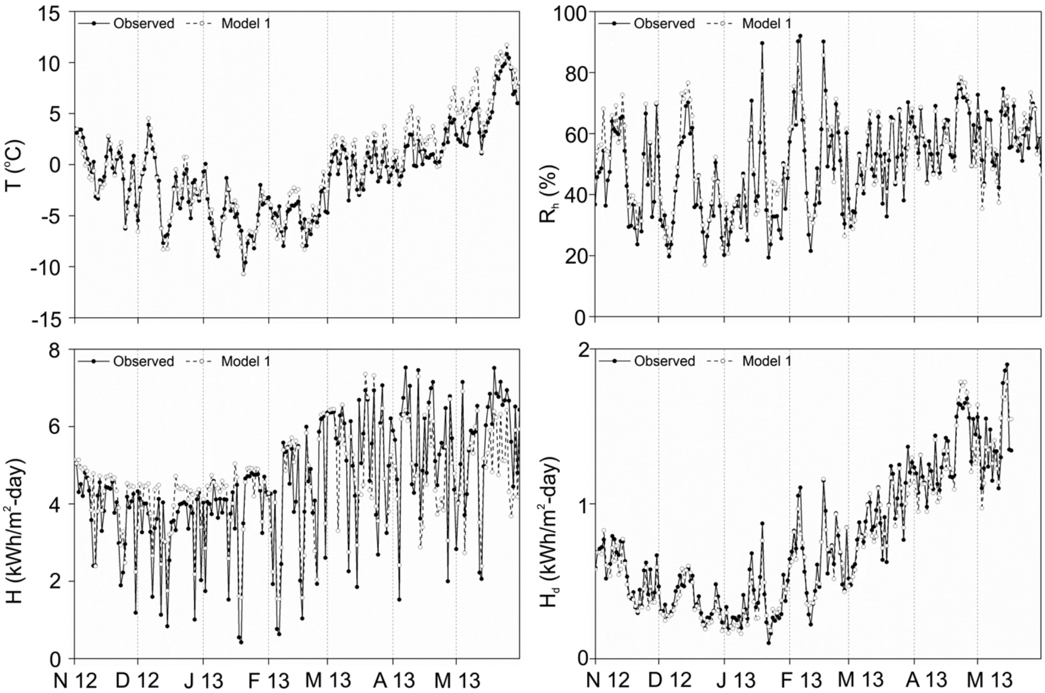

Figure 4. Comparative plot of observed and modelled temperature (T), relative humidity (R_h), incoming global (solar) radiation (H), and diffuse radiation (H_d) for testing dataset (November 2012–May 2013) of Base camp site, Chorabari Glacier valley.

Reliability of the proposed model was checked by correlation coefficient; apparently R^2 (0.93) and adjusted R^2 (0.92) values were very close to one, which reflects fair performance of the proposed model 1 (Table 7). Applying model 1, the daily temperature data of Base camp site were computed for the next seven months (November 2012–May 2013). Comparison between observed and estimated values revealed that the proposed equation showed good correlation and could be accepted (Figure 4). Accuracy of the equation was also assessed by various statistical predicators. The statistical predictors (Table 7) showed that MPE for the developed equation was –11.70% and MBE was 0.70 (Table 7). RMSE also yielded good result, with a value of 1.32. In t-test, level of significance was considered at 5% and threshold value of t at 5% probability level was 1.96. The proposed correlation between temperature of two sites will be accurate if the calculated value of t is higher than $t_{0.05}$. Since computed t (9.08) is greater than $t_{0.05}$ (1.96), the estimations made using the proposed model (model 1) are in good agreement with the measurements and the model gives satisfactory results.

For relative humidity of Rambara (R_{h1}) and Base camp (R_{h2}) sites, a logarithmic relationship was found to give the best fit resulting in less increase in R_{h2} compared to R_{h1} (Figure 3 *b*). The main reason is the rapid increase in air temperature of the Base camp. A fairly good correlation between R_{h2} and R_{h1} was confirmed by R^2 and adjusted R^2 with values of 0.78 and 0.77 respectively (Table 7). An acceptable agreement between observed and estimated values using model 2 of R_h for testing dataset (Figure 4) has been defined through statistical errors which are 0.84% (MPE), 0.29 (MBE), and 1.91 (RMSE), implying excellent performance of the proposed model. The statistical t-test also proves validity of the model as t (2.05) > $t_{0.05}$ (Table 7).

Equation for global radiation

A study on the observed incoming global radiation (H) at two points (Rambara and Base camp) of the glacier valley was carried out. It is apparent from Figure 3 *c* that a linear function describes variation of H_2 (Base camp) with H_1 (Rambara) with a satisfactory coefficient of determination (R^2) of 0.65 and adjusted R^2 of 0.64 (Table 7). This indicates that H_2 increases with H_1 and vice versa. Figure 4 shows good agreement between observed and estimated H values using the developed model 3 (Table 6) for Base camp site during November 2012–May 2013. The statistical errors MPE, MBE and RMSE were 9.28%, 0.02 and 0.79 respectively (Table 7). Low value of MPE and RMSE indicates good agreement between observed and estimated values of H_2, whereas positive MBE shows underestimation of H_2 by model 3. Good result from the model is also reflected by t-test. The t-value is 2.98 > $t_{0.05}$ (1.96), implying that the developed correlation between H_2 and H_1 is significant (Table 7). Thus, the proposed model provides good estimation of incoming global radiation at the Base camp site of the glacier valley.

