Meteorological analysis of high altitude Automatic Weather Station data from the Everest Region

IN PARTIAL FULFILLMENT FOR THE REQUIREMENT OF MASTER'S DEGREE OF SCIENCE IN HYDROLOGY AND METEOROLOGY

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A DISSERTATION SUBMITTED TO

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Dedicated To my Parents

DECLARATION

Thesis entitled **“Meteorological analysis of high altitude Automatic Weather Station data from the Everest Region”** is being submitted to the Central Department of Hydrology and Meteorology, Institute of Science and Technology (IOST), Tribhuvan University, Nepal for the achievement of the Degree of Master of Science (M.sc). This is a research work carried out by me under the supervision of Assistant Prof. Dr. Dibas Shrestha, Central Department of Hydrology and Meteorology, Tribhuvan University. This research has not been submitted earlier in this or any other university or institute, here or elsewhere, for the achievement of any degree.

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This is to certify that Mr. **Arbindra Khadka** has prepared the dissertation entitled **"Meteorological analysis of high altitude Automatic Weather Station data from the Everest Region''** to fulfill the partial requirements for Master's degree in Hydrology and Meteorology. The study done by him has been carried out under my supervision and guidance.

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ACCEPTANCE

The present dissertation entitled **"Meteorological analysis of high altitude Automatic Weather Station data from the Everest Region''** submitted by **Mr. Arbindra Khadka** has been accepted as the partial fulfillment for master's degree in Hydrology and Meteorology.

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ABSTRACT

This study presents a high-altitude meteorological variables in the Everest region since October 2010 to December 2018 by using different seven automatic weather stations (AWS) data ranging in elevation from 4200 to 6400 m a.s.l. Some are still operating at Mera and Changri Nup glacier site in the Inkhu/Hunga and Khumbu valley. Four stations are in the glacier and three are near the glacier measures air temperature, wind speed and direction, air pressure, change in surface height of snow, incoming shortwave and long wave radiation, and outgoing shortwave and long wave radiation.

Annual, seasonal, and diurnal observed meteorological variables are compared between the sites. Since 2013-14 to 2017-18 air temperature at Mera, Naulek and Changri-Nup glacier sites found highly increased where the winter temperature growth found highest. There is strong influence of solar radiation and wind pattern on diurnal cycle of temperature and vapour pressure. Similarly, local topography and local scale circulations also affect wind speed and precipitation cycle. Extreme event have a significant role in non-monsoonal seasonal cumulative precipitation.

The comparison of temperature gradient at Mera glacier site is found different in all scale, higher negative in winter and least negative in monsoon. The calculated zero degree isotherm is found 5000 m a.s.l in all over the monsoon and increased up to 7000 m a.s.l indicates most of the monsoonal precipitation at this elevation is in liquid form. And in monsoon the 6.11hPa isoline is above 5000 m a.s.l which suggest that the glacier in this area loses a lots of mass/energy by evaporation and sublimation in monsoon.

Kew words; high-altitude, radiation, glacier, gradient

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LIST OF ABBREVIATIONS/ACRONYMS

CDHM	Central Department of Hydrology and Meteorology
DHM	Department of Hydrology and Meteorology
IRD	Institut de recherche pour le développement
ICIMOD	International Center for Integrated Mountain Development
ELR	Environmental Lapse Rate
IPCC	Intergovernmental Panel on Climate Change
HMA	High Mountain Asia
RCP	Regional Climate Projection
AWS	Automatic Weather Station
GLOF	Glacier Lake Outburst Flood
T	Temperature
U	Wind
ϴ	Wind direction
P	Precipitation
L↓	Incoming Long-wave Radiation
L↑	Out-going Long-wave Radiation
K↓	Incoming Short-wave Radiation
K↑	Incoming and Out-going Short-wave Radiation
RH	Relative Humidity
UGB	Upper Ganges Basin
UIB	Upper Indus Basin
VPG	Vapour Pressure Gradient
TG	Temperature Gradient
e_s	Saturation vapour pressure
e_a	Actual vapour pressure
RCP	Representative Concentration Pathway

LIST OF UNITS

hPa	Hectopascal Pressure Unit
W/m^2	Watt per meter Square
°C	Degree Celsius
Km	Kilometer
Yr^{-1}	Per year
D^{-1}	Per Decade
m^3/s	Meter cube per second
m/s	Meter per second

CHAPTER 1: General Introduction

The Himalayan region mostly the part of eight country, also called ‘the third pole’ and the water tower of Asia, is the most glaciated area in the world outside polar regions, having stocks of water in the form of ice and snow (Dyhrenfurth 1955; Bajracharya and Shrestha 2011; Bajracharya et al. 2015; Bolch et al. 2008). Warming in the Himalayan region will affect water resources for hundreds of millions of people with whole biodiversity system, yet we know little about how the high-altitude climate has already changed there, and how it may continue to in the future. Nepal is one of the mountainous country in Himalayan region with five peak higher than 8000m with lots of glacier and glacial lakes(Shrestha and Aryal 2011). Most of the rivers of Nepal are snow and glacier feed including all three river Koshi, Gandaki, and Karnali which are drain into the Ganges, bearing cultural and religious significance. Further, these rivers are also important for agriculture, industries and ecosystems and treated as a basic requirement for the overall development of the country. However, a recent trend of warming in the Himalayas is posing a major threat to glacier melting (Fort 2015), and after the start of 19th century the number of glacial lake outburst floods (GLOFs) increased in the Himalaya (Richardson and Reynolds 2000). There is an overwhelming evidence of rapid deglaciation in the Himalayas with supporting formation, growth and likely outburst of glacial lake are phenomena directly related to climate change (Shrestha and Aryal 2011).

Meteorological studies in high-mountain environments form the basis of our understanding of catchment hydrology and glacier accumulation and melt processes, yet high-altitude (>4000 m above sea level,) observatories are rare (Shea et al. 2015). The Glacier mass balance as well as meteorological variables needed to analyze regularly (Fujita 2008; Shea et al. 2015; Wagnon et al. 2012) because the glaciers in the Himalaya and Tibetan Plateau are the sources of the major rivers (Immerzeel et al. 2010), and in addition, their status is a sensitive indicator of regional climate change at high altitudes, where few meteorological data are available. Changes in the glacier may have a significant impact on the quantity and timing of water availability.

Debris cover can either increase or decrease ablation rates depending on debris thickness (Adhikary et al. 2000; Östrem 1959), thus influencing glacier mass balance and dynamic behavior (Anderson and Mackintosh 2012; Nicholson and Benn 2013). Understanding the different mechanisms controlling changes in both debris-free and debris-covered glaciers is therefore important for predicting glacial runoff and the future response of glaciers to climate change (Bolch et al. 2012). In Koshi basin the debris covered glacier area is 220km^2 (19% of total) in which 110 km^2 is lies in Dudh Koshi sub basin (Wester et al. 2018).

A precondition for understanding glacier behavior is a comprehensive understanding of local meteorological conditions and the surface energy balance, which provide important insights into surface/atmosphere interactions at high elevations (Mölget al., 2014)). Meteorological measurements and energy-balance modeling has been carried out on mountain glaciers and ice sheets worldwide on debris-free (van den Broeke 1997; Giesen et al. 2009) and debris-covered glaciers (Anderson and Mackintosh 2012; Reid and Brock 2010). However, obtaining in situ records of glacial meteorology and energy balance is often difficult because of the logistical problems involved in operating in the harsh high-altitude environment of the Himalaya. In addition, the complex orography results in major climatic variability over short horizontal/vertical distances and the representativeness of limited measurements needs to be addressed (Maussion et al. 2014).

Over the last 5 years (2010–15), the rate of mass loss of the three monitored glaciers located in different parts of the same Everest region varies strongly from balanced conditions for Mera Glacier to extremely rapid mass wastage for the debris-covered Changri Nup glacier (Sherpa et al. 2017). Ice and snow melt at 0°C surface temperature (but not necessary at air temperature >= 0°C) depends on the local energy balance, which is controlled by meteorological conditions and properties of the surface.

Understanding the varying effect of different meteorological variables on glacial melting is essential for understanding the problem of different types of glaciers to climate change. The effects of difference in wind speed, gradient of temperature, precipitation, actual vapor pressure, albedo, incoming short wave and long wave radiation are directly related to the change in volume of glaciers(Fujita 2008; Hock 2005; Lie, Dahl, and Nesje 2003).

In this study, I analyzed the change in temperature and vapour pressure altitudinal gradients using data from December 2010 to April 2019. Local variation was interpreted with the help of additional meteorological variables measured at different Automatic Weather Stations (AWS) located at the debris-free Mera and Naulek glaciers and debris-covered Changri Nup glacier, which are located 30 km apart in the Everest region. And the purpose of the study is to understand the recent climatic condition and short term trend of temperature at above 5000m a.s.l.

1.1 Objectives

The major objective in this study to characterize and compare meteorological conditions in two high-altitude glacierized catchments one is Hunga/Inkhu sub-basin of and another is upper Dudh Koshi basin Dudh Koshi river system in the Everest region, assessed from in situ measurements.

1.1.1 Specific Objectives

- To better understand the air temperature environment of last five years for the three high elevation glacier level stations of Dudh Koshi basin
- To understand the air temperature and vapour pressure gradient in Mera site with zero degree isotherm and 6.11hPa isoline

CHAPTER 2: Literature review

2.1 Air Temperature and Precipitation trends in High Mountain Nepal

Precipitation in Nepal is dominated by the Asian monsoon system and the main occupation is agriculture, largely based on rain-fed farming practices. Summer monsoon precipitation and the melting of the large reserves of snow and glaciers in the Himalayan highlands are the major source of water. Tourism based on high altitude adventures is one of the major sources of income for the country. Nepal has a large hydropower potential, while only 0.75% of the theoretical hydropower potential has been tapped, Nepal can greatly benefit from this natural resource reserved solid water in the future. Climate change can adversely impact upon water resources and other sectors of Nepal. Observations show clear evidences of significant warming. The average warming trend in the country is 0.06°C per year (Shrestha et al. 1999). The warming rates are progressively higher for high elevation locations. The warming climate has resulted in rapid shrinking of majority of glaciers in Nepal (Shrestha and Aryal 2011).

Study done from 1994 to 1999 on Khumbu valley state that air temperature drops below freezing during the non-monsoonal seasons with few minimum temperatures above 0°C. During winter, days with temperatures above freezing occurred with an average frequency of 68%, with the highest frequency of 78% in February, the coldest month. During the pre-monsoon and post-monsoon seasons, days with freezing prevailed (an average of 71%). Over the course of a year, only around a quarter of the days showed a minimum temperature above 0°C. The warmest month was July, when 94% of the days had a minimum temperature above 0°C. Moreover, during summer, the maximum temperature was constantly above 0°C at EvK2-CNR Pyramid, Khumbu (Bollasina, Bertolani, and Tartari 2002).

In the Paris Agreement of 2015, 195 nations agreed on the aspiration to limit the level of global air temperature rise to 1.5 degrees Celsius (°C) above pre-industrial levels. However, it is not known what an increase of 1.5 °C would mean for the glaciers in High Mountain Asia (HMA) (Kraaijenbrink et al. 2017) and in the (Wester et al. 2018) HiMAP suggested that an increase of 1.5° C temperature will reduce almost 45% of glacier (Ohara et al. 2014). The temperature rise by 2.1 ± 0.1 °C in the HMA at the end of 21st century will reduce the preset day solid water in the HMA by $36 \pm 7\%$. The 1.5 °C goal is extremely ambitious and is thus projected by only a small number of climate models of the conservative

Intergovernmental Panel on Climate Change IPCC's Representative Concentration Pathway (RCP)2.6 ensemble (Kraaijenbrink et al. 2017).

Shrestha et al. (1999) analyzed the temperature data in different elevation regions of Nepal from 1971-94, which shows that the warming trends after 1977 ranging from 0.06 °C to 0.12 °C yr^{-1} in most of the Himalaya and mountain regions. Distributions of seasonal and annual temperature trends show high rates of warming in the high-elevation regions of the country (Middle Mountains and Himalaya).

Table 1 Regional mean temperature trends for 1977-1994 (°C /yr) (Shrestha et al. 1999)

	Seasons				Annual
Region	Winter	Pre-monsoon	monsoon	Post-monsoon	
Trans-Himalaya	0.124	0.005	0.109	0.099	0.090
Himalaya	0.090	0.050	0.062	0.075	0.057

Kattel and Yao (2013) presented the three decades (1980-2009) data from thirteen mountain station with elevations between 1304 to 2566 m above sea level from varied topography. From this the average temperature change in Okhaldhunga station which is in the Dudh Koshi basin of Nepal is 0.66 °C per decade (Nayava et al. 2017).

DHM (2017) presented air temperature and precipitation trends, as well as altitudinal temperature gradient in Nepal. All Nepal trend analysis shows a significant positive trend in annual and seasonal maximum air temperature. A significant positive trend in all Nepal minimum air temperature is observed only during the monsoon season and the monsoonal precipitation in decreased by 11% in the upper Dudh Koshi basin(Salerno et al. 2015) District level trend analysis shows a robust positive trend (significant at 99.9% confidence level) in maximum temperature in all districts of Nepal for all seasons, except in the Tarai districts in winter season. The significance of minimum temperature and in precipitation are only limited to a few districts and seasons.

Table 2 Seasonal and Annual precipitation and temperature trends (per year) and significance level in bracket for Solukhumbu Districts (DHM 2017)

	Winter	Pre-monsoon	Monsoon	Post-monsoon	Annual
Precipitaton (mm)	-0.358	-0.15	-3.03	-0.94	-4.36
Maximum Temperature (°C)	0.1	0.056	0.068	0.084	0.076
Minimum Temperature (°C)	-0.037	-0.016	-0.007	-0.017	-0.01

Table 3 Maximum and minimum temperature coefficient (lapse rate) (°C/km) (DHM 2017)

Months	Maximum temperature lapse rate		Minimum temperature lapse rate	
	Doti : Simikot	Jiri : Pyramid	Doti : Simikot	Jiri : Pyramid
Jan	-5.45	-5.81	-7.57	-3.20
Feb	-6.71	-6.41	-8.67	-3.99
Mar	-7.47	-6.77	-8.07	-4.34
Apr	-6.87	-6.87	-5.96	-4.58
May	-6.74	-6.36	-5.80	-4.81
Jun	-5.76	-5.73	-6.01	-4.97
Jul	-4.65	-5.59	-5.10	-4.97
Aug	-4.92	-5.71	-5.04	-5.00
Sep	-4.93	-6.01	-5.46	-5.06
Oct	-4.92	-6.25	-6.56	-5.74
Nov	-4.83	-5.75	-6.47	-3.66
Dec	-3.90	-5.36	-7.87	-2.90

In the upper Indus Basin (UIB), stream flow is dominated by glacier melt water, contributing 40.6% of the total runoff. Despite its larger relative glacierized area, glacier melt contributes only 11.5% of the total runoff generated in the upper Ganges Basin (UGB), owing to the monsoon-dominated precipitation regime in the UGB (Lutz et al. 2014).

Meteorological analysis between 1994-1999 in Pyramid AWS, Khumbu (Bollasina et al. 2002) shows that the average annual precipitation was 465 mm and almost 90% was from monsoon, in monsoon (12th June to 5th October) average precipitation was 400mm and 85% of the day have precipitation in summer monsoon with highest frequency in August.

2.2 Wind and local circulation

By grouping together wind speed profiles from the non-monsoon seasons, Bollasina et al. (2002) showed that the wind was generally weaker during summer than in other seasons, with the exception of the 18:00-22:00 period, when the valley breeze was still blowing. The highest daily-averaged values were recorded during winter (2.1 m/s) when the large-scale flow was characterized by strong eastward winds associated with the Subtropical Jet Stream, while the summer monsoon winds were the weakest (a daily average of 1.5 m/s).

2.3 Temperature lapse rate in previous studies

Decrease in air temperature with an increase in elevation is widely known as temperature lapse rate, which is a very important variable in glacio-hydrological modeling. The dynamics of lapse rates in different seasons of the year are very different in the Nepalese Himalaya. Here are some studies of temperature lapse rate from the high Himalayan region.

Kattel et al. (2013) presents the study about the monthly, seasonally and annual temperature lapse rate of southern slope of Himalayas from the 56 automatic weather stations (from 72 m a.s.l to 3920 m a.s.l) by taking 20 years data from 1985 to 2004. He established a temperature-elevation relationship by using the simple linear regression method (Table 4).

Table 4 Mean seasonal temperature lapse rate 1984-2004 (Kattel et al. 2013)

	Mean Lapse Rate (°C/km)	Maximum Lapse Rate (°C/km)	Minimum Lapse Rate (°C/km)
Pre-monsoon	-5.9	-6.5	-5.3
Monsoon	-5.1	-5	-5.1
Post-monsoon	-5.3	-5.4	-5.2
Winter	-4.7	-5.0	-4.3
Annual	-5.2	-5.4	-4.9

In the upper Langtang catchment of the central Himalaya, Immerzeel et al. (2014) calculated temperature lapse rate from the six temperature logger were established at the elevation ranges from 1406 m a.s.l in Syafru Besi to the summit of Langtang Lirung at 7234 m a.s.l in the period of 8-May 2012 to 30-April 2013 (Table 5).

Table 5 Mean seasonal temperature lapse rate calculated on Langtang by Immerzeel et al. (2014)

	Mean Lapse Rate (°C/km)	Maximum Lapse Rate (°C/km)	Minimum Lapse Rate (°C/km)
Pre-monsoon	-6.4	-5.4	-7.0
Monsoon	-4.6	-4.0	-5.3
Post-monsoon	-4.9	-3.4	-5.9
Winter	-5.8	-4.5	-6.7

Fujita and Sakai (2000) reported that the mean temperature lapse rate in Langtang were -5.1 °C/km and -5.4 °C/km similarly at daily time scale vertical temperature gradient vary from -6 to -8 °C/km during the winter and post monsoon and less during the monsoon (-4 to -5 °C/km) according to Shea et al. (2015) in Langtang valley.

