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surface energy balance measurements on Himalayan glacier: A case of Chhota Shigri glacier

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8/1/2015

The Cryosphere, 2014

The Cryosphere, 8, 2195–2217, 2014
www.the-cryosphere.net/8/2195/2014/
doi:10.5194/tc-8-2195-2014

The Cryosphere
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Processes governing the mass balance of Chhota Shigri Glacier (western Himalaya, India) assessed by point-scale surface energy balance measurements

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Hypothesis behind this study

❖ Comprehensive glacier surface energy balance (SEB) studies are very useful for understanding of glacier–climate relationship.

❖ Very few studies have been carried out in the High Himalayan glaciers till date *(e.g., Glacier AX010, Kayastha et al., 1999)*

❖ Unfortunately glacier SEB studies from Indian Himalaya (covering Western, some Central and Eastern parts of Himalaya) are not available.

❖ Therefore, there is an urgent need to conduct detailed SEB studies in different regions of Himalaya.

❖ Chhota Shigri is the most well studied glacier in the Indian side of the Himalaya as well over the whole Himalayan arc.

Use of AWS

❖ Use of Automatic weather station (AWS) provides the noble opportunity to obtain long and continuous records of meteorological data and to study the seasonal and inter-annual variations in SEB at point locations (e.g., Oerlemans, 2000)

❖ However, surface conditions in the melt zones of glaciers are very unstable (high melt rates, forming of crevasses, development of melt water streams, etc.), and consequently it has taken some time to develop stations with a satisfactory performance.

❖Other problems involve energy supply, moisture, and riming.

❖Therefore, one cannot expect hat an AWS on a glacier has the accuracy of a regular manned weather station

Objectives

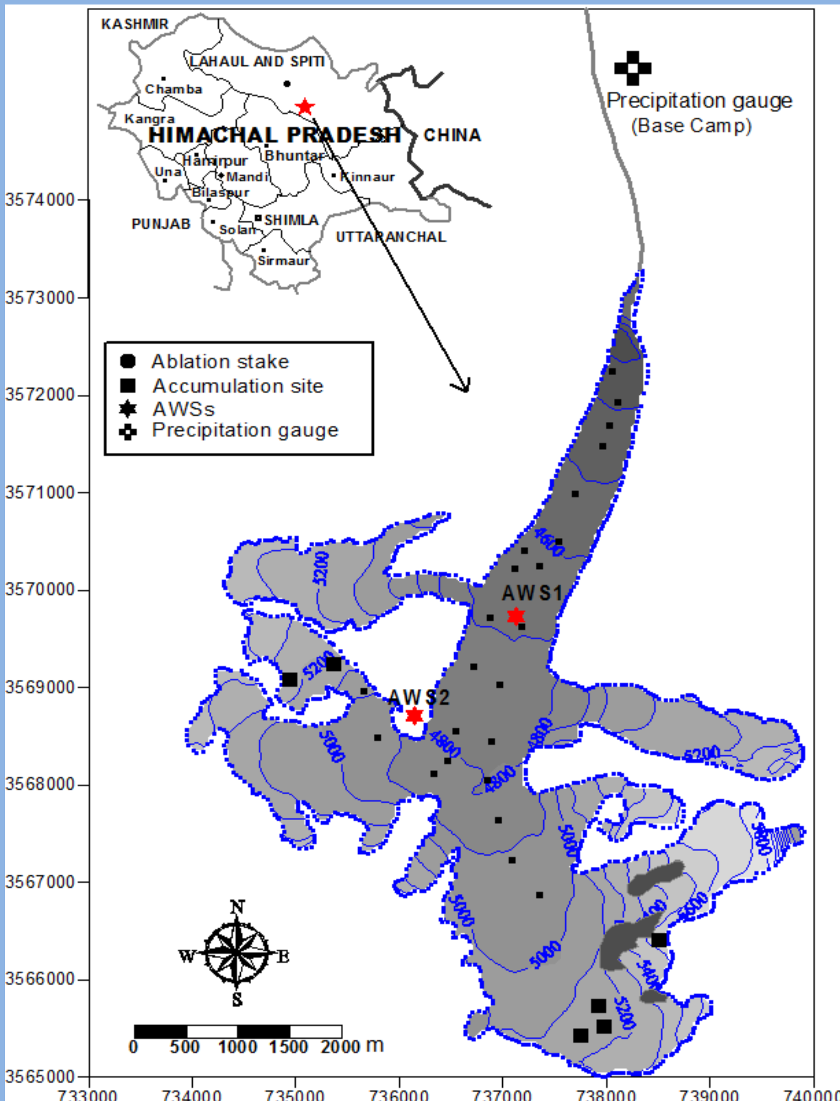
EB analysis of Chhota Shigri Glacier, using in-situ AWS measurements

1. Glacier's microclimate analysis using AWS established on lateral moraine.

2. Analysis of the Surface Energy Balance components- total budget of incoming and outgoing

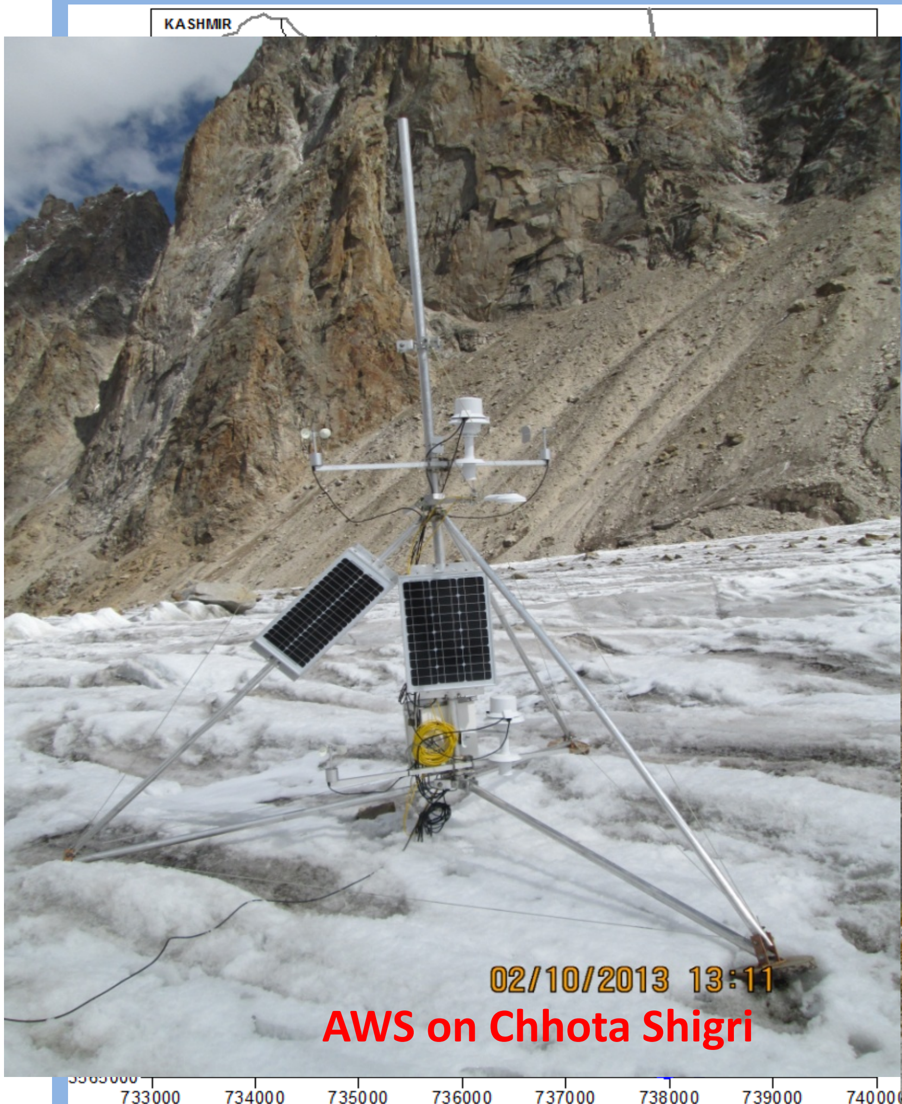
3. Role of energy fluxes (budget) on the Mass balance of Chhota Shigri glacier.

