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Spatial and temporal variation of surface air temperature at different altitude zone in recent 30 years over Nepal

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सार – इस शोध पत्र में नेपाल के पूरे क्षेत्र में फैले हुए 22 स्टेशनों (15 सिनॉप्टिक स्टेशन और 7 जलवायु स्टेशन) के वायु तापमान आँकड़ों के आधार पर सतही वायु तापमानों की लंबी अवधि (30 वर्षों की) में ऊँचाई के अनुसार भिन्नताओं की पड़ताल की गई है। अनेक शोधकर्त्ताओं ने नेपाल में वायु तापमान में वृद्धि की दर को दर्शाया है जो पर्वतीय एवं तराई क्षेत्रों की तुलना में हिमालयी क्षेत्र (~3500 मी. ए एस एल अथवा अधिक) अधिकतम देखा गया है। यद्यपि पूर्ववर्त्ती शोधकर्त्ताओं के परिणामों के विपरीत इस शोध पत्र में यह बताया गया है कि वार्षिक औसत तापमान में वृद्धि तराई तथा पर्वतीय क्षेत्रों की तुलना में पहाड़ियों में (1000 से 2000 मी. ए एस एल) अधिक हुई है। नेपाल (70 से 5050 मी. ए एस एल) के विस्तृत ऊँचाई वाले रैंज में तापमान में गिरावट की दर –5.65° सेल्सियस प्रति कि. मी. रही है। तराई और ट्रान्स हिमालय (जोमसोम) में ऊष्णता दर क्रमश: 0.024° एवं 0.029° सेल्सियस प्रति वर्ष रही है।

ABSTRACT. This paper investigates long term (30 yrs) altitudinal variations of surface air temperatures based on air temperature data of countrywide scattered 22 stations (15 synoptic and 7 climate stations) in Nepal. Several researchers have reported that rate of air temperature rise (long term trend of atmospheric warming) in Nepal is highest in the Himalayan region (~ 3500 m asl or higher) compared to the Hills and Terai regions. Contrary to the results of previous researchers, however this study found that the increment of annual mean temperature is much higher in the Hills (1000 to 2000 m asl) than in the Terai and Mountain Regions. The temperature lapse rate in a wide altitudinal range of Nepal (70 to 5050 m asl) is -5.65 °C km^{-1}. Warming rates in Terai and Trans-Himalayas (Jomsom) are 0.024 and 0.029 °C/year respectively.

Key words – Terai, Hills and mountains of Nepal, Annual mean air temperature, Lapse rate.

1. Introduction

Global warming and the consequent environmental problems such as floods, draughts, heat waves, cold spans, forest fires and severe cyclonic storms have been experienced over the last few decades in many parts of the world (Sheikh *et al*., 2015; Easterling *et al*., 2000; Barry 2002; De *et al*., 2005; IPCC, 2007). Long term air temperature data recorded in different latitudes and altitudes clearly indicate that warming trend has been accelerating in the last two decades and the acceleration is attributed to increasing emission of anthropogenic greenhouse gases (Xu *et al*., 2003; Kumar *et al*., 2006; Liu *et al*., 2006; Zhang *et al*., 2006; Bhutiyani *et al*., 2007; You *et al*., 2010). Some studies on elevation-dependent warming suggest that warming is more rapid at higher elevations (Pepin *et al*., 2015; Rangwala and Miller, 2012); e.g., warming in Himalayas has been observed to be much higher than the global average (0.74 °C over the last hundred years).

There are a few studies of temperature trends in Nepal that report different annual increments of temperature [average annual maximum: 0.06 °C (Shrestha *et al*., 1999), 0.043 °C (Practical Action, 2009) and 0.065 °C (Kattel and Yao, 2013); average annual minimum: 0.007 °C (Practical Action, 2009), 0.011 °C (Kattel and Yao, 2013); average annual mean: 0.025 °C (Practical Action, 2009), 0.02 °C (Shrestha, 2012), 0.038 °C (Kattel and Yao, 2013). The inconsistency of the temperature increments are probably due to insufficient number of meteorological stations existing in the mountains regions of Nepal, inconsistency of the considered yearly data and some errors in the collected data (Sheikh *et al*., 2015; Klein Tank *et al*., 2006). Although the increments obtained based on very limited data are dissimilar, significant warming in the Himalayas is confirmed through glaciological studies as several glacier there have been found to be retreated considerably (Kadota *et al*., 1997; Fujita *et al*., 2001, 2006; Shekhar *et al*., 2010). The reported rate of retreat of

TABLE 1

Details of the meteorological stations in Nepal (indicates no index number)**
The stations have been grouped according to the altitudinal ranges

