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Future changes over the Himalayas: Maximum and minimum temperature

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ABSTRACT

An assessment of the projection of minimum and maximum air temperature over the Indian Himalayan region (IHR) from the COordinated Regional Climate Downscaling EXperiment- South Asia (hereafter, CORDEX-SA) regional climate model (RCM) experiments have been carried out under two different Representative Concentration Pathway (RCP) scenarios. The major aim of this study is to assess the probable future changes in the minimum and maximum climatology and its long-term trend under different RCPs along with the elevation dependent warming over the IHR. A number of statistical analysis such as changes in mean climatology, long-term spatial trend and probability distribution function are carried out to detect the signals of changes in climate. The study also tries to quantify the uncertainties associated with different model experiments and their ensemble in space, time and for different seasons. The model experiments and their ensemble show prominent cold bias over Himalayas for present climate. However, statistically significant higher warming rate (0.23–0.52 °C/decade) for both minimum and maximum air temperature (T_{min} and T_{max}) is observed for all the seasons under both RCPs. The rate of warming intensifies with the increase in the radiative forcing under a range of greenhouse gas scenarios starting from RCP4.5 to RCP8.5. In addition to this, a wide range of spatial variability and disagreements in the magnitude of trend between different models describes the uncertainty associated with the model projections and scenarios. The projected rate of increase of T_{min} may destabilize the snow formation at the higher altitudes in the northern and western parts of Himalayan region, while rising trend of T_{max} over southern flank may effectively melt more snow cover. Such combined effect of rising trend of T_{min} and T_{max} may pose a potential threat to the glacial deposits. The overall trend of Diurnal temperature range (DTR) portrays increasing trend across entire area with highest magnitude under RCP8.5. This higher rate of increase is imparted from the predominant rise of T_{max} as compared to T_{min}.

1. Introduction

Intergovernmental Panel on Climate Change (IPCC) has reported unambiguous warming of the atmosphere and ocean in the recent past. According to IPCC, this recent warming of the climate system results in the deviation of the mean behavior of various atmospheric parameters such as rainfall and precipitation, which leads to more climate extremes. The recent warming of the climate system might be attributed to the increase in the concentration of the greenhouse gases (hereafter, GHG) through anthropogenic activities (IPCC Assessment Report 5, Stocker et al., 2014). This temperature rise may result in the loss of deposited glacial areas in the high mountainous regions. The Agenda 21 of United Nations Conference on Environment and Development (UNCED, Rio de Janerio, June 1992) on sustainable development for the first time recognized that the mountains are a major component of global environment and also expressed concerns regarding the deteriorating environmental condition over these ecologically sensitive regions. The mountains occupy 25% of the continental area, 26% of world population lives in mountains or in the foothills and they serve 40% of the global population with supply of fresh water (Beniston, 2003). The mountainous region is reported to be more susceptible and vulnerable to the impacts of climate change as compare to the other land features present over the same latitude (Messerli and Ives, 1997). The Himalayas are largest mountain ranges of the world and shared by India, Afghanistan, Kazakhstan, Pakistan, China, Nepal and Bhutan (Palazzi et al., 2013). These are also the youngest, highest and geologically active mountain ranges and are vulnerable to anthropological and natural processes as there are very sensitive to the climate variability and change (Caldwell et al., 2013; Xu, 2005). The Himalayas have third largest glacial deposits after Arctic and Antarctic and are the source of several perennial rivers (Bolch et al., 2012). The melting of ice provides the origin of many perennial rivers and hence termed as 'Water tower of Asia' (Viviroli et al., 2007; Immerzeel et al., 2010). The Himalayan mountain ranges greatly influences the meteorology and

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hydrology of a vast region and hence influencing the lifestyle and economy of a huge population though water resources, goods and services form various ecosystems. To study the climate change over Himalayan region, air temperature is considered as one of the worthy indicator because it precisely describes the energy budget over Earth's surface (Vinnikov et al., 1990; Thapliyal and Kulshrestha, 1991). The air temperature also varies, like precipitation, on a very short distance over the mountainous region (Becker, 1997). So the mountain systems are considered as the most sensitive and key areas for early detection of climate change signal and its consequences on the associated system such as ecology, society and economy (Beniston, 2003). A slightest change in the climate over the Himalayas may lead to disastrous consequences for the people depending on various resources of Himalayas as well as for the people living in downstream areas.