Chhota Shigri galcier



- ➢ Longest glaciological mass balance data on Indian Himalaya- glacier-wide annual mass balance has been monitored since 2002
- ➢A valley-type glacier located in the Chandra- Bhaga River basin, Pir Panjal Range, India
- ➢ Total glacierized area 15.7 km^2
- ➢ Mostly free of debris (only 3.4 %)
- ➢The equilibrium-line altitude for a zero annual mass balance (ELA) was found to be close to 4900 ma.s.l.
- ➢ Between 2002-2013, mean annual-wide mass balance -0.59±0.40 m w.e yr^{-1}

AWS locations



AWS on Chhota Shigri

Sensors

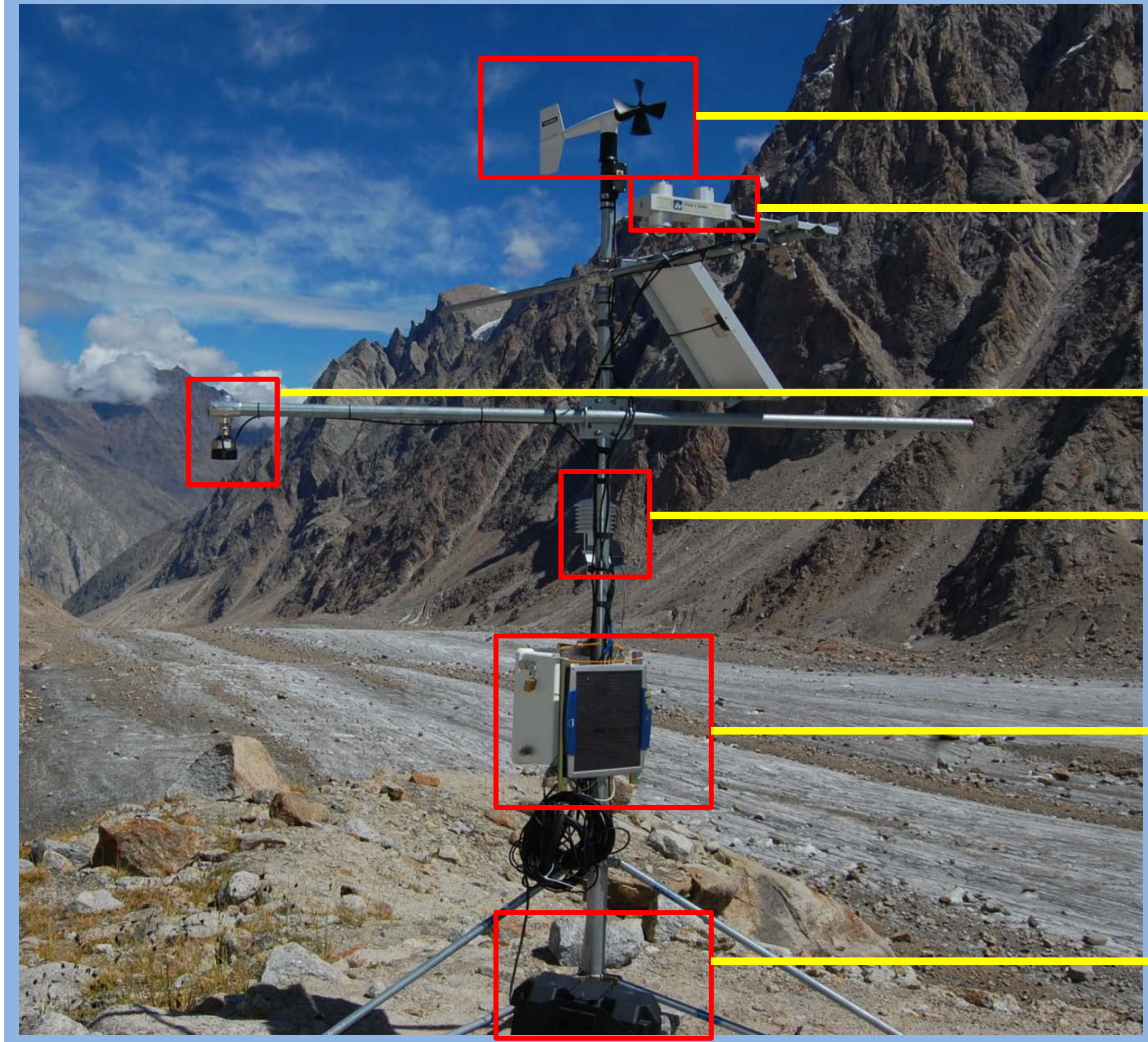
On surface

Variable	symbol (unit)	Sensor	initial height (m)	stated accuracy
AWS1				
air temperature	T_{air} (°C)	Campbell HMP155A[a]	0.8 & 2.5	±0.1 at 0 °C
relative humidity	RH (%)	Campbell HMP155A[a]	0.8 & 2.5	±1 % RH at 15 °C
wind speed	u (m s^{-1})	A100LK, Vector Inst.	0.8 & 2.5	±0.1 m s^{-1} up to 10 m s^{-1}
wind direction	WD (degree)	W200P, Vector Inst.	2.5	±2 deg
incoming and outgoing short wave radiations	SWI, SWO (W m^{-2})	Kipp & Zonen CNR-4	1.8	±10 % day total
incoming and outgoing long wave radiations	LWI, LWO (W m^{-2})	Kipp & Zonen CNR-4	1.8	±10 % day total
air pressure	P_{air} (hPa)	Young 61302V	1	±0.3 hPa
accumulation/ablation	SR50A (m)	Campbell SR50A[b]	1.6[c]	±0.01 m or 0.4 % to target
AWS2				
air temperature	T_{air} (°C)	Campbell H3-S3-XT	1.5	±0.1 at 0 °C
relative humidity	RH (%)	Campbell H3-S3-XT	1.5	±1.5 % RH at 23 °C
wind speed	u (m s^{-1})	Campbell 05103-10-L	3.0	±0.3 m s^{-1}
incoming short wave radiation	SWI (W m^{-2})	Kipp & Zonen CNR-1	2.5	±10 % day total
incoming long wave radiation	LWI (W m^{-2})	Kipp & Zonen CNR-1	2.5	±10 % day total
Precipitation (base camp)	(mm)	Geonor T-200B	1.7 (inlet height)	±0.6 mm

On moraine

[a] aspirated during daytime with RM Young 43502 radiation shields,
[b] mounted on a separated aluminum pole drilled into the ice,
[c] 1.6 m was initial height for SR50A sensor.

Sensors



Wind speed and direction

Solar Radiation(incoming and outgoing both)

