Study Area, Instrumentation and Data Acquisition
3.1 Chorabari Glacier: Geographical and Climate Setting

The Chorabari Glacier valley lies between latitudes of N 30°41’ to 30°48’ and longitudes of E 79°1’ to 79°6’; comprises catchment area of 63.8 km$^2$ in the Mandakini River basin (1,657 km$^2$), upper Ganga catchment, Garhwal Himalaya, Uttarakhand (Fig. 3.1). In this valley, two well constrained valley glaciers (the Chorabari and the Companion glaciers) and four unnamed small glaciers (including ice apron, hanging glaciers, glacierete and cirque glacier) are identified covering an area of about 16 km$^2$ (25 % of total area). The Chorabari (a compound valley type bench mark glacier) is the largest glacier (7.5 km) and can be considered as representative glacier of the valley.

The Chorabari Glacier located on the southern slope of the Mandakini basin. It is a medium-sized (6.66 km$^2$) and extends between altitude 6400 and 3895 m from North to South with an average bed slope of 20°. The accumulation area (2.99 km$^2$) is formed by two cirque glaciers below from the Bhartekhunta (6578 m a.s.l.) and the Kedar peaks (6940 m a.s.l.). A number of longitudinal and transverse crevasses are observed in the accumulation zone (6400-5200 m a.s.l.) and near the ELA (5080 m a.s.l. in 2010). The ablation area (3.67 km$^2$) is wide (0.1-0.4 km) with a gentle slope and is covered with substantial amount of the supraglacial debris (Fig. 3.2). Debris-covered area accounts for ~ 80 % of total ablation area (~53 % of total glacier area) and thickness of debris (ranging from ~ 2 to 220 cm) increases along the glacier flow-line (Dobhal et al., 2013a; Kesarwani et al., 2015).
Fig. 3.1. (a) Location map of study area (b) and Upper Mandakini basin with location of the Chorabari Glacier catchment. (Background image: SRTM DEM of 90 m spatial resolution).
Fig. 3.2. Synoptic view of the Chorabari Glacier showing different surface features.
The characteristic feature of this glacier is that it has a large ablation area and small accumulation area, exceptionally found in the Himalaya. In addition, few small supraglacial water ponds (lakes) are marked in the ablation zone (5000-3895 m a.s.l.) below 4200 m a.s.l. which are generally drained out at the end of the summer or frozen during the winter (Fig. 3.2). These water ponds are unstable in their characteristics and a common phenomenon of their formation and depletion is over the ablation area. The snout (3895 m a.s.l.; source of the Mandakini River) of this glacier is wide (＞200 m) with arched shaped containing large amount of supraglacial debris in the middle portion (＞200 cm thick).

There is another glacier named the Companion Glacier (Length: 4.5 km; Area: 3.5 km$^2$ in 2010) which flows parallel to the ablation area of the Chorabari Glacier ranging from 3810 to 4250 m a.s.l. Chaujar et al. (2009) reported that in past this valley has one main glacier which was separated in two parts (Chorabari and Companion glacier) by medial moraine due to shrinkage. The Companion Glacier does not have a well-defined accumulation area and generally, accumulates mass through sliding snow avalanches. It is covered with thick layers of supraglacial debris (＞80 % glacier area). Extension of lateral moraines in the Mandakini valley is observed up to ~8 km downstream at Rambara town (2760 m a.s.l.), showing the evidences of past glacier extension (Mehta et al., 2012). Now, this town has been completely washed away during the recent devastation that occurred in the valley on 16 June 2013 (Dobhal et al., 2013b). Salient features and geomorphological characteristics of the Chorabari Glacier are given in Table 3.1. Like most of the glaciers in the Himalayan region, the Chorabari Glacier has also been losing its mass over the past century and probably at an increasing rate (Dobhal et al., 2013a; Mehta et al., 2014; Kesarwani et al., 2015). Monitoring of this glacier began in 2003 with setting up of the Conventional Meteorological Observatory (CMO; 3820 m a.s.l.) near the snout (Dobhal et al., 2013a). Dobhal et al., (2013a) estimated that from 1962 to 2010, the glacier has retreated about 327 m with an average recession rate of 6.8 m a$^{-1}$. The average specific mass balance was estimated as - 0.73 m w.e. a$^{-1}$ from 2003 to 2010. Further, Mehta et al. (2014) estimated that the frontal area of this glacier has been shrunk by 1 % showing loss of 344 ± 24 m in length, with an average recession rate of 6.8 ± 0.5 m a$^{-1}$ from 1962 to 2012. Geologically, the area falls under the north of the Pindari Thrust. It comprises of augen and granitic gneisses, calc-silicate schist, granite and pegmatite apatite veins belonging to the Pindari Formation (Valdiya et al., 1999).
### Table 3.1. Salient features and geomorphological parameters of the Chorabari Glacier.

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glacier Name</td>
<td>Chorabari Glacier</td>
</tr>
<tr>
<td>Glacier ID</td>
<td>5O 132 02 003</td>
</tr>
<tr>
<td>Coordinates</td>
<td>30°46′20.58″ N, 79°2′59.381″ E</td>
</tr>
<tr>
<td>Basin Name</td>
<td>Mandakini</td>
</tr>
<tr>
<td>Basin ID</td>
<td>5O 132 02</td>
</tr>
<tr>
<td>SOI Toposheet No.</td>
<td>53 N/1 and 53 N/2</td>
</tr>
<tr>
<td>Location</td>
<td>Rudraprayag (District), Uttarakhand (State), India (Country)</td>
</tr>
<tr>
<td>Landmark</td>
<td>Kedarnath Town</td>
</tr>
<tr>
<td>Elevation extension</td>
<td>6420-3895 m a.s.l.</td>
</tr>
<tr>
<td>Surface Area</td>
<td>~ 6.66 km²</td>
</tr>
<tr>
<td>Length</td>
<td>~ 7.5 km</td>
</tr>
<tr>
<td>Orientation</td>
<td>South</td>
</tr>
<tr>
<td>Average Surface Slope</td>
<td>20°</td>
</tr>
<tr>
<td>Mean Total Width</td>
<td>0.43 km</td>
</tr>
<tr>
<td>Mean Depth†</td>
<td>80 m</td>
</tr>
<tr>
<td>Ice Volume†</td>
<td>0.982 km³</td>
</tr>
<tr>
<td>Snout</td>
<td>3895 m a.s.l.</td>
</tr>
<tr>
<td>Accumulation Area -</td>
<td></td>
</tr>
<tr>
<td>Elevation extension</td>
<td>6420-5100 m a.s.l.</td>
</tr>
<tr>
<td>Area</td>
<td>~ 2.99 km²</td>
</tr>
<tr>
<td>Length</td>
<td>2.77 km</td>
</tr>
<tr>
<td>Slope</td>
<td>30°</td>
</tr>
<tr>
<td>Orientation</td>
<td>South</td>
</tr>
<tr>
<td>Characteristic Features</td>
<td>Small and having steep slope, formed by two tributary glaciers</td>
</tr>
<tr>
<td>Ablation Area -</td>
<td></td>
</tr>
<tr>
<td>Elevation extension</td>
<td>5000-3895 m a.s.l.</td>
</tr>
<tr>
<td>Area</td>
<td>~ 3.67 km²</td>
</tr>
<tr>
<td>Length</td>
<td>4.73 km</td>
</tr>
<tr>
<td>Slope</td>
<td>10°</td>
</tr>
<tr>
<td>Orientation</td>
<td>South-East</td>
</tr>
<tr>
<td>Characteristic Features</td>
<td>Thickly debris covered, supraglacial lakes, bounded by well developed lateral moraines,</td>
</tr>
<tr>
<td>Equilibrium-Line Altitude (ELA)</td>
<td>5070 m a.s.l. in 2010 (Dobhal et al., 2013a)</td>
</tr>
<tr>
<td>Accumulation-Area Ratio (AAR)</td>
<td>0.44</td>
</tr>
<tr>
<td>Accumulation/Ablation Area Ratio</td>
<td>1 : 1.6</td>
</tr>
<tr>
<td>General Climate</td>
<td>Humid temperate in summer and dry cold in winter</td>
</tr>
<tr>
<td>Geology (Rock type)</td>
<td>Crystalline rocks, mainly augen and granitic gneisses</td>
</tr>
</tbody>
</table>