Index No.	Station Name	Latitude (°N)	Longitude (°E)	Elevation (m)	Orientation
1111	Janakpur	26° 43'	85° 58'	90	Plain land, Airport
705	Bhairhawa	27° 31'	83° 26'	109	Plain land, Airport
1319	Biratnagar	26° 29'	86° 16'	72	Plain land, Airport
909	Simra	27° 10'	84° 59'	130	Valley floor
1320	Tarahara	26° 42'	87° 16'	200	Plain, facing south
207	Tikapur	28° 32'	81° 07'	140	Plain land , forest area
902	Rampur	27° 37'	84° 25'	256	Valley floor
218	Dipayal	29° 15'	80° 56'	652	Small Valley floor
406	Surkhet	28° 36'	81°37'	720	Valley floor, Airport
804	Pokhara	28° 13'	84° 00'	827	Valley floor, Airport
1030	Kathmandu	27° 42'	85° 22'	1337	Valley floor,
1029	Khumaltar	27 °40'	85° 20'	1350	Valley floor
303	Jumla	28° 35'	81° 37'	2300	Valley floor, West open
1103	Jiri	27° 38'	86° 14'	2003	Valley floor
1206	Okhaldhunga	27° 19'	86° 30'	1720	Hill top, ridges
104	Dadeldhura	29° 18'	80° 35'	1818	Ridges
1307	Dhankuta	26° 59'	87° 21'	1445	Hill top
1407	Taplejung	27° 21'	87° 40'	1732	Ridges, slope
1043	Nagarkot	27° 42'	85° 31'	2163	Mountain top
1007	Kakani	27° 48'	85° 15'	2064	Ridges, facing south
601	Jomsom	28° 47'	83° 43'	2744	River valley floor
**	Namche	27 °48'	86° 42'	2163	Small enclosed , open to west
**	Lukla	27° 41'	86° 43'	2660	Narrow valley, north-south oriented
**	Pheriche	27° 53'	86° 49'	4260	Valley, north south oriented
**	Laboche	27° 57'	86° 48'	5050	Valley, north-south oriented
**	Syangboche	27° 49'	86° 43'	3833	Mountain top

glaciers in the Nepal Himalayas ranges from several meters to 20 m/year.

The climate model projections show that there will be a rise in the average annual temperature over Nepal and that it will vary both spatially and temporally. The National Adaptation Programs of Action (NAPA) reports climate projections conducted by the Organization for Economic Cooperation and Development (OECD, 2003) and the Nepal Climate Vulnerability Study Team (NCVST, 2009). The OECD analysis used Global Climate Models (GCMs) with the SRES (Special Report on Emissions Scenarios) B2 (low emissions) scenario and projects mean annual temperature increases of 1.2 °C by 2030, 1.7 °C by 2050 and 3 °C by 2100 relative to a pre-2000 baseline. The NCVST study used GCM and Regional Circulation Models (RCMs) and projected mean annual temperature increases of 1.4 °C by 2030, 2.8 °C by 2060 and 4.7 °C by 2090.

Nepal is one of the unique countries in the world, where all types of climate prevail due to altitudinal variation from 60 m asl to 8848 m asl within a short (<200 km) North-southeast distance. Considerable rise of air temperature, a key climatic parameter and its impact on forest, agriculture, biodiversity, water resources

TABLE 2

The regression equations obtained for the maximum, minimum and mean temperature at the Meteorological stations in Nepal

Station	Maximum	Minimum	Mean
Janakpur	y = 0.011 *x* + 30.38	y = 0.040 *x* + 18.74	y = 0.023 *x* + 24.63
Bhairhawa	y = 0.012 *x* + 30.65	y = 0.020 *x* + 18.41	y = 0.015 *x* + 24.56
Biratnagar	y = 0.021 *x* + 29.88	y = 0.042 *x* + 18.32	y = 0.032 *x* + 24.09
Simra	y = 0.010 *x* + 30.2	y = 0.033 *x* + 17.49	y = 0.022 *x* + 28.86
Tarahara	y = -0.014 *x* + 30.17	y = 0.037 *x* + 17.62	y = 0.011 *x* + 23.90
Tikapur	y = 0.039 *x* + 29.76	y = 0.021 *x* + 17.08	y = 0.030 *x* + 23.42
Rampur	y = 0.016 *x* + 30.65	y = 0.059 *x* + 16.85	y = 0.038 *x* + 23.76
Dipayal	y = -0.008 *x* + 30.69	y = 0.057 *x* + 14.45	y = 0.025 *x* + 22.57
Surkhet	y = 0.061 *x* + 27.03	y = 0.017 *x* + 15.23	y = 0.028 *x* + 21.34
Pokhara	y = 0.036 *x* + 20.16	y = 0.042 *x* + 14.79	y = 0.045 *x* + 20.39
Kathmandu	y = 0.089 *x* + 24.30	y = 0.057 *x* + 11.31	y = 0.074 *x* + 17.8
Khumaltar	Y= 0.072 *x* + 23.36	Y= 0.048 *x* + 10.92	Y = 0.060 *x* + 17.14
Jumla	y = 0.064 *x* + 19.75	y = 0.015 *x* + 16.85	Y = 0.044 *x* + 12.17
Jiri	y = 0.028 *x* + 20.26	y = 0.001 *x* + 08.07	y = 0.019 *x* + 14.11
Okhaldhunga	Y = 0.127 *x* + 19.47	Y = -0.018 *x* + 14.26	Y = 0.054 *x* + 16.50
Dadeldhura	Y = 0.141 *x* + 18.70	Y = 0.009 *x* + 11.45	Y = -0.067 *x* + 5.07
Dhankuta	y = 0.206 *x* + 20.12	y = 0.028 *x* + 14.28	y = 0.117 *x* + 17.20
Taplejung	y = 0.078 *x* + 19.68	y = 0.025 *x* + 11.42	y = 0.048 *x* + 15.55
Nagarkot	y = 0.028 *x* + 19.10	y = 0.002 *x* + 9.58	y = 0.019 *x* + 14.35
Kakani	y = 0.017 *x* + 17.58	y = 0.094 *x* + 9.314	y = 0.056 *x* + 14.45
Jomsom	y = 0.004 *x* + 17.66	y = 0.015 *x* + 16.85	y = 0.029 *x* + 11.10

in the different altitudinal zones of Nepal should be significant.