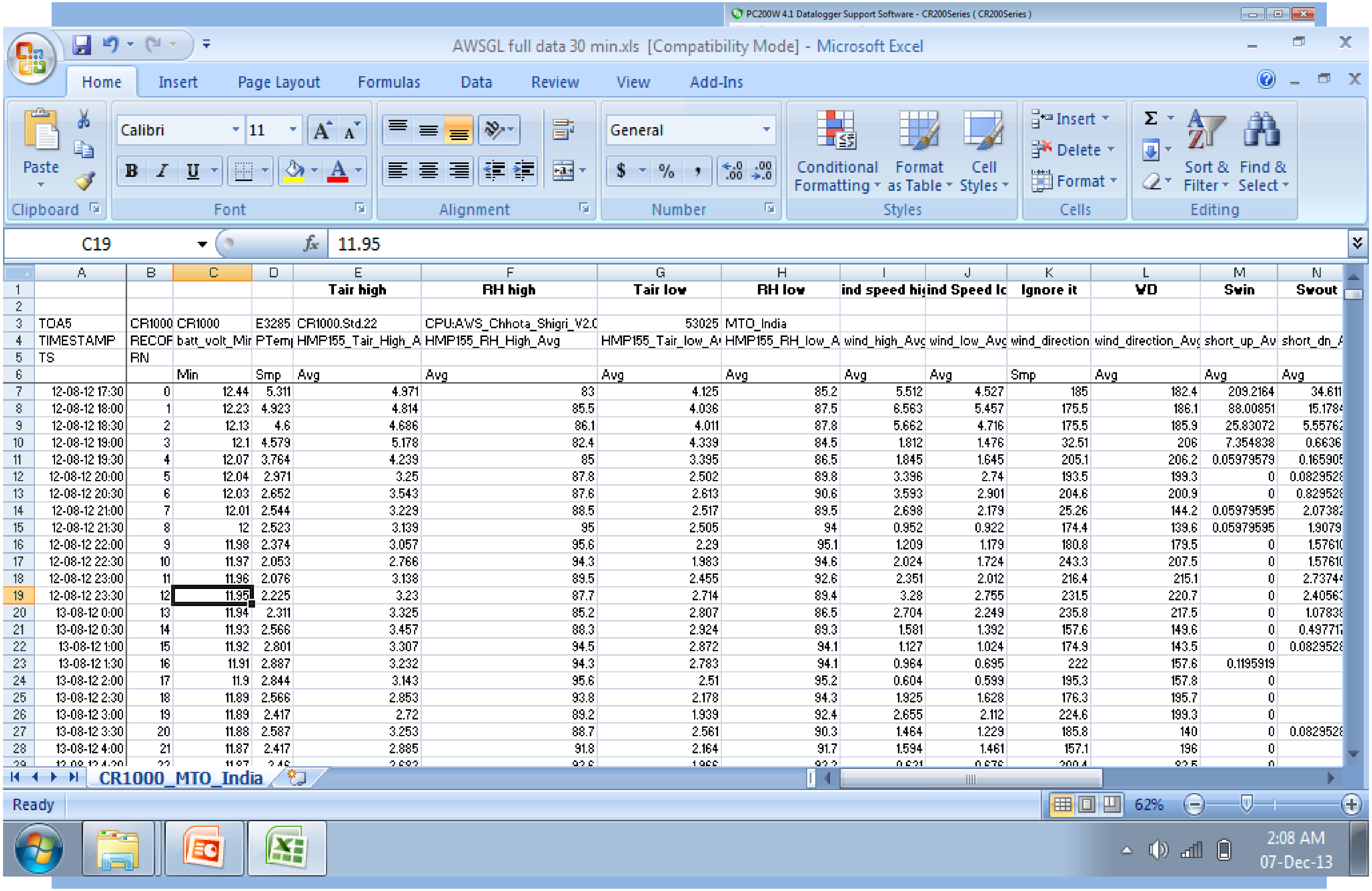
Sonic ranger (surface fluctuation)

Air temp. and Humidity

Data logger

Energy supply (battery)

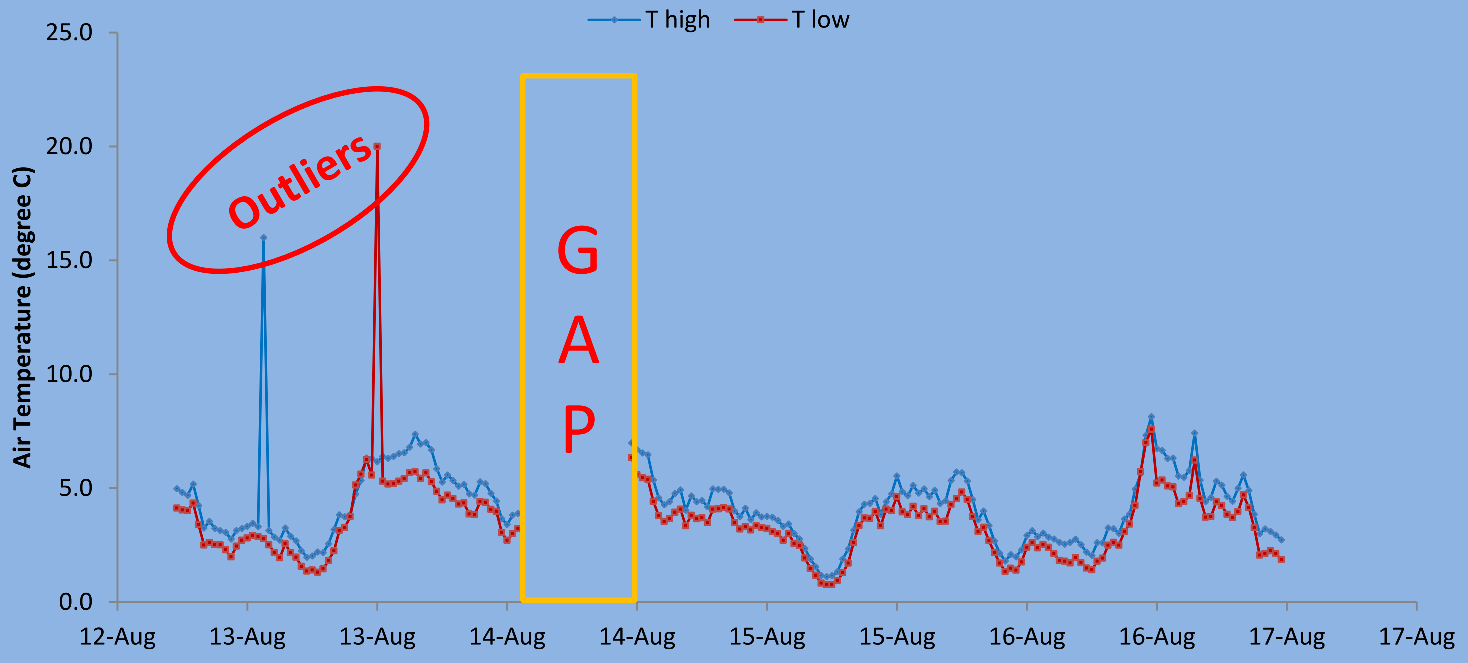
Data Collection Process (in-situ data collection)



	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1					Tair high	RH high	Tair low	RH low	ind speed hi	ind Speed lc	Ignore it	WD	Swin	Swout
2														
3	TOA5	CR1000	CR1000	E3285	CR1000.Std.22	CPU:AWS_Chhota_Shigri_V2.0	53025	MTO_India						
4	TIMESTAMP	RECOR	batt_volt_Min	PTem	HMP155_Tair_High_A	HMP155_RH_High_Avg	HMP155_Tair_low_A	HMP155_RH_low_A	wind_high_Avg	wind_low_Avg	wind_direction	wind_direction_Avg	short_up_Av	short_dn_A
5	TS	RN												
6			Min	Smp	Avg	Avg	Avg	Avg	Avg	Avg	Smp	Avg	Avg	Avg
7	12-08-12 17:30	0	12.44	5.311	4.971	83	4.125	85.2	5.512	4.527	185	182.4	209.2164	34.611
8	12-08-12 18:00	1	12.23	4.923	4.814	85.5	4.036	87.5	6.563	5.457	175.5	186.1	88.00851	15.1784
9	12-08-12 18:30	2	12.13	4.6	4.686	86.1	4.011	87.8	5.662	4.716	175.5	185.9	25.83072	5.55762
10	12-08-12 19:00	3	12.1	4.579	5.178	82.4	4.339	84.5	1.812	1.476	32.51	206	7.354838	0.6636
11	12-08-12 19:30	4	12.07	3.764	4.239	85	3.395	86.5	1.845	1.645	205.1	206.2	0.05979579	0.165905
12	12-08-12 20:00	5	12.04	2.971	3.25	87.8	2.502	89.8	3.396	2.74	193.5	199.3	0	0.0829528
13	12-08-12 20:30	6	12.03	2.652	3.543	87.6	2.613	90.6	3.593	2.901	204.6	200.9	0	0.829528
14	12-08-12 21:00	7	12.01	2.544	3.229	88.5	2.517	89.5	2.698	2.179	25.26	144.2	0.05979595	2.07382
15	12-08-12 21:30	8	12	2.523	3.139	95	2.505	94	0.952	0.922	174.4	139.6	0.05979595	1.9079
16	12-08-12 22:00	9	11.98	2.374	3.057	95.6	2.29	95.1	1.209	1.179	180.8	179.5	0	1.57610
17	12-08-12 22:30	10	11.97	2.053	2.766	94.3	1.983	94.6	2.024	1.724	243.3	207.5	0	1.57610
18	12-08-12 23:00	11	11.96	2.076	3.138	89.5	2.455	92.6	2.351	2.012	216.4	215.1	0	2.73744
19	12-08-12 23:30	12	11.95	2.225	3.23	87.7	2.714	89.4	3.28	2.755	231.5	220.7	0	2.40563
20	13-08-12 0:00	13	11.94	2.311	3.325	85.2	2.807	86.5	2.704	2.249	235.8	217.5	0	1.07838
21	13-08-12 0:30	14	11.93	2.566	3.457	88.3	2.924	89.3	1.581	1.392	157.6	149.6	0	0.497717
22	13-08-12 1:00	15	11.92	2.801	3.307	94.5	2.872	94.1	1.127	1.024	174.9	143.5	0	0.0829528
23	13-08-12 1:30	16	11.91	2.887	3.232	94.3	2.783	94.1	0.964	0.695	222	157.6	0.1195919	
24	13-08-12 2:00	17	11.9	2.844	3.143	95.6	2.51	95.2	0.604	0.599	195.3	157.8	0	
25	13-08-12 2:30	18	11.89	2.566	2.853	93.8	2.178	94.3	1.925	1.628	176.3	195.7	0	
26	13-08-12 3:00	19	11.89	2.417	2.72	89.2	1.939	92.4	2.655	2.112	224.6	199.3	0	
27	13-08-12 3:30	20	11.88	2.587	3.253	88.7	2.561	90.3	1.464	1.229	185.8	140	0	0.0829528
28	13-08-12 4:00	21	11.87	2.417	2.885	91.8	2.164	91.7	1.594	1.461	157.1	196	0	

