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Dynamics of the Himalayan Climate: A Study of the Kaligandaki Basin, Nepal

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ABSTRACT

Studies on climate change in the last two decades are growing rapidly that might have shadowed some of the other fields of studies. The changes have spatial characteristics and studies are yet to cover many isolated areas of the world. Existing literature showed abrupt change in the Himalaya climate. However, such generalisations are not appropriate for the Himalaya because of the complex topography of the region that has caused several microclimates in the region. Understanding climate dynamism in microclimatic regions is an important component of climate change research, particularly to comprehend impacts of climate change on the social-ecological systems of the Himalaya and to assess adaptive capacity of the communities. This paper examines climate dynamics in the Himalaya in reference to the meteorological records of four decades (1971-2010) at three stations of the Kaligandaki Basin. The findings suggest that the climates of the basin are changed, with variable rates across the stations located at different ecological zones. The extreme maximum and maximum temperatures of Lumle and Rampur stations, minimum temperature of Jomsom and Rampur stations, and extreme minimum temperatures of all of the studied meteorological stations increased significantly. Contrary to the increase in the temperatures, precipitation data revealed trend-less but inter-annual variability. Annual numbers of wet-days weredecreased at Rampur and Lumle stations while rainy days were increased at Jomsom. In addition, extreme rainfall events were increased in general in the basin.

Keywords: Climate change, Himalaya, Kaligandaki Basin, Microclimate, Nepal

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INTRODUCTION

In the last two decades, research by scholars has been overly concentrated on the study of climate change, its impacts, adaptation to and mitigation of change. The

Intergovernmental Panel on Climate Change (IPCC) stated, "Warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia … the concentrations of greenhouse gases have increased" (IPCC, 2013, p.2). Consequently, global temperatures between 1880 and2012 had risen by 0.85°C (IPCC, 2013). The characteristics of many climatic elements such as the precipitation, extreme events, and drought have changed, and are projected to be more intense and frequent (Salinger, 2005; Stern, 2006; IPCC, 2007a; Schewe *et al.*, 2011; IPCC, 2013). However, spatial and temporal (inter-annual to decadal) variability in the rate of changes are experienced and are projected (Christensen *et al.*, 2007; Christensen *et al.*, 2013).

Literature claimed that warming in the Greater Himalayas was remarkably higher than any other areas in the world (Shrestha *et al.*, 1999; Chaulagain, 2006; ICCP, 2007a; NRC, 2012; Shrestha *et al.*, 2012). Such a high rate of warming in the Himalaya has already resulted in a fast melting of the Himalayan glaciers (Xu *et al.*, 2007; Prasad *et al.*, 2009; Sveinbjörnsson & Björnsson, 2011; NRC, 2012). Glacier melts supplies about 44.8%, 9.1%, and 12.3% of water for major Himalayan Rivers - Indus, Ganges, and Brahmaputra respectively. The shares of the glacier-melts in these rivers are projected to increase until 2050s and decline thereafter (Xu *et al.*, 2009). Reduced share of snow-melted water has resulted in reduced water availability for the fertile plains of India, Bangladesh, Nepal and Pakistan (Lal, 2011). This change would have grave impacts in the South Asian agriculture and livelihoods.

Increase in precipitation is also expected because of rising temperature. Wentz *et al.* (2007) reported a 7% increase in global mean precipitation by per °C increase in temperature. Many scholars have studied monsoon behaviour and found that the monsoon characteristics are changing (Kripalani *et al.*, 2007; Turner & Slingo, 2009; Cherchi *et al.*, 2011; Schewe *et al.*, 2011). Literature also reported increased extreme rainfall incidents, and the monsoon of the region has become violent (IPCC, 2007a; UNDP & DFID, 2007). Nevertheless, spatial variations in the rate of warming and in the rate of precipitation dynamics within the Himalaya have also been reported (Shrestha *et al.*, 1999; Shrestha *et al.*, 2000; Chaulagain, 2006; Manandhar *et al.* 2011; Gentle & Maraseni, 2012; Rawat *et al.*, 2012).

The temperature in the mountains decreases by 1°C with an increase of 160m in altitude in general. The complex physiography of the Himalaya hence, has resulted in innumerable microclimatic regions. However, climate change studies in the Himalaya have not focused on such small clusters. This study was conducted based on the assumption that the microclimates of the Himalaya are responding to global climate change differently, so the generalisation made through the limited studies in the Himalaya may not represent the actual situation of climate dynamics in the Himalaya. Therefore, location-specific studies are required. This work is one among a number of required studies on microclimate dynamics in the Himalaya. The aim of this study is to explore spatial variation in climate change in the Kaligandaki Basin, Himalaya, Nepal.