Despite being an ecological sensitive and strategically important region, very less number of scientific studies have been conducted over Himalayan region to understand present climate and future climate projections (Panday et al., 2015). The background information of the present climate over the Himalayan region is very less due to the complex topography and inaccessibility. The setting up and maintenance of meteorological station in such harsh climate is very difficult especially over higher altitudes. Therefore, most of the stations are located in the valley due to the logistic regions thereby under representation of the meteorological variables (Fowler and Archer, 2006; Winiger et al., 2005).There are also uncertainties across different dataset and seasons; which are attributed to the availability of observational data in the high altitudes (Mishra, 2015), different algorithm used in the gridding techniques (Hofstra et al., 2008), very lower station density (Schmidli et al., 2001) and irregular distribution of stations (Haslinger et al., 2013). In order to overcome the problem of understanding the present climate, various climatic processes and future climatic condition on a more regional scale or on a basin level, various new generation climate models are being used. Various Global Climate Models (hereafter, GCMs) have been used for this purpose for impact study, warning system, forecasting and decision making tool (Lobell et al., 2008; Mote et al., 2011). The GCMs are generally of coarser resolution and they have limitation in simulating the climatology over a very small region with complex topography (Kumar et al., 2013). Whereas the Regional Climate Models (hereafter, RCMs) are well known for resolving various fine scale atmospheric processes over complex and heterogeneous topography like Himalayas. The advantages with RCMs are their higher resolution and inclusion of subgrid scale topography, better representation of local climate processes and feedback along with improved physical parameterizations (Giorgi and Bates, 1989; Beniston, 2003; Rummukainen, 2010). The use of GCMs and RCMs have been increasingly popular in studying the issues related to climate change. Therefore, the validation of the model w.r.t. the available observation to get an idea about the quantitative biases and other systematic errors is equally important. Although RCMs are advantageous but still they do not completely resolve the complex local interaction occurring inside mountains due to sophisticated physiography. This limitation is a big setback for the accurate climate projection due to the poor representation of specific climate response over a mountainous region like Himalayas. But, still the use of RCMs is very famous among scientific community and widely used. The reason being they are the best available tools bench tested against observation and to develop a comprehensive process based understanding till date; which is very useful to interpret further implications of future climate change. Few studies using RCMs have been carried over complex terrain to understand the climate features (Giorgi et al., 2009; Dimri and Niyogi, 2013; Haslinger et al., 2013, Ghimire et al., 2015, Choudhary and Dimri, 2017, Nengker et al., 2017, Kumar et al., 2018). Most of them show cold bias over mountains (Giorgi et al., 2004; Solman et al., 2008; Maharana and Dimri, 2014) attributed to overestimation of precipitation in the model environment linked to snow cover, moisture and evaporation feedbacks (Haslinger et al., 2013). Akhtar et al. (2009) revealed that the cold bias in RCM comes from the GCM forcings and is more prominent over the higher elevation.

The climate change studies exclusively over the Himalayas reported a consistent warming in the present climate (Liu and Chen, 2000; Shrestha et al., 1999; Dimri and Dash, 2012) with rate of warming much higher than the global average of 0.4 °C (Solomon, 2007). The reported rate of warming over Nepal is 0.6 °C/decade during 1977–2002 (Shrestha and Aryal, 2011); 0.6 °C/100 year during 1901–2002 over the eastern Himalaya, Tibetan plateau and Brahmaputra basin with largest increase during spring season (Immerzeel, 2008); 0.2 °C/decade during 1971–2005 over northeast India (Dash et al., 2012); over warming of 1.6 °C across the north-western Himalayan region during last century (Bhutiyani et al., 2007). In addition, Dimri and Dash (2012) found a significant warming trend of 0.23–0.43 °C/decade over western Himalayas; a significant decadal warming rate of 0.16 and 0.17 °C is also found over northwestern Himalayasfor annual and winter temperature; while a warming rate of 0.27–0.54 °C/decade is reported over Pakistan Himalayas (Fowler and Archer, 2005) and Hindukush Himalayan region and Tibetan plateau (Qing-Long et al., 2017). Furthermore, a significant increasing trends of T_{min} and T_{max} are also reported over Hindukush Himalayan region (Ren, 2017).

Few studies have been dedicated to assess the climate models for the future projections over Himalayas (Panday et al., 2015). The GCM outputs from Coupled Model Intercomparison Project phase 3 (CMIP3) and phase 5 (CMIP5) are analyzed and estimated a projected temperature rise of 2.5–4 °C and 2.8–4.5 °C over eastern and western Himalayan region respectively by the end of 21st century. The CMIP3 models examined over Tibetan plateau suggested a rising temperature trend and the rise of mean temperature which varies from 1.2–7.4 °C across different models (Hao et al., 2013). Rajbhandari et al. (2015) used dynamical downscaling technique and reported significantly higher warming in the projected climate over upper Indus basin as compared to the lower basin parts. Although the present climate shows, significant cold bias over upper Indus basin, the projected increase in the mean temperature ranges from 0.5–2.0 °C under RCP4.5 and 2.2–5.8 °C under RCP8.5 between 2006 and 2100. Also, Dash et al. (2014) found a rise 0.64–5.15 °C in the mean annual temperature over eastern Himalayas by the end of 21st century.

In addition to all, few more studies are dedicated to the seasonal response of the warming over Himalayas. Literature shows the wintertime (December–February) warming rate is much higher as compared to other seasons across most part of the Himalayas, such as over northwest Himalayan region, Chinese Himalayas, Indian and Nepal Himalayas (Bhutiyani et al., 2007; Shrestha and Devkota, 2010; Shrestha et al., 1999). The wintertime highest warming trend of maximum temperature (T_{max}) is reported over western Himalayan region during 1975–2006 (Dimri and Dash, 2012; Ren et al., 2017). During the same period, pre-monsoon cooling was also found over the same region (Yadav et al., 2004). Another study reported a contrasting result of rising temperature trend during pre-monsoon (Gautam et al., 2009). The contrasting results is due to the limitation of the model to resolve the atmospheric processes occurring in these difficult terrains and also is a motivation to carry forward the analysis to improve our knowledge over this ecologically sensitive regions. All seasons except monsoon show increasing trend of mean temperature over lower Indus basin (Singh et al., 2008); an increase of 0.5 °C during non-monsoonal seasons over Bhutan Himalaya during 1985–2002 (Tse-ring et al., 2012) is reported along with winter warming trend over upper Indus basin (Fowler and Archer, 2005; Khattak et al., 2011). Similar increasing temperature trend over Tibetan plateau w.r.t. seasons have been reported in several previous studies (Du et al., 2004; Liu and Chen, 2000; You et al., 2008).

Besides the seasonal variation in warming trend, the regions with complex topography also show a kind of unique trait of elevation dependent warming which is more significant over tropical region