*SOI- Survey of India
†Raina and Srivastava, 2008
To understand the seasonal variability in meteorological parameters, an Automatic Weather Station (AWS) was installed in May 2007 with upgrading the CMO (Dobhal et al., 2013a). The observed daily mean air temperature fluctuates between +12°C and -18°C (June – October). Similarly, the average daily sunshine duration was 190 min and wind speed was 2.5 m s⁻¹. The average rainfall (at CMO) was recorded to be 1253 mm (June-October) between 2007 and 2010 (Dobhal et al., 2013a). However, the winter precipitation generally occurs between December and March when the WD is dominant and the area receives maximum snow accumulation during this period. Since, adequate surface melting is observed in the month of October, a fixed date system from 01 November to 31 October of the following year (glaciological / hydrological / mass-balance year) is used for the estimation of annual surface mass budget and the surface energy balance modelling. The climate of the study area is humid-temperate in the summer (May-October) and dry-cold in the winter (November - April). The Mandakini basin receives precipitation (Rain/Snow) with both the Indian Summer Monsoon (ISM) during the summer and the Western Disturbance (WD) during the winter (Mehta et al., 2012; Dobhal et al., 2013a).

3.1.1 Debris Characteristics

One of the most important characteristic features of the Chorabari Glacier is that its ablation zone is covered with thick layers of supraglacial debris. The supraglacial debris layer is found to be highly heterogeneous, from silt size to big boulders exceeding several meters. The supraglacial debris layer is composed of different rock types that have different reflective (albedo) and thermal properties (thermal conductivity, thermal resistance, thermal inertia, emissivity etc.) consequently variable impacts on the surface energy balance of a glacier. Therefore, the knowledge and mapping of lithological composition of the supraglacial debris is of great importance as composition of debris will have direct bearing on energy interactions within the debris layer which in turn influence the surface velocity and ablation rates of the ice beneath the debris layer. Petrographic analysis on major rock type supraglacial debris collected from ablation zone carried out to identify the supraglacial debris characteristics. Results suggested that the supraglacial debris comprises predominantly of gneissic rock which includes augen gneiss, banded
gneiss, felsic gneiss and fine-grained gneiss with some mixture of calc silicate schist, meta-sedimentary, amphibolites, leucogranite and marble rocks.

### 3.1.2 Debris Thickness Measurement

Debris thickness measurements were performed over the ablation zone by dividing the area into twelve horizontal (area-altitude) zones from 3900 to 5000 m a.s.l. with 100 m contour interval (Fig. 6.1 of Chapter 6). 60 measurements in each altitude zone (20 measurements each in left, right and central part) were performed except for the upper ablation zone (> 4600 m a.s.l.) where the area is steep as well as crevasse-prone and average debris thickness was measured ~ 10 cm. Debris thickness between < 3900 and 4600 m a.s.l. shows large variability and non-linearity in distribution and average debris thickness was estimated to be 25 cm in the ablation zone with maximum thickness of 220 cm measured in the central portion of terminal zone.

### 3.2 Instrumentation

To study the various meteorological parameters on the local as well as regional scale, and their effect on surface ablation rate of the Chorabari Glacier, different automatic and non-automatic instruments are used. The detailed description of these instruments are given as-

#### 3.2.1 Automatic Weather Station (AWS)

The long and continuous meteorological records can be easily obtained by using AWS (Oerlemans, 2000; Reijmer and Oerlemans, 2002). A network of three AWSs (K1, K2 and K3) was setup in the Chorabari Glacier catchment during October 2011 at different altitudes (Fig. 3.3). K1 AWS (4270 m a.s.l.; Glacier Camp), was set up on the bed of debris-covered ice which is near the confluence of the Chorabari and a tributary glaciers. K2 (3820 m a.s.l.; Base Camp) was installed near the snout and K3 (2760 m a.s.l.; Rambara) was set up at the right bank of the Mandakini River in Rambara town (non glacierized area). K1, K2 and K3 sites represents three distinctive regime viz. glacierized, transitional and non glacierized zone, respectively of the valley.
Fig. 3.3. Locations of meteorological observatories (K1, K2 and K3) in a satellite image of the Chorabari Glacier valley, Garhwal Himalaya taken by ASTER on November 22, 2007. Photograph showing the AWSs sites for glacierized (K1), transitional (K2) and non-glacierized (K3) zone at different altitude of the valley.

