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To study elevation dependent warming over complex terrain of the Uttarakhand Himalaya through regional climate simulation using WRF

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Abstract:-

The Himalayas are most vulnerable to climate change and its impacts over the surroundings. But the progress and interpretation on this subject was limited due to the paucity of the observations. The study on altitude dependent warming/cooling is the quintessential part to resolve the controls of mountain climate change. This study examines mechanism for elevation dependent warming over the Uttarakhand Himalaya using recently available regional model simulations (1975–2049). The primary objective of this study is to understand the mechanism behind elevation dependent warming in future climatic projections over Himalayan region and to investigate its seasonal response.

Introduction:-

Mountains and highland regions are among the most vulnerable areas to climate change and to its impacts over their surroundings (Xu et al. 2009). Barry (1992) discussed on pronounced amplitude of climate variability and change at various scales in several mountainous regions across the globe and the study limitations that exist therein which are associated with scarcity of observations and lack of theoretical understanding of physical processes related with mountain climate. Using station observations over various mountain ranges, Diaz and Bradley (1997) provided a comprehensive survey of differential temperature changes with altitude and found strong evidences of high altitude warming in parts of Asia and Europe. Liu and Chen (2000) illustrated elevation dependent warming, i.e., significant amplification of warming rates with elevation, analysing temporal trends of temperature measured at 197 in situ stations over the Tibetan Plateau. Thompson et al. (2003) showed elevation dependency in millennium scale temperature trend record from Tibet. Similar studies over the Alps (Giorgi et al. 1997) and the Rocky Mountains (Fyfe and Flato 1999; Snyder et al. 2002) were carried out. Nogues-Bravo et al. (2007) using 5 AOGCMs to simulate future climate under IPCC scenarios for major mountain regions did not find any consistent difference in warming between the high elevations and low-lying areas at the same corresponding latitudinal belt. In a study based on 1000 high elevation stations across the globe, Pepin and Lundquist (2008) found no globally concurrent relationships between warming rates and elevation. However, they found strongest warming trends near 0° isotherm due to snow-ice feedback and also concluded that mountain summits and free draining slopes are better indicators of global warming as they are more exposed to free-air advection. Rangwala et al. (2009) studied the influence of changes in surface specific humidity on down-welling longwave radiation (DLR) which is responsible for pronounced warming during winter season over higher altitudes in

Tibetan Plateau. In their study over high-altitude stations in Alps, Ruckstuhl et al. (2007) noted elevation dependent warming and found it to be related with enhanced DLR at high elevations due to its increased sensitivity to surface water vapour. Liu et al. (2009) reported elevation dependent changes over most of the mountain ranges across the globe, including Tibetan plateau. They have shown it in the instrumentation records and NCAR CCSM3 based future projections in different elevation zones. During winter and spring, warming is more pronounced at higher elevation ranges than over lower elevation ranges with similar tendency in future. Qin et al. (2009) have shown higher warming over 2000 to 4800 m asl in Tibetan Plateau using satellite information of Moderate Resolution Imaging Spectrometer (MODIS). In a study carried out over 10 major mountain ranges across the world, Ohmura (2012) found temperature variability and trend to increase with elevation. He linked this elevation dependent warming to enhanced diabatic processes in the middle to high troposphere as a result of the cloud condensation. Rangwala and Miller (2012) have given a comprehensive review over the global mountain ranges and provided corresponding four mechanisms of warming in details due to (1) snow/ice albedo feedback, (2) cloud cover, (3) water vapour modulation of longwave heating and (4) aerosol impact. Further, using a 1-D radiative transfer model, Rangwala (2013) has shown the possibility of strong modulation of surface DLR caused by increase in atmospheric moisture in high altitudes (>3000 m) during winter which is responsible for winter warming. A review of studies from different mountain regions of the world by Pepin et al. (2015) finds strong and emerging evidence of higher rate of warming over elevated regions, thus leading to impact on the adjacent environment. Based on global climate simulations from CMIP5, Rangwala et al. (2016) have shown that amplified warming during winter season in higher elevation regions of boreal midlatitudes is strongly correlated with elevation dependent increase in water vapour. In another model-based study, carried out by Palazzi et al. (2018), where the GCM- EC-EARTH is applied at different resolutions, it is found that the most significant drivers of elevation dependent warming in different mountain regions across the globe are changes in surface albedo and DLR. However, the same study shows that over Himalayan region an additional key driver is the change in surface specific humidity with elevation. In view of such findings, altitude dependent warming/cooling or climate signal thereof is one of the prime research interests for mountain researchers. The Himalayas are identified as a climate and climate change hot-spot, especially since they host numerous glaciers representing a water source for northern Indian rivers, as well as a hotspot of biodiversity. The progress and interpretation on this subject was limited due to the paucity of the observations. Most of the studies discussed above and others have shown warming over the Tibetan Plateau in the recent decades. There are very few studies which are focused on the Uttarakhand Himalayan region. This region of the Himalayas is much less monitored and plays a crucial role in defining hydro-climatic regime of the Indian sub-continent. Debate on disappearing glacier (Bolch et al. 2012), snow pack and cover, permafrost, acceding snowline, receding treeline etc. in this region is looming large as it can have significant consequences for the hundreds of millions of people living in Indian sub-continent. Keeping these in mind and with few available researches over this region of the Himalayas, this study examines mechanism for elevation dependent warming over the Uttarakhand Himalaya using recently available regional model simulations (1975–2049).