The rationale behind this research is to understand climate change at micro level. This is important to evaluate the impacts of climate change on the social-ecological systems, and design adaptation and mitigation strategies. The IPCC has claimed that no one on the planet will be 'unaffected' by climate change (IPCC, 2014). Studies have also stated that on-going changes in the climate system have already affected the social-ecological system of different parts of the world (Adger, 1999; Barnett & Adger, 2003; Chandrappa *et al.*, 2011; Lereboullet *et al.*, 2013). Furthermore, it is expected that the projected warming would decrease agricultural yields and pose a challenge for food security both regionally and globally (Parry *et al.*, 2004; Schmidhuber & Tubiello, 2007; Mendelsohn & Dinar, 2009; Lal, 2011). Nepal is one of the poorest countries in the world. Out of 187 countries Nepal is ranked at the 157th place in the Human Development Index (HDI) in 2012. The country's 44.2% of the population lived in multidimensional poverty (the MPI 'head count') while an additional 17.4% were vulnerable to multiple deprivations in 2011 (UNDP, 2013). The country's 36.1% Gross Domestic Products (GDP) comes from the agriculture sector that employs 76% of the country's work force Nepal is predominantly rural as 83% of the population live in the rural areas (WB, 2012). Studies have revealed that the places where the majority of poverty and hunger are concentrated coincide with the higher level of climate change impacts (Adger, 2006; Rao *et al.*, 2011; Hossain & Moji, 2011; Hare *et al.*, 2011). To respond to the poverty and hunger that prevailed in the agro-based livelihood systems of Nepal through adaptation strategies, an understanding of the behaviour of microclimates (location-specific) is urgent.

This paper is divided into five sections. The first section outlines the issue of climate change briefly. In the second section, methods and materials used in the study are presented. The results are discussed in the third section while the fourth section compares the findings with existing literature. The fifth section concludes the paper.

METHODS AND MATERIALS

This study analysed meteorological data observed at three meteorological stations located at different ecological zones within the Kaligandaki Basin,[1] Nepal (Fig.1). The Rampur station is located at 256masl and represents hot and wet sub-tropical climate of the Tarai with an average maximum temperature of around 35° Celsius, minimum temperature of around 15° Celsius and annual average precipitation of over 200cm. Lumle is stationed at 1740masl, symbolises warm and wet temperate climate of the Middle-Mountain with an average maximum temperature of around 20° Celsius, a minimum temperature of 15° Celsius and over 540cm annual precipitation. The Jomsom station lies at 2744masl and indicates cool and dry temperate climate of the Trans-Himalaya having about 15° Celsius average maximum temperature and 8° Celsius minimum temperature, and little above 26cm annual rainfall.

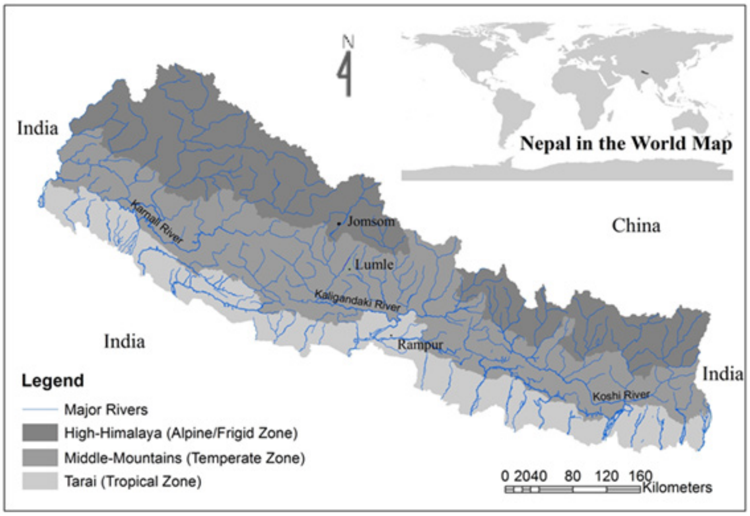

Fig 1: Location of the Selected Meteorological Stations (Jomson, Lumle, and Rampur) in the Kaligandaki Basin, Nepal.

The meteorological records (monthly averages of minimum, maximum, monthly extreme minimum, and monthly extreme maximum temperatures, and daily rainfall) for 40 years (1971-2010) were obtained from the Department of Hydrology and Meteorology (DHM), Nepal. The study locations lack hourly readings of temperature and hourly gauging of precipitation. Consequently, the daily minimum and daily maximum temperatures were used in this study. Daily rainfall refers to 24 hours' of total

[1] The Kaligandki Basin is well known for its environmental diversities. The Kaligandaki Gorge is the deepest gorge in the world. The basin consists of tropical to tundra ecological belts. The catchment of the Kaligandaki River consists both windward and leeward side of tropical monsoon, representing both the highest and the lowest rainfall area in Nepal (annual average precipitation of over 5400cm at Lumle in the windward side of the Greater Himalaya and just little over 26cm (at Jomsom) in the cold desert of the Trans-Himalaya or the leeward side of the Greater Himalaya. The altitude of the basin ranges from about 100masl to above 8000masl. The catchment is well known for its human settlements at the highest altitude (up to over 3900masl) and is rich in social-ecological diversity.

rainfall (between 8am yesterday and today for example). In the case of extreme temperature, the annual average of monthly extreme minimum and monthly extreme maximum temperatures were studied. Although obtained meteorological data are of relatively poor quality, particularly due to lack of hourly records, there was no alternative except relying on available data. From the available data sets, annual averages of each temperature (minimum, maximum, extreme minimum, extreme maximum), and annual total rainfall, rainy days[2], extreme rainfall events[3], and erosive rainfall[4] events were produced and analysed. The temperature and rainfall data were analysed using the line statistics method (LINEST in MS Excel). Linear trends accompanied with Coefficient of Variance (R^2) were plotted. The findings were further supported by a linear regression analysis (at 95% confidence level) and Mann-Kendall's Tau correlation (at both 99% and 95% confidence levels). Accordingly, rainfall anomalies (distance of rainfall of a particular year from the 40 year's mean) were calculated to understand the variability. Yet, the analysis of extreme temperatures and rainfall reserve special attention because such events hold prominent power to affect the social-ecological systems and impose challenges for adaptation process on the one hand, but were largely ignored by previous studies especially in Nepal on the other.