List of Automatic Weather Stations set up in the Chorabari Glacier valley and their locations are given in Table 3.2. The AWSs are equipped with sensors of air temperature ($T_a$), relative humidity ($R_h$), surface temperature ($T_s$, at K1 AWS only) incoming and outgoing shortwave radiation ($S↓$ and $S↑$), Net Radiation ($R_n$), wind speed and direction ($W_s$ and $W_d$), atmospheric pressure ($P_a$), Snow depth ($h$) and rainfall ($R$) measurement. These sensors are connected with CR-1000 (Campbell Scientific) data logger for storing the data on diurnal and daily basis. Details of meteorological parameters and specification of measurement sensors are described in
Table 1. The comprehensive description of each sensor and data logger installed at AWSs are-

**Table 3.2.** Description of Automatic Weather Stations installed in the Chorabari Glacier valley.

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Station Name (zone)</th>
<th>Abbreviation</th>
<th>Altitude (m a.s.l.)</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Glacier Camp (Glacierized)</td>
<td>K1</td>
<td>4270</td>
<td>30°46’3.19”N-79°03’03.56”E</td>
</tr>
<tr>
<td>2.</td>
<td>Base Camp (Transitional)</td>
<td>K2</td>
<td>3820</td>
<td>30°44’42.8”N-79°03’48.4”E</td>
</tr>
<tr>
<td>3.</td>
<td>Rambara (Non-Glacierized)</td>
<td>K3</td>
<td>2760</td>
<td>30°41’50.0”N-79°03’21.2”E</td>
</tr>
</tbody>
</table>

(a) **Air Temperature and Relative Humidity Probe (HC2S3)**

Air temperature and relative humidity records were collected using HC2S3 probe (Fig. 3.4). The probe contains two sensors- (i) 100 Ω PRT sensor for air temperature measurements and (ii) Rotronic’s IN1 capacitive sensor to measure the relative humidity. The sensor measures the temperature in the range of -40°C to +60°C and relative humidity in the range of 0-100%. It is a digital probe with 0 to 1 V linear output signals for temperature and humidity.

![HC2S3](image)

**Fig. 3.4.** (A) HC2S3 temperature and Relative humidity measurement probe and (B) HC2S3 covered with radiation shield at field site.
(b) Infrared Temperature Sensor (4000.4ZL)

Surface temperature measurement was recorded by analog infrared temperature sensor (Fig. 3.5). The sensor measures the temperature from -40°C to 50°C with a resolution of 0.1°C and accuracy of ±0.5°C. Output of the sensor is analog millivolt (10 mV/°C).

![Infrared Temperature Sensor](image)

**Fig. 3.5.** Analog infrared temperature sensor (4000.4ZL) for measuring the surface temperature.

(c) Wind Speed and Direction Sensor (05103 Wind monitor)

For measuring the horizontal wind speed and direction, a wind propeller (Young 05103) was used (Fig. 3.6). The sensor is a helicoids-shaped, four-blade propeller. Rotation of the propeller produces AC sine wave signal with frequency proportional to wind speed.

![Wind Propeller](image)

**Fig. 3.6.** Wind monitor sensor for measuring the horizontal wind speed and direction.
The wind monitors use a potentiometer (10 kΩ) to measure wind direction. With a precision excitation voltage applied, the output voltage is proportional to wind direction. The sensor measures the wind speed up to 100 m s\(^{-1}\) with an accuracy of 0.3 m s\(^{-1}\) or 1 % of the reading. Similarly, it can measure the wind direction up to 355° (5° open) with an accuracy of ± 3°.

**(d) Pyranometer (CMP3-L)**

Global incoming solar radiation is measured by Kipp & Zonen CMP3-L Pyranometer (Fig. 3.7). The sensor contains blackened (black absorbent coating) thermopile which provides a flat spectral response (from 300 to 3000 nm) for the measurement of full solar spectrum range and allow the sensor for reflected radiation measurements or when sky is cloudy. To protect the thermopile from external influences, it is covered with a robust 4 mm thick glass dome. The thermopile absorbs the radiation and converts it to heat. As a result due to temperature difference, an electromagnetic field is generated and this produces a millivolt signal which is measured directly by CR-1000 data logger and expressed in W m\(^{-2}\). For measuring the reflected/outgoing shortwave radiation another CMP3-L pyranometer is mounted back-to-back (Fig. 3.7). The typical accuracy of these sensors are ± 5 %.

![CMP3-L Pyranometer](image)

**Fig. 3.7.** Two CMP3-L pyranometer set up back-to-back for measuring the incoming and outgoing/reflected shortwave radiations.
(e) Net Radiometer (NR-LITE)

The energy balance between incoming shortwave and longwave infrared radiations relative to surface reflected shortwave and outgoing longwave infrared radiations were directly measured in the field by using Kipp & Zonen NR-LITE Net radiometers (Fig. 3.8). This sensor includes two high output blackened thermopile - (i) one facing upward and (ii) the other facing downward. Both the thermopile is coated with Teflon which makes them resistant to any weather condition. The upwards facing thermopile measures the solar energy and far infrared energy that is received from the entire hemisphere (180°-field of view). However, the downwards facing thermopile measures the energy reflected / emitted from the surface. Obtained readings are automatically subtracted and the result converted to a single output millivolt signal that is measured directly by a Campbell Scientific CR-1000 data logger. This output represents the net radiation and expressed in W m\(^{-2}\). Used thermopiles are calibrated to an identical sensitivity coefficient.

![Net Radiometer (NR-LITE) for measuring the energy balance between incoming and outgoing all-wave radiation.](image)

(f) Sonic Ranging Sensor (SR50A)

Snowfall measurements were performed by using sonic ranging sensor (SR50A) which measures the distance from the sensor to target with an accuracy of ± 1 cm (Fig. 3.9). The sensor is based on a 50 kHz (Ultrasonic) electrostatic transducer. The sensor makes use of a unique echo processing algorithm to ensure measurement
reliability. It sends out ultrasonic pulses and listen the returning echoes that are reflected from the surface. Based on the time from transmissions to return of an echo it calculates the distance measurement. The sensor is capable of picking up small targets which are highly absorptive to sound, such as low density snow.

![Sonic Ranging Sensor (SR50A) for snowfall measurement.](image)

**Fig. 3.9.** Sonic Ranging Sensor (SR50A) for snowfall measurement.

#### (g) Barometric Pressure Sensor (61302V)

Atmospheric pressure of the area is measured by using the 61302V Barometric Pressure Sensor (Fig. 3.10). The sensor measures the atmospheric pressure in the range of 500 to 1100 hPa.

![Barometric Pressure Sensor (61302V) for measuring the atmospheric pressure.](image)

**Fig. 3.10.** Barometric Pressure Sensor (61302V) for measuring the atmospheric pressure.
(h) **Tipping Bucket Rain Gage (TE525M)**

Rainfall measurements were carried out by using a Tipping Bucket Rain Gage (TE525M). The sensor measures rainfall in 0.1 mm increments (3.11).