Evidence and mechanism of EDW

Sources of inconstancy between studies in the significance and structure of EDW incorporate the diversity of geographic regions studied (including many different mountain ranges in different climate zones), time periods considered (including different past and future periods), and methodologies applied (including different observational datasets and modeling frameworks). Observational studies of EDW face challenges associated with the lack of climate records over mountainous terrain that are long-term and homogeneous (e.g., devoid of non-climatic artifacts, such as might be caused by changes in measurement practices). These studies show mixed results depending on the region, season, and dataset considered (Pepin et al. 2015). Global station data do not show a simple monotonic increase in warming with elevation (Pepin and Lundquist 2008). While observations appear to show significant EDW over many regions (e.g., Liu et al. 2009; Vuille et al. 2015), results can be highly sensitive to the dataset used. For instance, over the Tibetan Plateau and the U.S. Rocky Mountains, some homogenized datasets, where artifacts associated with changes in measurement practices have been removed, do not reproduce the EDW found in other studies of the same regions (You et al. 2010; Oyler et al. 2015).

Various studies have used RCMs to investigate patterns of climate warming over mountainous terrain, including the Tibetan Plateau (Guo et al. 2016), the European Alps (Giorgi et al. 1997; Kotlarski et al. 2012, 2015), and the mountains of the western United states (Salathé et al. 2008; Rangwala et al. 2012; Letcher and Minder 2015; Minder et al. 2016; Rupp et al. 2017; Walton et al. 2017). All of these RCM studies show evidence of EDW under future climate change, with warming either increasing with elevation or maximizing at mid-elevations.

Investigation area

The study area, Uttarakhand Himalaya is located from 28.5^0 N to 31.5^0 N latitude and 77^0 E to 81^0 E longitudes and comprises an area of 53483 km^2. Uttarakhand Himalaya region is located in Indian Himalayan monsoonal subcontinent and mainly three seasons are present in a year, i.e.warm summer (March to June), humid warm summer (July to June), winter season (November to February). The climatic conditions of the Garhwal Himalayan region vary from the tropical to glacial cover zone. On the basis of temperature, precipitation and altitude, Garhwal Himalaya can be divided into seven different climatic zones from south to north: tropical (< 300 m), subtropical (301-800 m), warm temperate (801-1600 m), cool temperate (1601-2400 m), cold temperate (2401-3200 m), sub-alpine (3201-4000), and glacial cover