Salerno et al. (2015) analyzed the temperature lapse rate in the Koshi basin by taking the annual mean temperature from various stations (865-7987m., 1994-2013) and found an annual temperature gradient of -6. 0°C/km.

CHAPTER 3: Study Area and Data

3.1 Study area

The study area is one of the most famous area for tourist where the world highest peak Mt. Everest lies. Several research had been already done in this area and also a World Highest Research Lab is in the study area at the elevation of 5000 m a.s.l. named as EvK2-CNR (since 1994) in the Khumbu, near Mt. Everest base camp.

In this study, I focus on two glaciers, Mera Glacier located at Makalu Barun National Park in the Hunga and Inkhu sub basins of the Dudhkoshi river system, and Changri-Nup Glacier in the Khumbu valley of upper Dudh Koshi basin as shown in Figure 1. All three sub basin are part of the Dudh Koshi basin, dominated by the summer monsoon.

Mera glacier (27.7° N, 86.9° E, 5.1 km^2) is a clean type glacier which has been continuously studied since 2007. Mera Peak is one of the most southern mountains of the region, and thus occupies a frontal position against the Indian monsoon flux (e.g. Bookhagen and Burbank 2006) and its 5 to 7 day access from Lukla airport. From the summit at 6420 m a.s.l., the glacier flows north and divides into two main branches at 5800 m a.s.l. The main branch flows north and then west down to its snout at 4940m a.s.l. while the second branch is northeast orientated with its lowest elevation at 5260ma.s.l. These two branches are referred as Mera and Naulek, respectively(Sherpa et al. 2017; Wagnon et al. 2012).

East Changri Nup Glacier (27.987° N, 86.785° E, 2.4 km^2) is a debris covered glacier located near Mt. Everest base camp in Khumbu valley. Changri-Nup glacier is monitored since 2010 (Sherpa et al. 2017; Vincent et al. 2016) which is located ∼25 km north of Mera Glacier (Fig. 1). And another Pokalde Glacier (27.9° N, 86.8° E; 0.1 km^2) is a very small and clean glacier. This north-oriented glacier flows from 5690 to 5430 m a.s.l., is accessible from Ev-K2-CNR Pyramid permanent research observatory, and has been monitored since 2009 (Bookhagen and Burbank 2006; Wagnon et al. 2012).

From the various sector like tourism, agriculture, industrial, hydropower etc. the solid water reserved naturally in this area is very important for the upstream plus downstream and also to be aware of the potentially dangerous glacial lake are like Imja in this catchment.

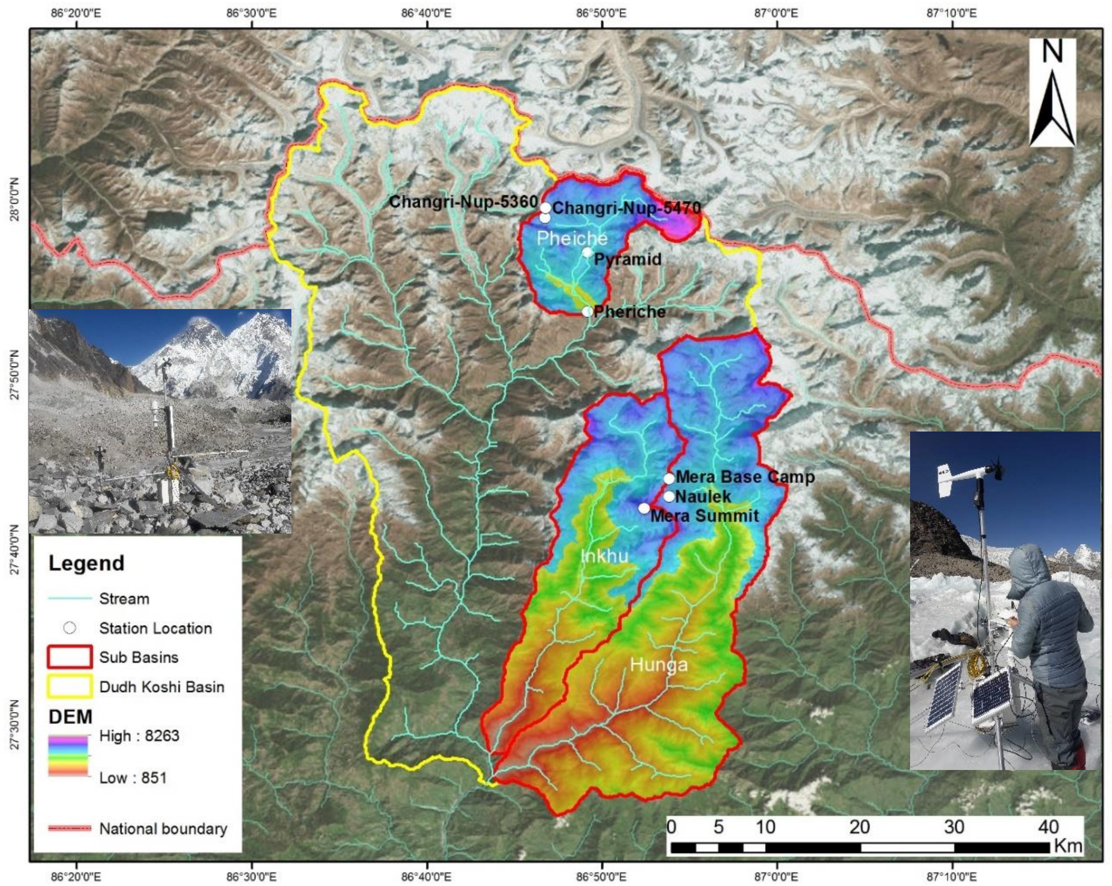

Figure 1 Location of automatic weather station in the Mera site and Khumbu site of upper Dudh Koshi basin

3.2 Data

Data were collected from AWSs located on Hungu/ Inkhu sub-basin of Dudh Koshi basin and the Khumbu valley of upper Dudh Koshi basin.

Mera AWS (5350 m a.s.l.) is in the bed rock at near the base camp of Mera Peak, Naulek (5360 m a.s.l.) and Mera Summit (5360 m a.s.l.) AWSs are on debris-free glacier surface of Mera glacier, Changri-Nup5360 (5360 m a.s.l.) and Changri-nup5470 (5470 m a.s.l.) AWSs are located on the debris covered part of Changri-Nup glacier, and the precipitation data were collected from the Pyramid (5000m a.s.l.) and Pheriche (4200 m a.s.l.) station. The reason to install the AWS in different surface and elevation is to understand the variation and differentiation of meteorological parameter and to calculate gradients. Details of the installed sensors, measured parameters and recorded data period are shown in Table 6.

Table 6. Stations elevation, sensors, accuracy, data period, data gap and the station location surface type (T= temperature, RH= relative humidity, U= wind speed, Ө= wind direction, K↓= short wave incoming, L↓= longwave incoming, K↑= short wave outgoing,L↑= long wave outgoing and P= precipitation)

Stations (elevation)	Parameters	Sensors	Accuracy	Data period	Data gap period (parameters)	Surface of AWS location
Mera 5350m asl	T, RH U, Ө K↓,L↓ K↑,L↑	Vaisala-hmp155 Young 05103-5 Kipp&ZonenCNR4" "	±0.2°C, ±2% ±0.3m/s, ±3degree ±3% ±3%	Nov2013-Apr2019		AWS on bed rock near Mera base camp
Mera summit 6352m asl	T, RH U, Ө K↓,L↓ K↑,L↑	Vaisala-hmp155 Young 05103-5 Kipp&ZonenCNR4" "	±0.2°C, ±2% ±0.3m/s, ±3degree ±3% ±3%	Nov2013-Aug2016	28/8//2014-10/12/2014(all) 1/3/2015-11/4/2015(only SW and LW) after 9/4/2015 no wind direction	AWS on clean glacier just below the South summit of Mera peak
Naulek 5360m asl	T, RH U, Ө K↓,L↓ K↑,L↑	Vaisala-hmp155 Young 05103-5 Kipp&ZonenCNR4" "	±0.2°C, ±2% ±0.3m/s, ±3degree ±3% ±3%	Nov2013-Apr2019	14/2/2014-31/3/2014(only radiation) 19/10/2014-24/10/2014(all) 24/10/2014-28/10/2014(only some night values) 18/4/2015-7/5/2015(all values) 9/12/2015-19/4/2016(radiation & wind) Dec2017- Dec2018(all values)	AWS on debris free Naulek glacier
ChangriNup 5350m asl	T, RH U, Ө K↓,L↓ K↑,L↑	Vaisala-HMP45C Young 05103-5 Kipp&ZonenCNR4" "	±0.2°C, ±2% ±0.3m/s, ±3degree ±3% ±3%	Oct2010-Nov2018	15/12/2013-9/4/2014(all) 2/7/2015-16/7/2015(radiation & wind) 10,11,12/5/2016(some morning values of all parameters) Aug-Sept2016(some morning data in between 1-8AM) Oct2016(some morning data in between 4-8AM) Nov2016(some morning data in between 5-6AM)	AWS on flat part of the glacier
ChangriNup 5470m asl	T, RH U, Ө K↓,L↓ K↑,L↑	Vaisala-HMP45C Young 05103-5 Kipp&ZonenCNR4" "	±0.2°C, ±2% ±0.3m/s, ±3degree ±3% ±3%	Nov2014-Nov2016	20/12/2015-1/5/2016 (wind speed and direction)	AWS on flat part of the glacier
Pyramid 5035m asl	Pptn	Geonor T-200BM (shielded)	±15%	Jun2012-Apr2016		Flat grassy moraine
Pheriche 4260m asl	Pptn	Geonor T-200BM (shielded)	±15%	Jun2012-May2016		Flat grassy moraine

3.3 Climatic Condition

3.3.1 Precipitation climatology of Nepal:

The Himalayas and the Tibetan Plateau play an important role in the monsoon circulation system, both as an elevated heat and moisture source/sink in the upper troposphere (due to the strong warming/cooling of the ground and the release of large quantities of condensation heat) and as an orographic barrier to wind flows (Murakami 1987; Yanai, Li, and Song 1992). The Indian monsoon flow is strongly correlated to the snow cover in these areas as demonstrated in several studies on the topic (e.g., Dickson 1984; Bamzai and Shukla 1999).

The distribution of precipitation has high spatial variation in Nepal. Nepal experiences the seasonal summer monsoon rainfall from around June to September. Most of the days during June to September are cloudy and rainy. About 80 % of the annual precipitation in the country falls in this time period. The amount of precipitation varies considerably from place to place because of the non-uniform rugged terrain. However, the amount of summer monsoon rains generally declines from southeast to northwest (DHM 2015).

The winter months, December to February, are relatively dry with clear skies. However, a few spells of rain do occur during these months. In winter the major weather systems are the western disturbances, so rain decreases in amount from northwest to both southward and eastward direction. The direction of predominating wind is northwesterly during this season. During March to May the country experiences pre-monsoon thundershower activities. The pre-monsoon rainfall activities are more frequent in the hilly regions than in the southern plains. The period of October and November is considered as a post monsoon season and a transition from summer to winter. During October the country receives a few spells of post-monsoon thundershowers, similar in character to the pre-monsoon ones (DHM 2017).

The spatial variation of precipitation has been analyzed from the observations of 1961 to 2012 in a recent DHM report. Only the stations with the data available for at least 10 years out of these years were used. However, in order to cover high altitude areas above 3000m stations with data for at least 5 years were also used. The mean annual precipitation of Nepal was found to be around 1800mm with the highest annual precipitation recorded in Lumle of Kaski District with mean annual precipitation of about 5500 mm. The lowest precipitation site is recorded in Upper Mustang Dhiee, Lomanthang area of Mustang District with mean annual precipitation of less than 150mm. Both of these highest and lowest precipitation sites of the country are in the Annapurna area (DHM 2015).

3.3.2 Meteorology and Glacier mass balance in Everest Region

Meteorological conditions affect the annual mass balance of glaciers and, as a consequence, the availability of water in the plains. The Central Himalaya mountain ridge is situated in the subtropical climate zone, characterized by annual thermal amplitude of about 12°C at high elevations, which allows a separation into summer and winter seasons. Furthermore the distribution of precipitation defines climatic zones. There are three different types of climatic zones in the Hindu Kush Himalaya (HKH) region, i) monsoon influenced ii) monsoon-arid transition zone iii) snow dominant alpine region. First kind of climatic zone is found in eastern and central Himalaya of Nepal, with maximum precipitation amounts in the summer, characterized by summer accumulation type glaciers (Ageta and Higuchi 1984).

The mean annual cycle of monthly precipitation and monthly air temperature (1994 - 2013) recorded at meteorological stations operated by Ev-K2-CNR in Pyramid, Khumbu (5035 m a.s.l) is shown in Figure 2. Tipping buckets are used as precipitation sensors at this location for rainfall measurements; however this may under catch part of the solid precipitation. Therefore, this station, which is located at quite a high altitude, is likely to underestimate the precipitation (Wagnon et al. 2012). The data from Pyramid is sufficient to describe the local climatic condition at level above 5000m a.s.l. Using twenty years 1994-2013 dataset, the mean annual cycle of monthly mean, maximum and minimum temperature and precipitation has been obtained by averaging all the monthly temperature and monthly cumulative precipitation of the whole year (from January to December) between 1994 to 2013 (Figure 2). Both the air temperature and precipitation shows a strong seasonality with more than 80% (i.e. 398mm on monsoon) of precipitation during monsoon with a mean annual temperature of -2.48 ^{0}C. A long-term time series of meteorological observations thus proves fundamental in the study of glacier fluctuations as a response to global climate change (Bollasina et al. 2002).

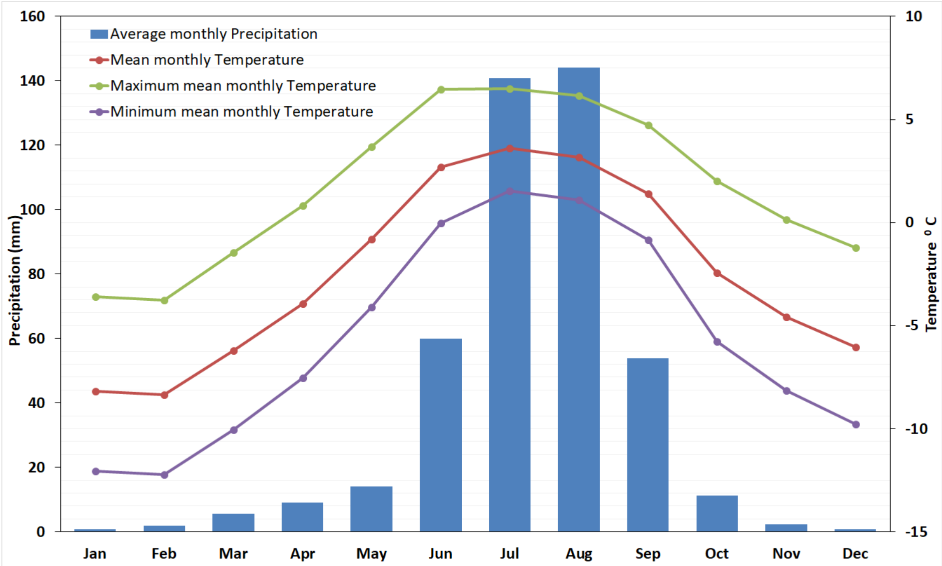

Figure 2: Total mean cumulative monthly Precipitation recorded at EvK2-CNR Pyramid stations from 1994 to 2013, a mean annual maximum temperature 1.7 °C and a mean annual minimum temperature of -5.65°C.

Glacier Mass balance

Figure 3 shows the glacier wide mass balance recorded on Changri-Nup, Pokalde and Mera glaciers between Nov 2007 and Nov 2018. The result is obtained from several extensive field expeditions that has been done between 2007-2018. Changri-Nup glacier had the most negative mass balance of all three glaciers. Out of three glacier, observation shows highest negative mass balance in Changri-Nup glacier and lowest in Mera glacier.

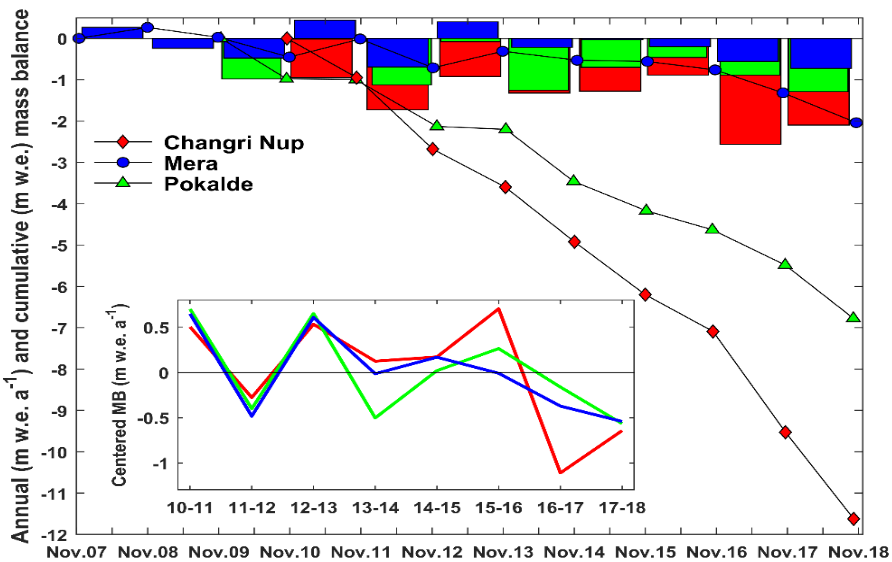

Figure 3 Annual mass balance of Mera, Pokalde and Changri-Nup Glacier from Nov2007-Nov2018 ©Patrick Wagnon

3.4 Identification of errors and Data processing

Installation, regular monitoring and data collection at the higher elevation above 5000m asl is challenging (Shea et al. 2015) and errors in the data are not unusual. The data downloaded from the AWSs needs to filter, sometime correction before the analysis. So, here for the five meteorological AWSs, the values of incoming shortwave radiation (K↓) lower than 7 Wm^{-2} were set to zero, the maximum albedo was corrected to 0.95 for the observations where albedo exceeds 0.95 and two precipitation stations some steps were taken to eliminate erroneous data as listed below:

3.4.1 Precipitation data correction

Noise and evaporation correction: Precipitation data at the Pyramid and Pheriche sites are extracted from the bucket weight, which is recorded with a Geonor T-200BM at 15-minute intervals (or 30 min interval after May 2016). To extract the precipitation at each time step, I first calculate the change in bucket content, which is supposed to be always positive given that evaporation is blocked with a layer of oil spread out over the water. However, the vibrating device used to weigh the bucket is sensitive to external perturbations such as wind, which results in a background noise i.e. small positive or negative changes every 15-minute time step. To smooth the signal and avoid any negative precipitation, I compensate each negative change recorded over a 15-minute time step by summing it with the neighboring positive change, thus giving a 30 minute time interval. Periods with prolonged evaporation (negative values) are put to 0.