The main objective of this study is to examine annual maximum, minimum and mean air temperature trends at different altitudinal zones of Nepal based on 30 years (1981-2010) data collected from 22 meteorological stations and short term data from five stations from Pyramid Meteorological Networks (EVK2) up to 5050 m asl of Khumbu Valley (*i.e.*, elevation ranged from 72 m asl to 5050 m asl). Interpretation of the trends and possible reasons of differential temperature increments at different altitudinal zones are also discussed. Although previous researchers carried out similar studies on temperature trends (Kattel and Yao, 2013) (Data period from 1980 to 2009; elevation range from 1304 m asl to 2566 m asl) and temperature lapse rate (Kattel *et al.*, 2013) (Data period from 1985 to 2004; elevation range from 72 m asl to 3920 m asl) in Nepal, the present study covers temperatures over a wider topographical range. Also, as one of the authors of this paper is a pioneer of establishing the stations' network in Nepal, it was possible to carefully select synoptic stations and data sets to ensure reliability and consistency of the data.

2. Data and methodology

There are about 100 climate stations, which have been recording surface air temperature in Nepal. A long term data for the same period for all those stations are not available. In this study, 22 stations have been selected, in which fifteen stations out of 22 stations are synoptic stations. The rest of seven stations have been selected to represent the various elevation of Nepal. The long term history of those 22 selected stations are personally known and verified and the time period of 1981 to 2010 has been considered based on all those information. Mean monthly maximum temperature, mean monthly minimum temperature and mean temperature of all those stations for 30 years were prepared except Dipayal, as the station was only established in 1983 and data was considered from

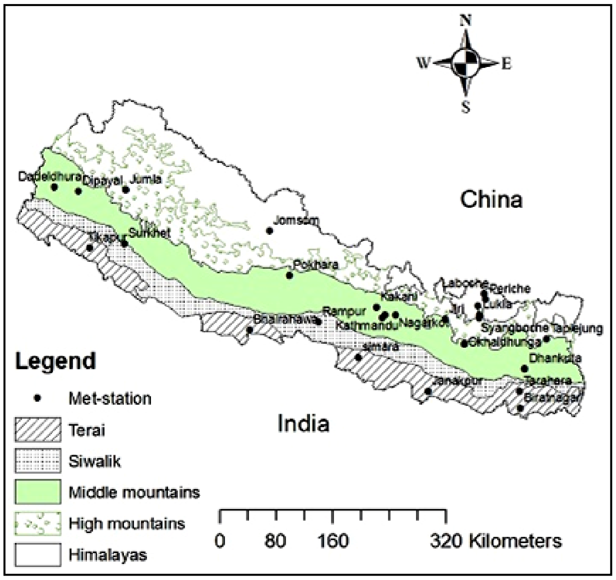
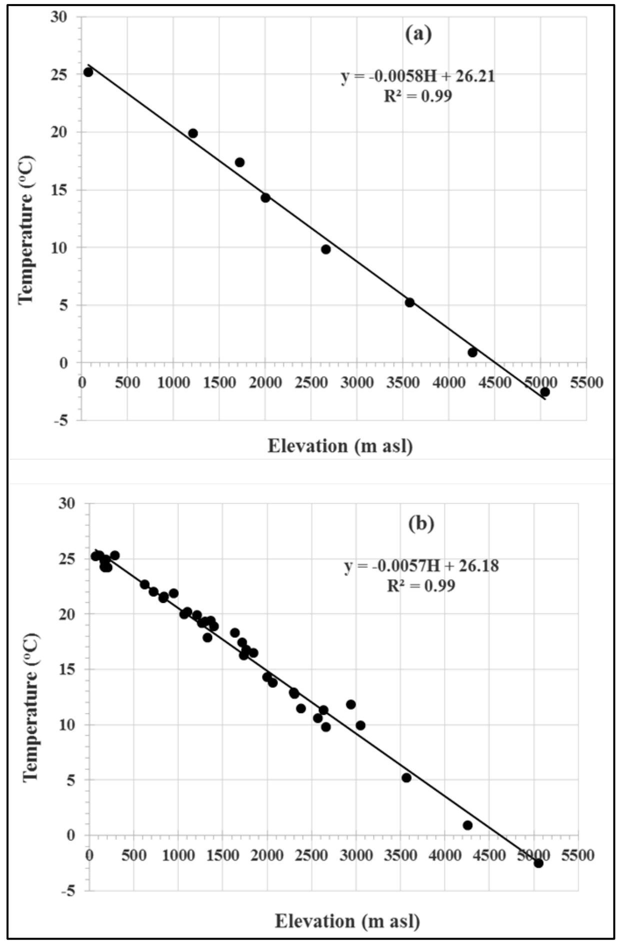


Fig. 1. Location of meteorological stations in Nepal selected for this study



Figs. 2(a&b). Altitudinal variation of mean annual temperature for (a) eastern Nepal and (b) for whole Nepal

that time. Similarly there was one more station namely Surkhet also has data only from 1983. Data have been thoroughly checked and evaluated. The data for all those stations were extracted from the different publications from the Department of Hydrology and Meteorology, Nepal. In addition to 22 stations, the data from five Pyramid Meteorological Networks (EVK2 up to 5050 meters of Khumbu Valley) have also been considered to study the spatial variation of temperature. The location of all those climate stations that covered an elevation range from 72 m asl in the south to 5050 m asl in the north of Nepal have been presented in Table 1. Monthly, seasonal and annual means of temperatures were calculated using the arithmetic mean method. A statistical method such as the simple linear regression model, which was widely adopted by several researchers (Rolland, 2003; Mokhov and Akperov, 2006; Blandford *et al*., 2008; Kattel and Yao, 2013) was used to determine maximum, minimum and mean temperature trends and coefficient of determination (R^2) for the significance of the trends. Also, altitude versus annual mean temperature relationship (lapse rate) is established using the regression method.

