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# Mid-21st century projections of hydroclimate in Western Himalayas and Satluj River basin

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A B S T R A C T

The Himalayan climate system is sensitive to global warming and climate change. Regional hydrology and the downstream water flow in the rivers of Himalayan origin may change due to variations in snow and glacier melt in the region. This study examines the mid-21st century climate projections over western Himalayas from the Coupled Model Intercomparison Project Phase 5 (CMIP5) global climate models under Representative Concentration Pathways (RCP) scenarios (RCP4.5 and RCP8.5). All the global climate models used in the present analysis indicate that the study region would be warmer by mid-century. The temperature trends from all the models studied here are statistically significant at 95% confidence interval. Multi-model ensemble spreads show that there are large differences among the models in their projections of future climate with spread in temperature ranging from about 1.5 °C to 5 °C over various areas of western Himalayas in all the seasons. Spread in precipitation projections lies between 0.3 and 1 mm/day in all the seasons. Major shift in the timing of evaporation maxima and minima is noticed. The GFDL_ESM2G model products have been downscaled to Satluj River basin using the weather research and forecast (WRF) model and impact of climate change on streamflow has been studied. The reduction of precipitation during JJAS is expected to be > 3–6 mm/day in RCP8.5 as compared to present climate. It is expected that precipitation amount shall increase over Satluj basin in future (mid-21st century) The soil and water assessment tool (SWAT) model has been used to simulate the Satluj streamflow for the present and future climate using GFDL_ESM2G precipitation and temperature data as well as the WRF model downscaled data. The computations using the global model data show that total annual discharge from Satluj will be less in future than that in present climate, especially in peak discharge season (JJAS). The SWAT model with downscaled output indicates that during winter and spring, more discharge shall occur in future (RCP8.5) in Satluj River.

## 1. Introduction

It has been well documented that climate change is expected to have a strong impact on water resources, especially in mountain regions (Buytaert, 2012). In a regional scale, some of the noticeable impact would be rapid melting and reduction of glaciers leading to the increased magnitude of surface runoff (Beniston, 2003; Nogués-Bravo et al., 2007). The impact of climate change would be even more in the Himalayas where the rise in temperature, which is higher than the global average, has a significant effect on the cryosphere (Eriksson et al., 2009; IPCC, 2013). Several impact studies under climate change scenarios (Representative Concentration Pathways, RCPs) have been carried out over rivers basins located in different countries using outputs from the models of the Coupled Model Intercomparison Project Phase 5 (CMIP5 as well as other climate models (e.g. Christensen et al., 2004, Gosain et al., 2006 and Elshamy et al., 2009)).

Many studies have documented the impact of climate change over the Indian subcontinent considering temperature and precipitation projections (Chaturvedi et al., 2012; Pattnayak et al., 2013; Dash et al., 2014). Chaturvedi et al. (2012) noted that temperatures will increase from of 2 °C (RCP2.6) to 4.8 °C (RCP8.5) over India from 1880s to 2080s. It is projected that the all-India precipitation will increase by 6% to 14% under various RCP scenarios from the base climate. Sengupta and Rajeevan (2013) have examined the CMIP5 simulated results over the Indian region in detail and have ranked these models in terms of skill of precipitation and temperature simulations. Pattnayak et al. (2017) have examined output from several CMIP5 global models and concluded that the signals of rate of increase or decrease in precipitation and temperature over the countries nearing the Bay of Bengal are stronger in RCP8.5 than that in RCP4.5. However, no such studies exist

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**Table 1**
List of CMIP5 climate models used in this study.

| Models | Modelling centre/group | Resolution (Lat × Lon) | Simulation period | Reference |
|---|---|---|---|---|
| GFDL_ESM2G | NOAA Geophysical Fluid Dynamics Laboratory, USA | 2.0° × 2.5° | 2001–2060 | Dunne et al. (2013) |
| GFDL_ESM2M | NOAA Geophysical Fluid Dynamics Laboratory, USA | 2.0° × 2.5° | 2001–2060 | Dunne et al. (2013) |
| GISS_E2_H | NASA Goddard Institute for Space Studies, USA | 2.0° × 2.5° | 2001–2060 | Schmidt et al. (2014) |
| HadGEM2_AO | Met Office, Hadley Centre, UK | 1.25° × 1.875° | 2001–2060 | Martin et al. (2011) |
| HadGEM2_CC | Met Office, Hadley Centre, UK | 1.25° × 1.875° | 2001–2060 | Martin et al. (2011) |
| HadGEM2_ES | Met Office, Hadley Centre, UK | 1.25° × 1.875° | 2001–2060 | Collins et al. (2011) |
| MIROC_ESM | JAMSTEC, AORI and NIES, Japan | 2.81° × 2.81° | 2001–2060 | Watanabe et al. (2011) |

for the western Himalayan region.