Data treatment and corrections

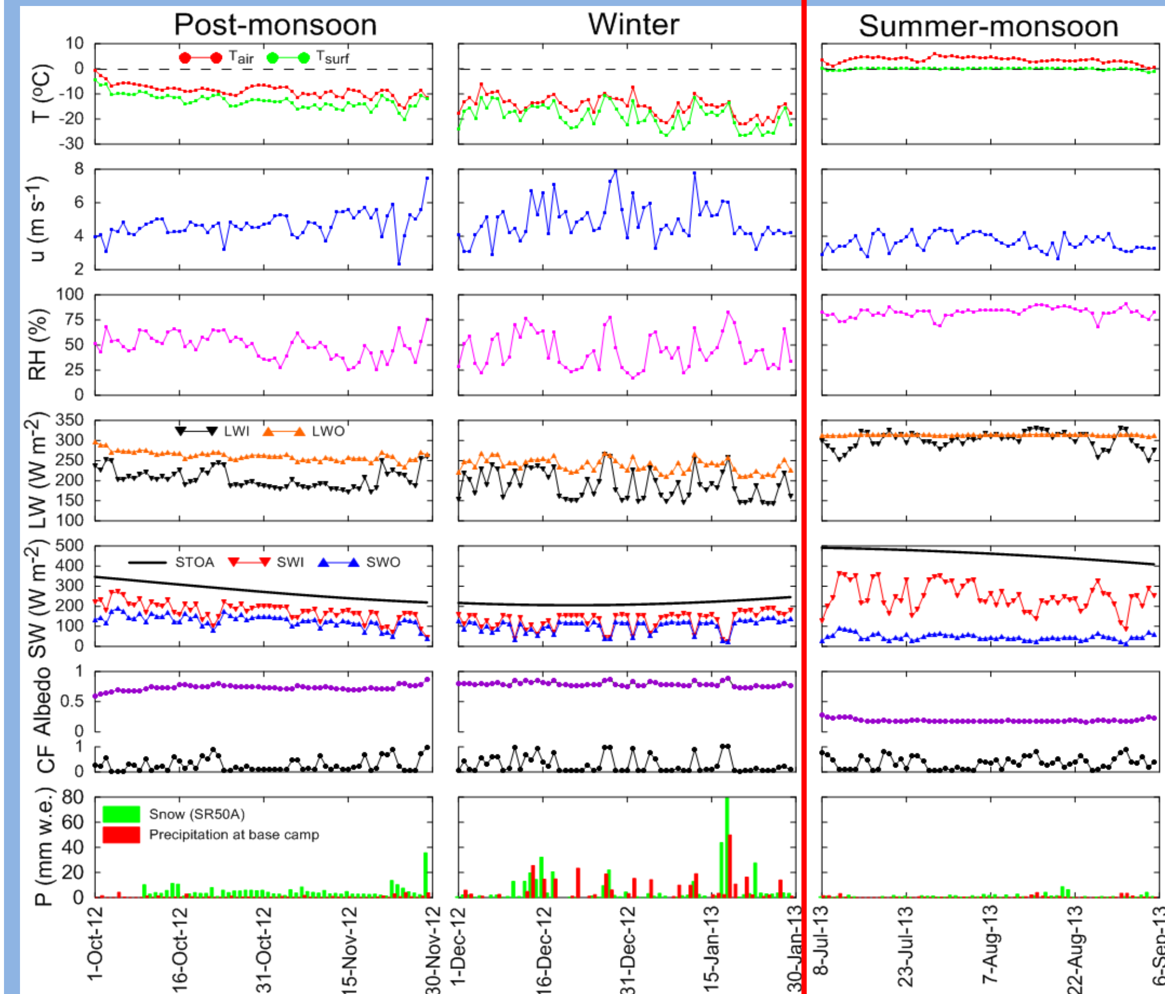
1. Find the data gap
2. Identify the outliers
3. Remove the outliers



For short period data gap (e.g. 2-3 days) we fill through linear interpolation. Weather dose not vary much in 2-3 days.

Strictly we use 30min data for every calculation- to get more temporal changes

Micrometeorology from AWS-moraine



Tair and Tsurf always near 0 or >0 °C

Wind speed quite low resulting high temperature compared to other seasons

Humidity quite high due to high temperature

SW and LW both are quite high- mainly high SWI

Albedo also dose not fluctuates much ~0.4. Less snowfall

Cloud covers follows the LW radiation

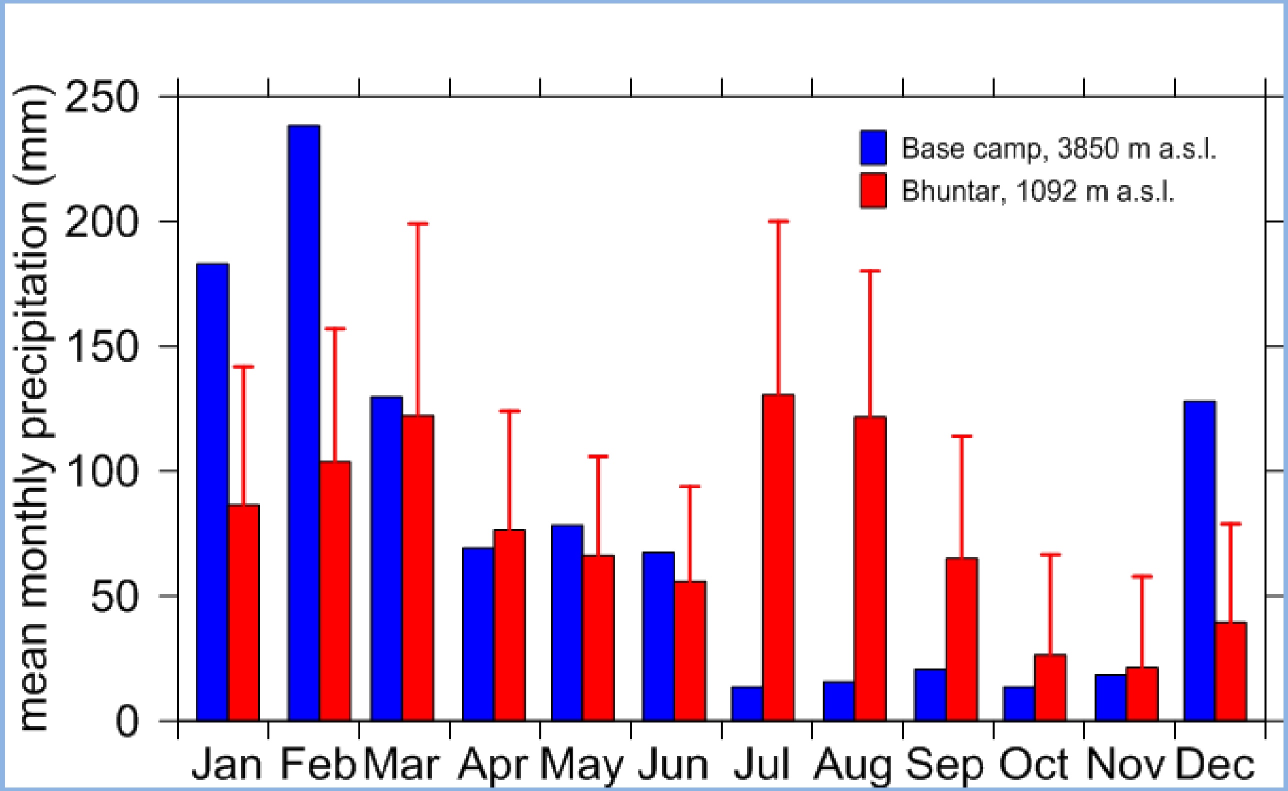
Very less precipitation through ISM is summer