Correction recommended by World Meteorological Organization (WMO): Such kind of device is known to under catch precipitation in case of snowfall. So a second treatment is done using Tair data (for phase discretization: rain vs snow) and wind speed (the correction is largely dependent on wind speed). This correction following (Førland et al. 1996) is recommended by WMO and has been applied in high elevation tropical environments that experience snowfall (Wagnon et al. 2009). The accuracy is estimated at +/-15%.

3.4.2 Shortwave incoming and outgoing

When the short wave incoming data is less than 7 Wm^{-2} and shortwave outgoing is less than 6 Wm^{-2} then the data were replaced by 0. And when the albedo value found above 0.95, in these case the shortwave incoming is recalculated by

$$SWin = SWout/0.95 \quad (1)$$

3.4.3 Wind

When the wind speed is found 0m/s, the data were removed as the anemometer considered to be stuck.

3.4.4 Missing Data

Nighttime power losses occurred at Naulek AWS from 24/10/2014 to 28/10/2014 and May-Nov2016 at Changri-Nup5360 AWS. Mean daily values for these time periods at these site are used for illustration purposes only, and when evaluating the mean daily cycle, mean hourly values computed only for periods where more than 80% of observations are available.

Mean monthly and mean seasonal values are computed only where more than 80% of observations are available similar to Shea et al. (2015).

3.5 Derived meteorological quantities

3.5.1 Vapour pressure

The actual vapour pressure ($\mathbf{e_a}$) is a function of the saturation vapour pressure ($\mathbf{e_s}$) and relative humidity (*RH*) and ranges from 0 to 100%.

$$e_a = e_s RH \quad (2)$$

And to calculate the saturation vapour pressure (e_s) following the (Bolton 1980),

$$e_s = 6.112 * \exp(17.67 * T/(243.5 + T)) \quad (3)$$

Where, T is the observed temperature in ^{0}C.

Near surface temperature (T) and actual vapour pressure (e_a) are key variables needed for glacio-hydrological modeling. At the Mera site, Temperature (T) and Relative Humidity (RH) from two in-glacial AWS having elevation difference nearly one kilometer from at 5350m and 6350m were used to calculate the vapour pressure gradient (Ye_a, hPa/km) and temperature gradient (Yt, °C/km).

$$Yt = \frac{T1 - T2}{Z1 - Z2} \quad (4)$$

$$Ye_a = \frac{e_{a1} - e_{a2}}{Z1 - Z2} \quad (5)$$

Where, T1, T2, Z1, Z2, e_{a1} and e_{a2} temperature, elevations and actual vapor pressure at Mera summit and Naulek AWS respectively.

3.5.2 Zero degree isotherm and 6.11hPa isoline

Temperature gradient (Yt, °C/km) and vapour pressure gradient (Ye_a, hPa/km) both are very important for the calculation of sensible heat and latent heat fluxes additionally required to calculate the 0 degree isotherm ($Z_{t=0}$) and 6.11hPa isoline (Ze_a) elevation, thus helps to understand the seasonal changes in elevation of equilibrium line altitude .

$$Z_{t=0} = \frac{-Tn}{Yt} + Zn \quad (6)$$

$$Ze_{a=6.11} = \frac{6.11 - e_{an}}{Ye_a} + Zn \quad (7)$$

Where,Tn, e_{an} and Zn are temperature (T, °C), actual vapour pressure (e_{a2}, hPa) and elevation of Naulek AWS respectively.

3.5.3 Albedo

Albedo is calculated by using the formula (Sakai et al., 1998)

$$\alpha = K\uparrow / K\downarrow \quad (8)$$

Where, K↓ and K↑ are incoming and outgoing shortwave radiation.

3.6 Methods of data analysis

To compare annual seasonal and diurnal patterns of each meteorological dataset first I arrange the whole data to annual basis (i.e. 2013-2018) and after that the year is divided in to four seasons: winter (December-February), pre-monsoon (March-May), monsoon (June-September), and post-monsoon (October-November) similar to the Shea et al. (2015). Mean daily temperature gradient, vapour pressure gradient, were calculated for Naulek and Mera summit to examine the zero degree isotherm and 6.11 hPa isoline similar to Shea et al. (2015).

CHAPTER 4: Results

4.1 Comparison of meteorological variables of different AWSs

The time series plot of mean daily air temperature, vapour pressure, wind speed, albedo, incoming longwave and shortwave radiation from different five AWSs are shown in Figure 4.

4.1.1 Temperature and Vapour pressure

The mean daily temperature calculated from the half hourly data downloaded from the five different AWS shows that during the monsoon, temperature was found to be higher and with less variability and high variability in winter and pre-monsoon (Figure 4). The mean daily air temperature at all AWS site is strongly co-related at mean daily time step (r= 0.95 – 0.99). At Mera and Changri-Nup-5360 AWS site, the mean daily air temperature exceeded 3 °C but in Naulek AWS site it was always less than 3°C. In Mera Summit (6352 m a.s.l.) AWS site, the air temperature found 2.5 °C on monsoon 2016, which is the highest mean daily air temperature at that elevation. The mean annual temperature is calculated by using the half hourly data from December to November (for example the mean annual temperature for 2013-14 is calculated by using temperature data recorded on Dec2013 and the first 11 month of 2014 to include all four month of 2013-2014). The linear trend of mean annual temperature is calculated in Mera, Naulek and Changri-Nup AWS. The temperature trend is found to be 0.25 °C/yr in Mera (from 2013-14 to 2017-18) and 0.24 °C/yr in Naulek (from 2013-14 to 2016-17). But unexpectedly lower trend (0.015 °C/yr) is found in Changri-Nup-5360 in 2010-11 to 2017-18 whereas comparable temperature trend (0.24 °C/yr) is observed in the period of 2013-14 to 2017-18 (Figure 7). The unexpected temperature trend in Changri-Nup-5360 is might be attributed to large data gap in 2013 and 2014 (Table 7).

The correlation coefficient between the air temperature and incoming longwave radiation is found between 0.73 to 0.85 similarly air temperature and outgoing long wave radiation is found in the range of 0.93- 0.97.

Table 7 Mean annual temperature (°C) recorded at different AWS from 2010-11 to 2017-18, in bracket the number of missing mean daily data and calculated temperature trend

Year/ Stations	2010-11 mean(missing)	2011-12 mean(missing)	2012-13 mean(missing)	2013-14 mean(missing)	2014-15 mean(missing)	2015-16 mean(missing)	2016 -17 mean(missing)	2017-18 mean(missing)	Linear Trends (°C/yr)
Mera				-4.08	-3.78	-2.97	-3.25	-3.07	0.25
Naulek				-5.3(11)	-5.4(13)	-4.6	-4.83		0.24
Mera Summit				-12.1(96)	-11.03(9)				
Changri-5360	-3.74	-3.76(6)	-3.82(4)	-3.4(112)	-4.49	-3.38	-3.8	-3.55(22)	0.015 0.24(2013-18)
Changri-5470					-5.04	-4.3(20)			

Table 8 Maximum mean daily temperature (°C) recorded at Mera, Naulek, Mera Summit, Changri-Nup5360 and Changri-Nup5470 AWS respectively

	2013-2014 (Dec-Nov)maximum	2014-2015 maximum	2015-2016 Maximum	2016-2017 maximum	2017-2018 maximum
Mera	3.40(6Aug)	4.58(13Jul)	4.65(20Aug)	3.83(7Jul)	4.23(7Jul)
Naulek	2.31(12Jul)	2.46(14Jul)	2.63(9Jul)	2.71(7Aug)	
Mera Summit	-0.42(19Aug)	2.54(13Jul)	1.43(30Jun)		
Changri5360	3.60(10Aug)	5.07(13Jul)	4.91(20Aug)	3.57(7Jul)	4.65(7Jul)
Changri5470		3.43(13Jul)	3.11(15Jul)		

Table 9 Minimum mean daily temperature (^{0}C) recorded at Mera, Naulek, Mera Summit, Changri-Nup5360 and Changri-Nup5470 AWS respectively

	2013-2014(Dec-Nov) minimum	2014-2015 minimum	2015-2016 Minimum	2016-2017 minimum	2017-2018 minimum
Mera	-16.80(16Feb)	-16.84(8Jan)	-15.55(27Jan)	-17.19(2Jan)	-16.85(2Jan)
Naulek	-16.87(14Dec)	-20.38(17Jan)	-17.36(25Jan)	-19.72(3Jan)	
Summit	-27.46(14Dec)	-25.64(8Jan)	-23.94(20Jan)		
Changri5360	-16.58(15Dec)	-18.71(8Jan)	-16.53(25Jan)	-18.71(2Jan)	-17.29(2Jan)
Changri5470		-18.65(17Dec)	-16.72(26Jan)		

The evolution of the actual vapour pressure calculated from relative humidity and air temperature are highly correlated (r=0.94-0.99) in daily time step. Vapour pressure are found different between Mera Summit AWS and the other lower AWS (Mera, Naulek, Changri5360 and Changri5470) (Table 10). During the monsoon 2014-2015, vapour pressure at Mera Summit remains 2-3 hPa lower than the other AWS sites located at lower elevation, but this difference is reduced to less than one by the end of monsoon 2014-2015(Figure 4). Most of the mean daily value of vapour pressure calculated at Mera AWS is higher than Changri-Nup5360 and Naulek during monsoon period.

Table 10 Mean annual vapour pressure calculate from mean daily data from Nov2013 to Nov2018 and the no of missing data in the bracket.

Year	2013-14	2014-15	2015-16	2016-17	2017-18
Mera	3.19(1)	3.2(4)	3.34(2)	3.41(2)	3.44(14)
Naulek	2.87(16)	2.92(26)	3.91(141)	2.99(0)	
Mera Summit	1.74(97)	2.01(11)	1.71(124)		
Changri-Nup5360	4.01(131)	2.91(0)	2.50(112)	3.07(0)	3.11(22)
Changri-Nup5470		2.46(50)	2.85(23)		

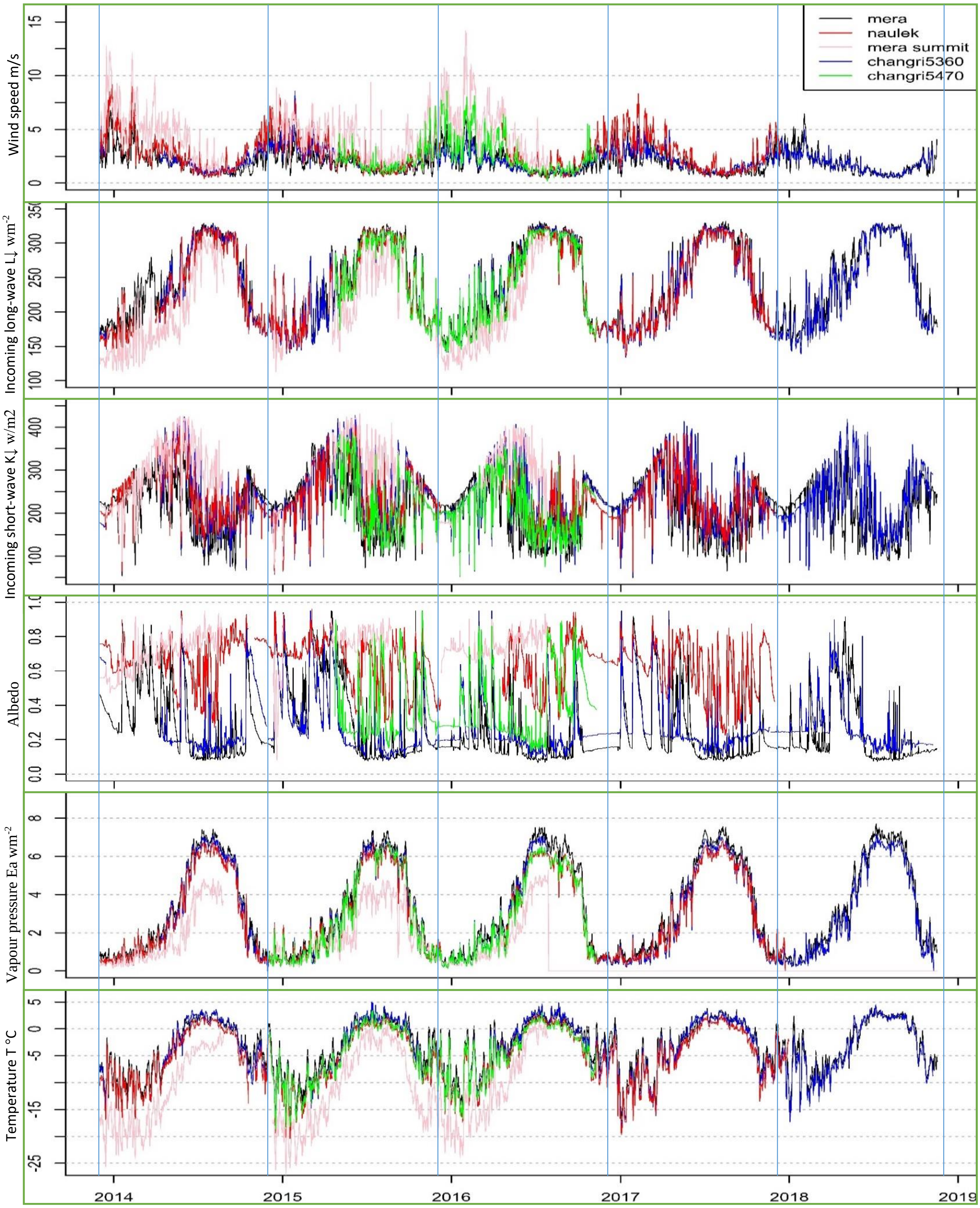

Figure 4; Mean daily comparison of meteorological data Dec2013-Nov2018. From top to bottom, mean daily wind speed (U), incoming long wave radiation (L↓), mean daily incoming shortwave radiation (K↓), albedo (), actual vapour pressure (Ea) and temperature (T).

4.1.2 Incoming short-wave and long-wave radiation

The mean daily incoming short wave were gradually increasing from winter to pre-monsoon and after the start of monsoon it were decreased with high variability. In the pre-monsoon the incoming short wave again starts decreasing with less variability. The longwave radiation are found opposite pattern of incoming shortwave radiation, higher in monsoon with less variability and gradual decrease after monsoon, pre-monsoon with high variability. Mera Summit AWS site have different/higher K↓ than other same elevation site in monsoon. The correlation coefficient of mean daily incoming shortwave radiation are found between (r=0.29-0.9). The lowest correlation is found between Mera and Mera Summit(r=0.29). The incoming long wave radiation are strongly correlated (r=0.94-0.98) between the sites with highest in monsoon with higher stability and less stability were found in pre-monsoon.

Table 11 Mean annual incoming long-wave radiation (wm^{-2}) calculated from mean daily data and missing daily data in the bracket

	2013-14	2014-15	2015-16	2016-17	2017-18
Mera	242.63(0)	238.72(0)	242.40(0)	241(0)	244.36(14)
Naulek	234.71(50)	237.69(57)	262.59(33)	234.66(0)	
Mera Summit	196.19(96)	231.91(176)	198.8(119)		
Changri-Nup5360	254.61(16)	228.61(14)	238.98(0)	235.61(0)	238.18(22)
Changri-Nup5470		259.43(144)	240.15(20)		

Table 12 mean annual incoming short-wave radiation (wm^{-2}) calculated from mean daily data and missing daily data in the bracket

	2013-14	2014-15	2015-16	2016-17	2017-18
Mera	215.92(0)	224.51(0)	206.57(0)	211.51(0)	203.60(14)
Naulek	239.9(57)	244.83(20)	217.12(35)	229.61(0)	
Mera Summit	291.52(97)	307.37(177)	270.17(126)		
Changri-Nup5360	234.56(18)	255.80(15)	228.47(0)	236.39(1)	231.07(22)
Changri-Nup5470		223.78(144)	211.29(20)		

4.1.3 Wind

The mean daily wind speed is gradually decreased after the starts of monsoon and again increased after the start of post monsoon. The observed wind speed are found highest in winter and pre-monsoon and lowest in monsoon. The wind speed is found little difference in between different land cover sites at the same elevation and also found higher in Mera Summit than lower site. In winter, higher wind speed (> 5m/s), compared to Mera and Changri-Nup-5360, recorded at Naulek and Mera Summit sites. The highest mean daily speed is found 14.2 m/s at Mera summit on 31/1/2016 (Figure 4)

4.1.4 Albedo

In altitude above than 4500m a.s.l., albedo calculated from the incoming and outgoing shortwave radiation gives information about the form of precipitation and the duration of snow cover (before melting) in different season at different site. Albedo value at Mera site, the only station outside the glacier, is always lower than other AWS site (Figure 4). Naulek site also have lower albedo in monsoon than other season. Mostly mean daily albedo in monsoon is consistently lower at lower elevation site than Mera summit.