[2] If a particular day received rainfall of over 0.1mm, the day is considered as a rainy day

[3] The paper does not define extreme rainfall events per se because of highly variable rainfall in the study area, However, rainy days with different rainfall thresholds such as 25mm, 50mm, 100mm, and over 150mm are analysed

[4] Erosive rainfall is defined as rainfall over 72mm in 24 hours because of not having hourly rainfall data. However, erosive rainfall is mostly defined as rainfall of over 1.5mm in 30 minutes (Kemp, 1984) in the context of Nepali

RESULTS

Changes in Maximum and Minimum Temperatures

The present study found significantly increased maximum temperature at Lumle by 0.059^{O}C yr-^{1} (p=0.000) and at Rampur by 0.029^{O}C yr-^{1} (*p=0.001*). The Mann Kendall's Tau (non-linear rise in temperatures) also revealed these increases as statistically significant at 99% confidence level (Lumle) and at 95% level (Rampur). On the contrary, Jomsom recorded slightly decreased (-0.006^{O}C yr-^{1}) maximum temperature, though it was not statistically significant (Fig.2a, Table 1, Table 2).

Global land areas have experienced significant warming in both maximum and minimum temperature extremes since 1950 (Donat *et al.*, 2013). The IPCC Assessment Report (AR) five has observed faster increase in minimum temperature extremes than maximum temperature extremes, supporting earlier findings of the IPCC AR4 (Hartmann *et al.*, 2013). Nevertheless, the report of the IPCC AR4 for South Asia (India) was different that mentioned increase in both cold and warm extremes (Christensen *et al.*, 2007), supporting earlier conclusions that is, increased diurnal temperature range due to a decrease in minimum temperatures (IPCC, 2001).

Not many studies conducted in Nepal have considered analysing changing minimum temperature. Chaulagain (2006) analysed location-specific minimum temperature (four stations) for 1971-2000 while Gentle and Maraseni (2012) analysed national average of minimum temperature. In the global context, an increase in minimum temperature was more rapid than that of maximum temperature. The IPCC (2001) revealed the increase in minimum temperature nearly twice of maximum temperature since 1950s, and it was increased almost everywhere. Salinger (2005) also found average night-time daily minimum temperatures over land in the world have increased by twice the rate of daytime daily maximum temperatures (i.e., approximately 0.2^{o}C, compared with 0.1^{o}C per decade) since 1950. The analysis of minimum temperatures in the present study demonstrated its significant increase at Rampur (0.06^{O}Cy-^{1}) with *p* value 0.000, followed by Jomsom (0.05^{O}Cy-^{1}) with *p* value 0.001. These increases were also significant in the Mann Kendall's Tau. As opposed to this, the minimum temperature at Lumle is almost constant (Fig.2b, Table 1 and Table 2).

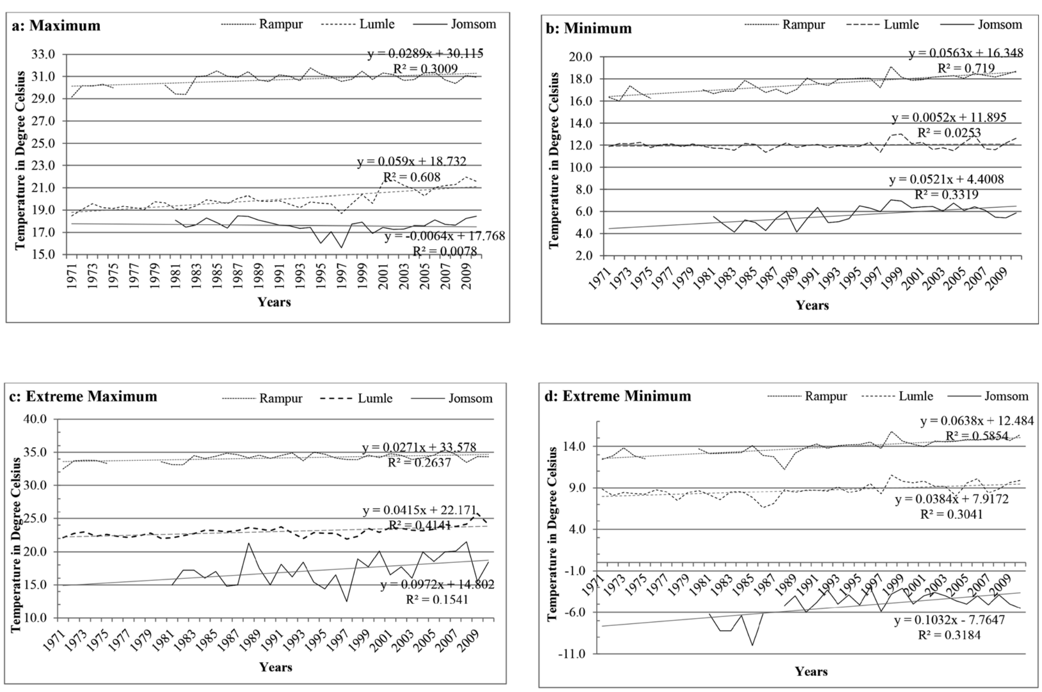

Fig 2: Trends in Annual Averages of Monthly Temperatures by Meteorological Stations of the Kaligandaki Basin, Nepal (1970-2010)