Data and Methods

The required regional climate simulations are performed with the Weather Research and Forecasting (WRF) model in the version WRF-ARW 3.7.1 in its non-hydrostatic mode. WRF offers multiple physics schemes for microphysics, cumulus, radiation, planetary boundary layer, and land surface process parameterization. The applied setup uses the following main physical options for all three nests: the WRF Single-Moment 6-class scheme (WSM6) microphysical parametrization, the Grell-Freitas scale-aware scheme for convective parametrization [30], the Noah land surface model, the Yonsei University (YSU) parameterization for the planetary boundary layer, and the RRTMG short-wave and long-wave radiation schemes. This configuration was chosen by evaluating several combinations for the year 2008 and using the ERA-Interim reanalysis as boundary condition (not shown here), closely following Katragkou et al., and Garcia et al. who evaluated multi-physics hindcast ensembles using WRF with a spatial resolution of 0.44°.WRF regional climate simulations considered here are performed within the framework of Coordinated Regional Climate Downscaling Experiment-South Asia (CORDEX-SA) where the necessary forcings are provided by global climate simulations from- MPI-ESM-LR (Giorgetta et al. 2013). CORDEX-SA is a part of larger regional climate modeling initiative called CORDEX (Giorgi et al. 2009) which is coordinated by World Climate Research Programme. The horizontal resolution of the model simulation in the present study is 0.44° (approximately 50 km). The study period considered here is 1975–2049 to assess the long-term changes in climate over the study region beginning from the recent past. Here, the regional climate data for the period 1975–2005 is obtained by GCM forcings under historical emissions whereas that for the period 2006–2049 is obtained by GCM forcings under projected emissions based on the representative concentration pathway RCP2.6 scenario. The RCP2.6 was formulated by the modeling team- IMAGE from Environmental Assessment Agency of Netherlands. This emission pathway represents the trajectory of achieving the least greenhouse gas concentration levels in future through a stringent climate policy (Van Vuuren et al. 2011). Under this mitigation scenario, the radiative forcing level first rises up to a value of around 3.1 W/m2 by mid-century, and then comes down to 2.6 W/m2 by 2100 (Van Vuuren et al. 2006). A single pathway RCP2.6 is chosen here to see specifically how Himalayan region, which is considered to be sensitive to even a small scale change in the global climate, responds to the most conservative of all emission scenarios. First, the long-term linear trend (1975–2049) of near surface mean air temperature and its altitudinal distribution over Himalayan region is examined for identifying signals of elevation dependency of warming rate. This is done for four seasons- December–January–February (DJF), March–April–May (MAM), June– July–August–September (JJAS) and October–November (ON) to assess the seasonal response of elevation dependent warming. Next, to understand the importance of different climatic drivers in contributing to this elevation dependent warming, long-term trends in other variables for the same period and RCP scenario are studied with respect to its elevation dependent response. These variables are- DLR, total cloud fraction, total soil moisture, near surface specific humidity and surface snow melt along with surface albedo as an indirect measure of snow cover. The surface albedo is calculated here as the ratio (in %) of reflected to incident shortwave radiation. Further, the elevation dependency of the sensitivity of warming rate to that of moisture is examined. For this purpose, the ratio of the trend of temperature with that of near-surface specific humidity is studied with respect to its altitudinal distribution.