4.1.5 Precipitation

Total daily precipitation is highly different during winter, pre-monsoon and monsoon at Pheriche and Pyramid which are only in few kilomiters horizontal distance from each other and 775 m altitude difference. The highest one day precipitation recorded on 14/10/2013 at Pyramid and Pheriche is 91 and 58 mm which which is caused by Typhoon Phailin event. Another event in 1/3/2015 at Pheriche recorded 50 mm of precipitaion. Many extreme precipitation events happened in non-monsoonal season having more than 20mm precipiation in Pyramid and Pheriche which are the main contributer to total seasonal precipitation like in winter 2012-2013, 2014-2015 and post monsoon 2012-2013.

Table 13 Total seasonal and annual precipitation recorded at Pyramid and Pheriche

Season	2012-13		2013-14		2014-15		2015-16	
	Pyramid	Pheriche	Pyramid	Pheriche	Pyramid	Pheriche	Pyramid	Pheriche
Winter	49.39	106.33	28.65	27.32	60.9	87.12	37.5	46.89
Pre-monsoon	81.98	99.96	120.29	128.382	167.48	214.303		133.52
Monsoon	387.16	330.87	397.37	334.004	331.929	286.072		
Post-monsoon	100.76	155.03	48.653	49.771	24.504	23.26		
Annual	619.29	692.19	594.96	539.477	584.813	610.755		

Results from (Bollasina et al. 2002) shows that the average precipitation in khumbu valley is 465 mm and almost 400 mm precipitate in summer monsoon. But slighlty different result with total annual precipitation above 500 mm and monsonnal precipitation below 400 mm in both Pyramid and Pheriche site were identified in this result.

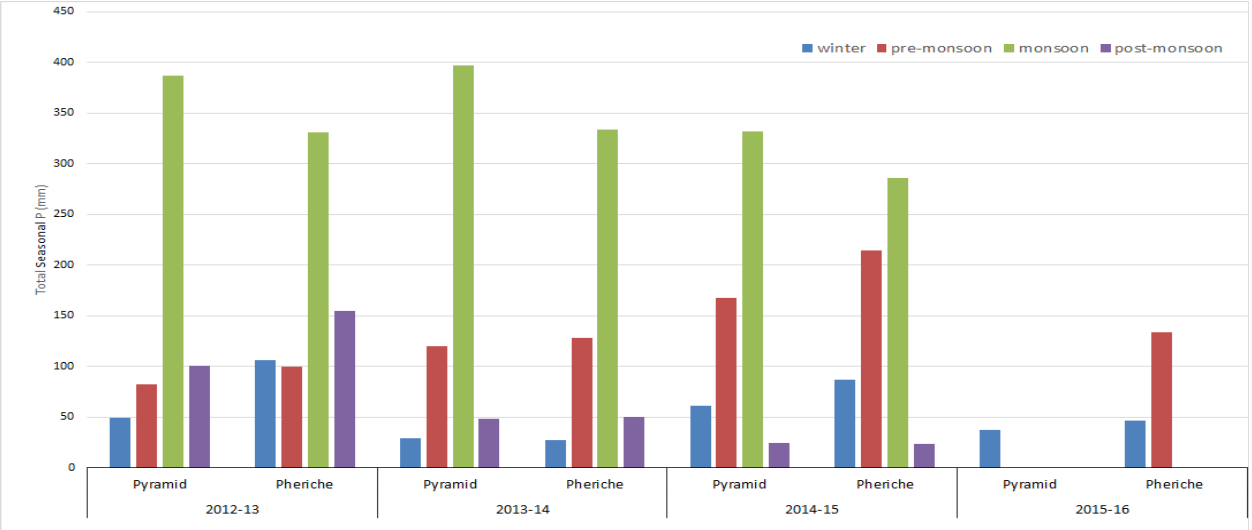

Figure 5; Seasonal precipitation (P) in Pyramid and Pheriche.

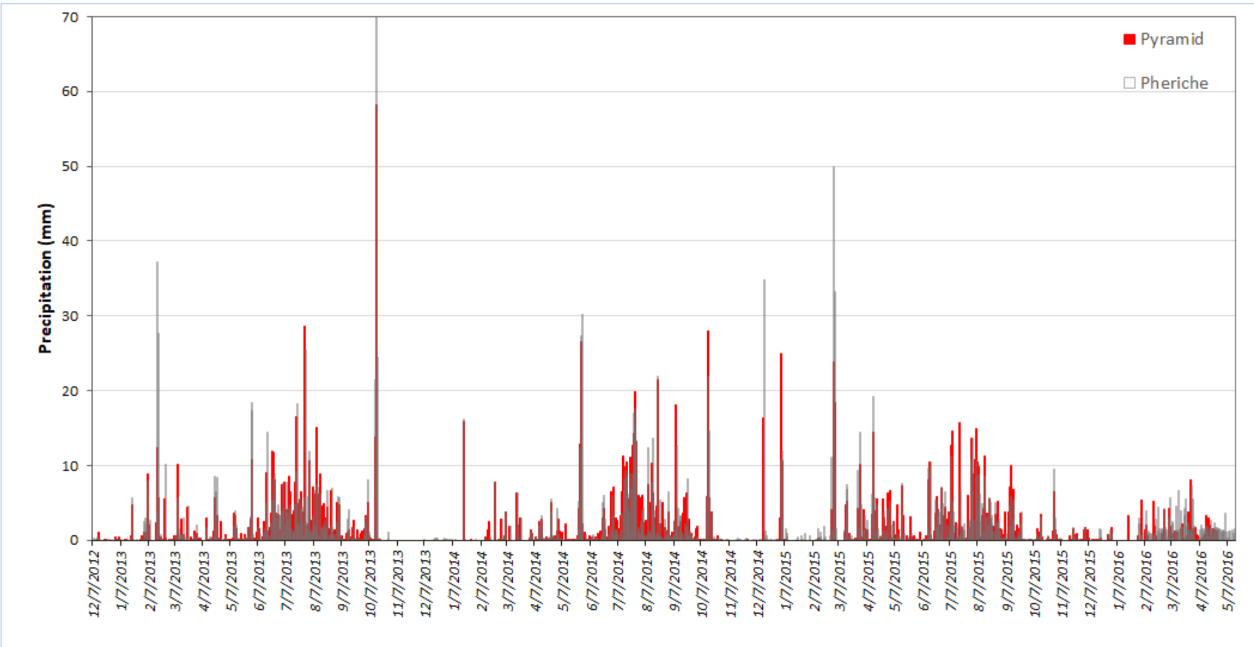

Figure 6 Total daily precipitation in mm from Dec2012 to May2016 in Pyramid and Pheriche Genor

4.2 Seasonal variation in temperature gradient (TG) and zero degree isotherm

Figure 7 shows the temperature gradient and zero degree isotherm line plot of half-hourly value and mean daily values of temperature gradient from Dec1st 2013 to 25th of Aug2014. Most of the mean daily temperature gradient during winter 2013-14 are less than Environmental Lapse Rate (ELR) and increased after the pre-monsoon. During monsoon, temperature gradient reached up to -1.52°C/km on 19/8/2014 from the lowest mean daily gradient -9.4°C/km on 4/1/2014. The zero degree isotherm derived from the temperature gradient varies from 2713 m (4/1/2014) to 6073 m (19/8/2014), and all the estimated derived height are above 5000 m a.s.l. on the monsoon.

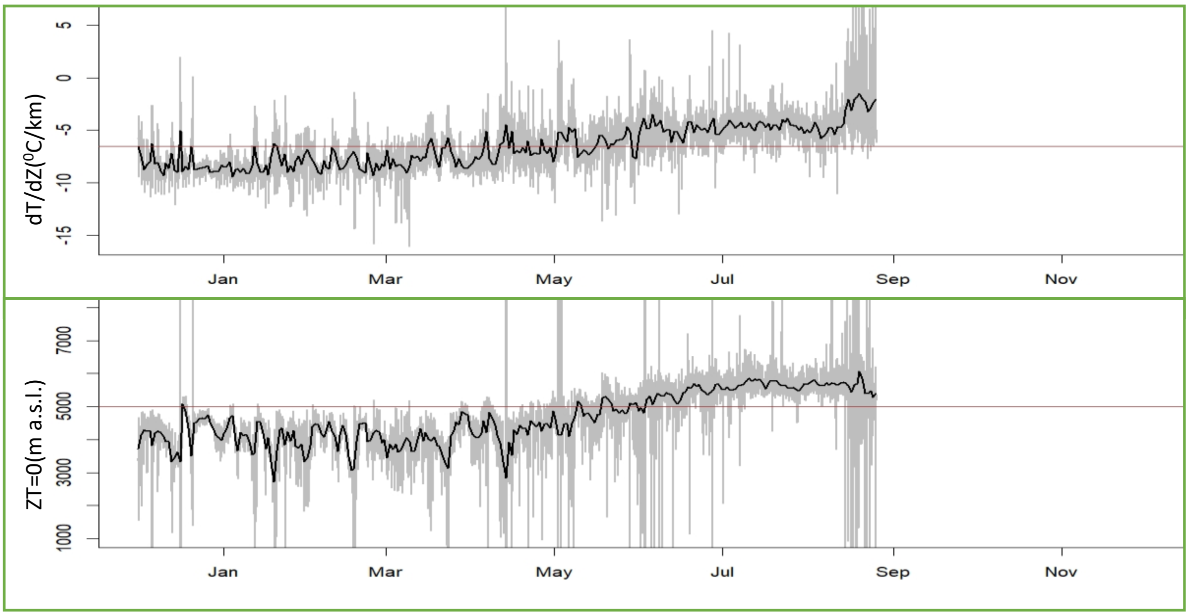

Figure 7 Temperature gradient (top) and height of zero degree isotherm (bottom) in the Mera glacier site from Dec2013 to Nov2014. Mean daily value in black and half-hourly value in grey. The horizontal line represents the environmental lapse rate (-6.5°C/km) and 5000m a.s.l elevation line

During 2014-15, half-hourly temperature gradient (TG) and zero degree isotherm are highly fluctuated in monsoon (Figure 8). During winter season of the same period, mean daily TG is found -7.2 ^{0}C/km. TG in monsoon is observed higher than ELR, which reached up to +0.33 ^{0}C/km on 13/7/2015. Moreover, after the end of monsoon TG found higher negative up to -9.84^{0}C/km on 15/11/2015 (**Error! Reference source not found.**). Calculated mean daily TG lies etween -9.58^{0}C/km (10/12/2015) and -3.03°C/km (27/2/2016) in winter 2015-16. In pre-monsoon of 2015-16, -8.81°C/km (22/4/2016) and -1.38 °C/km (7/5/2016) shows the high fluctuation of TG before the monsoon. From the May 2016 most of the mean daily TG found higher than ELR. The calculated mean daily zero degree isotherm line is located at 7747m on 30/6/2016.

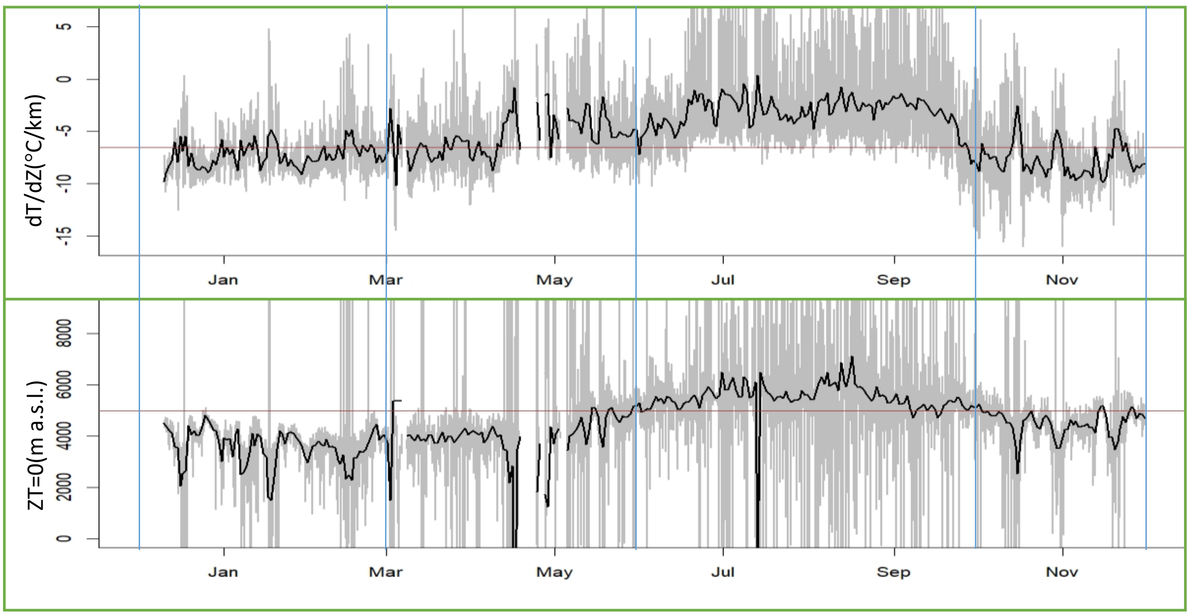

Figure 9 Temperature gradient (top) and height of zero degree isotherm (bottom) in the Mera glacier site from Dec2014 toNov2015. Mean daily value in black and half-hourly value in grey. The horizontal line represents the environmental lapse rate (-6.5°C/km) and 5000m a.s.l elevation line

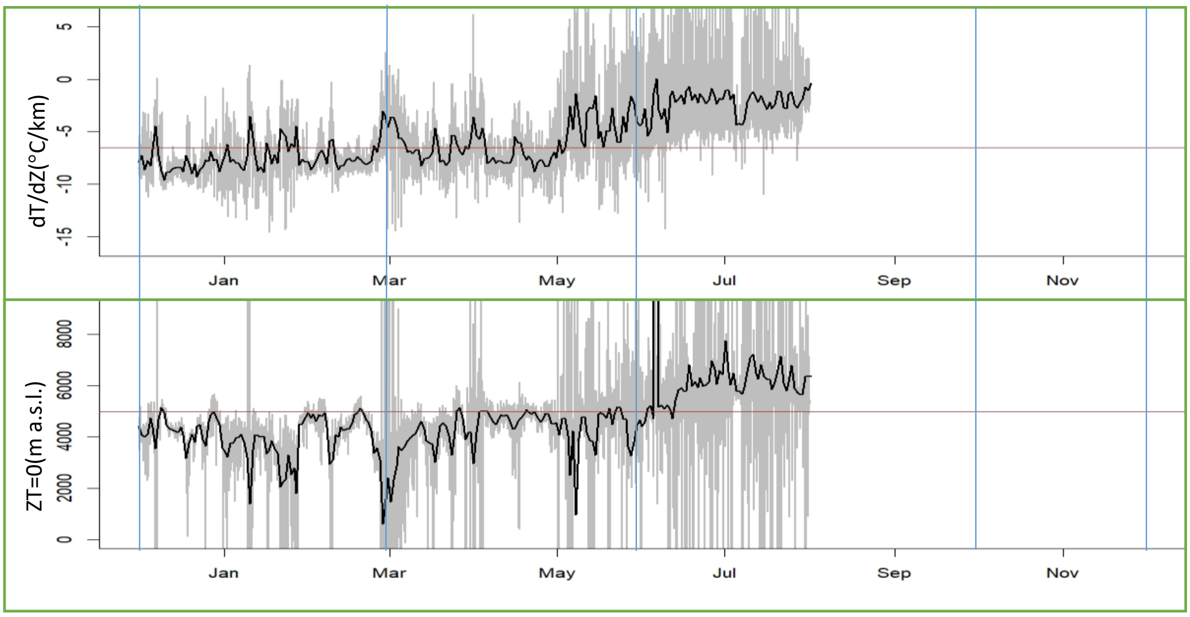

Figure 8 Temperature gradient (top) and height of zero degree isotherm (bottom) in the Mera glacier site from Dec2015 to Jul2016. Mean daily value in black and half-hourly value in grey. The horizontal line represents the environmental lapse rate (-6.5°C/km) and 5000m a.s.l elevation line

4.3 Seasonal variation in Vapour pressure gradient (VPG) and 6.11hPa Isoline

Vapor pressure calculated from air temperature and relative humidity at Naulek and Mera Summit AWS lies between 0 to -3hPa/km, with the most negative values occurring during monsoon. The higher negative gradient results in 6.11hPa isoline values of above 500m asl and the lower values in the rest of the year. The diurnal cycle of vapor pressure calculated are almost similar except the monsoon2014-2015. In monsoon 2014-2015 the vapour pressure gradient found higher than 2hPa from 10 AM to 10 PM.