Micrometeorology from AWS-moraine

Seasonal means and annual mean (standard deviations) of Tair, RH, u and SWI over four hydrological years between 1 October 2009 and 30 September 2013

	Winter (DJFM)	Pre-monsoon (AM)	Summer-monsoon (JJAS)	Post-monsoon (ON)	Annual mean
T_{air} (°C)	−13.4 (0.9)	−5.3 (0.7)	2.5 (0.6)	−7.8 (1.4)	−5.8 (0.2)
RH (%)	42 (2)	52 (2)	68 (1)	39 (6)	52 (2)
u (m s^{-1})	5.5 (0.6)	3.5 (0.2)	2.8 (0.1)	4.4 (0.5)	4.1 (0.2)
SWI (W m^{-2})	161 (12)	299 (34)	266 (7)	176 (18)	221 (14)
LWI (W m^{-2})	192 (3)	231 (2)	289 (17)	187 (8)	230 (6)
P (mm w.e.)	679	148	117	32	976

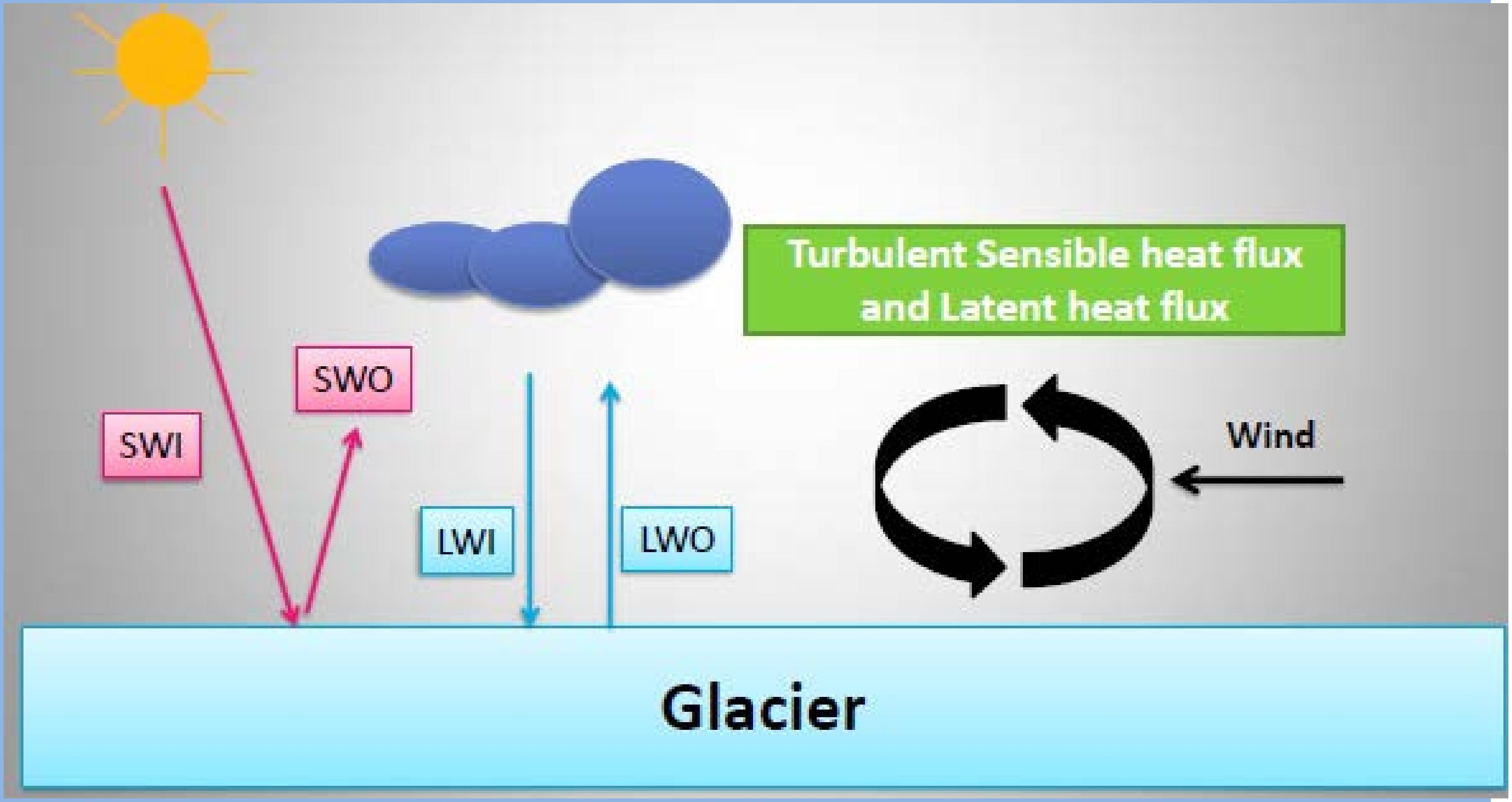
Micrometeorology- Precipitation



The **ISM contributed only 21%** while MLW added 79% precipitation to the annual precipitation (976 mm) at Chhota Shigri base camp.

Energy Balance- equation and methods

$$Q_M = Q_N + Q_H + Q_L + Q_G + Q_R$$



Energy Balance- equation and methods

✓ If sum of net radiation is positive on a temperate glacier,

Then the energy goes towards:

heating of snow/ice, when the snow/ice temperature at the surface is negative.

melting, when the snow/ice temperature at the surface is zero.

✓ If the sum of net radiation and sensible and latent heat fluxes is negative,

Then the glacier cools:

Melting is zero and the energy balance is closed by cooling of the glacier (positive ground heat flux).

Energy Balance- equation and methods

Turbulent fluxes:

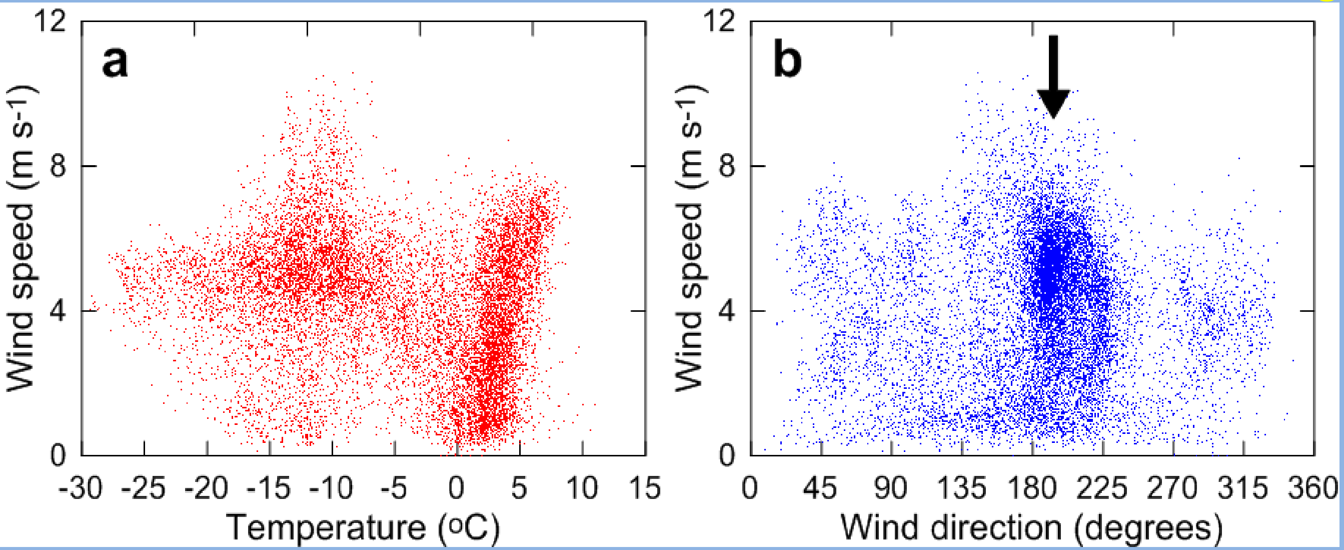
Latent (LE) and Sensible heat (H) fluxes were calculated using bulk aerodynamic method (Azam et al., 2014b)