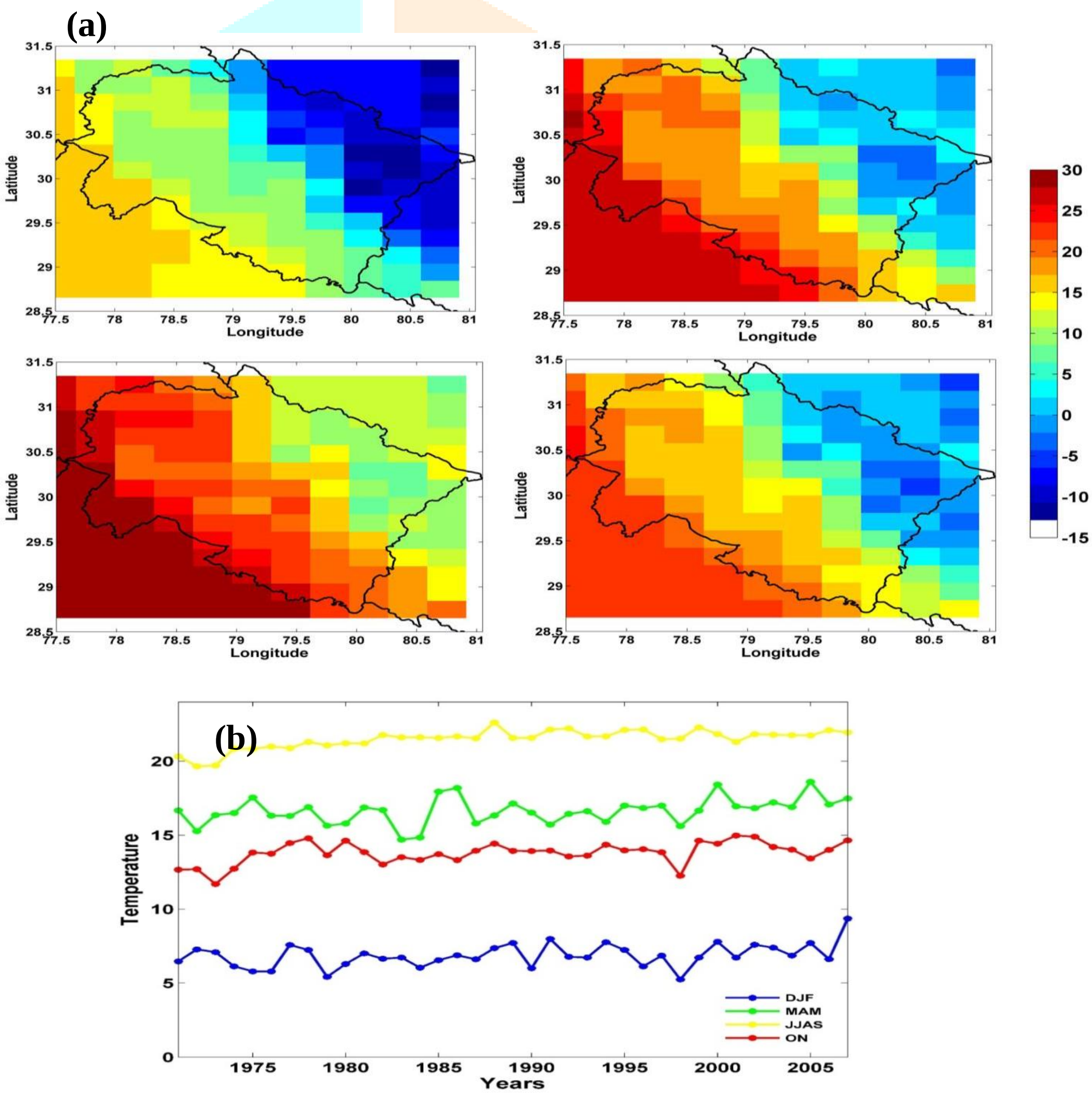


Fig. 1. *Average seasonal temperature for Uttarakhand.* **(a)** *seasonal average of DJF, MAM, JJAS & ON.* **(b)** *seasonal temperature trend for 1975-2005.*