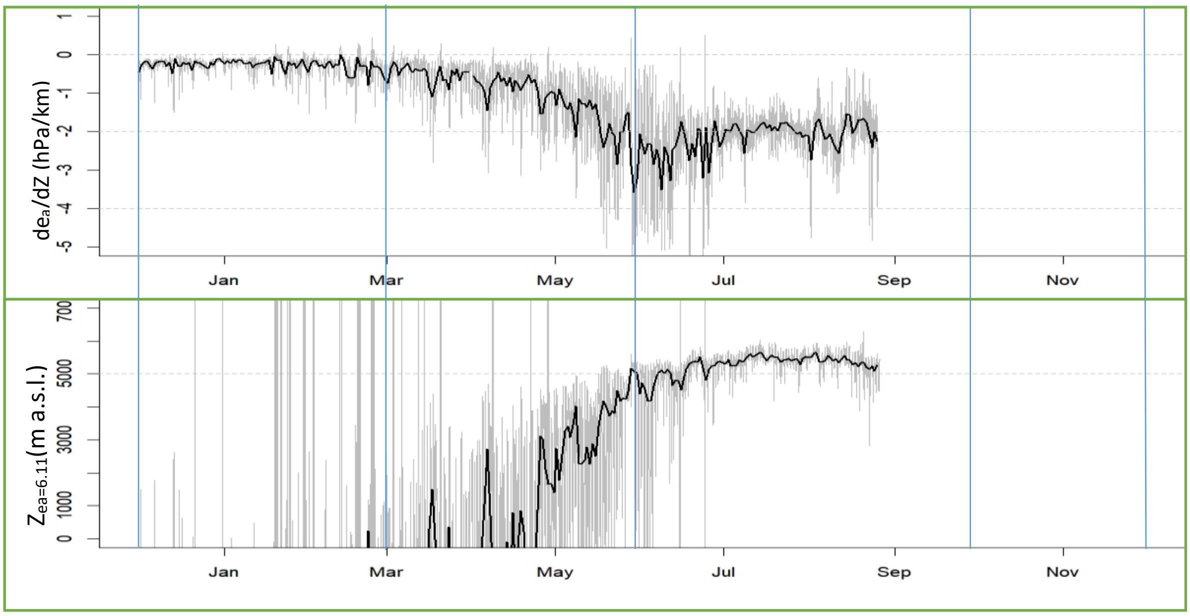

Figure 10 Vapour pressure gradient (top) and height of 6.11hPa isoline (bottom) in the Mera glacier site from Dec2013 to Aug2014. Mean daily value in black and half-hourly value in grey

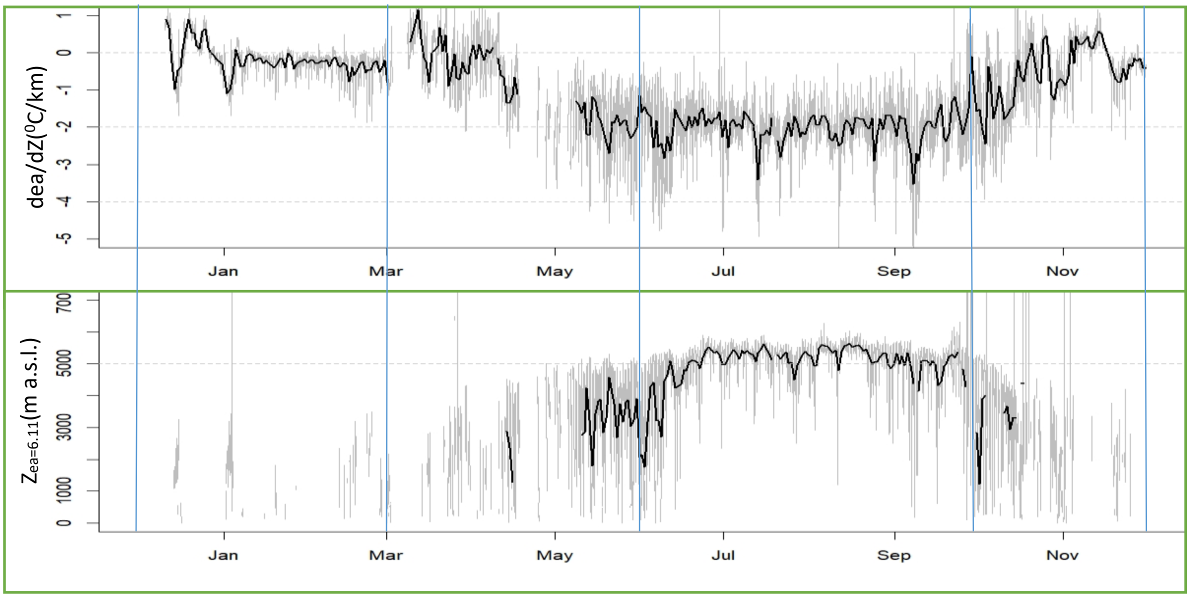

Figure 11 Vapour pressure gradient (top) and height of 6.11hPa isoline (bottom) in the Mera glacier site from Dec2014 to Nov2015. Mean daily value in black and half-hourly value in grey

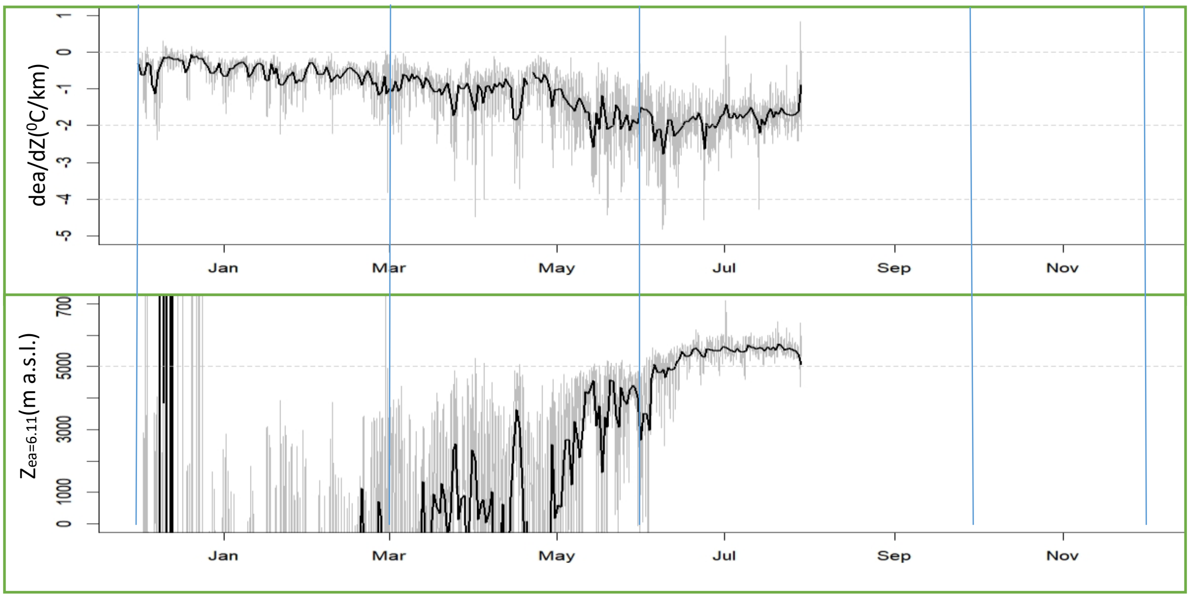

Figure 12 Vapour pressure gradient (top) and height of 6.11hPa isoline (bottom) in the Mera glacier site from Dec2015 to Jul2016. Mean daily value in black and half-hourly value in grey

4.4 Diurnal Cycle of Meteorological components

4.4.1 Temperature and Vapour pressure

Figure 16-19 evinces the robust effect of incoming shortwave and long-wave radiation on temperature and vapour pressure. The diurnal cycle of temperature at Mera AWS found very high interannual variability. The diurnal range of mean hourly air temperature in is strongly increased in winter from 2013-2014 to 2017-2018, where in the pre-monsoon and post-monsoon diurnal cycle increased from 2013-2014 to 2015-16 and then in decreased. At Naulek, the diurnal range of mean hourly air temperature is strongly reduced on monsoon than all of year. In pre-monsoon 2015-16 the temperature from 7 AM to 4 PM is strongly higher than other year. Also the morning 7-8 AM value of pre-monsoon 2016-17 is higher because the ventilation started lately only after 8 AM because of the wrongly directed solar panel. In the Mera Summit AWS, only three years (2013-2016) data are available for winter and pre-monsoon. The daytime temperature is strongly increased on winter and pre-monsoon of 2014-15 and 2015-16 than that of 2013-2014 which may be due to the problem in ventilation. The diurnal range of mean hourly air temperature is reduced during winter than other season, which is different from the result of other station.

Mean hourly air temperature on winter is increased where on pre-monsoon and post-monsoon have contrasted pattern in Changri-Nup5360. The temperature increased from

2013-2014 to 2015-2016 on pre-monsoon and post-monsoon and then again decreased. On monsoon, diurnal pattern of the temperature seems unchanged since last five year.

In Changri-Nup-5470, there is only two years data available. The diurnal cycle of temperature seems increased in all three season except monsoon and the change in temperature at morning (8-10 AM) is not so much higher than rest of the day.

The diurnal pattern of vapour pressure also shows the high inter annual variability and diurnal pattern mostly higher in midafternoon and follows a similar diurnal pattern with minimum variation and value is found minimum in winter and maximum in the monsoon. Maximum vapour pressure observed at late afternoon and minima found between 5:00 AM to 8:00 AM in the morning. Except Mera summit AWS, all lower AWS have vapour pressure lies between 4-6 hPa, whereas the Mera Summit AWS have above 4 hPa vapour pressure only on mid-afternoon (1-3 PM). The diurnal pattern on winter and pre-monsoon at Naulek seems highest and lowest on monsoon and post-monsoon in last five years. In Changri-Nup-5360 diurnal pattern is quite smooth than Mera glacier site.

4.4.2 Incoming short-wave (K↓) and long-wave (L↓) radiation

Incoming shortwave (K↓) and longwave (L↓) radition is mostly affect by the atmospheric transitivity and the cloud cover. The diurnal pattern of L↓ follows same like temperature and vapour pressure with maximum value at 1:00-5:00 PM of the day and minima at 5:00-7:00 AM in the morning. In mid-day time at Mera AWS site the K↓ is decreased from 2013-2014 to 2017-2018 in winter, pre-monsoon and post monsoon but in the monsoon it was increased (Figure19, 20).

4.4.3 Wind speed and direction

Diurnal cycle of wind speed is found in same pattern in all site (Figure 14, 18). At Naulek site, the wind is little higher than other similar elevation site. The wind speed is highest at around 14:00-15:00 PM and lowest in the morning between 8:00-10:00AM in all site but the Summit has different, higher in morning and lowest in the afternoon.

The rose diagram for all site are shown in Figure 14 shows the valley wind is stronger in Mera Summit and Changi-Nup5-360 site. The wind at Naulek site is dominated by the up-valley wind whereas the Changri-Nup-5470 has bimodal type of wind direction with dominant by down glacier (South) and secondary up valley (North) winds. Only the Mera summit has high frequency of wind between 10 to 20 m/s than other site.

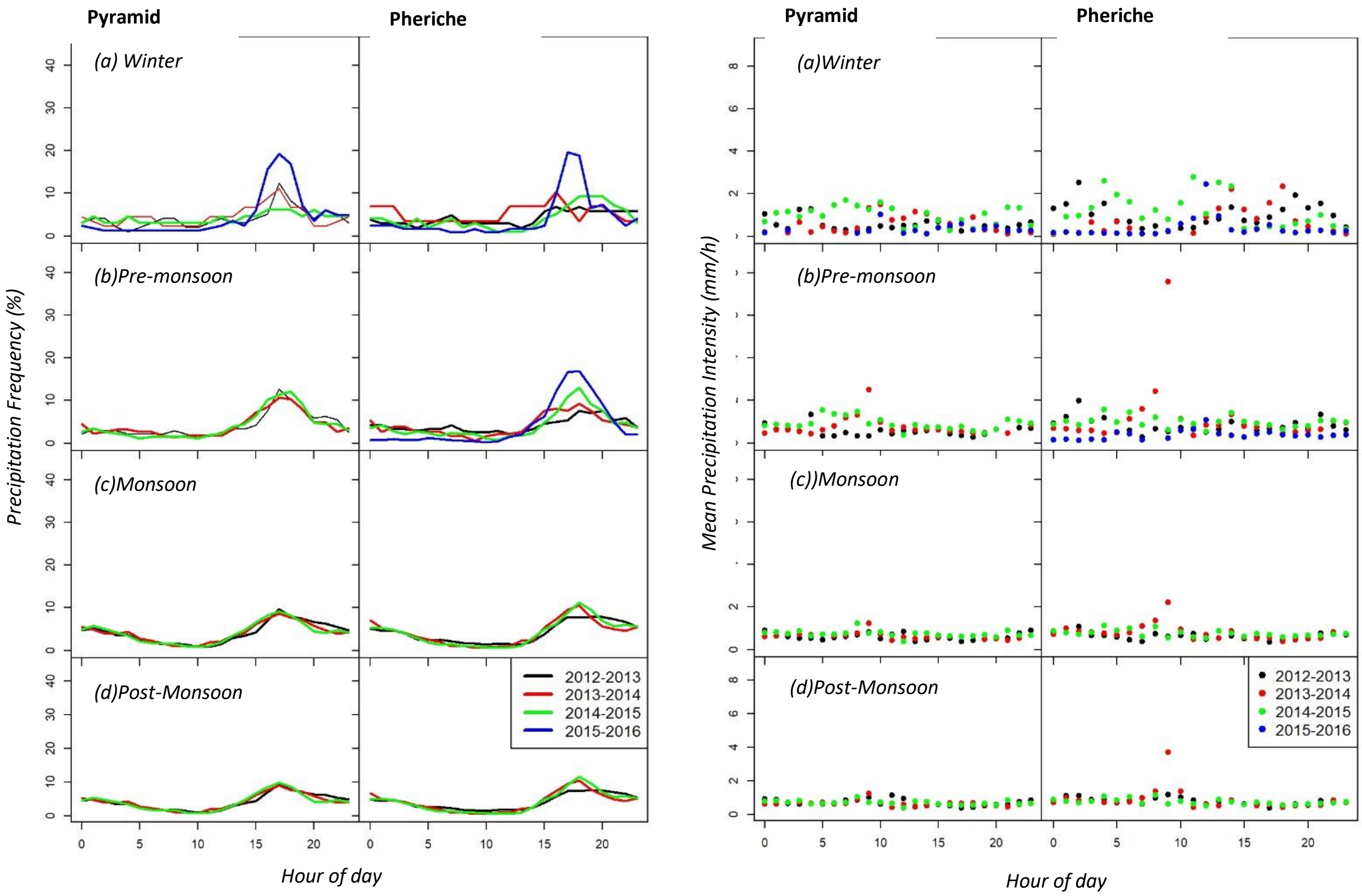

Figure 13 Hourly Precipitation frequency (%, two left column) and intensity (mm/h, right two column) for (a) winter, (b) Pre-monsoon, (c) Monsoon and (d) Post-monsoon at Pyramid and Pheriche AWS from 2012 to 2016

4.4.4 Precipitation

The diurnal variation of the rainfall frequency and intensity with different durations, as well as their seasonality, were analyzed by using the hourly rainfall data neglecting the rainfall below 1mm/hr at two (Pyramid and Pheriche) stations in the Khumbu during 2012-2016 and presented in Figure 13 which shows the highest variation of intensity in winter and minimum variation in monsoon. The frequency of precipitation is highest between 3-8 PM in all season. In pre-monsoon 9 AM, 2013-14 the intensity found 7.90 mm/hr highest intensity of my study period. In monsoon the intensity at both station is found below 1.5 mm/hr expect one event in 9AM in 2013-14 monsoon at Pheriche (Figure 13).

The intensity found highly inter annual variable due to some extreme event in pre-monsoon, post-monsoon. There do not appear to be any consistent diurnal patterns of precipitation intensity except in the pre-monsoon season, when intensities are greatest in the afternoon. (Higuchi 1977)suggested that 60% of the total precipitation at Rikha Samba was received between 17:40 and 05:40 (Shea et al. 2015)found similar values but here I found 59% of total precipitation is occurs between 17:00 to 6:00 in Pyramid and 71% in Pheriche. The intensity between Pyramid and Pheriche is highly different in winter, higher intensity found in

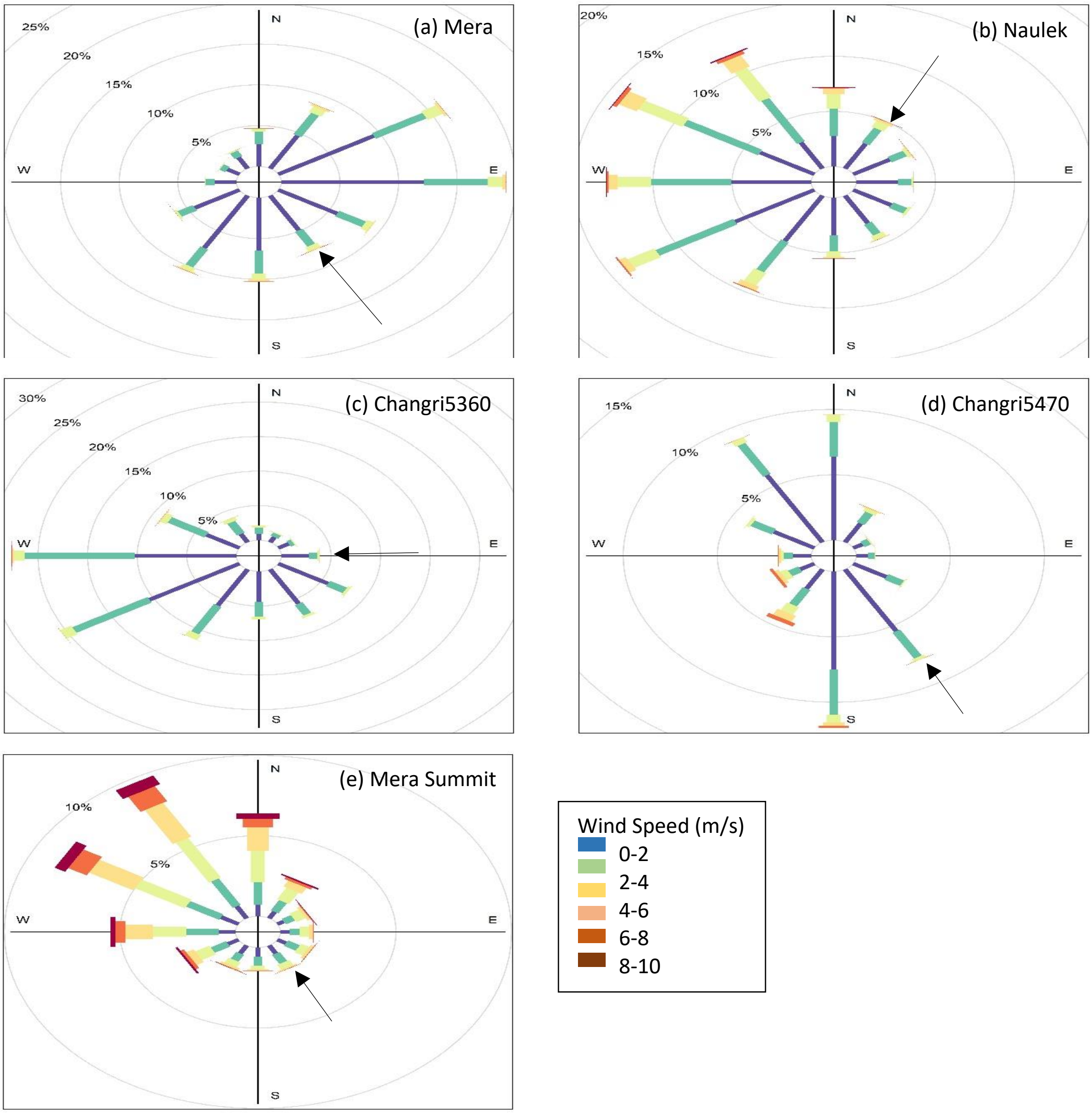

Figure 14 Wind rose for (a) Mera, (b) Naulek, (c) Changri-Nup5360 (d) Changri-Nup5470 and (e) Mera Summit automatic weather stations. Up valley directions are indicated by arrows

Pheriche than Pyramid. When comparing the season of one year to another year for the same station, the intensity is found lowest in 2015-2016.