![Tipping Bucket Rain Gage](image)

**Fig. 3.11.** Tipping Bucket Rain Gage (TE525M) for rainfall measurements.

(i) **Conventional Rain Gauge (IS 5225)**

Besides the automatic rain gauge, an ordinary rain gauge (certified by Indian Meteorological Department, Pune) was also installed at K2 observatory to collect the rainfall data during the summer monsoon of every year (Fig. 3.12). The rain gauge consists of a rain water collector (2 liters) and a measuring bottle having markings on it. The rain collector funnel area is 200 cm\(^2\).

![Conventional Rain Gauge](image)

**Fig. 3.12.** Conventional Rain Gauge (IS 5225) for rainfall measurements.
(j) Data Logger (CR-1000)

The CR1000 data logger is widely used to collect the data in long-term climatological monitoring, meteorological research, and routine weather measurement applications (Fig. 3.13). It provides precision measurement capabilities in a rugged, battery operated package. The data logger consist a measurement & control module and a wiring panel. The module measures all the connected sensors, drives direct communications and telecommunications, controls external devices, reduces data and stores data & operating programs in on-board, non-volatile storage. However, the wiring panel includes switchable 12 V, redistributed analog grounds, un-pluggable terminal block for 12 V connections, gas-tube spark gaps, and 12 V supply on pin 8 to power communication series. Recorded data is stored in a table format. The storage capacity of the data logger is 2 MB which is increased by using a 1 GB compact flash card. An inbuilt battery-backed clock assures accurate time keeping.

![Synoptic view of installed CR-1000 data logger.](image)

Fig. 3.13. Synoptic view of installed CR-1000 data logger.

(k) Tower Base

A 10 m tower (having 5 sections of 2 m each) with concrete base was installed to mounting all the equipments in each site. The structure is coupled with 3 supporting hard cables so that it can bear the force of wind speed \( > 50 \text{ m s}^{-1} \). In addition, to protect it from lightning, we have fixed the tower with a copper base plate of \( 2 \times 2 \) feet and earthen protection of good quality. Complete set-up of AWS tower with installed sensors are given in Fig. 3.14.
Fig. 3.14. AWS installed at upper ablation zone (4270 m a.s.l.) of the Chorabari Glacier showing a complete set up of meteorological sensors mounted in 10 m tower. (Photo: May, 2012)
### Table 3.3. Details of meteorological parameters and sensors of AWS with specifications.

<table>
<thead>
<tr>
<th>Meteorological Elements</th>
<th>Symbol (Unit)</th>
<th>Range</th>
<th>Stated Accuracy</th>
<th>Resolution</th>
<th>Scanned time</th>
<th>Manufacturer (Model)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Temperature</td>
<td>( T_a ) (°C)</td>
<td>-40° to +60°C</td>
<td>± 0.1°C</td>
<td>15 s</td>
<td>30 s</td>
<td>Rotronic Instrument Corporation</td>
</tr>
<tr>
<td>Surface Temperature</td>
<td>( T_s ) (°C)</td>
<td>-40° to +100°C</td>
<td>± 0.5°C</td>
<td>0.1°C</td>
<td>&lt; 1 s</td>
<td>Everest Interscience (4000.4ZL)</td>
</tr>
<tr>
<td>Relative Humidity</td>
<td>( R_h ) (%)</td>
<td>0 to 100%</td>
<td>± 0.8%</td>
<td>15 s</td>
<td>30 s</td>
<td>Rotronic Instrument Corporation</td>
</tr>
<tr>
<td>Net Radiation</td>
<td>( R_n ) (W m(^{-2}))</td>
<td>± 2000 W m(^{-2})</td>
<td>± 5%</td>
<td>20 s</td>
<td>5 s</td>
<td>Kipp &amp; Zonen (NR-LITE)</td>
</tr>
<tr>
<td>Incoming Radiation</td>
<td>( S_\downarrow ) (W m(^{-2}))</td>
<td>2000 W m(^{-2})</td>
<td>± 5%</td>
<td>18 s</td>
<td>5 s</td>
<td>Kipp &amp; Zonen (CMP3-L)</td>
</tr>
<tr>
<td>Outgoing Radiation</td>
<td>( S_\uparrow ) (W m(^{-2}))</td>
<td>2000 W m(^{-2})</td>
<td>± 5%</td>
<td>18 s</td>
<td>5 s</td>
<td>Kipp &amp; Zonen (CMP3-L)</td>
</tr>
<tr>
<td>Wind Speed</td>
<td>( W_s ) (m s(^{-1}))</td>
<td>0-100 m s(^{-1})</td>
<td>± 0.3 m s(^{-1})</td>
<td>0.098 m s(^{-1})</td>
<td>5 s</td>
<td>RM Young (Young 05103)</td>
</tr>
<tr>
<td>Wind Direction</td>
<td>( W_d ) (°)</td>
<td>0-360° Mechanical</td>
<td>± 3°</td>
<td></td>
<td></td>
<td>RM Young (Young 05103)</td>
</tr>
<tr>
<td>Atmospheric Pressure</td>
<td>( P_a ) (h Pa)</td>
<td>500 to 1100 hPa</td>
<td>± 0.3 h Pa (-40° to +60°C)</td>
<td>0.01 h Pa</td>
<td>1 h</td>
<td>Campbell Scientific (61302V)</td>
</tr>
<tr>
<td>Snow depth</td>
<td>(m)</td>
<td>0.5 to 10 m</td>
<td>± 0.01 m or 0.4% of distance of target</td>
<td>Less than 1.0 s</td>
<td>30 s</td>
<td>Texas Scientific (SR50A)</td>
</tr>
<tr>
<td>Rainfall</td>
<td>( R_T ) (mm)</td>
<td>0-1000 mm</td>
<td>+ 0.35% (2 to 3 inch/h)</td>
<td>1 tip</td>
<td>1 h</td>
<td>Texas Scientific (TE525M)</td>
</tr>
<tr>
<td>Rainfall</td>
<td>( R_o ) (mm)</td>
<td>0-4000 ml</td>
<td>1.0 mm</td>
<td>-</td>
<td>Data collection (0830 &amp; 0530 h; IST*)</td>
<td>OrdinaryNon-Recording Rain Gauge (IS 5225)</td>
</tr>
<tr>
<td>Data Logger</td>
<td></td>
<td>-55° to 50°C (operating temperature)</td>
<td>± (0.12% of reading + offset), -25° to 50°C</td>
<td>0.67 μV</td>
<td>5 s</td>
<td>Campbell Scientific (CR 1000)</td>
</tr>
</tbody>
</table>

*IST represents Indian Standard Time zone
Details of meteorological parameters and measurement sensors of AWS with specifications are given in Table 3.3. For each sensor, sample frequency varies and data of each sensor is sampled at every 10 minutes intervals excluding wind direction (5 min average wind speed values are used for the vectorial averaging procedure of the wind direction estimate), rainfall (1 h total), air pressure (1 h) and snow depth (sample frequency 1 h, instantaneous value), then converted into hourly mean values. The hourly mean values stored on a Campbell CR-1000 data logger with separate memory module. Power was supplied to AWS by 12 V sealed maintenance free battery which was continuously charged through 18 V solar panel (directed towards south). Instead of an automatic rain gauge, an ordinary non-automatic rain gauge was also installed at K2 observatory to collect the rainfall during the summer season of every year. On an average during the summer (as access to the glacier in winter is restricted), K1 was monitored every week while K2 and K3 were regularly monitored.