Very little work has been carried out in India on the impact of climate change on hydrology (Divya and Mehrotra, 1995). The major river systems of the Indian subcontinent, which originate in the Himalayas, are expected to be more vulnerable to climate change because of the substantial contribution from snow and glaciers into these river systems (Nogués-Bravo et al., 2007). Snow in the Himalayan region is often close to its melting point. Therefore, any minor changes in temperature would affect snowmelt process rapidly. Due to global warming in the future, regions experiencing snowfall will increasingly experience precipitation in the form of rain. Beniston (2003) has noted that for every °C increase in temperature, the snowline will rise by about 150 m. It is also seen that shifts in snow-pack duration and amount due to sustained climate change will crucially affect water availability. The temperature rise and associated reduction of precipitation in recent few decades in the western Himalayan region have been studied by Bhutiyani et al. (2007, 2010). The hydrological response of these changes indicates reduction of stream flow in most of the western Himalayan Rivers (Thayyen and Gergan, 2010; Bhutiyani et al., 2008). Singh and Bengtsson (2004) have studied the impact of climate on melt and evaporation for the rain-fed, snow-fed and glacier-fed basins in the Himalayan region and suggested that snow-fed basins are more sensitive in terms of reduction in water availability in a warming climate. Immerzeel et al. (2013) have found that contrary to the climate response during the past three decades, the CMIP5 climate models predict increase in precipitation over many of the river basins in the western Himalayas which would lead to increased streamflow through the current century. In a warmer world, a shift in peak river runoff to winter and early spring is expected (Barnett et al., 2005).

Satluj is one of the important rivers for the Indian subcontinent with its origin in Himalayas. The river discharge depends on snowmelt as well as rainfall runoff. Singh and Kumar (1997) have investigated the effect of climate change on the snow water equivalent, snow/glacier melt runoff total streamflow and their distribution for the Spiti River, tributaries of the Saluj River. Tiwari et al. (2015, 2016a) have made a detailed examination of interannual variability of snowfall, snow accumulation and snowmelt in Satluj river basin.

Limitations of the global climate models in resolving physical processes such as cloud/convection and land-surface processes in local to regional scales become far more important especially in regions with topography such as the Himalayas (Wilby et al., 2004, Randall et al., 2007 and Fowler et al., 2007) and have described how the coarse resolution GCMs are insufficient for detailed assessment of climate change impacts at local or regional scales. Several downscaling methodologies have been developed to represent the sharp physiographic features of mountain areas in regional climate models (Tiwari et al., 2016b; Tiwari et al., 2017a).

From the foregoing discussion, it is found that no detailed study on the projected climate for the future has been undertaken so far for the western Himalayan region. The results of global climate models have not been downscaled to river basin scale. Moreover, snowmelt runoff models and the future climate data have not yet been used for Satluj River. Therefore, the main objective of the present work is to reduce these knowledge gaps. Mid-21st century projections of seven CMIP5 models have been examined for the western Himalayan region. Products of one GCM have been downscaled using the Weather Research and Forecast (WRF) model and simulated products have been used to force a snowmelt runoff model (Soil and Water Assessment Tool, SWAT) to simulate discharge of Satluj River in mid-21st century. The models, data used, analysis methodology as well as downscaling experiments are presented in Section 2. The global model results are provided in Section 3. The results from downscaling runs are described in Section 4. Section 5 has the application of projected hydroclimate data on the streamflow projections in Satluj River. The study is concluded in Section 6.

## 2. Data, model and methodology

### 2.1. Data used

Among the available CMIP5 model simulations, seven models have been chosen to analyze the present-day (historical) and projected climate in RCP 4.5 and 8.5. Moss and Edmonds (2010) have assigned priority to the RCPs. The highest emission scenario RCP8.5 is the first priority and the scenario with stabilization without overshoot i.e. RCP4.5 is the second priority. Thus, these two scenarios have been selected for this study. The climate models used in this study are listed in Table 1, together with their host institutions, and their abbreviations as used in this study. Availability of the model projections for dynamic downscaling has been one of the criteria for selecting the models for the present study. Data compiled by Climate Research Unit (CRU) of East Anglia, UK have been used for observations. CRU surface temperature (Ts) and precipitation at 0.5° × 0.5° (Harris et al., 2014) for the period 1901 to 2012 are used in the present study. Observing stations in the inaccessible area of western Himalayas are few. Although, in recent years, few high-quality observing stations have been setup, the observational information provided by station data in this area remains extremely uneven and nonhomogeneous. Harris et al. (2014) and references there-in, have described various data sources used in preparing the CRU data. New et al. (2000) have provided the distribution of temperature and precipitation stations used in its preparation. It may be noted that in the study region, at least 5 number of stations exist in a 5° × 5°°grid box for temperature (Jones et al., 2012). Mitchel and Jones (2005) have described the elaborate procedure for homogenization of data and merging the data from various sources. New et al. (2001) has reviewed the existing precipitation data sets and analysed the information about precipitation trends and variability on a global perspective. Precipitation stations in the study region are more, however, the rain gauge network covers mainly valleys and lowland areas. This may lead to a bias toward the lower elevations in the observations. The APHRODITE temperature data are available only for the period of 1973–2007. Observing station data from India Meteorological Department (IMD) are only available for the region within the Indian boundary. Palazzi et al. (2013) have compared precipitation in the Hindu-Kush Karakoram Himalaya from various sources. Therefore, while, the CRU data for temperature and precipitation have been