4.4.5 Temperature and Vapour pressure gradient

The mean diurnal cycle of temperature gradient calculated from the two on-glacier station Naulek and Mera Summit from Dec 2013 to May 2016 are reported in Figure 15. The temperature gradient is found least negative in 8:00 AM in the morning. TG in winter is always found higher negative than -7 °C/km, for pre-monsoon and monsoon the TG is higher negative (-6°C/km) for the night time and least for the day. The TG in monsoon is least negative for all diurnal cycle than other season, and it was found always least negative than -6 °C/km almost near to zero (0 to -1 °C/km for the 12:00-13:00 noon of the day) (Figure 15).

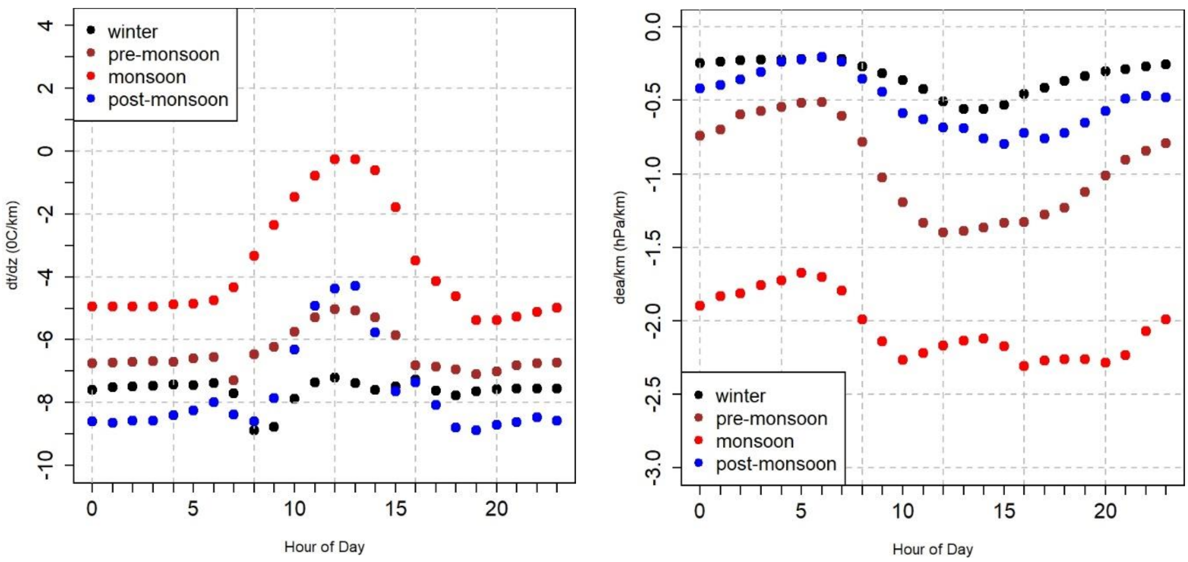

Figure 15 Cycle of mean hourly temperature gradient vapour pressure gradient between Naulek and Mera Summit for the period between Dec2013-May2016

The vapour pressure calculated in the diurnal cycle for different season is highly different higher negative for the monsoon between -1.5 to -2.5 hPa/km and least negative for the winter and post monsoon between 0 to -1hPa/km.

Table 14 Minimum, maximum and mean value of diurnal cycle of temperature gradient (TG) (hour of the day) (°C/km) for different season from Dec2013 to May2016

	Winter			**Pre-monsoon**			**Monsoon**			**Post-monsoon**		
	min °C/km	max °C/km	mean °C/km	min °C/km	max °C/km	mean °C/km	min ^{0}C/km	max °C/km	mean °C/km	min °C/km	max °C/km	mean °C/km
2013-2014	-8.8 (8am)	-7.59 (6am)	-8.18	-7.68 (7am)	-6.56 (12pm)	-6.92	-4.96 (7pm)	-3.59(1pm)	-4.51			
2014-2015	-8.22 (8am)	-5.71 (12pm)	-7.25	-7.01 (7pm)	-3.01 (1pm)	-5.76	-5.68 (8pm)	2.08 (1pm)	-3.13	-8.89 (7pm)	-4.29 (1pm)	-7.69
2015-2016	-9.25 (8am)	-6.76 (4pm)	-7.21	-7.24 (7am)	-3.85 (1pm)	-5.96						
In average	-8.89 (8am)	-7.38 (6am)	-7.63	-7.09 (7pm)	-5.08 (1pm)	-6.15	-0.26 (1pm)	-5.38 (8pm)	-3.26	-8.89 (7pm)		-7.7

Table 15 Mean monthly temperature gradient (°C/km) between Naulek and Mera Summit

	Temperature Gradient (°C/km)			
Month	2013-14	2014-15	2015-16	Average
Dec	-8.21	-7.71	-8.06	-7.99
Jan	-8.17	-7.23	-7.05	-7.48
Feb	-8.17	-6.95	-7.11	-7.41
Mar	-7.71	-6.66	-6.36	-6.91
Apr	-6.92	-5.36	-7.25	-6.51
May	-6.13	-4.63	-4.3	-5.02
Jun	-4.84	-3.55	-2.13	-3.50
Jul	-4.55	-2.75	-2.13	-3.14
Aug	-3.69	-2.44		-3.06
Sep		-3.79		-3.79
Oct		-7.28		-7.28
Nov		-8.11		-8.11
Winter	-8.19	-7.3	-7.4	-7.63
Pre-Monsoon	-6.93	-5.55	-5.97	-6.15
Monsoon	-4.36	-3.14	-2.13	-3.21
Post-Monsoon		-7.7		-7.7
Annual	-6.49	-5.54		-6.17

CHAPTER 5: Discussion

Glaciological and meteorological data observation and collection in the Nepalese Himalaya is always tough and continuous data for long time in such elevation is tougher. However, these high elevation data are most important for calibrating the glacio-hydrological models (Ragettli et al. 2013; Shea et al. 2015). The temperature trend, form and pattern of precipitation, temperature gradient, vapour pressure gradient, 0 degree isotherm, 6.11 hPa isoline have been updated in this study. Continuous study of meteorological variables helped to obtain the total meteorological condition and changing pattern and also helps to understand the mass balance study, changed glacier area and impacts of precipitation form in glacier mass balance.

The day time radiation and valley wind circulation plays significant role ins in daytime temperature and wind speed (Shea et al. 2015). The correlation of mean daily and diurnal pattern of air temperature and vapour pressure between Mera, Naulek and Changri-Nup-5360 AWS have been found highly correlated (r=0.94-0.99), and while correlating mean daily air temperature with other parameter with in the same station, the correlation of air temperature have been found higher only with mean daily incoming (r=0.73-0.85) and outgoing longwave(r=0.93-0.97) radiation (Table 17). Among these three different land surface station the correlation is higher in on-glacier AWSs (i.e. Naulek and Changri-Nup5360 than Mera AWS). In this period of study from 2013 to 2018, the temperature trend is found to be higher year by year with the trend 0.25 °C/yr at Mera. 0.24 °C/yr at Naulek and Changri-Nup5360 but the study from Shrestha et al., (1999) shows that the temperature trend in the Nepal is 0.06 °C per year and ≥0.12 °C in some middle mountain region which one is quite old. Observed climate analysis report from DHM (2017) shows that the mean annual temperature trend in the Solukhumbu Nepal is 0.076 °C/yr, both these results of temperature trend were lower than our result from Mera and Naulek. The higher trend in this study than DHM (2017) may be because of the study is point based and shorter period. But this study also indicates the similar elevation-dependent temperature warming as observed by Thakuri et al.(2019) .

Winter, pre-monsoon and monsoonal temperature trend at Mera and Naulek closely resemble the yearly temperature trend in these AWS sites, with the winter showing the greatest and decreasing trend in the post monsoon. The mean winter air temperature on 2013-14 is found -9.3°C and in winter 2017-18 the mean temperature is -6.17°C at Mera AWS which is similar to the Baidya et al. (2008) analysis of temperature in the lower elevation of Nepal shows the annual occurrence of increasing in warm nights and decreasing in cold nights and the majority.

The mean diurnal temperature amplitude (Table 20) seems quite interesting, lower (8-11°C) in monsoonal month and higher in non-monsoonal month (10-15°C). The average monthly maximum temperatures amplitude have been found between 8-15°C and the mean monthly have been found approximately 12.25°C for Mera, 13.30°C for Naulek and 12.25°C for Changri-Nup 5360 higher than Wagnon et al. (2012).

Results from (Bollasina et al. 2002) shows that the average precipitation in Khumbu valley is 465 mm and almost 400 mm precipitate in summer monsoon and in this study total annual precipitation is above 500 mm and monsonnal precipitation is below 400 mm in both Pyramid and Pheriche site. The lower precipitation on the Bollasina et al., (2002) may be the data used is under catch or the precipitation in this region is increased. The precipitation intensity found highly inter annual variable due to some extreme event in pre-monsoon, post-monsoon. There do not appear to be any consistent diurnal patterns of precipitation intensity except in the pre-monsoon season, when intensities are greatest in the afternoon. Higuchi (1977) suggested that 60% of the total precipitation at Rikha Samba was received between 17:40 and 05:40 (Shea et al. 2015) found similar values but here I found 59% of total precipitation is occurs between 17:00 to 6:00 in Pyramid and 71% in Pheriche. The intensity between Pyramid and Pheriche is highly different in winter, higher intensity found in Pheriche than Pyramid. When comparing the season of one year to another year for the same station, the intensity is found lowest in 2015-16. The precipitation and cloud phenomena in the high altitude Himalayas can be explain by seasonal trends of two factor, i) the moisture supply by Indian Ocean area in monsoon ii) the subtropical jet stream in non-monsoonal season and iii) the cloud formed by convection (Yasunari 1976). In non-monsoonal season the precipitation could be identify the factors by its intensity but it is hard in monsoon. The precipitation with higher intensity must be due to the subtropical jet stream in pre-monsoon and post-monsoon.

The temperature gradient calculated for winter (-7.63 °C/km) is steeper and less steep in the monsoon (-3.26 °C/km) and the gradient on pre-monsoon(-6.15 °C/km) and post-monsoon(-6.18 °C/km) is nearby ELR is the similar result by (Shea et al. 2015) except in monsoon. The mean TG on monsoon calculated on Shea et al., (2015) is in between 4-5 °C/km and in here we found the TG on monsoon is lesser i.e. -3.26 °C/km. The mean annual TG calculated by the Fujita and Sakai (2000) is -6°C/km, Shea et al., (2015) is -6.0°C/km and we found -6.17°C/km.The sub-diurnal variations of temperature gradients will strongly affects the melt estimated using mathematical degree day model (Petersen and Pellicciotti 2011). The diurnal pattern of hourly temperature gradient for different season (Figure 15) is different than the result by Shea et al. (2015). The diurnal pattern of TG in Langtang, there is a higher negative value of TG in the day time and least in day time but this study found TG is higher negative in the night time and least negative in day time, also strongly different than (Fujita and Sakai 2000).

The derived height of the estimated 0 °C isotherm and 6.11hPa isoline is below 5000 m a.s.l in the winter and in monsoon it is found more than 5000 m a.s.l. Even the 0 °C isotherm is observed above 7000 m a.s.l in monsoon 2016. Glacier in in this region are situated mainly between 4000 and 6000 m a.s.l. (Bajracharya et al. 2011), which would suggest that most of the glacier in this area experienced both snow/glacier melt and the liquid precipitation in monsoon (Shea et al. 2015).

The vapour pressure gradient calculated (Figure 10-12) ranges from 0-3hPa/km is similar to the previous study by Shea et al., (2015). The higher negative value of vapour pressure gradient during monsoon results the 6.11hPa isoline values about 5000m asl, and lower values for other season, which indicates that the glaciers are experiencing sublimation/evaporation from the surface in this region. Both sublimation and evaporation are important for the energy balance melt models and glacier mass balance.

CHAPTER 6: Conclusion

In High Mountain Asia the meteorological observation is most required for the glacio-hydrological monitoring plan and policies. This study presents 2 to 9 year of annual, seasonal and daily meteorological analysis by using the different AWS data from Mera, Naulek, Mera Summit from Hunga/Inkhu sub basin of Dudh Koshi river system and Changri-Nup, Pyramid and Pheriche site of Khumbu valley in the Everest region, which are most important for the calibration and validation for the different dynamically and statically downscaled model.

Based on this analysis of seasonal and diurnal pattern of meteorological variables: The meteorological variables are highly correlated between Mera, Naulek and Changri-5360 and clearly differentiate the monsoon with regard to other seasons at each AWS site. In last five years the air temperature environment at Mera, Naulek and Changri-Nup-5360 is very unusual with very high diurnal amplitude. Air temperature is increased 0.24-0.25°C per year since 2013-14 in both basin and there is continuous negative mass balance after 2013-14.

Calculated temperature gradient and vapour pressure gradient by using data from only two on-glacier AWS shows the importance of glacier mass balance and energy balance in the Mera glacier both in seasonal and annual basis. The zero degree isotherm in monsoon found above 6000 m a.s.l. and at the same time vapour pressure gradient is higher negative than other season signals a higher mass loss chances through sublimation and evaporation. The isotherm line also helps to identify the form of precipitation and here this found the zero degree isotherm sometimes above 6000 m a.s.l shows that most of the precipitation in monsoon is either drizzle or rain even above 6000 m a.s.l. The liquid precipitation have negative impact on glacier health, because it has a direct impact on albedo, a key variable which has a direct impacts on energy balance and glacier surface melt. But extreme events with higher amount of snow precipitation in non-monsoonal season have significant positive effect on the positive mass balance of glacier.

Most of the glacierized surface experiences near-surface vapour pressure below 6.11hPa for most of the year but in monsoon the 6.11hPa isoline is above 5000m a.s.l and sometimes even above 6000m a.s.l. Together with the negative vapor pressure gradients during monsoon, this indicates that the glacier surface loses large amount of mass/energy through evaporation/sublimation.

This study provides key meteorological information at high-altitude region where the data availability is limited. Long term operation of these stations and corresponding glaciological measurements will facilitate the glacier-climate interaction and impacts of climate in the regional water availability. Also the high altitude meteorological network with glacier study in the different region of Nepal would provide important information for the future water resource assessment in the Nepalese Himalaya.