Source: Data obtained from DHM, GoN

TABLE 1
Linear Regression Coefficients (Dependent Variable: Year)

Meteorological Stations	*Unstandardized Coefficients*		*Standardized Coefficients*	*t*	*Sig. (95% Confidence level)*
	B	Std. Error	Beta		
Annual Average of Maximum Temperature					
Jomsom	-1.2360	2.6112	-0.0891	-0.4733	0.640
Lumle	10.2935	1.3418	0.7795	7.6713	0.000*
Rampur	10.3873	2.7179	0.5482	3.8219	0.001*
Annual Average of Minimum Temperature					
Jomsom	6.3852	1.7090	0.5768	3.7362	0.001*
Lumle	4.8704	4.9298	0.1582	0.9879	0.329
Rampur	12.7709	1.3686	0.8481	9.3317	0.000*
Annual Average of Extreme Maximum Temperature					
Jomsom	3.9256	2.0817	0.3357	1.8858	0.070
Lumle	10.0430	1.9164	0.6477	5.2406	0.000*
Rampur	9.6842	2.7886	0.5117	3.4728	0.001*
Annual Average of Extreme Minimum Temperature					
Jomsom	5.1465	1.4983	0.5445	3.4349	0.002*
Lumle	7.9896	1.9388	0.5558	4.1209	0.000*
Rampur	9.2032	1.3154	0.7682	6.9965	0.000*
Annual Total Precipitation					
Jomsom	0.0239	0.0210	0.1863	1.1376	0.263
Lumle	0.0059	0.0031	0.2943	1.8984	0.065
Rampur	0.0071	0.0055	0.2042	1.2859	0.206
Annual Total Rainy Days					
Jomsom	0.1707	0.1355	0.2055	1.2602	0.216
Lumle	-0.0438	0.1350	-0.0526	-0.3248	0.747
Rampur	-0.0298	0.1401	-0.0345	-0.2130	0.832
Extreme Rainfall Events >50mm					
Jomsom (>25mm)	-.208	1.626	-.021	-.128	.899
Lumle	0.7582	0.3040	0.3751	2.4943	0.017*
Rampur	0.46414	0.52493	0.14198	0.88420	0.3822
Extreme Rainfall Events >100mm					
Jomsom					
Lumle	0.7700	0.4631	0.2604	1.6628	0.105
Rampur	-1.1381	1.4140	-0.1295	-0.8049	0.426
Extreme Rainfall Events >150mm					
Jomsom					
Lumle	2.4909	1.0544	0.3578	2.3623	0.023*
Rampur	1.1511	3.1711	0.0588	0.3630	0.719

*Statistically Significant Change (Increase) as the value is <0.04

TABLE 2
Rank Correlation (Mann Kendall's Tau) between Meteorological Data and Time Series (Year) by Meteorological Stations (1971-2010)

Variables	Jomsom	Lumle	Rampur
Annual Average of Maximum Temperature	-0.071	.556**	.293*
Annual Average of Minimum Temperature	.362**	0.024	.702**
Annual Average of Extreme Maximum Temperature	.331*	.490**	.308**
Annual Average of Extreme Minimum Temperature	.324*	.405*	.695**
Annual Total Precipitation	0.143	0.203	0.13
Annual Total Rainy Days	0.196	-0.026	0.087

*. Correlation is significant at the 0.05 level (2-tailed).
**. Correlation is significant at the 0.01 level (2-tailed).

Changes in Extreme Maximum and Extreme Minimum Temperatures

Studies on the changes in extreme temperatures are important component of climate change research. The social-ecological system is expected to adapt to gradual changes; however, it would be highly affected by the extreme cases. This study found increased extreme maximum temperatures of the studied meteorological stations. The rate of increases varied spatially though. The increase at the Jomsom station was the highest i.e. 0.097^{O}Cy-^{1} (though it was not significant statistically in the linear regression model but significant at 95% confidence level in the non-linear - the Mann Kendall's statistics). The increase of 0.04197^{O}Cy-^{1} at Lumle (*p=0.000*) and of 0.027^{O}Cy-^{1} at Rampur (*p=0.001*) were statistically significant, also in the Mann Kendall's Tau at 99% confidence levels (Fig.2c, Table 1 and Table 2).

This study found significantly increased extreme minimum temperatures (in both the linear regression analysis and in the Mann Kendall's Tau) of all the referenced stations (Fig.2d, Table 1 and Table 2). The increase was the highest (0.1^{O}C yr-^{1}) at Jomsom followed by Rampur (0.06^{O}C yr-^{1}) and then by Lumle (0.04^{O}C yr-^{1}).