3. Data analysis and results

Since temperature is a function of not only the altitude but also different physiographic conditions such as orientation, *i.e*., slope, aspect, hill tops and valley and therefore temperature analysis is classified here based on altitude and orientation.

A long term trends of mean monthly maximum temperature, mean monthly minimum temperature and mean monthly average temperature of all the 22 stations have been analyzed separately. The regression equations are tabulated for the maximum, minimum and mean temperature and this way each station showed their respective results and the results have made grouping depending upon their elevation (Table 2). In Terai, increment of the minimum temperature trends of the stations having elevations less than 1000 m are generally higher than that of the maximum trends. On the other hand the trends on maximum temperature showed much higher increment in the Hills, except Jomsom where minimum temperature trends showed a little higher than the trend of maximum temperature. In addition to monthly analysis of temperature, seasonal analysis of temperatures was also performed.

When one studies air temperature in Nepal, variation of temperature at different altitudes is quite important to consider owing to a large topographical variation within a short North-South distance. Therefore, annual mean air temperature data from the above mentioned 22 stations

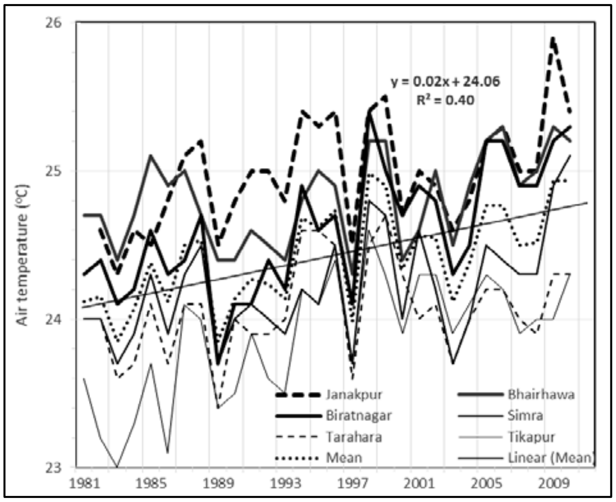


Fig. 3. Annual mean temperatures recorded in Terai

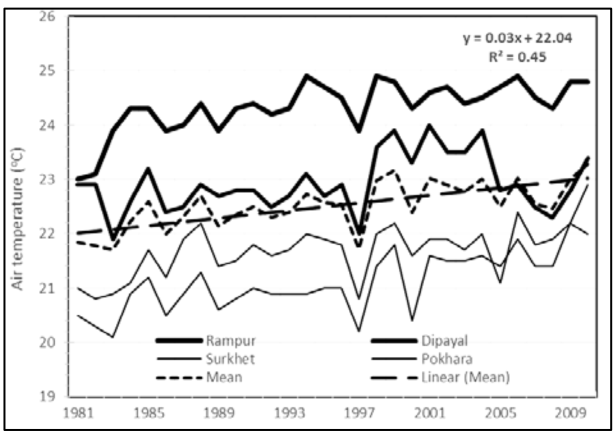


Fig. 4. Annual mean temperatures recorded in valley floor, 200 to 1000 m asl

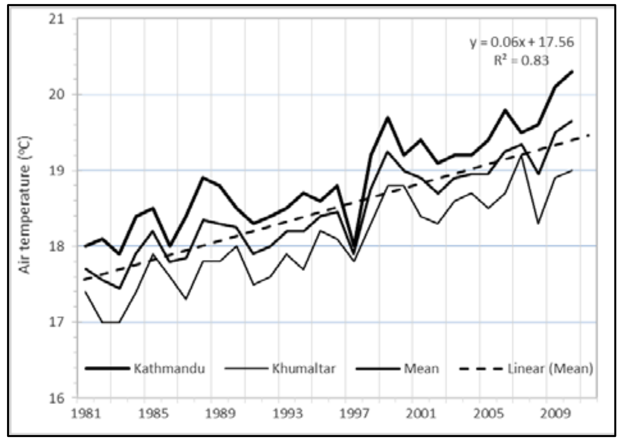


Fig. 5. Annual mean temperatures recorded in valley floor, 1000 to 2000 m asl

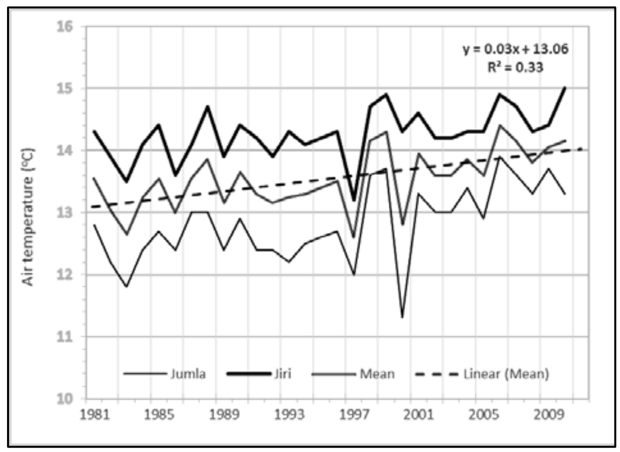


Fig. 6. Annual mean temperatures recorded in Mountain valley floor, 2000 to 2500 m asl

and five EVK2 high altitude stations for 2005 have been selected and plotted [Figs. 2(a&b)], which helps to classify the climate station to study the temperature distribution in Nepal. Figs. 2(a&b) shows altitudinal variation of annual mean temperature and temperature trend for the stations located in the Eastern region of Nepal [Fig. 2(a)] and all the stations throughout the country (Fig. 2b). The trend for the eastern Nepal and for whole Nepal are found to be almost similar (*i.e.*, R^2 = 0.99 and regression coefficient = -0.0058 °C for eastern Nepal, and R^2 = 0.99 and regression coefficient = -0.0057 °C for whole Nepal). The high and consistency of the correlation coefficients for both the cases suggest that an inverse linear relationship between temperature and elevation is applicable regardless of the fact that stations are spread out across a range of topography at different spatial locations.