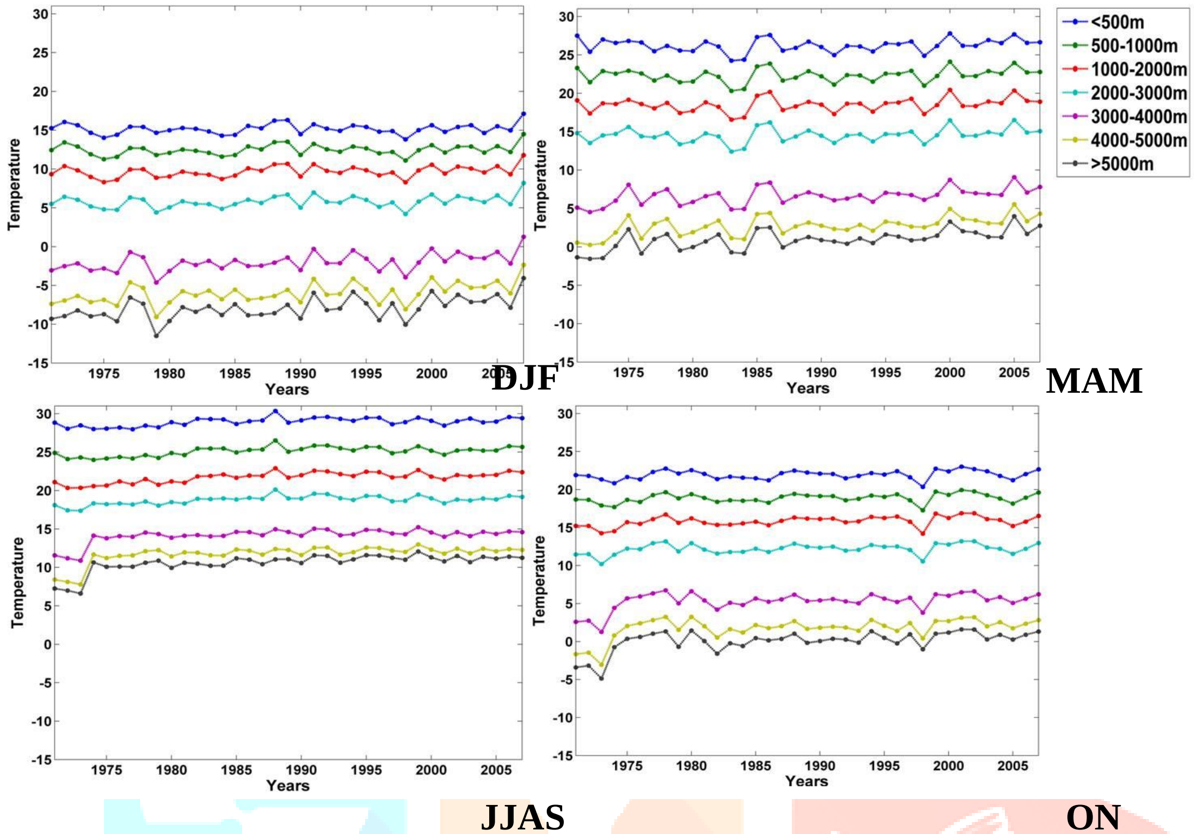
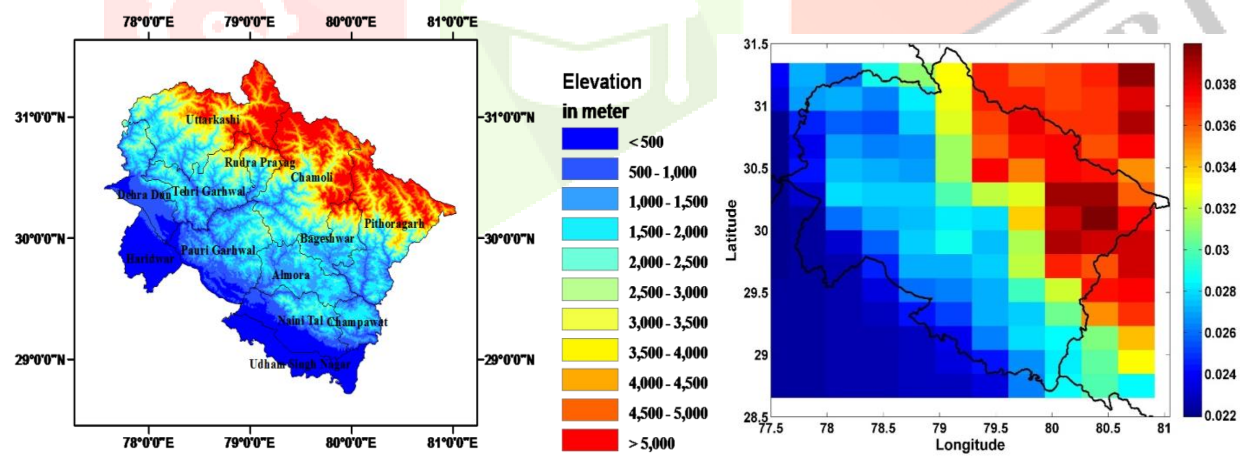