Changes in Precipitation

The summer monsoon of South Asia has become unstable, uncertain and erratic in recent decades (Shrestha *et al.*, 2000; Kripalani *et al.*, 2007; Turner & Slingo, 2009; Cherchi *et al.*, 2011; Mirza, 2011; Zhang & Zhou., 2011; Wang *et al.*, 2012.). The effects of such changes are immense in the South Asian socio-ecosystems and livelihoods of subsistence farmers. Nepal is located within the spheres of influence of summer monsoon and the monsoon is a life-giving component of climate system of Nepal. The rainfall mechanism in Nepal is orographic, which holds a higher spatial variability within the short areal distance, particularly due to the acts of altitude and slope aspects (windward or leeward side of mountains). Hence, the monsoon behaviour in the Himalaya cannot be generalised but requires an analysis at microclimatic regions. The following section analyses dynamics in monsoonal rainfalls at different locations (Jomsom, Lumle, and Rampur).

Changes in Annual Precipitation

The Lumle station represents the highest rainfall area of Nepal with the highest annual rainfall of 656.2cm recorded in 1995. Per contra, the Jomsom station symbolises the lowest rainfall region in the country with the lowest annual rainfall of only 10.0cm recorded in 1979. Yet, these stations are located only about 30km apart of areal distance. The Rampur station on the other hand, collects a moderate rainfall. Rainfall patterns in the studied stations are highly variable (Fig.3 and 4) though some increases in annual rainfall - by 14.5mm yr^{-1} at Lumle, by 2.5mm yr^{-1} at Jomsom, and by 2.4mm yr^{-1} at Rampur - are observed. Yet, none of these increases is statistically significant (Fig.3a and 3b, Table 1 and Table 2).

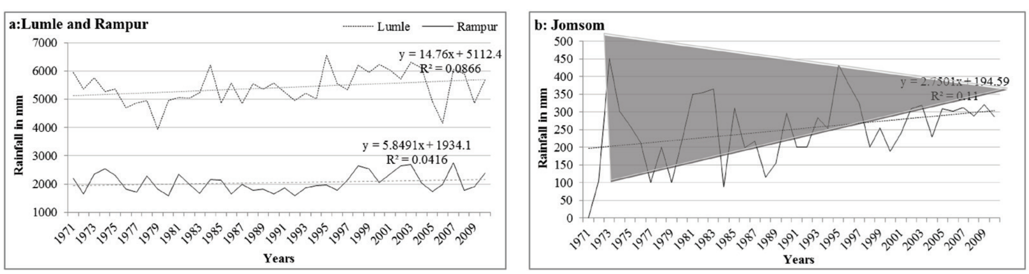

Fig 3: Changes in Annual Rainfall across the Meteorological Stations of the Kaligandaki Basin, Nepal (1970-2010).
Source: Daily Rainfall Data obtained from DHM, GoN

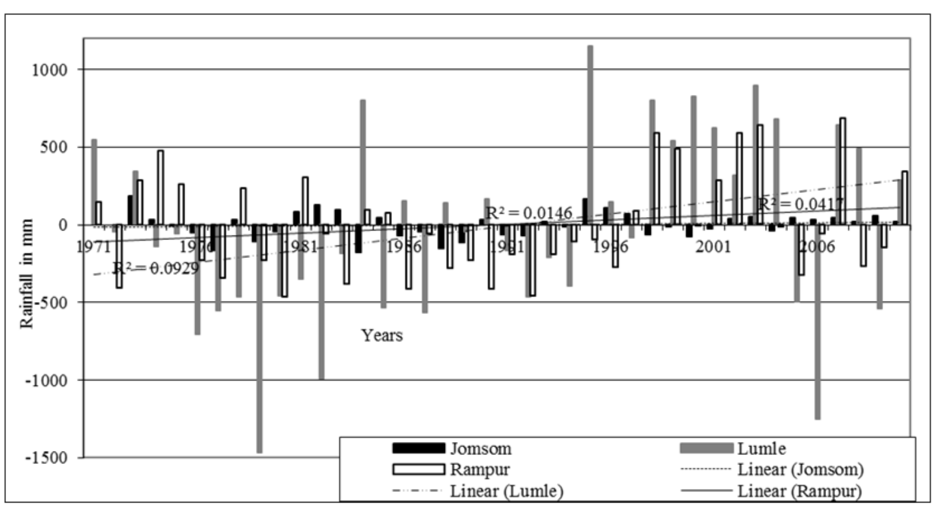

Fig 4: Anomalies of Annual Rainfall in the Kaligandaki Basin, Nepal, by Meteorological Stations for 1971-2010.

The anomaly analyses of rainfall data (Fig.4) showed some exceptional cases of rainfall events at Lumle. There were 10 typical years (1971, 1984, 1995, 1998, 1999, 2000, 2001, 2003, 2004, and 2007), those received more than 50cm of excess annual rainfall than that of the long-term average. Counter wise, the other nine different years (1976, 1977, 1979, 1982, 1985, 1987, 2005, 2006, and 2009) recorded decreased annual rainfall by more than 50cm. It is noted that both the years with decrease and increase in annual rainfall varied between Lumle and Rampur until 1990s and have become similar after 1995. However, the rate of anomalies varies between the stations (Fig.4). The rainfall anomaly of Jomsom was also high though it was almost invisible as seen in Fig.4. This is because data of high rainfall regime (Lumle and Rampur) are also presented together in the graph.