Significant increment of temperature between 1000 to 2000 meters is evident in the figure. Three data points above 3000 m asl (see data and method section) have been incorporated in order to get a long range altitudinal changes of air temperature. The plotted data points are quite close to the trend line suggesting an excellent fit (R^2 = 0.99) between altitude and air temperature. The same figure also shows that the general decrease of temperature per 1000 meters is -5.7 to -5.8 °C.

In order to understand altitude-dependent air temperature comprehensively and systematically the altitudinal zones and stations within them are classified as below:

(*i*) There are ten stations below 1000 m asl, among them six stations fall on plain low land, less than 200 m asl, Terai, which lies on the southern parts of Nepal and this low land used to be bread basket of Nepal. Above 200 m asl, Churiya Range and Mahabharat Range prevail where four of the remaining stations are generally

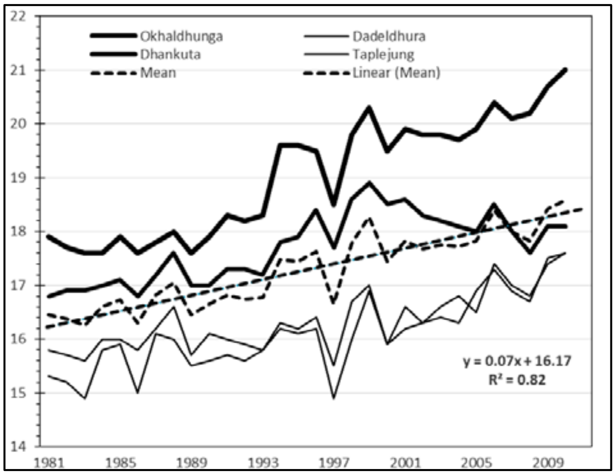


Fig. 7. Annual mean temperatures recorded in Hill top, 1500 to 2000 m asl

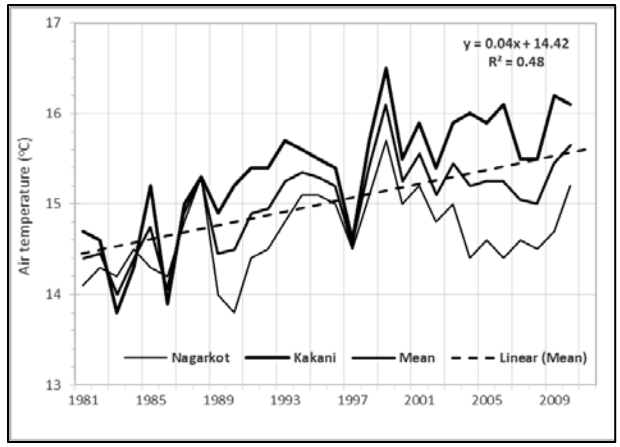


Fig. 8. Annual mean temperature recorded at 2000 to 2500 m asl

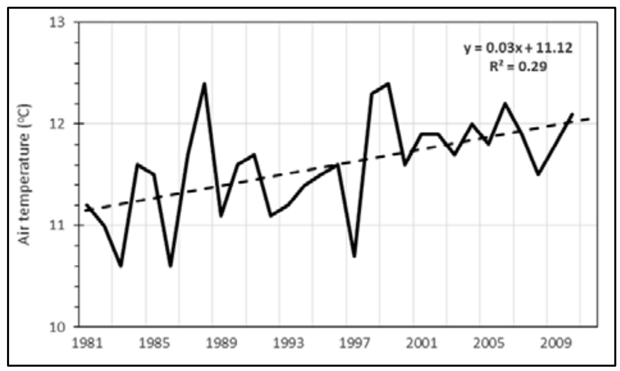


Fig. 9. Annual mean temperature recorded in Trans Himalaya, Jomsom, 2744 m asl

located at valley floor below 1000 m. These stations are analyzed separately.

(*ii*) Within the selected stations, there are eleven stations below 2500 m asl. Four groups are made within 11 stations, the valley floor between 1000-2000 m asl and 2000- 2500 asl are separately analyzed and these stations fall on warm temperate and cool temperate climates. Similarly mountain tops stations are also analyzed accordingly.

(*iii*) Only one station, Jomsom falls on Trans Himalaya. The snow line varies from 5500 to 6000 m asl which depends upon the slope and aspect of that place. Greater than snow line is called the Himalayan Range.

3.1. *Surface air temperature changes at Terai at elevation ≤ 200 m asl*

There are six stations below 200 m asl, namely Tikapur, Bhairhawa, Simra, Janakpur, Biratnagar and Tarahara. These six stations show less than 0.02 °C increment of annual maximum temperature and one station namely Tikapur shows 0.038 °C increment of maximum temperature. In terms of annual minimum temperature, the increment shows 0.02 °C to 0.04 °C. In this way, the increment of annual mean temperature ranges from 0.01 °C to 0.03 °C in Terai Region of Nepal. The annual mean temperatures recorded at the stations in Terai region is shown in Fig. 3. Although absolute values of temperatures are different the inter-annual cycles of the temperatures follow similar trends. The interannual fluctuation of temperatures are quite high. It is clear in the figure that there are general uptrends of temperatures in different locations in Terai. The average air temperature warming rate across the Terai was found to be 0.024 °C/year. While looking at the temperature patterns in Fig. 3, Tikapur that belongs to Far Western part of Nepal shows lower temperature than the other stations. On the other hand Janakpur and Bhairhawa generally show higher temperature.