3.2.2 Steam-Driven Heucke Ice Drill

The Steam-Driven Heucke Ice drill was used for drilling the holes in the glacier surface to insert the wooden stakes for ablation and accumulation measurements (Fig. 3.15). As the name suggest, this is working on the principal of steam generation through boiling of the water and generated steam was used to make hole into the ice. The equipment contains an aluminum chamber in which water is heated by two gas flames to produce steam, which flows through an insulated hosepipe to a nozzle. Propane gas cartridge was used to light the flame. When the gas pressure valve is opened the issuing steam condenses, and the heat released which is used through a drilling pipe. The pipe outlet diameters range from 25 to 45 mm and maximum drilling depth of the equipment is 15 m in the ice. Technical details of the instrument are given in Table 3.4.
Fig. 3.15. Portable Steam-Driven Heucke Ice Drill.

Table 3.4. Technical details of Steam-driven Heucke ice drill.

<table>
<thead>
<tr>
<th>Particulars</th>
<th>Technical details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boiler Volume</td>
<td>5 litres</td>
</tr>
<tr>
<td>Operating Temperature</td>
<td>115 to 130°C</td>
</tr>
<tr>
<td>Operating pressure</td>
<td>0.8 to 1.9 bar</td>
</tr>
<tr>
<td>Heating</td>
<td>1 Gas burner (4.4 kW; working pressure 80 mbar)</td>
</tr>
<tr>
<td>Fuel</td>
<td>Propane or Butane</td>
</tr>
<tr>
<td>Gas consumption</td>
<td>360 gram/hour</td>
</tr>
<tr>
<td>(for 1 m drilling in ice 15 to 20 grams used)</td>
<td></td>
</tr>
<tr>
<td>Time needed to heat up</td>
<td>12 to 15 minutes (from 0 to 100°C with full boiler)</td>
</tr>
<tr>
<td>Operation time</td>
<td>45 to 60 minutes (with one full boiler)</td>
</tr>
<tr>
<td>Drilling speed</td>
<td>11 to 15 minutes to drill a hole of 6 m into ice</td>
</tr>
<tr>
<td>Hole diameter</td>
<td>25-45 mm</td>
</tr>
<tr>
<td>Maximum drilling depth</td>
<td>15 m (= length of hose)</td>
</tr>
</tbody>
</table>
3.2.3 Density Measurement Kit

Density of snow/ice is an important component in the mass balance measurement. A density measurement kit was used for measuring the density of snow/firn/ice (Fig. 3.16). The kit contains two 1000 cc and one 500 cc tube style stainless steel cylinder, weighing machine and a measurement tape.

![Density Measurement Kit](image)

*Fig. 3.16. Snow/Firn/Ice density measurement kit.*

3.2.4 Accumulation-Ablation Stakes

The eco-friendly wooden stakes (especially bamboo) were used to measure the glacier surface ablation (Fig. 3.17). The stakes used for measurement are of length ~ 220 cm and their diameters ranges from 30 to 40 mm. Generally, steel or aluminum stakes are widely used for glacier surface ablation / accumulation measurements. The most significant drawback of using metallic stakes is that they are good conductor of heat and during the day they gets more warmer as compare to the surrounding near-surface air temperature which results more melt surrounding of the stake location in nearby area of the stake. This may create error in surface melting measurements. However, the wooden stakes such as bamboo are the most reliable compared to metallic stake and have high insulating property, consequently the bad conductor of heat which helps in reducing the errors of melting measurements. The most important benefits of using the bamboo stakes is that they are eco-friendly, easily decomposed, cost effective and light weighted.
Study Area, Instrumentation and Data Acquisition

3.2.5 Hand-Held GPS (Global Positioning System)

For obtaining the location of accumulation-ablation stakes over the glacier surface, AWS, snout position and tracking, a hand-held Magellan eXplorist 310 GPS Receiver with vertical accuracy (z) 1–5 m and horizontal accuracy (x, y) 3 m (0.01’) was used (Fig. 3.18).

Fig. 3.17. Accumulation-Ablation wooden stake (bamboo).

Fig. 3.18. Magellan eXplorist 310 GPS Receiver.
3.2.6 Total-Station

Total-Station (*Leica Geosystems* TPS1201+), is used for the high accuracy angle measurements and precise long-range distance measurements backed by automatic fine pointing and fast, reliable reflector location. The range of this equipment integrated with Global Navigation Satellite System (GNSS), is 3 km to a single prism that has the accuracy of 1 mm + 1.5 ppm and resolution 0.1 mm. This instrument was used for surveying changes in the terminus position, change in terminus area and computation of Chorabari Glacier area (Fig. 3.19).

![Total Station (Leica Geosystems TPS1201+)](image)

**Fig. 3.19.** Total Station (*Leica Geosystems* TPS1201+)

3.2.7 Planimeter

A planimeter is a measuring precision instrument which is widely used to compute the area of an arbitrary two-dimensional shape (Fig. 3.20). It has two arms - One arm is weighted at one end and has a pin point that rests on the table surface, and the other end fits into a hole in the second arm. The surface area of a basin can be found easily from the map through the use of a planimeter.
The GPS, Total Station and planimeter are surveying equipments and frequently used in the mapping of staking networking, glacier features, snout position as well as tracking the route and location marking of equipments over the glacier catchment.