The results of the anomaly analysis suggested that the precipitation in the Himalaya is changing but is trend less. Rather, it has become more variable and uncertain. Yet, the level of variability has somehow decreased at Jomsom over time (Fig.3b - overlapped triangle).

Changes in Annual Rainy Days

Rainfall data have reflected variability in the number of rainy days over time. An annual average of 192 wet-days[5] was observed at Lumle, which was 129 for Rampur and only 48 for Jomsom. The findings showed that the Lumle and Rampur stations experienced some decreases in annual numbers of wet-days while Jomsom observed an increase (Fig.5a). However, none of these changes was statistically significant (Table 1). The increase in annual rainfall while decreasing annual numbers of rainy days can be translated into increased extreme rainfall events in the Kaligandki Basin, Nepal.

Changes in Extreme Rainfall Events

The anthropogenic climate change is reported in cases of increased rainfall extremes. The monsoon flooding is ranked as the fourth biggest disaster in the globe in terms of loss of life between 1970 and 2000 (Tompkins, 2002). Such extreme events are ever increasing (floods in Ganges Basin in 2002, in Mumbai in 2005, in Koshi Basin in 2008, in Ganges Basin in 2013 and in 2014) and are reported to have devastated the communities and the social-ecological systems of the affected area. The term 'extreme' rainfall event, however, is multifaceted. The DHM Nepal defines it as an event that exceeds 100mm rainfall in a particular day (08:00 hours of previous day to 08:00 hours of today). This threshold has some problems indeed, since the place, the Trans-Himalaya (Jomsom), receives very little annual rainfall. Contrary to Jomsom, 421 events exceeded 100mm rainfall at Lumle station in 40 years with 22 events occurring in one single year (1984), questioning whether 100mm of rainfall is the extreme rainfall for Lumle.

[5] Wet-days (used as synonyms to rainy days) are defined as the days those received the rainfall of 0.1mm or over rainfall

The IPCC also had difficulties in providing a universally valid definition of extreme precipitation. Given the diverse climates across the globe, the IPCC used various indices to define extreme events (Hartmann *et al.*, 2013). Therefore, the rainfall events of the studied stations were categorised (prototype) using different thresholds of extremes (Fig.5b, 5c, 5d, and 5e). The trend analysis showed some increases in extreme events. However, only the increases in the events that exceeded 50mm rain/day (increased by 0.18days yr-[1]) and that exceed 150mm rain/day (increased by 0.04days yr-[1]) at Lumle were statistically significant (Fig.5b, 4c and 5d and Table 1).

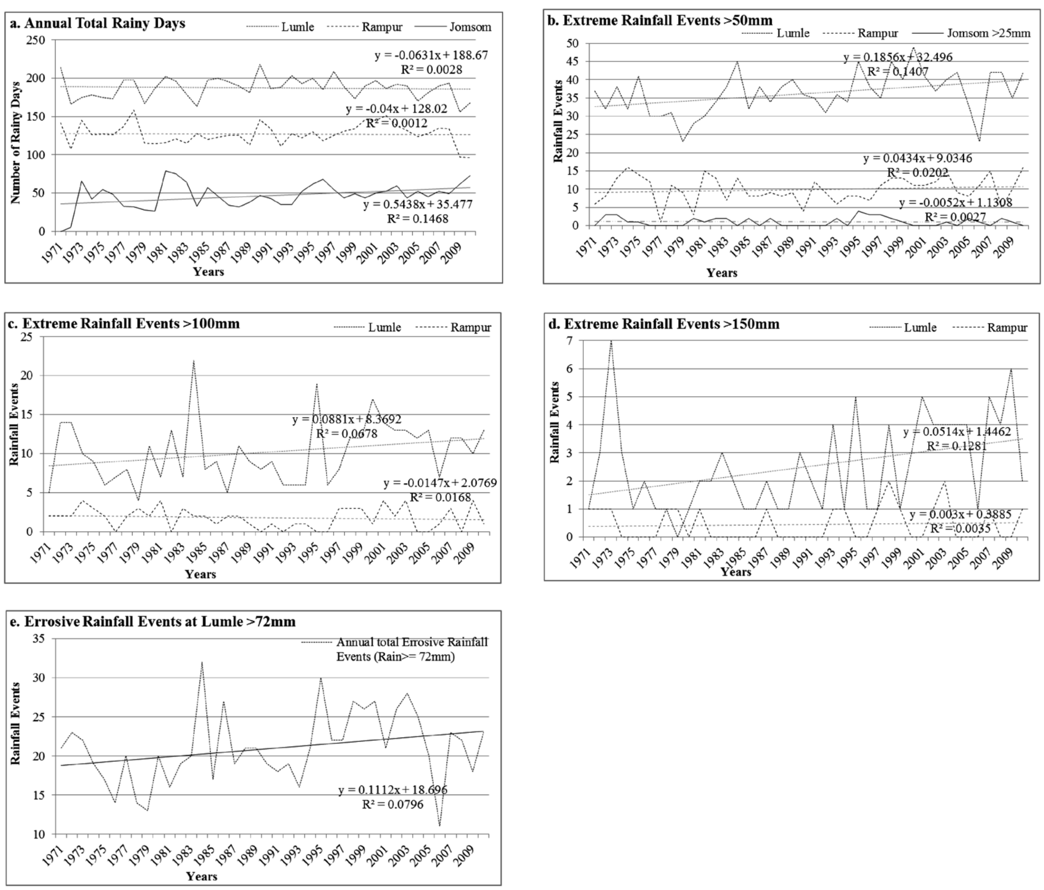

Fig 5: Change in Annual Rainy Days and Extreme Rainfall Events in different Meteorological Stations of the Kaligandaki Basin, Nepal (1971-2010).
Source: Daily Rainfall Data obtained from DHM, GoN