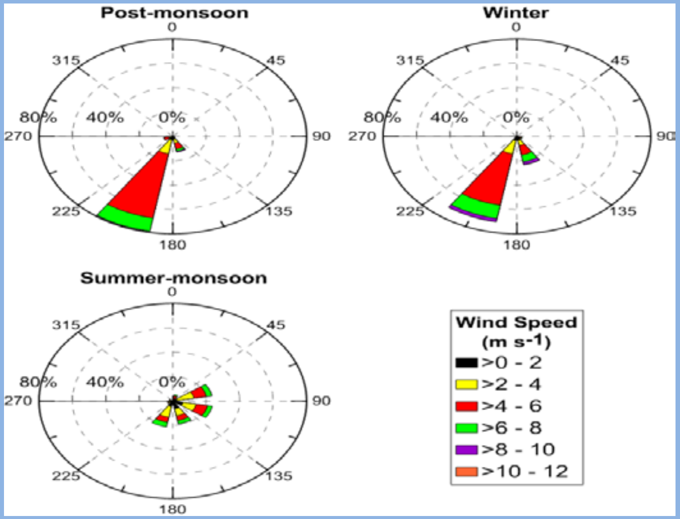
$$H = \rho \frac{C_p k^2 u (T_{air} - T_{surf})}{\left(In \frac{z}{z_{0m}}\right)\left(In \frac{z}{z_{0T}}\right)} (\Phi_m \Phi_h)^{-1}$$

$$LE = \rho \frac{L_S k^2 u (q - q_{surf})}{\left(In \frac{z}{z_{0m}}\right)\left(In \frac{z}{z_{0q}}\right)} (\Phi_m \Phi_v)^{-1}$$

Wind regime- on glacier surface- using surface AWS

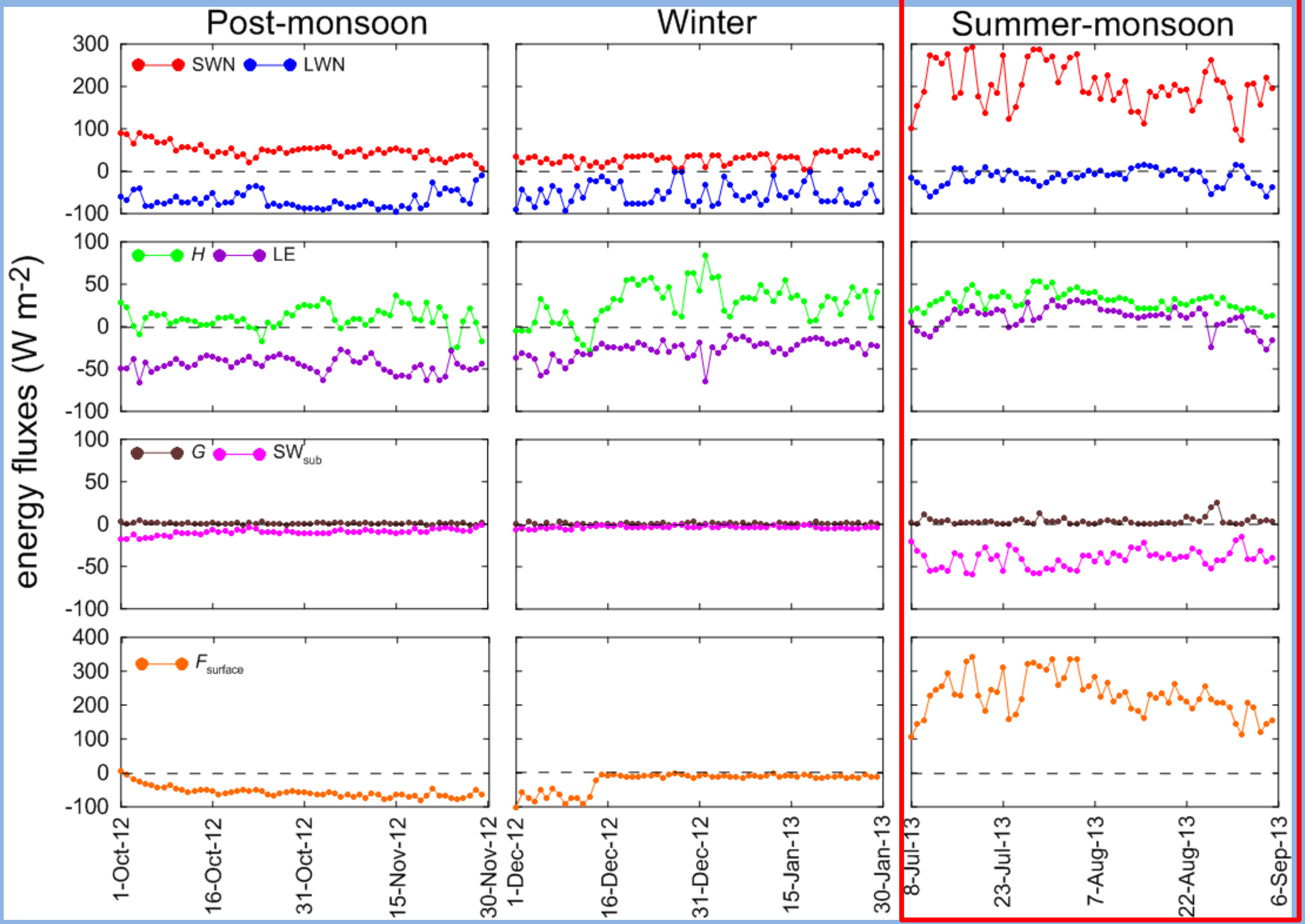
direction of the local flow line of the glacier.