3.2. *Temperature changes at valley floor, 200 to 1000 m asl*

There are 8 valley floor stations in between 200 m asl and 2500 m asl (Table 1, Figs. 3 to 8). The annual mean air temperatures recorded at four different valley floor stations having altitudinal range 256 to 827 m asl is shown in Fig. 4. Generally, the absolute values of temperature are aligned according to the respective altitudes; the higher the altitude is the lower the air temperature records. Inter-annual fluctuation of temperature is generally high. The figure demonstrates that there is a steady annual increase of air temperature in all the stations except Dipayal, where exceptional rise of temperature is seen during 1997 to 2004 and later 2008 to 2010. The unusually lower pattern of temperature at Dipayal cannot be explained at the moment. The average mperature warming rate across the altitudinal range was 0.034 °C/year.

3.3. *Temperature changes at Hill valley floor, 1000 to 2000 m asl*

The annual mean temperatures recorded at two different stations, namely Kathmandu (1337 m asl) and Khumaltar (1350 m asl) in Kathmandu valley is shown in Fig. 5. The significant uptrends of annual mean air temperature in both the stations are quite clear. Nearly systematic cycles of increasing and decreasing air temperature are seen in the figure. Although the altitudinal difference between the stations are quite small the absolute temperature difference are clearly visible indicating that there are other factors responsible to limiting air temperature other than the altitude. The Khumaltar station is agricultural land and quite open to all direction, whereas Kathmandu station is very close to building and forest side. The average air temperature warming rate is found to be 0.063 °C/year in Kathmandu valley.

3.4. *Temperature changes at Mountain valley floor, 2000 to 2500 m asl*

The annual mean temperatures recorded at two different stations, namely Jumla (2300 m asl) and Jiri (2003 m asl) are shown in Fig. 6. The overall trends show temporal increasing of air temperature with high inter-annual fluctuation. The fluctuation is quite large in between 1997 to 2001. The average air temperature warming rate is found to be 0.033 °C/year.

3.5. *Temperature variation at Hill top, 1500 to 2000 m asl*

There are 7 Hill tops stations in between 1500 m asl and 2500 m asl [Table 1, Figs. (7&8)]. The annual mean air temperatures recorded at five different Hill top stations having altitudinal range 1445 to 1848 m asl is shown in Fig. 7. The average air temperature warming rate across the altitudinal zone was 0.072 °C/year, with all the stations showing dramatic increase of air temperatures. The stations higher than 1000 m asl show remarkably much higher increment of temperature. For example, Dadeldhura and Dhankuta show 0.09 °C and 0.11 °C increment of annual mean temperature. The inter-annual fluctuation of temperature is generally small except the middle part of nineties.

3.6. *Temperature variation at Mountain top, 2000 to 2500 m asl*

The annual mean temperatures recorded at two different Hill top stations, namely Nagarkot (2163 m asl) and Kakani (2064 m asl) are shown in Fig. 8. The average air temperature warming rate across the altitudinal zone was 0.038 °C/year, with all the stations showing dramatic increase of air temperatures. The inter-annual fluctuation of temperature is quite large. The rate of increase of temperature in recent year is quite different patterns; Kakani is increasing trend and Nagarkot is decreasing trend. Although altitudinal differences between the stations are quite small, the temperature patterns are just opposite and reasons behind such discrepancies are not known at the moment.

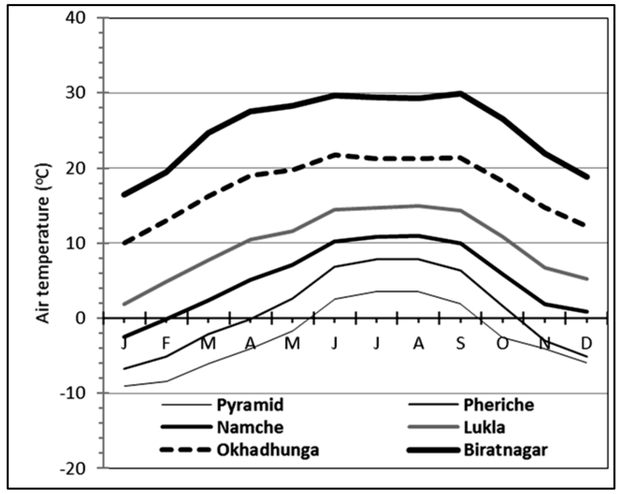


Fig. 10. Altitude wise (station wise) monthly mean air temperature in Nepal

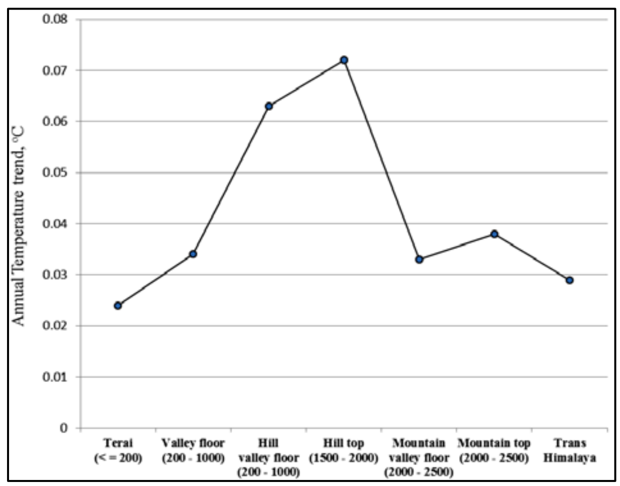


Fig. 11. Region-wise annual mean temperature trend and elevation (m asl) range

3.7 *Temperature variation at Trans Himalaya, Jomsom, 2744 m asl*

The annual mean air temperatures recorded at Jomsom, 2744 m asl, which is located in Trans-Himalayan