Accordingly, erosive rainfall – an event that receives more than 1.5mm rainfall in 30 minutes, is a form of extreme rainfall event. It was as high as 39% of the total rainfall in Fewa watershed, Nepal (Kemp, 1984). The stations studied in this research lacked hourly rainfall data. Hence, daily rainfalls that exceed 72mm/day are considered as erosive rainfall events for the present purpose. While considering this threshold, 11.13% of the total rainfall events were erosive at Lumle and is increased by 0.06 events a year (Fig.5e). The Rampur station is located at a plain surface so the concept of erosive rainfall does not apply. Additionally, the Jomsom station does not receive the rainfall that is defined as 'erosive rainfall'. Therefore, the erosive rainfall is analysed only for the Lumle station.

DISCUSSION

The analyses of temperatures and precipitation data above demonstrated variability in the rates of change within a small spatial unit (the Kaligandaki Basin) in the Himalaya. The cases of both positively and negatively changed as well as generally stable positions were observed in different types of temperatures and meteorological stations located at different ecological zones. Nevertheless, the cases of observed warming demonstrated higher rates of warming (Fig.2)[6] than that of the global average of 0.006°C/year or 0.85°C between 1880 and 2012 (Hartmann *et al.*, 2013).

The IPCC AR5 claimed to be virtually certain that both the maximum and minimum temperatures were increased, though the AR4 had publicised faster increase in minimum daily temperatures than that of the maximum daily temperatures (Hartmann *et al.*, 2013). There are many uncertainties in the behaviour of diurnal temperature range indeed. Not many scholarly works concerned the variability of diurnal temperature range in Nepal, and in South Asia. Nonetheless, Fowler and Archer (2006) found strong contrasts between the changes in maximum and minimum temperatures (significantly increased winter maximum and consistent decline of summer minimum) in the Upper Indus Basin (1961–2000). On the contrary, Sen Roy and Balling (2005) found significantly increased both maximum and minimum temperatures in India (1931–2002). Present observation at the Rampur station was consistent with the statement of the IPCC AR4 and the finding of Sen Roy and Balling (2005). In contrast to the Rampur station, the Lumle station showed increased maximum temperature and relatively stable minimum temperature, which is generally consistent with Fowler and Archer's findings (2006). The Jomsom station on the other hand demonstrated increased minimum and stable (even cooling) maximum temperatures.

Relatively speaking, a larger number of scholarly works in Nepal have analysed the behaviour of maximum temperature. Decreased maximum temperature at Jomsom (-0.006°C yr^{-1}) observed in

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[6] Minimum temperatures at Jomsom and at Rampur were increased by 0.05ºC/year and 0.06ºC/year respectively. Maximum temperatures at Lumle and at Rampur were increased by 0.059ºC/year and 0.029ºC/year respectively. Extreme minimum temperatures at Jomsom, at Rampur and at Lumle were increased by 0.1ºC/year, 0.06ºC/year, and 0.04ºC/year respectively. Extreme maximum temperatures at Lumle and at Rampur were increased by 0.04ºC/year and 0.027ºC/year respectively.

this study was contrary to the finding of Shrestha *et al.* (1999), who reported 0.06^{O}C yr-^{1} of annual warming (1977-1994) for the Trans-Himalaya. Dhakal (2003) on the other hand, had reported an average temperature rise of 0.5^{O}C per decade in Nepal, which was higher than that of the increase found by the current study at Rampur (0.029^{O}C yr-^{1}), and slightly lower than that of Lumle (0.059^{O}C yr-^{1}). Furthermore, the rate of increase at Lumle was notably higher than that of the global average (IPCC, 2013). Contrary to the situation at Jomsom and Lumle, the increase of maximum temperature at Rampur (0.029^{O}C yr-^{1}) was generally consistent with the finding of Shrestha *et al.* (1999) for the Tarai (0.03 to - 0.03^{O}Cy-^{1}). Furthermore, the rate of increase observed in minimum temperature at Jomsom (0.05^{O}C yr-^{1}) was also notably higher than that of global average, as well as the warming observed in the Tibetan plateau i.e. 0.16°C per decade (annual mean) for 1955–1996 (Liu & Chen, 2000). The finding of the present study generally suggested that winters were getting warmer in the Tarai and in the Trans-Himalaya, which was contrary to previous findings that showed higher rates of warming in the higher altitude (Shrestha *et al.*, 1999; Chaulagain, 2006; Ren *et al.*, 2007). The causes behind the variable finding could be the outcome of analysis of data for different periods[7], and representing different stations. Nevertheless, it is clear that the variations indicate that the microclimatic regions of the Himalaya are responding to global climate change heterogeneously because of the influence of local climatic elements. Therefore, the impacts of climate change within the Himalaya may vary spatially and so are the adaptation requirements.