3.3 Data Acquisition

The meteorological parameters were collected automatically through AWS whereas glacier surface ablation measurements were carried out manually. The detailed description of collecting both the meteorological as well as surface ablation data is given below-

3.3.1 Meteorological Data: AWS Programme

To collect the meteorological data at minute, hourly and daily timestamp, a programme was written for CR-1000 data logger. The developed programme is used in all the stations with some small changes in the atmospheric pressure and radiative fluxes. As the atmospheric pressure measurements depends on the geographical location and altitude of the location while the radiative fluxes measurements depends on the sensitivity of the sensor which is different for each sensor. The encoded programme for accurately measuring the sensor data is given as -
**Chapter 3**

********************************************************************************************
*PROGRAM FOR Automatic Weather Station–WIHG©

*Copyright © Wadia Institute of Himalayan Geology, Dehradun
*06TH October 2011
*Coded by Kapil Kesarwani, Researcher
*Center for Glaciology
*Wadia Institute of Himalayan Geology, Dehradun, Uttarakhand
*Email: kapilcfg@gmail.com, +91-9548730193
********************************************************************************************

********************************************************************************************
'MEASURING: HC2S3, 05103-10, 2 CMP3s, SR50A, NR-LITE, 61302V, 
'TE525M
'This program is written for CR-1000 data logger
*CM3 S/N 070936 Sensitivity 16.89 µV/W/m^2 facing skyward
*CM3 S/N 070938 Sensitivity 15.50 µV/W/m^2 facing downward
*NR LITE S/N 062352 Sensitivity 13.5 µV/W/m^2
*SR50A Set to SDI-12 address 0
'The distance must be measured from the SR50 to the bare
*ground (surface)
'AFTER INSTALLATION AND ENTERED AS CONSTANT (in meters) USING
*Numeric Mode
********************************************************************************************

'Data Output: Hourly and Daily

'Hourly Parameters

'Date and Time
'Average Air Temperature in DegC
'Maximum Air Temperature in DegC
'Minimum Air Temperature in DegC
'Sample Relative Humidity in %
'Wind Vector and Average Wind Direction in deg and Wind Speed
'in m/s
'Average SRad_In in W/m2
'Average SRad_Out in W/m2
'Albedo
'Totalize Sun Duration in Min
'Average Corrected Net Radiation in W/m2
'Sample Snow Depth in cm
'Total Rainfall/Snowfall in the hour
'Sun_Dur In minutes (cumulative for every hour through 24
hours and 'then reset. The resolution is 0.5 minute.
'Sun Duration Equation: If Rad_In >120 ÂµV/W/m2 then
'Sun_Dur = Sun_Dur + 0.5 every 30 seconds
'Average Snow Surface Temperature
'Maximum Snow Surface Temperature
'Minimum Snow Surface Temperature
'Daily Minimum Parameter Logging
'Minimum Battery Voltage in Volts
'Maximum Battery Voltage in Volts
'Minimum Air Temperature in DegC
'Maximum Air Temperature in DegC
'Average Air Temperature in DegC
'Minimum Relative Humidity in %
'Maximum Relative Humidity in %
'Wind Vector and Average Wind Speed in m/s
'Totalize Sun Duration in min
'Average Snow Depth in cm
'Total Rain/Snow fall of the day
'Maximum Snow Surface Temperature
'Minimum Snow Surface Temperature
'Average Snow Surface Temperature

'Declare Variables and Units
Public Batt_Volt
Public Air_Temp As Float
Public RH As Float
Public W_Spd As Float
Public W_Dir As Float
Public SRad_In As Float
Public SRad_Out As Float
Public Albedo As Float
Public Sun_Dur As Float
Public Constant As Float 'Enter the distance from SR50 to bare ground
Public Snow_Depth As Float
Public Quality As Float
Public NR_Wm2 As Float
Public Rain As Float
Public SST As Float
Public Snow_Depth_Corr As Float 'corrected distance
Public Press
Public Press_Corroten
Public e_hmp
Public e_sat_vp
Public VPD
Public Dew_point
Public SrkJ_SI
Public SrkJ_SOut
Public ET

'Declare Constants
Const Elevation = 4270
'This value must be added in order to correct for elevation (meters).

'Dim NR_Wm2 As Float
Dim SR50(2) As Float
Alias SR50(1) = Distance1
Alias SR50(2) = QLTY
Chapter 3

Units Batt_Volt = Volts
Units Air_Temp = Deg C
Units RH = %
Units W_Spd = meters/second
Units W_Dir = Degrees
Units SRad_In = W m^-2
Units SRad_Out = W m^-2
Units SlrkJ_Sin = kJ
Units SlrkJ_SOut = kJ
Units Sun_Dur = min
Units Albedo = %
Units Snow_Depth = Meter
Units Snow_Depth_Corr = Meter
Units NR = W m^-2
Units Rain = mm
Units SST = Deg C
Units Dew_point = %
Units e_satvp = kpa
Units e_hmp = kpa
Units VPD = kpa
Units ET = mm

'Define Data Tables
DataTable (Min_1,True,-1)
   CardOut (0,-1)
   DataInterval(0,1,Min,10)
   Average (1,Air_Temp,FP2,False)
   Average (1,RH,FP2,False)
EndTable

DataTable(Hourly,True,-1)
   CardOut (0,-1)
   DataInterval(0,60,Min,10)
   Average (1,Air_Temp,FP2,False)
   Maximum (1,Air_Temp,FP2,False,False)
   Minimum (1,Air_Temp,FP2,False,False)
   Sample  (1,RH,FP2)
   Average (1,RH,FP2,False)
   Maximum (1,RH,FP2,False,False)
   Minimum (1,RH,FP2,False,False)
   WindVector (1,W_Spd,W_Dir,FP2,False,0,0,0)
   FieldNames("W_Spd_S, W_Dir_D1, W_Dir_SD1")
   Average (1,SRad_In,FP2,False)
   Average (1,SRad_Out,FP2,False)
   Average (1,SlrkJ_SIn,IEEE4,False)
   Average (1,SlrkJ_SOut,IEEE4,False)
   Average (1,Albedo,FP2,False)
   Maximum (1,Sun_Dur,FP2,False,False)
   Average (1,NR_Wm2,IEEE4,False)
   Sample  (1,Snow_Depth,FP2)
   Average (1,Snow_Depth,FP2,False)
   Sample  (1,Snow_Depth_Corr,FP2)
   Average (1,Snow_Depth_Corr,FP2,False)
Average (1,Press,FP2, False)
Average (1,Press_Corrtosl,FP2, False)
Totalize (1, Rain,FP2, False)
Average (1, VPD,FP2, False)
Average (1, e_hmp,FP2, False)
Average (1, e_sat_vp,FP2, False)
Average (1, Dew_point,FP2, False)

ETsz(Air_Temp,RH,W_Spd,SlrkJ_SIn,78.8098,30.8630,4364,10,0,FP2,False)
FieldNames("ET,Rso")
Average (1,SST,FP2,False)
Maximum (1,SST,FP2,False,False)
Minimum (1,SST,FP2,False,False)