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Appendix

Table 16 mean monthly temperature and Sen's slope from 2010 to 2019 in Mera, Naulek, and ChangriNup5360

Mera								
Month	2013	2014	2015	2016	2017	2018	2019	trend
Dec	-8.1668	-6.49872	-7.04617	-3.70126	-4.34102	-12.1		0.560359
Jan		-10.1253	-11.3291	-10.3998	-11.6953	-6.08966	-13.923	-0.52332
Feb		-9.65069	-10.5086	-6.39653	-7.15872	-8.30749	-12.266	-0.52319
Mar		-9.24151	-8.10465	-7.10441	-8.4824	-8.0915	-9.75	-0.1017
Apr		-6.53987	-5.90807	-3.03639	-4.51941	-5.82179	-8.2	-0.33203
May		-2.3371	-2.16751	-2.66808	-2.32725	-2.39752		-0.04268
Jun		1.30545	0.946044	1.266955	1.128699	1.376488		0.036263
Jul		2.258815	1.927538	2.341544	2.293881	2.841667		0.164442
Aug		1.881593	2.044864	2.222745	2.418826	2.32305		0.166923
Sep		-0.05647	0.999228	0.517018	1.306968	1.212605		0.302007
Oct		-4.60373	-3.2758	-1.84403	-2.42744	-4.72942		0.196379
Nov		-4.0344	-3.98562	-3.55841	-6.13546	-6.04587		-0.59481

Naulek								
Month	2013	2014	2015	2016	2017	2018	2019	trend
Dec	-9.5106	-8.47885	-8.61782	-6.7649	-4.54676	-15.444		0.856975
Jan		-11.1575	-13.0409	-12.3175	-13.3374		-13.692	-0.48263
Feb		-10.225	-12.7117	-8.06309	-8.74222		-12.181	-0.12945
Mar		-10.4033	-9.5625	-8.69112	-9.78729		-12.1	-0.22587
Apr		-7.60272	-8.38887	-4.47456	-5.83552		-9.8	-0.39612
May		-3.40558	-3.21953	-3.73875	-3.52098			-0.0946
Jun		0.117217	-0.04831	0.531326	0.049131			0.013011
Jul		1.332431	0.879643	1.623019	1.317685			0.070189
Aug		0.765728	1.088359	1.018917	1.348511			0.162169
Sep		-1.36021	-0.67313	-0.47499	-0.09759			0.39914
Oct		-6.55001	-5.72956	-4.58375	-4.80751			0.700641
Nov		-7.11704	-6.49455	-7.07494	-8.03769			-0.44363

Changri-Nup5360										
Month	2010	2011	2012	2013	2014	2015	2016	2017	2018	trend
Dec	-8.628	-5.78	-7.891	-9.153	-8.05	-7.95	-5.769	-5.837		0.25
Jan		-10.70	-13.16	-10.04		-12.42	-11.64	-12.79	-7.845	0.25
Feb		-10.90	-10.59	-11.74		-12.14	-7.192	-8.313	-9.360	0.31
Mar		-8.285	-7.425	-9.23		-9.678	-8.102	-9.219	-9.136	-0.15
Apr		-6.286	-5.394	-5.331	-6.937	-7.297	-3.510	-4.875	-6.548	0.08

May		-0.896	-1.474	1.2477	-2.406	-2.386	-2.176	-2.257	-1.965	-0.15
Jun		1.8759	2.9516	3.8254	1.9494	1.6841	1.8678	1.6527	1.828	-0.04
Jul		2.8592	3.0394	3.8978	2.307	2.583	2.4200	2.2081	2.796	-0.09
Aug		2.2154	2.5604	2.9033	2.006	2.2890	2.6563	2.2606	2.226	-0.01
Sep		0.930	1.2496	1.6542	0.0750	1.1153	0.8790	1.4246	1.041	0.003
Oct		-4.575	-4.57	-2.976	-5.779	-4.292	-2.449	-2.914	-5.730	0.043
Nov	-4.71	-6.38	-6.583	-6.824	-5.58	-5.478	-5.452	-7.30	-6.78	0.007

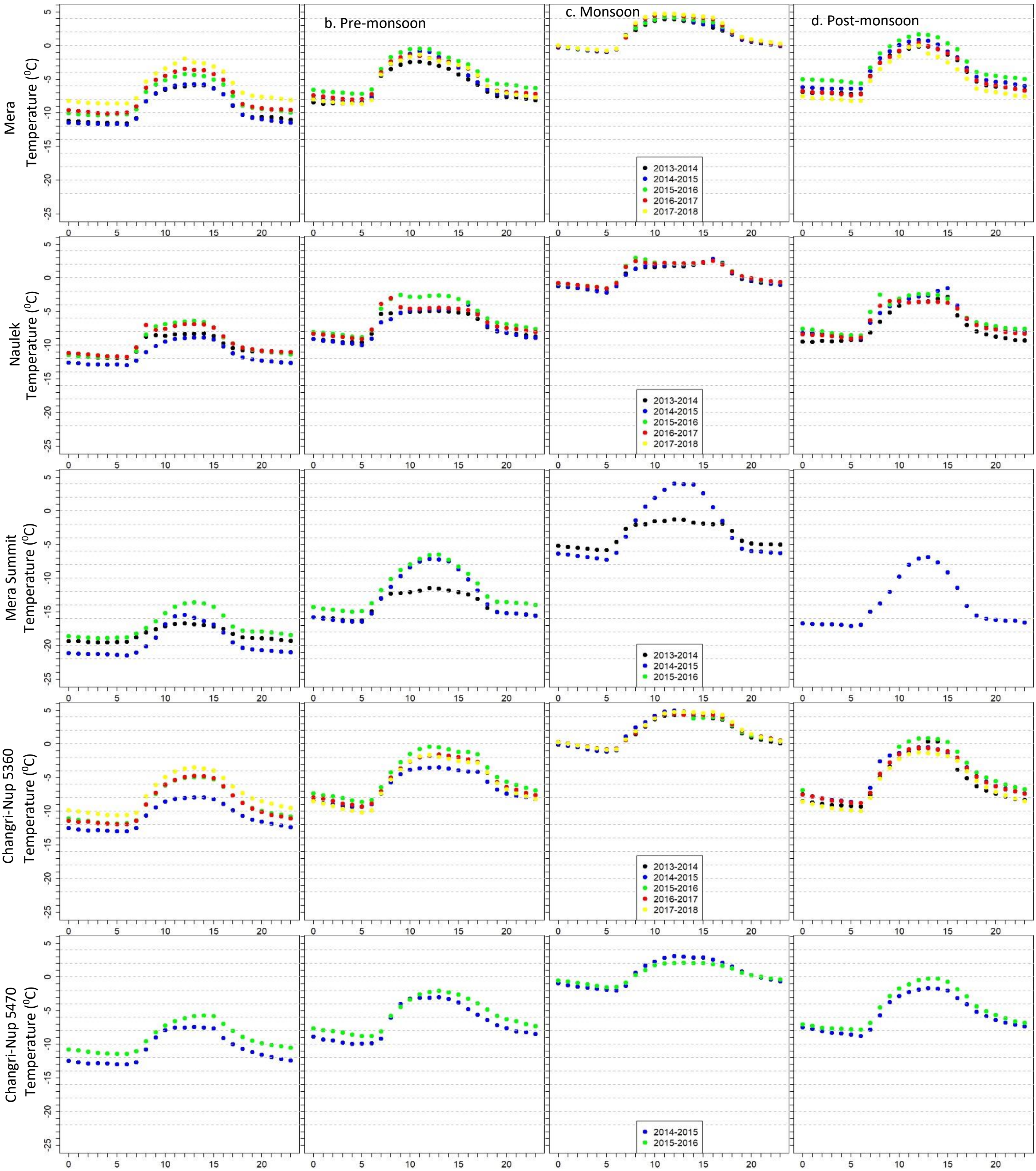

Figure 16 Diurnal cycle of temperature from Nov2013 to 2018 for (a) winter, (b) pre-monsoon, (c) monsoon and (d) post-monsoon, from Top to bottom, Mera, Naulek, Mera Summit, Changri-Nup5360 and Changri-Nup5470 site

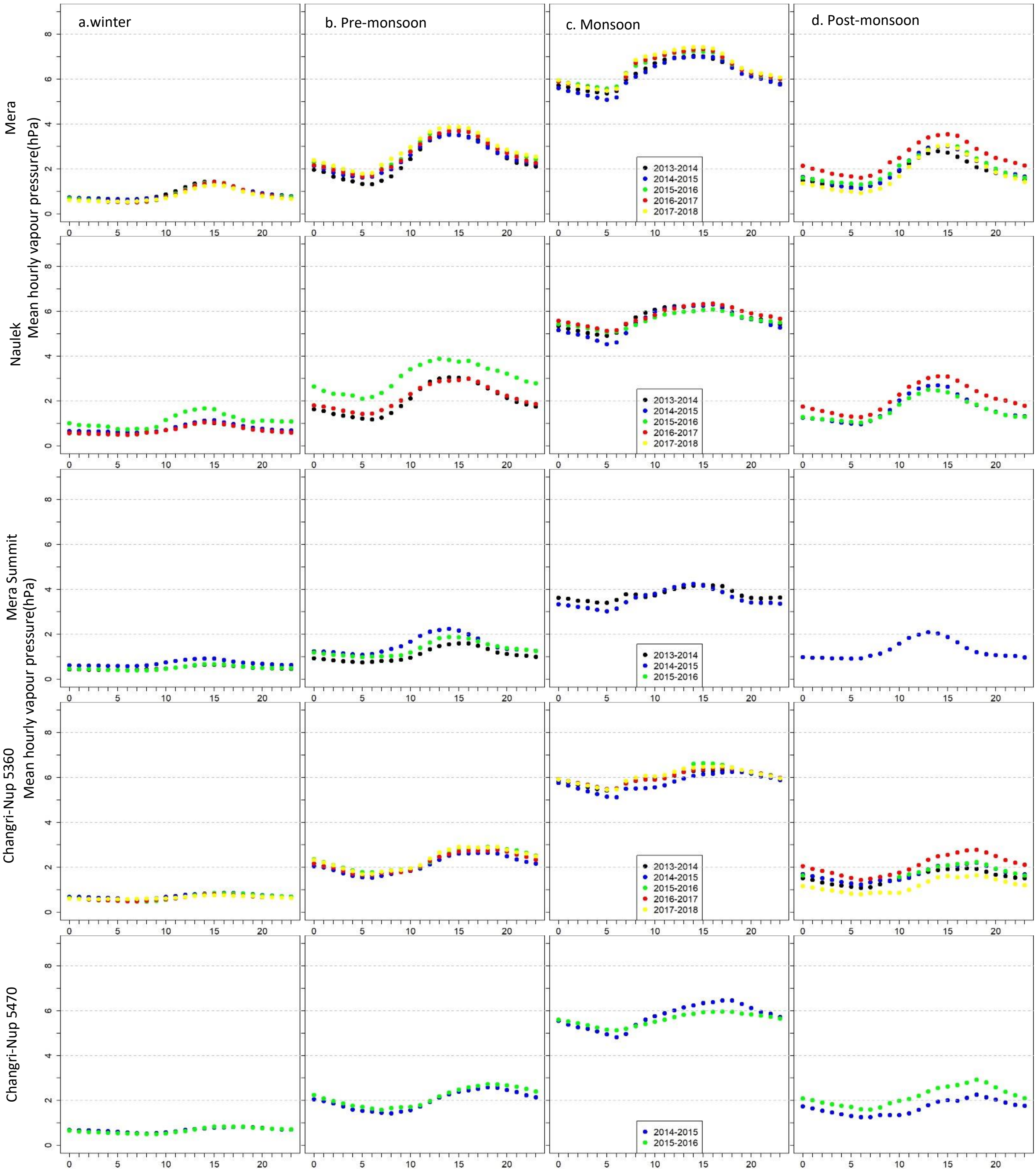

Figure 17 Diurnal cycle of vapour pressure from Nov2013 to 2018 for (a) winter, (b) pre-monsoon, (c) monsoon and (d) post-monsoon, from Top to bottom, Mera, Naulek, Mera Summit, Changri-Nup5360 and Changri-Nup5470 site.

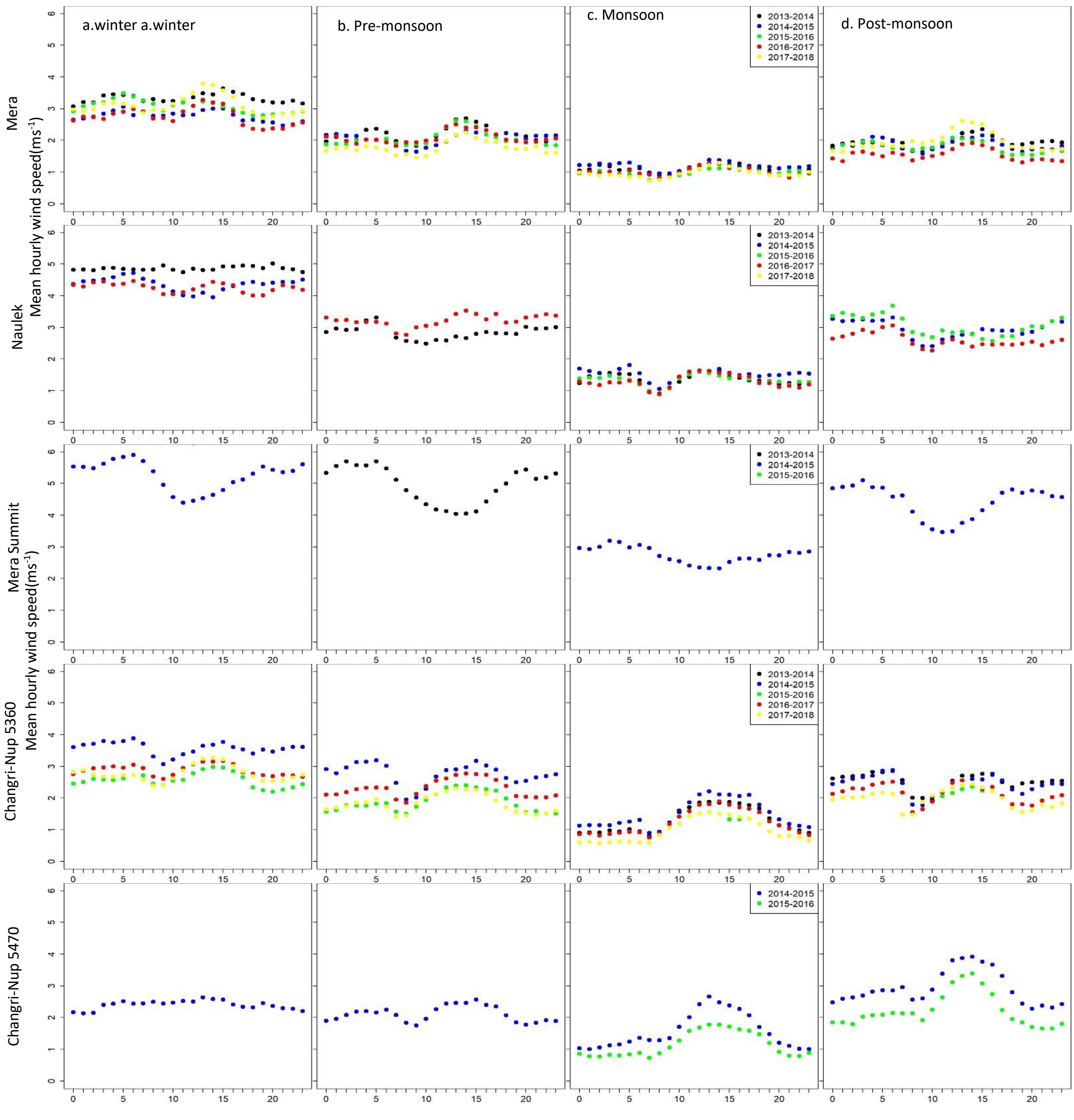

Figure 18 Diurnal cycle of wind speed from Nov2013 to 2018 for (a) winter, (b) pre-monsoon, (c) monsoon and (d) post-monsoon, from Top to bottom, Mera, Naulek, Mera Summit, Changri-Nup5360 and Changri-Nup5470 site.

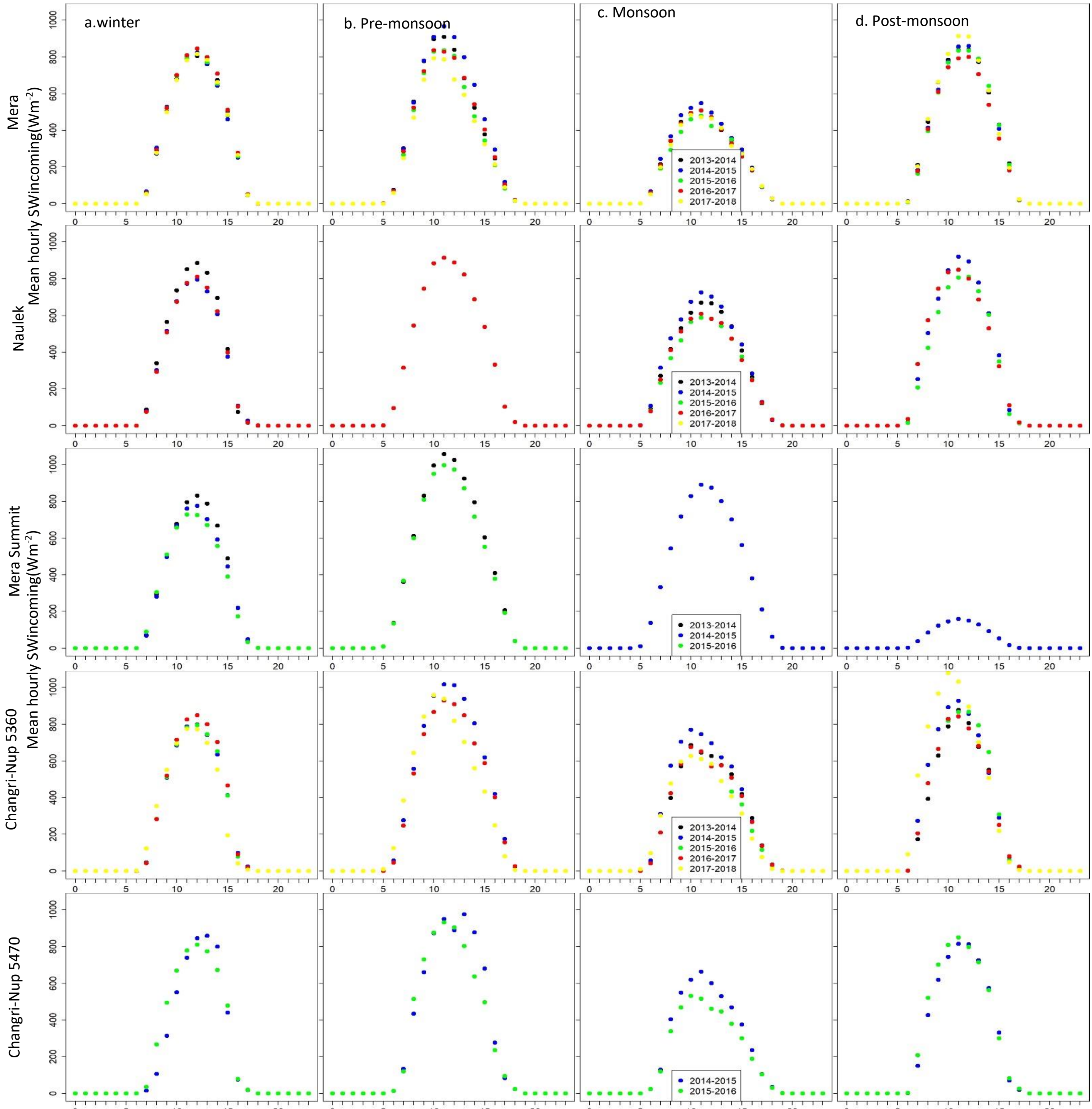

Figure 19 Diurnal cycle of shortwave incoming from Nov2013 to 2018 for (a) winter, (b) pre-monsoon, (c) monsoon and (d) post-monsoon, from Top to bottom, Mera, Naulek, Mera Summit, Changri-Nup5360 and Changri-Nup5470 site.