Fig.2. *Variation of mean seasonal (DJF, MAM, JJAS & ON) temperature along different elevation belts of Uttarakhand from 1975-2005 periods.*



(c)

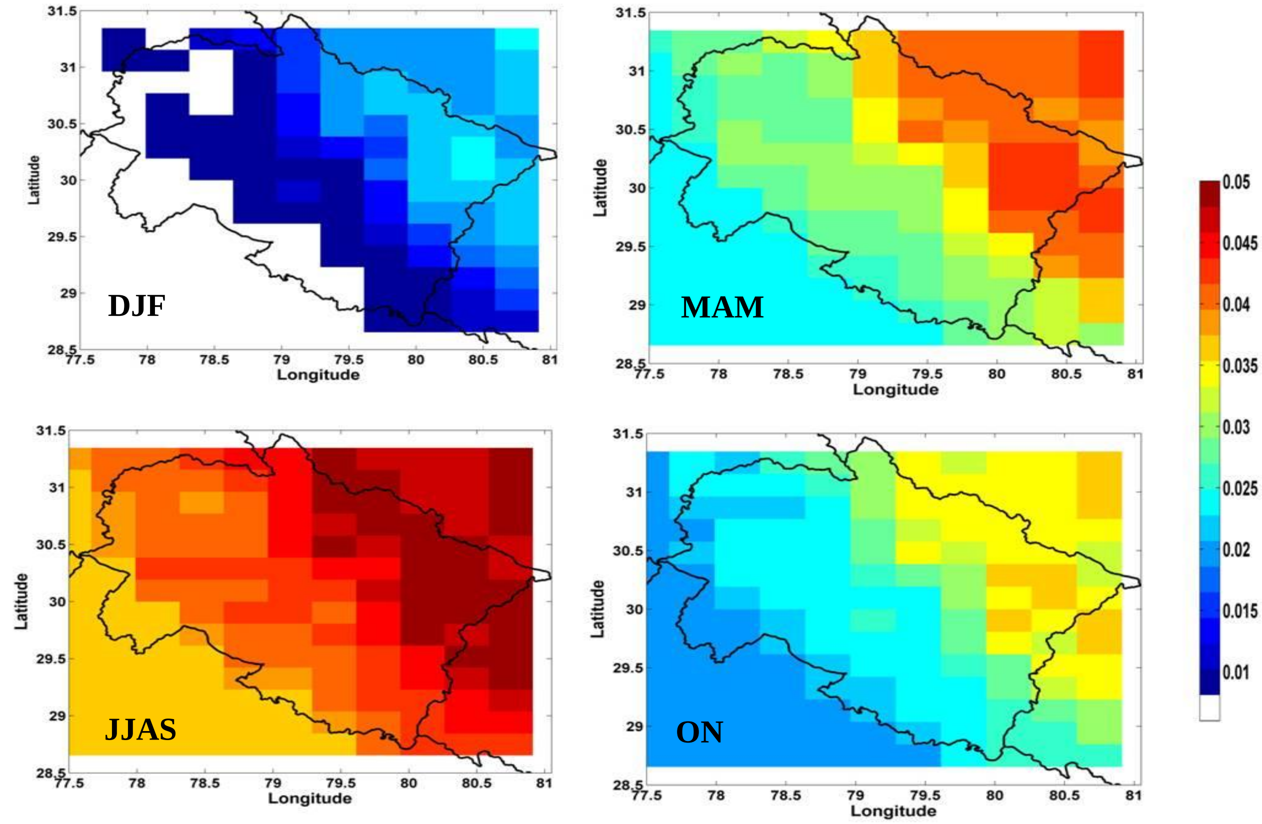
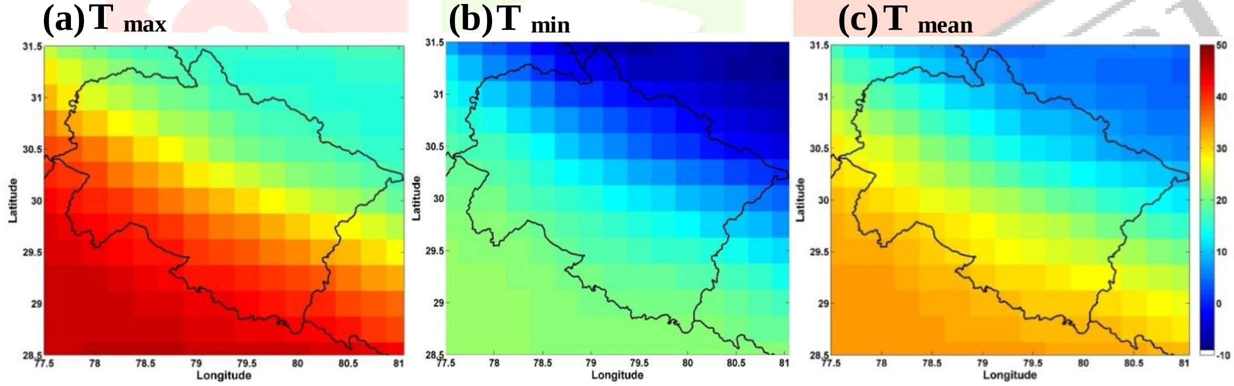
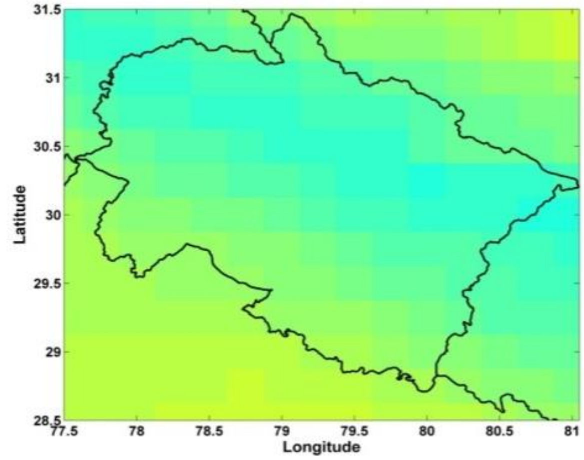