EndTable

DataTable(Daily,True,−1)

CardOut (0,−1)
DataInterval (1439,1440, Min, 10)
Minimum (1,Batt_Volt,FP2,False,False)
Maximum (1,Batt_Volt,FP2,False,False)
Minimum (1,Air_Temp,FP2,False,False)
Maximum (1,Air_Temp,FP2,False,False)
Average (1,Air_Temp,FP2,False)
Minimum (1,RH,FP2,False,False)
Maximum (1,RH,FP2,False,False)
Average (1,RH,FP2,False)
WindVector (1,W_Spd,W_Dir,FP2,False,0,0,0)
FieldNames("W_Spd_S, W_Dir_D1, W_Dir_SD1")
Average (1,SRad_In,FP2,False)
Average (1,SRad_Out,FP2,False)
Average (1,SlrkJ_SIn,IEEE4,False)
Average (1,SlrkJ_SOut,IEEE4,False)
Average (1,Albedo,FP2,False)
Maximum (1,Sun_Dur,FP2,False,False)
Average (1,NR_Wm2,IEEE4,False)
Average (1, Snow_Depth,FP2,False)
Average (1, Snow_Depth_Corr,FP2,False)
Average (1, Press,FP2,False)
Average (1,Press_Corrtosl,FP2,False)
Totalize (1, Rain,FP2,False)
Average (1, VPD,FP2,False)
Average (1, e_hmp,FP2,False)
Average (1, e_sat_vp,FP2,False)
Average (1, Dew_point,FP2,False)
Average (1,SST,FP2,False)
Maximum (1,SST,FP2,False,False)
Minimum (1,SST,FP2,False,False)
ETsz(Air_Temp, RH, W_Spd, SlrkJ_SIn, 78.8098, 30.8630, 4364, 10, 0, FP2, False)
    FieldNames("ET, Rso")

EndTable
SequentialMode

'Main Program
BeginProg
Scan(5, Sec, 1, 0)

'Battery Voltage measurement Batt_Volt: Battery(Batt_Volt)

'05103-10 Wind Speed & Direction Sensor measurements W_Spd and W_Dir:
PulseCount(W_Spd, 1, 1, 1, 1, .098, 0)

'Measure Wind Direction
BrHalf(W_Dir, 1, mv2500, 3, Vx2, 1, 2500, True, 0, _50Hz, 355, 0)
If W_Dir>=360 Then W_Dir=0
"WMO CONVENTION IS THAT IF WIND SPEED IS "0" WIND DIRECTION SHOULD ALSO READ "0"
If W_Spd=0 Then W_Dir=0

'NR-LITE Net Radiometer (dynamic wind speed correction) measurement NR_Wm2 and NR_Wm2:
VoltDiff(NR_Wm2, 1, mv25, 5, True, 0, _50Hz, 1, 0)
NR_Wm2= NR_Wm2*(1000/ 13.5) 'Converts mv reading to W/m2
If W_Spd>=5 Then
    NR_Wm2=NR_Wm2*(1+0.021286*(W_Spd-5))'This is for wind correction
Else
    NR_Wm2=NR_Wm2
EndIf
'Two CMP3 Pyranometers configured as an Albedometer. Output Solar Radiation
VoltDiff (SRad_In, 1, AutoRange, 3, True, 0, _50Hz, 1, 0, 0) 'CMP3 FACING SKYWARD
VoltDiff (SRad_Out, 1, AutoRange, 4, True, 0, _50Hz, 1, 0, 0)
'CMP3 FACING GROUNDWARD
If SRad_In <0 Then SRad_In=0

'Calculations to convert skyward CMP3 to solar radiation
SRad_In=SRad_In*(1000/16.89)
SlrkJ_SIn=SRad_In*0.2960332

If SRad_In>120 Then
    Sun_Dur = Sun_Dur+0.08333 ' since our scan rate is 5 second
EndIf
If TimeIntoInterval(0,1440,min) Then
    Sun_Dur=0
EndIf

'Calculations to convert groundfacing CMP3 to solar radiation
SRad_Out=SRad_Out*(1000/15.5)
S1rkJ_SOut=SRad_Out*0.32258

If SRad_in=0 Then
    SRad_Out = 0
EndIf

Albedo=(SRad_Out/SRad_In)*100
If SRad_In=0 Then
    Albedo = 0
EndIf

'Switch 61302V Sensor On 1 minute before the top of the hour
If TimeIntoInterval (59,60,Min) Then SW12 (1)
'Dpoll 61302V Sensor at the top of the hour
If TimeIntoInterval (0,60,Min) Then
    *** Measure Analog 61302V ***
    'VoltSe (Press,1,mV5000,4,1,0,50Hz,0.12,500)
    'Switch 61302V Sensor Off after polling
    SW12 (0)
    'Correct Barometric Pressure value for elevation above sea level (elevation must be in meters)
    'Press_Corrtosl = Press + 1013.25 * (1 - (1 - Elevation/44307.69231)^5.253283)
EndIf

'For TE525M Rain Gauge, use multiplier of 0.1 mm
PulseCount instruction
PulseCount(Rain,1,2,2,0,0.1,0)

'NextScan
'SlowSequence
'To measure HMP45C212 and SR50 @ 30 sec to save power
'Scan (30,Sec,3,0)

'HMP45C 212(7/8-wire, cable switched power) Temperature & Relative Humidity Sensor measurements Air_Temp and RH
BrHalf(Air_Temp,1,mV2500,1,Vx1,1,2500,0,True,0,50Hz,178.85,-72.789)
    'VoltSe (Air_Temp,1,mV2500,1,0,0,56Hz,0.1,0,40)
    PortSet(1,1)
    Delay(0,150,mSec)
VoltSe(RH,1,mV2500,2,0,0,_50Hz,0.1,0)
PortSet(1,0)
If RH>100 AND RH<108 Then RH=100

'HC2-S3 Temperature & Relative Humidity Sensor measurements Air_Temp and RH:
'VoltSe (Air_Temp,1,mV2500,1,1,0,_50Hz,0.1,-50)
'VoltSe(RH,1,mV2500,2,0,0,_50Hz,0.1,0)
'If RH>100 AND RH<108 Then RH=100

'Find the HC2S3 vapor pressure (kPa) using a sixth order polynomial (Lowe, 1977).
SatVP (e_sat_vp,Air_Temp)
e_hmp = e_sat_vp*(RH/100)
'Calculate VPD, vapour pressure deficit
VPD=e_sat_vp-e_hmp

DewPoint (Dew_point,Air_Temp,RH)
'measuring SST
'VoltDiff (SST,1,mV5000,6,True,0,_50Hz,0.1,0)