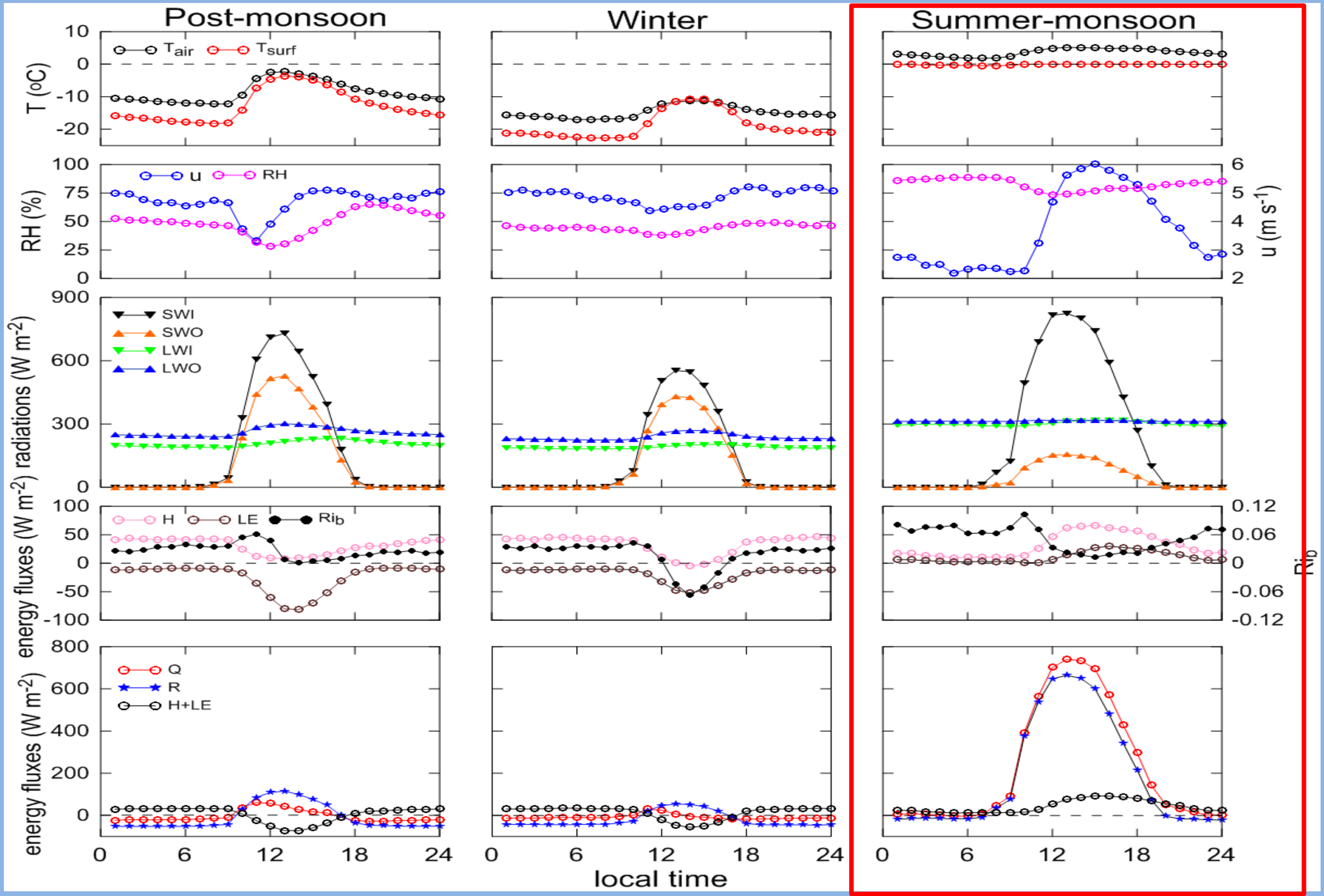
down-glacier wind coming from south to southwest during post-monsoon and winter periods

Energy Balance Components

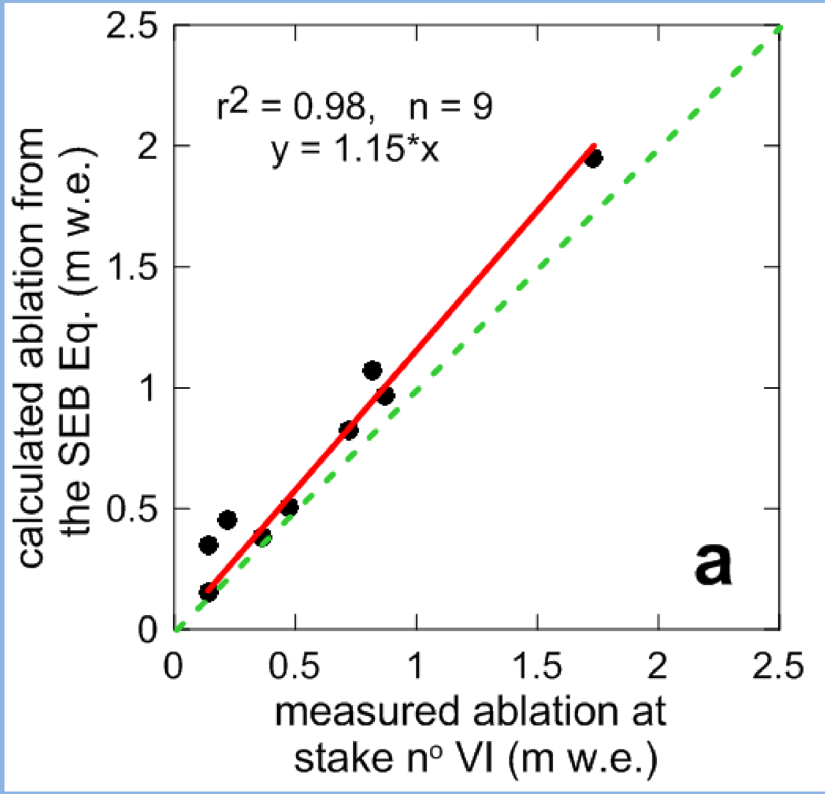


- ❖ Short wave incoming is the main driver for melt energy
- ❖ Q (melt energy) is always positive in summer monsoon
- ❖ **Latent heat flux = positive during summer-monsoon- less sublimation more melting**

Energy Balance- diurnal pattern



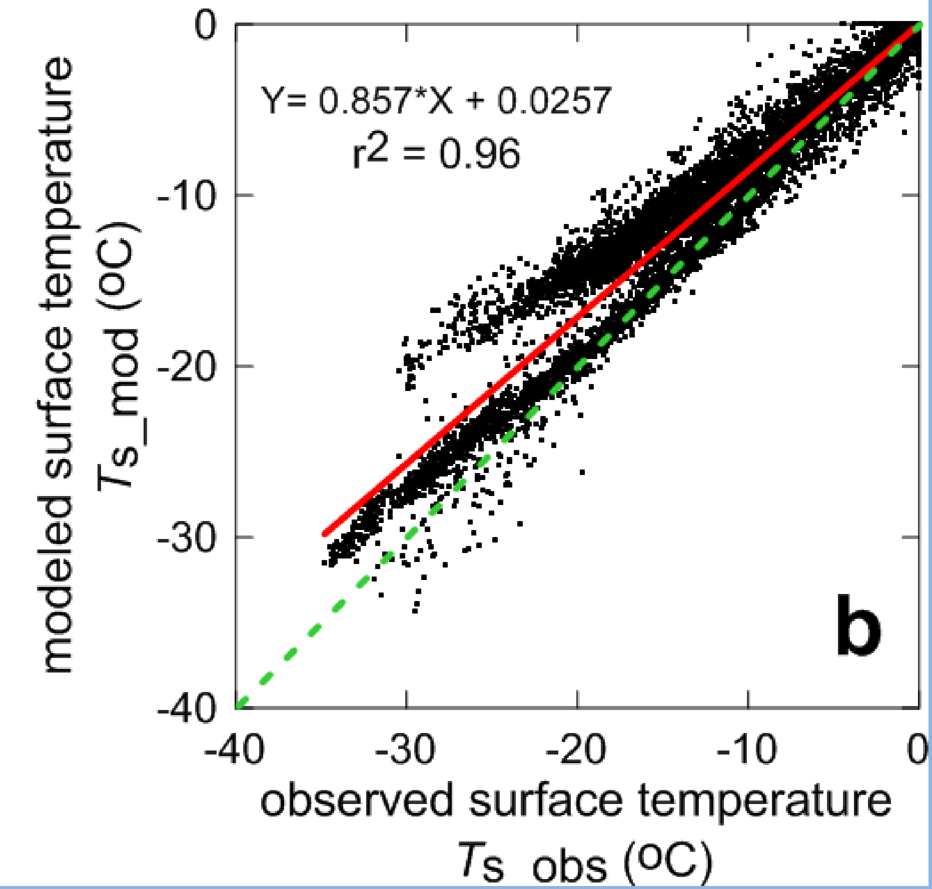
Model validation



Melting calculated through SEB compared with on glacier ablation stake.