Fig. 3. (a) *Elevation map of Uttarakhand. Color schemes indicates elevation in meters.* **(b)** *shows average rate of change of temperature along elevation. Color bar indicates rate of temperature in °C/decade.* **(c)** *Seasonal rate of change of temperature for DJF, MAM, JJAS & ON. Color bar represents rate of change of temperature in °C/decade.*

(a) T_{max} **(b)** T_{min} **(c)** T_{mean}



(d) T_{DTR}



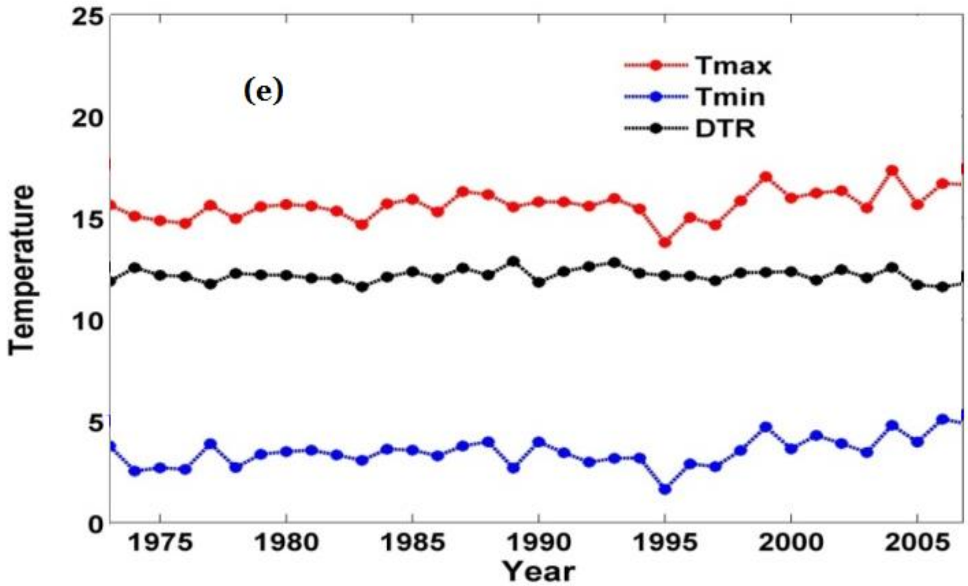


Fig. 4. *Temperature pattern of Uttarakhand.* **a), b), c), d)** *shows maximum, minimum, mean temperature & DTR respectively.* **(e)** *shows long term trend of maximum, minimum temperature and DTR from 1975-2005.*

Discussion

The present study analyzes a high-resolution long-term climate simulation of climate over Uttarakhand Himalaya to study elevation-dependent warming and its mechanisms over the region. Results indicate that enhanced increase in DLR flux at the higher elevation surface during winter is primarily responsible for high altitude warming amplification. Possible coupling between multiple land-atmosphere feedbacks could explain the magnitude and peculiar pattern of DLR variation during this season characterized by trend amplification above a certain altitude. The primary feedback which is responsible for higher trend of DLR beyond a certain altitude is the humidity- surface DLR feedback which is a significant player during winter season. However, the decrease in the rate of change of snow melt and dependent increase in that of surface albedo beyond 3000 m could subdue the DLR-moisture positive feedback effect on surface heating. On the other hand, there are counter acting mechanisms existing to this process. The reduction in cloud fraction trend values above 3000 m favors the enhancement in net solar radiation received at the surface, with further increase in snow melt/decrease in snow depth thus leading to the reduced surface albedo. This further allows the absorption of solar radiation at higher elevations implying more storage of heat at the higher elevation surface and thereby amplifying the temperature. Although the increase in DLR with increase in specific humidity occurs globally, the sensitivity of former to latter follows a non-linear relationship and is particularly high when the humidity levels are low which exists typically at high elevations during winter. In other words, the drier the atmosphere, magnified will be the impact of even smaller changes in humidity on the DLR. Changes in DLR are more sensitive to changes in humidity when the latter is less than 2.5 g/kg i.e. when the atmosphere is dry a condition which is more prevalent during winter in the elevated regions. Instead, this phenomenon does not occur during summer season since, as background humidity values are already very high, the sensitivity of surface DLR to any further increase of atmospheric moisture is much less. Also, as shown in the present study the sensitivity of longwave radiation to surface air humidity increases with altitude above a certain threshold (3000 m) corroborating the results found by Ruckstuhl et al. (2007). This means that, the same amount of changes in the surface air humidity will cause higher amount of changes in DLR at higher elevation sites in comparison to the lower elevation locations (Rangwala 2013). Increased DLR at the surface in higher elevations or above a critical altitude plays significant role in elevation dependent warming during winter through coupled feedbacks of moisture, cloud and snow cover with radiation. Since the simulation used in this study did not include any aerosol component, the role of this variable in influencing high elevation temperature changes could not be assessed. Incorporating aerosol feedbacks in climate model would imply nesting an aerosol component through parametrization of the related forcings or processes. Further, to properly represent the relevant mechanisms and provide a more realistic simulation of the changes in the cryosphere system of high elevation regions an interactive snow/glacier model feedback into a high-resolution regional climate model is required. There is also a need for increasing climate monitoring programmes at high elevation regions with greater number of climatic variables. This will aid in better understanding of present trends and processes that are affecting the climate and microclimate of Uttarakhand Himalaya as well as for validating the model generated information.

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