'SR50A Sonic Ranging Sensor (SDI-12 Output, address "0")
'SDI12Recorder(SR50(),3,"0","M1!",1.0,0)  'Command M1!

output distance in Meters and Quality Number
'Snow_Depth=Distance1*SQR((Air_Temp+273.15)/273.15)
'Snow_Depth_Corr=Constant-Snow_Depth    ' ConstantA is the measured distance (in meters) from the sensor to bare ground.
'Quality=QLTY

CallTable(Min_1)
CallTable(Hourly)
CallTable(Daily)

NextScan
EndProg

******************************************************************************************
******************************************************************************************
3.3.2 Glacier Surface Mass Balance Measurements

A network of 44 stake points at different locations on the glacier surface was created in October, 2011 for accumulation and ablation measurements. Each stake point was fixed to a depth of 6–10 m (depending upon the surface condition) by stream-driven ice drill. During the summers of 2011-2012 and 2012-2013 glaciological years, fortnightly (in every 15 days) ablation measurements were carried out. Likewise, at the end of every summer (preferable during the end week of October) surface accumulation measurements were carried out in the accumulation zone. Instead of stake measurements in the accumulation zone, the accumulation measurements were carried out by digging several snow pits up to firn line (previous year layer) as well as by probing. The detailed methodology of stake networking and surface ablation measurements are given in Chapter 6.

3.3.3 Accuracy in Data Collection

(a) Meteorological Data

The meteorological observations are recorded as per the World Meteorological Organization (WMO) standards. For the optimum results, all sensors are recalibrated annually as per the standards. Accuracy of the each sensor is given in Table 1. To avoid the temperature sensors (air and surface) buried in snow during the winter season, the sensors are shifted upward 4 m from the surface and again replaced at the initial height in the summer (for K1 and K2 sites only). The specific details of sensor installation, data acquisition and data processing are as follow-

**Air Temperature and Relative Humidity:** Measured with 1 minute sampling frequency. Errors introduced by radiation and overheating are prevented by covering the temperature and relative humidity probe with a white painted 10-Plate Gill radiation shield. Sometimes during heavy and continuous rainfall, the relative humidity values (< 0.5 %) reached higher than 100 % due to high moisture trapped in the radiation shield. These errors were fixed manually by replacing relative humidity values with 100 %.
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**Surface Temperature:** Measured with 10 min sampling frequency. The target ground surface (1.5 x 1.5 m) around the field view (30°) of infrared temperature sensor is made with natural debris and maintained vegetation free throughout the summer season.

**Wind Speed and Direction:** Measured with 10 minute sampling frequency. Orientation of the junction box of wind monitor was fixed with respect of true North. To avoid the errors introduced by mechanical rotation, sensor is recalibrated annually.

**Radiative Fluxes:** Measured with 10 min sampling frequency. The study area lies in the northern hemisphere; therefore, for global radiation measurements, the upward and downward pyranometer, and the net radiometer sensors were installed at the southern side of the valley to avoid the consequence of shadow. Upward pyranometer sensor is covered with white painted dome shape shield for preventing snow accumulation on the surface of sensor. The net radiometer is particularly higher sensitive to wind speed with a subsequent decrease in accuracy and corrected by using the wind speed correction *[Brotzge and Douch, 2008]* -

\[
R_{n_{corr}} = R_{n_{obs}} \quad \text{u} < 5 \text{ m/s} \quad (3.1)
\]

\[
R_{n_{corr}} = R_{n_{obs}} \times [1.0 + A \times (u-5.0)] \quad \text{u} > 5 \text{ m/s} \quad (3.2)
\]

where, \( R_{n_{corr}} \) is net radiation corrected for wind speed, \( R_{n_{obs}} \) is observed net radiation, \( u \) is the horizontal wind speed in m s\(^{-1}\) and \( A \) (0.021286) is the empirical constant.

**Air Pressure:** Measured with 1 hr sampling frequency. A sensor is fixed inside the data logger box. Atmospheric pressure is significantly affected by elevation; therefore, taking elevation as a prime component the pressure correction factor is calculated using the following relation (suggested by the manufacturer)-

\[
P_{corr} = 1013.25 \times \left[1 - \left(1 - \left(\frac{E}{44307.692313}\right)^{5.523283}\right)\right] \quad (3.3)
\]
where, $E$ is elevation is in meters above sea level and $P_{\text{corr}}$ is pressure correction factor in hPa. This can then be added to the measured value. An accuracy of ±0.3 hPa rms is maintained over the entire specified operating pressure and temperature range.

**Rainfall:** The tipping bucket rain gauge is mounted horizontally and 1.0 m above the ground level. The lip of the funnel, filter cap and bucket reservoirs is kept clean properly throughout the summer. To avoid the errors introduced by mechanical rotation of tipping bucket, sensor is recalibrated annually.

**Snow Accumulation:** Measured with 1 hour sampling frequency. A sensor calculates a target distance reading using the speed of sound (331.4 m s$^{-1}$) at 0°C. To acquire the accurate snow depth ($h$) from sonic ranging sensor, air temperature compensation has been applied to the sensor output using the relation (Gorodetskaya et al., 2013)

$$h = h^* \times \sqrt{\frac{T_o}{T_o}} \quad (3.4)$$

where $h^*$ is distance between the surface and sensor and $T_o = 273.15$ K.

**(b) Glacier Surface Measurement**

To create a stake point on glacier surface, 3 - 6 wooden (bamboo) stakes each of length ~ 220 cm connected together by binding wire (metallic) drilled vertically into the glacier (Fig. 3.21). For creating a stake point, number of stakes was used instead of single lengthy stake. The main reason to adopt this methodology is that a lengthy stake may be broken when it get exposed due to melting to ice. However, the connected stakes fall down near the stake point when the surface ice melts and it holds up with remaining stake which is inside the ice (Fig. 3.21). This method also maintains the accuracy in ablation measurements as well as more convenient in stake networking. The created stakes points were labelled Nos. 01 – 44 in sequence from the terminus to the accumulation zone of the glacier. Fortnightly ablation measurements during the summer were carried out by measuring tape with an accuracy of ± 1.0 cm. During the winter, few stakes were lost and replaced again following the standard procedure in summer. Similarly, for the precise measurements
of surface accumulation 5 – 6 snow pits were dug at different elevation in the accumulation zone. Instead of snow pits study, probing method was also used to measure the snow depth where snow pits were not possible to measure the accumulation.

**Fig. 3.21.** Schematic diagramme of stake point created in the ablation zone of Chorabari Glacier showing fallen stake when ice surface melted out.