The extreme events have irreparable impacts on the agriculture, forestry, and the social-ecological systems (McBean, 2004; Salinger, 2005; IPCC, 2007b; Wolf *et al.*, 2010). The present study found significantly increased extreme maximum temperature at Lumle and Rampur stations (increased but not significant at Jomsom), and significantly increased extreme minimum temperatures in all of the referenced stations. These findings were consistent with the findings of the global and regional literature in most of the cases. Hartmann *et al.* (2013), Schar *et al.* (2004), Ciais *et al.* (2005), Tomic (2003) have reported increased heat wave and extreme maximum temperature in the globe with temporal and spatial variability. Choi *et al.* (2009), Caesar *et al.* (2011), Chambers and Griffiths (2008) have reported highly variable findings: increased extremely warm days and nights, increased extremely cold days and nights, as well as increased heat waves in Southeast Asia and Oceania. Furthermore, it is believed that the changes in mean temperature (which is well noted in the Himalaya) will lead to higher temperature extremes and greater rainfall extremes (Mitchell

[7] Chaulagain (2006) used data prior to 2000 and the Jomsom station (Trans-Himalaya) was not included; Ren *et al.* (2007) analysis about projections; and Shrestha *et al.* (1999) used data prior to 1994

et al., 2006). The findings of the present research are generally consistent with this claim. However, a lack of hourly reading of temperatures to obtain the daily maximum and daily minimum temperatures and a lack of hourly rainfall data pose limitations to understand actuation of temperature and rainfall dynamics in the Himalaya.

The IPCC AR4 concluded that precipitation in the tropics (between 30^{o}S - 30^{o}N latitudes) has downward trends since the 1970s, though the AR5 reported no significant changes in the tropics but increased global average for the 1901–2008 period (Hartmann *et al.*, 2013). However, there are conflicting studies about the changes in monsoon precipitation in South Asia. Zhang and Zhou (2011) reported significantly decreased average precipitation of monsoon in the Northern Hemisphere from 1901 to 2001. In contrast, other studies claimed monsoon Asia has been experiencing higher and violent rainfall events (IPCCP, 2001; IPCC, 2007a; UNDP & DFID, 2007). The IPCC AR5 also reported increased summer monsoons, both the mean precipitation and extreme events (Christensen *et al.*, 2013). Shrestha *et al.* (2000) found similar scenario in Nepal. Yet, the present study, including other literature (Kripalani *et al.*, 2007; Conroy & Overpeck 2011), found complex and heterogeneous precipitation behaviour of monsoon, mostly caused by the local climatic factors.

Heavy precipitation events have been increased globally (Hartmann *et al.*, 2013). The extreme rainfall events of 24 hours and over have been increasing globally and regionally (Easterling *et al.*, 2000; Tompkins, 2002; Wilby & Keenan, 2012). Goswami *et al.* (2006) also found clearly increased extreme rainfall events in India though no particular trend in the total annual rainfall was observed. The findings of the current research are consistent with the literature that shows variability rather than a linear trend. The El Niño–Southern Oscillation (ENSO) is reported to be responsible for the fluctuation of climatic phenomena of monsoon regions. Scholars have found strong a connection between the rainfall and the Southern Oscillation Index (SOI) extremes (Shrestha *et al.*, 2000; Mirza, 2011). Increased extreme rainfall events in the highly dynamic Himalayan topography have severe impacts on the socio-ecological systems of the region. Therefore, the impacts of changing climates on the social-ecological systems should be studied to identify the adaptation requirement for the region.

CONCLUSION

Climate change has been receiving extraordinary research attention in recent decades. There is a consensus among the climate scientists that the global climate system is changing and that has affected regional climates variably. However, the response of microclimatic regions to the global change is being studied recently although research is yet to cover vastly diverse areas. The Himalaya is reported to have abrupt level of warming, However, the effects of complex topography, altitude, and slope aspects of the Himalaya have not been attributed while generalising climate dynamics in the Himalaya. In this paper, a small effort to narrow such a gap has been made.

The analyses of meteorological data demonstrated the rise in temperatures and increase in erratic rainfall events in the Kaligandaki Basin in general. However, there exists variability among the studied sites. Both the minimum and maximum temperatures have increased at Rampur, only the maximum temperature is increased at Lumle, and only minimum temperature is increased at Jomsom. The extreme rainfall events were also increased in general, with a significant increase at Lumle. Though not statistically significant, the numbers of wet-days were slightly decreased at Rampur and Lumle while they were increased at Jomsom.

The microclimatic regions of the Himalaya are responding to the global climate change variably. Without the study of the behavior of microclimates at several locations, climate change scenario of the Himalaya cannot be generalised, homogenised and simplified. Furthermore, observed changes in the climate system might have already impacted the social-ecological systems of microclimatic regions and have challenged the livelihoods of the poor farming communities. The impacts might also have encouraged local communities to adopt various adaptation measures. Nevertheless, detailed studies on climate impacts and adaptation response of the local communities are necessary.

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