TABLE 3

Seasonal temperature trend at the different altitudes in Nepal

Location	Mar - May	Jun - Sep	Oct - Nov	Dec - Feb
Terai: (<= 200 m asl)	0.02 -0.05	0.01-0.03	0.02-0.04	0.01-0.02
Valley: 200 to 1000 m asl	0.04-0.05	0.02-0.04	0.04-0.05	0.04
Hill Valley: 1000 to 2000 m asl	0.05-0.06	0.02-0.04	0.04-0.07	0.04-0.07
Hill top: 1500 to 2000 m asl	0.07-0.11	0.05-0.13	0.07-0.11	0.09-0.10
Mountain Valley: 2000 to 2500 m asl	0.04	0.03	0.02-0.04	0.03-0.06
Mountain top: 2000 to 2500 m asl	0.04-0.08	0.04	0.02-0.04	0.03-0.07
Trans Himalaya	0.03	0.01	-0.02	0.08

TABLE 4

Mean annual temperature trends for all stations

Station Name	R^2	*P*	Trend (°C/year)
Janakpur	0.29	0.0039	0.023
Bhairhawa	0.21	0.0143	0.015
Biratnagar	0.45	3.78E-05	0.032
Simra	0.03	0.4023	0.022
Tarahara	0.1	0.0803	0.011
Tikapur	0.42	4.85E-05	0.03
Rampur	0.49	2.21E-05	0.038
Dipayal	0.04	0.1895	0.025
Surkhet	0.36	0.0004	0.028
Pokhara	0.55	2.32E-06	0.045
Kathmandu	0.78	1.89E-10	0.074
Khumaltar	0.81	1.79E-11	0.06
Jumla	0.33	0.001	0.044
Jiri	0.24	0.0064	0.019
Okhaldhunga	0.58	5.59E-07	0.054
Dadeldhura	0.69	3.19E-08	-0.067
Dhankuta	0.86	8.16E-14	0.117
Taplejung	0.55	1.75E-06	0.048
Nagarkot	0.15	0.027	0.019
Kakani	0.57	7.58E-07	0.056
Jomsom	0.29	0.0022	0.029

region, a rain shadow area of southern part of Nepal is shown in Fig. 9. Temporal data fluctuation is unusually high. The overall trend indicates dramatic increase of air temperature; the average air temperature warming rate was found to be 0.029 °C/year.

3.8. *Variation of surface air temperature from 72 to 5050 m asl*

The monthly mean air temperature (derived from multi years' data) recorded at selected stations (altitude) representing a wide range of elevation (72 to 5050 m asl) in Nepal is shown in Fig. 10. The figure shows that there is a systematic seasonal and spatial variation of air temperature in the country. The trends patterns are nearly parabolic, and quite systematic and symmetrical showing much lower air temperatures at high altitudes than those at lower altitudes. In other words, the patterns of the curves follow the topographical variation of the country. The temperature data from the pyramid station at Labouche (5050 m asl) indicates that the Labouche station had positive temperature (>0 °C) during summer season (June to September) and negative temperature (<0 °C) for rest of the year. This clearly indicates that Labouche area is permafrost area for eight months. Looking at the temperature figures for June to September at Labouche, there is a good possibility that the elevation above 5600 meters will be permafrost areas for all the months. Above that elevation the precipitation will be only in the form of snow. This assumption still supports the snow.

Fig. 11 shows increasing temperature trends from Terai region of elevations range below 200 m to hill top up to 2000 m. Following the hill top of elevation range above 2500 m there is a tendency of decrease in temperature trend but still higher than Terai. The overall temperature trends indicate the tendency of increase of temperature trend at higher elevations than in the lower elevation. Because of the complex topography of the country, the temperature trends are far from uniform. Liu *et al*. (2009) found that altitude dependency is most likely caused by the combined effects of cloud-radiation and snow and ice albedo feedbacks. Also, Revadekar *et al*. (2013) reported temperature extremes over South Asian high-altitude sites appear to be more influenced by local factors and other factors, such as changes in free atmosphere and effects of urbanization (Pepin and Lundquist, 2008).

3.9. *Seasonal temperature trends and Mann-Kendall trend test for individual stations*

The mean annual surface air temperature trend sheds light on annual average as was described earlier for different altitudinal zones, and mean seasonal trends give more comprehensive ideas on seasonal basis that has been presented in Table 3. The results suggest that warming rates in different seasons and different physiographic zones have no distinct relationship but rather complex situation is evident. To assess the temperature variability the analysis is carried out using simple linear regression model and Mann-Kendall. The results suggest that there is a statistically significant positive linear trend in mean annual temperature at 5% level and a negative linear trend in Dadeldhura station (varying from -0.067 to 0.074 °C/year) with exception of Simra, Tarahara and Dipayal stations for individual stations which does not have significant trend as shown in Table 4. Robert *et al.* (1990) assessed increasing summertime mean temperature in relation to changes in the extreme maximum temperature and minimum temperature. Generally, rising mean temperature are associated with substantial changes in the occurrence of extreme minimum temperature (e.g., fewer days of extreme low minimum temperatures and more days of extreme high minimum temperatures). However, while the rising mean temperature strongly influence the occurrence of moderately high maximum temperatures, they are weakly associated with occurrence of extreme maximum temperature.