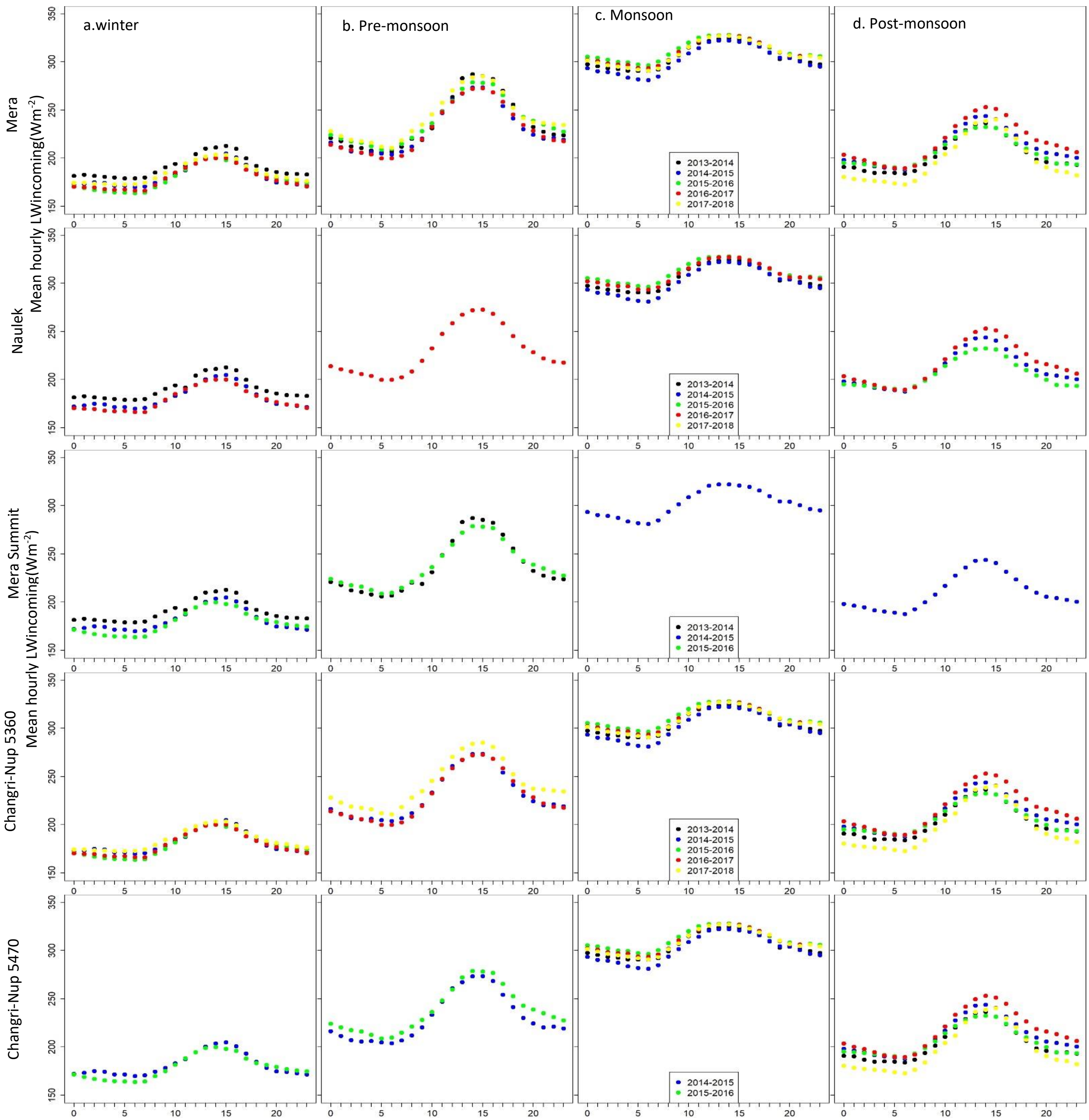

Figure 20 Diurnal cycle of longwave incoming from Nov2013 to 2018 for (a) winter, (b) pre-monsoon, (c) monsoon and (d) post-monsoon, from Top to bottom, Mera, Naulek, Mera Summit, Changri-Nup5360 and Changri-Nup5470 site.

Table 17 The correlation coefficient calculated between differnt variables from the same station for Mera, Naulek, Changri5360, Mera Summit and Chasngri5470 AWS

Mera										
	Tair	RH	ea	Wind	ISR	OSR	ILR	OLR	net_SW	net_LW
Tair	1									
RH	0.56	1								
ea	0.79	0.92	1							
Wind	-0.47	-0.72	-0.7	1						
ISR	-0.36	-0.62	-0.61	0.41	1					
OSR	-0.49	-0.26	-0.42	0.23	0.55	1				
ILR	0.73	0.94	0.95	-0.66	-0.66	-0.34	1			
OLR	0.93	0.48	0.72	-0.46	-0.32	-0.7	0.63	1		
net_SW	0.08	-0.43	-0.27	0.23	0.58	-0.36	-0.4	0.32	1	
net_LW	0.4	0.9	0.79	-0.57	-0.65	-0.05	0.9	0.23	-0.68	1
Naulek										
	Tair	RH	ea	Wind	ISR	OSR	ILR	OLR	net_SW	net_LW
Tair	1									
RH	0.69	1								
ea	0.85	0.94	1							
Wind	-0.61	-0.8	-0.79	1						
ISR	-0.08	-0.24	-0.25	0.17	1					
OSR	-0.31	-0.29	-0.38	0.26	0.71	1				
ILR	0.84	0.94	0.97	-0.76	-0.31	-0.37	1			
OLR	0.96	0.85	0.94	-0.72	-0.09	-0.3	0.92	1		
net_SW	0.23	-0.03	0.07	-0.04	0.63	-0.09	-0.04	0.21	1	
net_LW	0.65	0.92	0.9	-0.72	-0.46	-0.38	0.96	0.77	-0.23	1
Changri-Nup5360										
	Tair	RH	ea	Wind	ISR	OSR	ILR	OLR	net_SW	net_LW
Tair	1									
RH	0.59									
Ea	0.89	0.84	1							
Wind	-0.64	-0.68	-0.73	1						
ISR	0.5	0.09	0.24	-0.28	1					
OSR	0.66	0.32	0.46	-0.48	0.92	1				
ILR	0.85	0.87	0.96	-0.75	0.19	0.45	1			
OLR	0.97	0.73	0.95	-0.67	0.43	0.62	0.93	1		
net_SW	-0.21	-0.48	-0.41	0.37	0.49	0.1	-0.51	-0.27	1	
net_LW	0.6	0.88	0.83	-0.71	-0.08	0.21	0.92	0.71	-0.67	1

Mera Summit										
	Tair	RH	ea	Wind	ISR	OSR	ILR	OLR	net_SW	net_LW
Tair	1									
RH	0.59	1								
ea	0.89	0.84	1							
Wind	-0.64	-0.68	-0.73	1						
ISR	0.5	0.09	0.24	-0.28	1					
OSR	0.66	0.32	0.46	-0.48	0.92	1				
ILR	0.85	0.87	0.96	-0.75	0.19	0.45	1			
OLR	0.97	0.73	0.95	-0.67	0.43	0.62	0.93	1		
net_SW	-0.21	-0.48	-0.41	0.37	0.49	0.1	-0.51	-0.27	1	
net_LW	0.6	0.88	0.83	-0.71	-0.08	0.21	0.92	0.71	-0.67	1
Changri-Nup5470										
	Tair	RH	ea	Wind	ISR	OSR	ILR	OLR	net_SW	net_LW
Tair	1									
RH	0.64	1								
ea	0.82	0.94	1							
Wind	-0.42	-0.81	-0.72	1						
ISR	-0.22	-0.42	-0.45	0.33	1					
OSR	-0.29	-0.08	-0.24	-0.02	0.39	1				
ILR	0.77	0.94	0.96	-0.7	-0.51	-0.18	1			
OLR	0.95	0.69	0.83	-0.48	-0.11	-0.38	0.78	1		
net_SW	-0.05	-0.4	-0.33	0.36	0.82	-0.21	-0.43	0.12	1	
net_LW	0.53	0.91	0.85	-0.7	-0.64	-0.04	0.94	0.52	-0.65	1

Table 18 Correlation coefficient and level of significance of same meteorological variables from different AWS

1. Correlation of temperature					
	Mera	*Naulek*	*Changri5360*	*Mera Summit*	*Changri5470*
Mera	1.00				
Naulek	0.98(0.01)	1.00			
Changri5360	0.98(0.01)	0.98(0.01)	1.00		
Mera Summit	0.96(0.01)	0.97(0.01)	0.96(0.01)	1.00	
Changri5470	0.99(0.01)	0.99(0.01)	0.99(0.01)	0.96(0.01)	1.00
2. Correlation of Vapour Pressure					
	Mera	*Naulek*	*Changri5360*	*Mera Summit*	*Changri5470*
Mera	1.00				
Naulek	1.00	1.00			

Changri5360	0.99(0.01)	0.99(0.01)	1.00		
Mera Summit	0.96(0.01)	0.96(0.01)	0.95(0.01)	1.00	
Changri5470	0.99(0.01)	0.99(0.01)	1.00	0.95(0.01)	1.00
3. Correlation of wind speed					
	Mera	*Naulek*	*Changri5360*	*Mera Summit*	*Changri5470*
Mera	1.00				
Naulek	0.90(0.05)	1.00			
Changri5360	0.78(0.05)	0.84(0.05)	1.00		
Mera Summit	0.84(0.05)	0.84(0.05)	0.64	1.00	
Changri5470	0.89(0.05)	0.81(0.05)	0.85(0.05)	0.85(0.05)	1.00
4. Correlation of incoming short wave radiation					
	Mera	*Naulek*	*Changri5360*	*Mera Summit*	*Changri5470*
Mera	1.00				
Naulek	0.77(0.05)	1.00			
Changri5360	0.67	0.84(0.05)	1.00		
Mera Summit	0.30	0.67	0.73	1.00	
Changri5470	0.74	0.79(0.05)	0.90(0.05)	0.49	1.00
5. Correlation of incoming long wave radiation					
	Mera	*Naulek*	*Changri5360*	*Mera Summit*	*Changri5470*
Mera	1.00				
Naulek	0.99	1.00			
Changri5360	0.98	0.98	1.00		
Mera Summit	0.94	0.97	0.96	1.00	
Changri5470	0.98	0.98	0.99	0.96	1.00
6. Correlation of albedo					
	Mera	*Naulek*	*Changri5360*	*Mera Summit*	*Changri5470*
Mera	1.00				
Naulek	0.51	1.00			
Changri5360	0.73	0.46	1.00		
Mera Summit	-0.20	-0.06	-0.30	1.00	
Changri5470	0.34	0.43	0.59	0.05	1.00

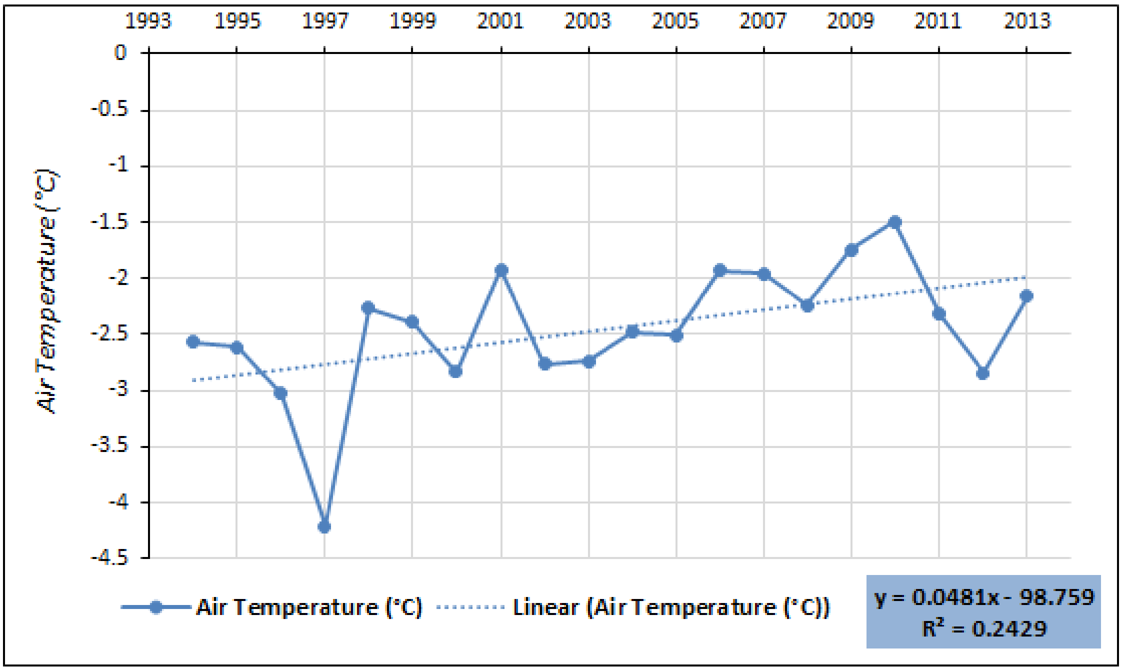

Figure 21 Mean Annual Temperature and trend of EvK2-CNR Pyramid from 1994 to 2013

Table 19 Mean annual diurnal range of temperature

annual	2013-14	2014-15	2015-16	2016-17	2017-18	trend
Mera	7.86	8.39	8.02	7.38	8.61	0.049
Naulek	7.14	7.29	8.38	8.31		0.46
Changri-Nup5360	8.42	7.96	8.31	8.42	8.27	0.016

Table 20 Mean monthly maximum and minimum amplitude of temperature

Date	**Max Mera**	**Max Naulek**	**Max Changri5360**	**Min Mera**	**Min Naulek**	**Min Changri5360**
Dec-13	11.62	12.89	11.04	4.30	2.36	
Jan-14	12.93	11.84		4.92	3.42	
Feb-14	13.11	19.89		4.14	3.53	
Mar-14	11.60	12.55		5.55	3.85	
Apr-14	12.53	13.59	12.33	6.38	5.88	
May-14	12.51	14.82	14.33	4.69	3.15	2.31
Jun-14	10.26	13.38	11.09	4.25	4.08	3.14
Jul-14	10.14	8.86	8.76	3.77	3.19	3.02

Aug-14	10.10	11.49	9.02	2.91	3.53	3.42
Sep-14	10.79	9.30	11.46	3.44	2.29	2.99
Oct-14	13.95	16.58	16.85	3.87		5.39
Nov-14	11.28	15.74	19.18	5.95	5.46	
Dec-14	13.94	13.52	14.53	4.04	2.87	2.39
Jan-15	12.96	11.26	10.72	3.91	3.18	2.53
Feb-15	13.20	10.76	10.08	4.41	2.72	3.71
Mar-15	16.63	13.28	10.26	4.25		2.39
Apr-15	16.58	11.65	10.70	6.92		5.30
May-15	14.93	13.07	13.96	6.54		5.19
Jun-15	11.35	9.26	11.61	2.12	1.38	4.08
Jul-15	10.23	10.43	13.12	3.92	2.37	4.14
Aug-15	10.06	10.09	11.17	3.64	3.52	3.69
Sep-15	11.93	12.33	12.85	3.40	4.50	3.47
Oct-15	11.93	14.68	12.88	5.44	6.13	5.31
Nov-15	12.66	16.75	13.04	5.85	4.55	4.67
Dec-15	11.82	15.38	12.69	5.08	3.60	4.83
Jan-16	13.27	16.12	13.05	5.09	3.82	4.00
Feb-16	11.43	18.10	12.44	4.93	3.99	4.88
Mar-16	13.22	20.59	17.13	5.67	5.03	4.27
Apr-16	11.80	23.97	14.19	6.32	4.34	7.88
May-16	13.23	14.48	12.33	3.61	4.46	4.64
Jun-16	12.02	13.01	10.94	3.58	3.23	3.77
Jul-16	8.12	10.32	9.09	2.94	3.78	2.71
Aug-16	14.28	13.73	11.07	3.86	3.48	2.39
Sep-16	10.80	10.09	8.18	3.76		2.45
Oct-16	12.55	11.91	12.64	6.20	4.44	5.06
Nov-16	11.92	14.76	16.35	7.13	4.86	7.41
Dec-16	12.71	12.08	12.02	6.15	5.03	7.09
Jan-17	12.68	11.34	12.56	3.59	3.92	3.82
Feb-17	11.27	10.96	12.05	3.69	3.74	3.50
Mar-17	14.47	14.06	13.39	5.63	4.97	5.00
Apr-17	12.18	14.95	12.87	6.71	5.35	5.63
May-17	11.99	13.44	12.29	6.04	4.05	4.77
Jun-17	12.28	14.61	11.59	4.46	2.91	4.28

Jul-17	10.25	11.26	9.58	4.53	3.14	3.56
Aug-17	8.73	9.79	8.48	3.46	3.27	3.22
Sep-17	10.77	10.02	10.91	4.46	4.45	3.54
Oct-17	13.42	11.80	14.67	5.00	5.57	5.52
Nov-17	11.95	12.92	11.79	6.06	4.27	4.63
Dec-17	13.94	15.48	13.38	5.44	4.42	4.16
Jan-18	14.67	15.97	13.07	5.56	5.45	4.35
Feb-18	12.74	13.26	13.03	4.85	4.36	3.32
Mar-18	14.62	13.89	14.63	6.16	5.15	5.45
Apr-18	12.61	8.36	12.59	7.58		7.26
May-18	12.26		13.50	6.52		6.45
Jun-18	11.53		12.01	5.30		3.73
Jul-18	9.56		10.59	4.22		3.03
Aug-18	9.07		8.56	4.45		3.86
Sep-18	12.55		11.86	5.10		4.57
Oct-18	13.43		11.92	6.65		6.58
Nov-18	13.95		11.70			