Strong relationship between computed and measured melting (R^2= 98)

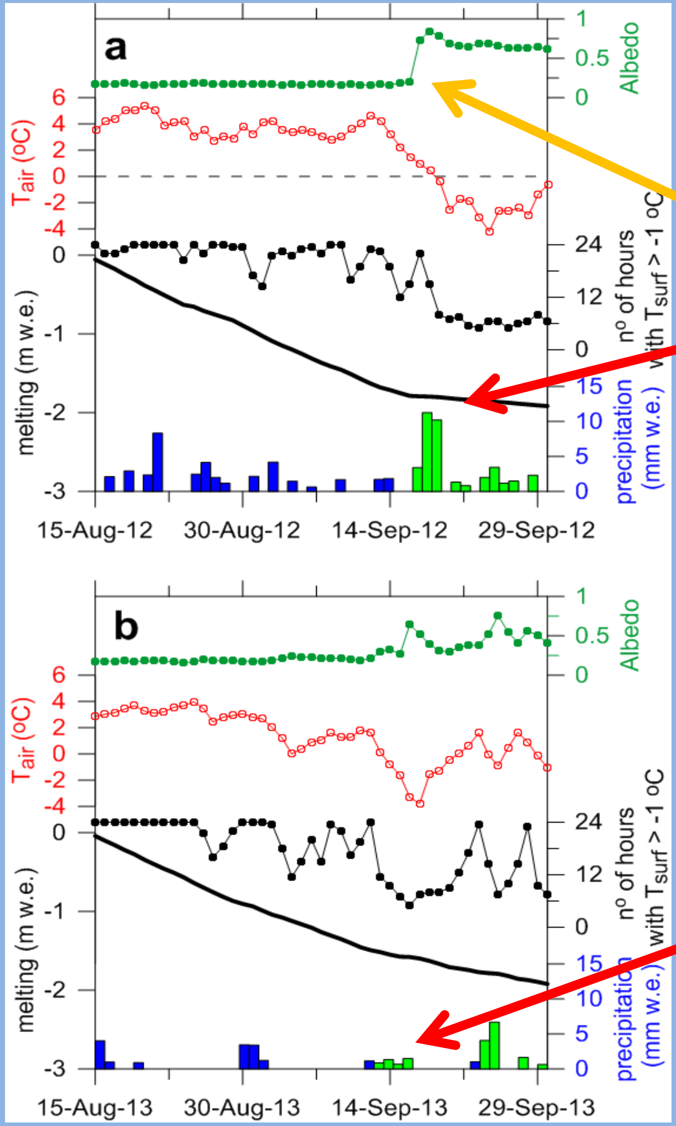
Model validation



Another approach,

We correlated observed/measured surface temperature and modeled surface temperature (using Stephen Boltzman).

Control of summer-monsoon snowfall on melting



❖ In summer-monsoon 2012 Chhota Shigri Glacier received one important snowfall on 17–19 September of 25mm w.e.

❖ This snowfall abruptly changed the surface conditions by varying the surface albedo from 0.19 to 0.73.

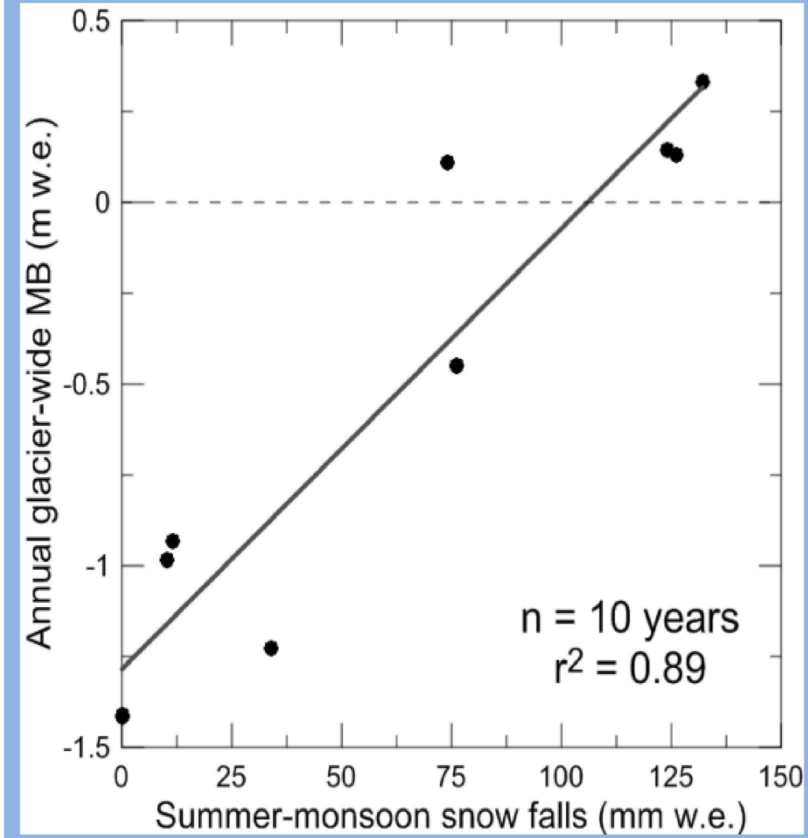
❖ light snowfalls, observed from 13 to 16 September 2013 and from 24 to 30 September 2013, were only able to protect the glacier from high melting for some days but could not maintain a persistent snow cover as in mid-September 2012.

Different Surface condition

In winter (very high albedo, less melt)

In summer (very low albedo, high melt)

Control of summer-monsoon snowfalls on melting- confirmation using long-term data



❖ Annual glacier-wide mass balances between 2002 and 2013 were compared with the largest summer-monsoon daily snowfalls of the corresponding season.

❖ Extrapolated using daily precipitation data from Bhuntar

❖ Best relationship is obtained when considering the sum of the three most important daily snowfall records of the corresponding summer-monsoon season

❖ The correlation is strong

❖(R^2 = 0.88, n = 11 years)

Comparison of SEB with other Himalayan/Tibetan Plateau glaciers

Glacier	Altitude (m a.s.l.)	Region (ISM dominated, Y or N)	Period of observation	R (W m^{-2})	H (W m^{-2})	LE (W m^{-2})	Rest (W m^{-2})	Q (W m^{-2})	Reference
Glacier AX010	4960	central Himalaya, Nepal (Y)	25 May- 25 Sep 1978	64 (85)	8 (10)	4 (5)	-	74 (100)	Kayastha et al., 1999
Glacier AX010	5080	central Himalaya, Nepal (Y)	25 May- 25 Sep 1978	55 (83)	8(12)	3 (5)	-	63 (100)	Kayastha et al., 1999
Xixibangma	5700	south central TP[a] (N)	23 Aug- 11 Sep 1991	28(86)	5(14)	-19 (57)	-	14(43)	Aizen et al., 2002
Parlung No. 4	4800	southeast TP (Y)	21 May- 8 Sep 2009	150 (84)	28 (16)	-1 (1)	-1 (1)	176 (98)	Yang et al., 2011
Zhadang	5660	central TP (N)	1 May - 30 Sep 2010	62 (86)	10 (14)	-8 (11)	-4 (5)	-61 (84)	Zhang et al., 2013
Zhadang	5660	central TP (N)	1 May - 15 Sep 2011	27 (77)	8 (23)	-10 (28)	-2 (5)	-24 (67)	Zhang et al., 2013
Keqicar	4265	southwest Tianshan (N)	16 June-7 Sep 2005[b]	63 (81)	14 (19)	-54 (70)	-	23 (30)	Li et al., 2011
Laohugou No. 12	4550	western Qilian, China (N)	1 June-30 Sep 2011	81 (93)	7 (7)	-13 (15)	-	75 (85)	Sun et al., 2014
Chhota Shigri	**4670**	**western Himalaya, India (Y)**	**8 July-5 Sep 2013**	**188 (82)**	**31 (13)**	**11 (5)**	**-**	**230 (100)**	**Present study**

[a]TP = Tibetan Plateau; [b]with a gap of 1 July to7 Aug 2005

SW radiation is the main source for melting on every glacier.

Conclusion

❖Sensible heat flux = positive all the time- transported heat towards the glacier surface

❖Latent heat flux = positive during summer-monsoon : resublimation.

❖Latent heat flux = negative during post-monsoon & winter : sublimation

❖ EB = positive in summer-monsoon period - melting

❖ Net all-wave radiation = 82% , H and LE = 13% and 5%, respectively

❖ Summer Monsoon snowfall event = is one of the important MB drivers

❖ Good validation of present model -reliable enough to make robust calculations of surface energy balance

Still, we need round the year/ long term data for better understanding


1st Indo-Swiss Capacity Building Programme on Himalayan Glaciology
Chhota Shigri glacier, September, 2013


Thank you for your kind attention and patience!!