4. Discussion

A relationship between annual mean temperature and elevation has been established (Fig. 2) based on the linear regression method. The high and consistency of the correlation coefficients obtained for eastern region of Nepal (R^2: 0.99) and all over Nepal (R^2: 0.99) suggest that inverse linear relationship between temperature and elevation is applicable regardless of the fact that stations are spread out across a range of topography at different spatial locations.

The following linear equations were obtained:

$$T = 26.21 - 0.0058 \times H \qquad \text{(for eastern Nepal)}$$

$$T = 26.18 - 0.0057 \times H \qquad \text{(for whole Nepal)}$$

where, T is the annual mean air temperature in °C, dependable variable, and H is the altitude in meter, independent variable. These equations are useful to calculate annual mean temperatures at any altitudes of Nepal. The temperature lapse rates obtained in this study (-5.7 °C km^{-1} for whole Nepal and -5.8 °C km^{-1} for eastern region of Nepal) are similar to the lapse rate (-5.2 °C km^{-1}) obtained by previous researchers (Kattel *et al*., 2013). These values are logical as the general tendency of lapse rate is -6.0 °C km^{-1}.

Comparing all the warming rates from different altitudinal zones (Figs. 3-6) of valley floor stations suggest that warming rates increased from Terai to the hills of 2000 m asl (*i.e*., 0.024 to 0.063 °C/year) and beyond this warming rate decreased dramatically towards higher altitudes. The present result is contrary to what was found by previous researchers (Shrestha *et al*., 1999). The hilltop stations showed similar trend with that of valley floor stations; warming rate (0.072 °C/year) at an altitudinal range of 1500 to 2500 m asl is much higher than the warming rate (0.038 °C/year) found at an altitudinal range of 2000 to 2500 m asl. However, warming rate in Trans-Himalayas (Jomsom) obtained in this study (0.03 °C/year) is much lower than the warming rate (0.09 °C/year) found by previous researchers (Jianchu *et al*., 2007). Although absolute values of the temperature at each station within each altitudinal range is different, the cyclic and consistent patterns of the temperature curves indicate the reliability of the data used in this study.

In most of the previous studies, stations were considered up to 3800 meters and beyond that altitude the data seemed extrapolated by different models. This study considers real data recorded at stations up to 5050 m asl, and also tested the climatic patterns in the eastern Region of Nepal from the lower altitude, such as Biratnagar, 72 m asl to Lobuche, 5050 m asl.

Interestingly, in all the stations an abrupt change in temperatures (sudden drop of temperature in 1997 and increased beyond that) appeared, as was also found by previous researchers (Kattel and Yao, 2013). The possible causes of such regime shift is not well understood.

The Terai Region shows much lower (0.024 °C) increment of annual temperature. Terai has much cooler climate due to fog persistent during the winter months. The dense and a long elongated fog has been persisting from northern India to Bangladesh passing through a low regions of Nepal and the temperature used to drop even up to 12 °C. According to personal observations and collection of data (unpublished) from one of the authors, those types of dense fog was noticed for the first time in 1983 and then 1993, and later frequently appeared almost every year. These may be one of the reasons that the temperature increment in the Terai Region is much lower than the national average.

The Hills shows exceptionally high warming (reaches up to 0.11 °C) and this is very interesting and alarming. Hills have been experiencing very high temperature changes than the national average. The high rate of warming in the hills is probably due to highest rate of forest degradation (2.3% per year) in the hills than the low altitude region including Terai, coupled with effect of urbanization in the hills (for example, urban area coverage in hilly regions was 3% in 1981 and later in 2001, coverage reached 20%) (CBS, 2008; Kattel and Yao, 2013). The stations in the valley floor have moderate increment such as 0.07 °C to 0.08 °C.

In this study, all the temperature trends demonstrate accelerated warming during the last one and a half decades, and this is attributed to the increasing greenhouse gases in the lower troposphere (IPCC, 2007).

5. Conclusions

Spatial (altitude-dependent) and temporal (monthly, seasonal and annual) variation of air temperature is caused by several factors such as, physiography (*i.e.*, slope, aspect, hill tops and valley), characteristics of the land cover, incoming solar radiation etc. So the warming observed in almost all the stations considered for this study must be influenced by several multiple factors. Quantification of the contribution of each factor is complicated and beyond the scope of this paper. The main conclusions are drawn as follows:

(*i*) The inverse linear relationship between temperature and elevation (temperature lapse rate) is valid independent of spatial locations of the stations. The temperature lapse rates obtained in a wide altitudinal range of Nepal (70 to 5050 m asl) are -5.7 °C km^{-1} for whole Nepal and -5.8 °C km^{-1} for eastern region of Nepal.

(*ii*) In the valley floor stations, warming rate increased from Terai to the hills of 2000 m asl (*i.e*., 0.024 to 0.063 °C/year) and beyond this warming rate decreased dramatically towards higher altitudes. The hills has exceptionally high warming rate (reaches up to 0.11° C/year) and this is very alarming.

(*iii*) In the hilltop stations, warming rate (0.072 °C/year) at an altitudinal range of 1500 to 2500 m asl is much higher than the warming rate (0.038 °C/year) at an altitudinal range of 2000 to 2500 m asl.

(*iv*) Warming rate in Trans-Himalayas (Jomsom) is 0.029 °C/year.

(*v*) In Terai region, increment of annual temperature is much lower (0.024 °C) than the national average.

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