Table 7. Statistical errors for the proposed models

Model no.*	$^{\dagger}R^2$	Adjusted R^2	MPE (%)†	MBE†	RMSE†	t-test ($t_{0.05}$ = 1.96)†
1	0.93	0.92	–11.70	0.70	1.32	9.08
2	0.78	0.77	0.84	0.29	1.91	2.05
3	0.65	0.64	9.28	0.02	0.79	2.98
4	0.94	0.93	–2.45	–0.13	0.98	19.98

*Listed in Table 6. †Abbreviations are defined in Table 4.

Extraterrestrial radiation

The variation of extraterrestrial radiation (H_o) over Rambara and Base camp sites of Chorabari Glacier valley throughout the year was obtained by applying eq. (2) (Figure 2). H_o was found to vary according to a Gaussian curve over the course of the year. It increases outside the Earth's atmosphere from January to June and then continues to decrease till December.

Equation for diffuse radiation

It is clear from Figure 2 that H_d is very low during December–February in Rambara. On the other hand, in July and August, H_d is high illustrating relatively higher amount of diffuse component of global radiation. The amount of diffuse radiation is also high in the first half of September, whereas after that there is a continual reduction in H_d. Observations reveal that July, August and early September being the monsoon months have comparatively high amount of diffuse component. The increase in diffuse fraction might be due to monsoon season and also due to cloudy sky during these months. However, at the end of the rainy period, a sustainable drop in H_d is noticed. The variation trend of H_d for Base camp is similar to Rambara for all months of the year. Thus, it can be stated that diffuse component of solar radiation fluctuates randomly every month and, it is higher during the monsoon season.

Further, an exercise was done to develop empirical equation for diffuse component of Rambara and Base camp sites to understand the trend of altitudinal variation of H_d. A linear equation (model 4 of Table 6) gives the best fit correlating diffuse component of one point to the other. Variation in H_d is linear with altitude, possibly due to same cloudiness conditions (major factor, responsible for change in H_d) and small aerial distance (~4.66 km) between these sites. Additionally, the coefficient of determination R^2 (0.94) and adjusted R^2 (0.93) confirm the reliability of the developed equation (Table 7). The estimated H_d from model 4 with the observed data (November 2012–May 2013) are plotted in Figure 4, showing fair performance of the generated model. The low values of other statistical predictors also illustrate excellent fitting of the proposed mathematical correlation with MPE of –2.45%, MBE of –0.13 and RMSE of 0.98 (Table 7). The negative value of MBE shows a little underestimation by the model. According to t-test, the model output is acceptable due to high value of t (19.98) compared to $t_{0.05}$ (1.96) indicating that the proposed equation for H_d is significant.

Clearness index and diffuse fraction

Figure 2 shows the calculated clearness index (K_t) and diffuse fraction (K_d) for Rambara and Base camp sites. K_t for Base camp site is found to be higher due to less cloud cover and high global radiation at the site during the study period. However, K_d is observed to be higher in Rambara site due to high attenuation and scattering of solar radiation caused by narrow valley and dense vegetation. Only few days in October and December, higher K_t and lower K_d are observed in Rambara site compared to Base camp, which might be due to more cloud cover over the Base camp region during these days.

Conclusion

In this study, empirical models have been developed to correlate the meteorological parameters of a non-glacier altitude (Rambara, 2760 m amsl) to a glacier altitude (Base camp, 3820 m amsl) of Chorabari Glacier valley. The developed models are calibrated using the dataset of one year (November 2011–October 2012) followed by further validation with the next year's dataset of seven months (November 2012–May 2013). Relationships have been developed for different meteorological parameters (air temperature, relative humidity and incoming global radiation). Additionally, extraterrestrial radiation, diffuse radiation, diffuse fraction and clearness index are estimated using the meteorological and geographical parameters of Rambara and Base camp sites during the study period. The results suggest that changes in meteorological parameters with altitude are not similar. Variation trend of air temperature is quadratic, whereas it is logarithmic for R_h. However, variation of H_2 and H_{d2} (Base camp) with H_1 and H_{d1} (Rambara) is linear. The performance of the proposed empirical models is tested using various statistical tests which confirm the validity of these models. Thus our proposed models give satisfactory and acceptable results, and the study presents an effort to correlate the meteorological parameter of a non-glacierized area to a site near the glacier of Chorabari Glacier catchment.

Although the developed correlations for the considered meteorological parameters are based on one-year available data, the models are able to give good match with observed data of the next seven months, which is confirmed by different statistical test methods. In future, the reliability of the generated equations can be tested and analogous study can be extended over the glacier. The present research is valuable in the studies of glacio-meteorology, filling the gap of meteorological data over the high-altitude glacierized regions, and modelling of glacier melt as there is a prerequisite to correlate altitudinal weather parameters.

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