Sub-regional scale process changes in the Western Himalayas

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Introduction

• Indus: a large river basin consisting of four countries China, Afghanistan, Pakistan and India with an apportioning an area of 1.1 million Km$^2$.

• High population density, thus important in terms of water resource as well as the livelihoods of a large population.

• Highly vulnerable to effects of climate change, being the water dependent socio-economic structure (Rees and Collins 2006; Immerzeel et al. 2009, 2010; Briscoe 2010).

• Greater warming in the projected climate (A1B scenario) in upper Indus basin in comparison to lower basin during wintertime (DJF) (Rajbhandari et al. 2015).

• Statistically significant increases in the winter mean and maximum temperatures have been reported from stations in the upper Indus basin (Fowler and Archer, 2005).
Himalayan Region
Observed (left) and CORDEX-SA experiment (right) JJAS precipitation (mm/day) climatology during 1970-2005 over the Himalayan region.
Altitudinal variation of summer monsoon mean precipitation for 1970-2005

(Left) Variation in the observed precipitation (mm/day) with elevation for the period (1970-2005) (Ghimire et al. 2015, *Climate Dynamics*) and (right) Distribution of trend (mm/day/year) with elevation for the same.
JJAS mean precipitation (mm/day) for the 130 year period (1970-2099) averaged over Himalayan region from Ensembles from CORDEX-SA Experiment for a) RCP2.6 b) RCP4.5 and c) RCP8.5. Red line represents the yearly values of the ensemble, the error bars represent ensemble mean ±1 standard deviation and the grey shading shows the minimum and maximum values over all ensemble members. The yearly values of observation (APHRODITE) are shown in black. Brown line represents the linear trend (as Theil-Sen slope) in seasonal mean precipitation. The dashed horizontal black lines represent mean ± one standard deviation for each experiment and their ensemble for the present climate period 1970-2005, which shows the range of baseline variability. ‘z’ is the Man-Kendall statistic for test of significance of trend at α=0.05 where n.s., ‘*’, ‘**’ and ‘***’ implies non-significant, poorly significant (P ≤ 0.05), moderately significant (P ≤ 0.01) and strongly significant (P ≤ 0.001) respectively. ‘s.s’ is the Theil-Sen slope parameter.
Observed seasonal temperature (°C) climatology during 1970-2005 over the Himalayas
Temperature Bias (°C) between model and the observation
Trends of (a) DJF (b) MAM (c) JJAS and (b) ON mean surface temperature (°C/yr) over the period 1970-2099 under RCP2.6 as simulated from REMO model under CORDEX-SA experiment.
Trends of (a) DJF [a-e] (b) MAM [f-j] (c) JJAS [k-o] and (b) ON [p-t] mean surface temperature (°C/yr) over the period 1970-2099 under RCP4.5 as simulated from CORDEX-SA experiments and their respective ensembles, except for LMDZ-IITM_REGCM4 experiment, for which the period is 1970-2060.
Trends of (a) DJF [a-c] (b) MAM [d-f] (c) JJAS [kg-i] and (b) ON [j-l] mean surface temperature (°C/yr) over the period 1970-2099 under RCP8.5 as simulated from CORDEX-SA experiments and their respective ensembles.
Near mean surface air temperature (mm/day) for the 130 year period (1970-2099) averaged over Himalayan region from Ensembles of CORDEX-SA Experiment for RCP4.5 for a) DJF b) MAM c) JJAS and d) ON seasons. Red line represents the yearly values of the ensemble, the error bars represent ensemble mean ±1 standard deviation and the grey shading shows the minimum and maximum values over all ensemble members. The yearly values of observation (APHROTEMP) are shown in light blue with dark blue representing mean ±1 standard deviation. Brown line represents the linear trend (as Theil-Sen slope) in seasonal mean temperature. The dashed horizontal black lines represent mean ± one standard deviation for each experiment and their ensemble for the present climate period 1970-2005, which shows the range of baseline variability. ‘z’ is the Man-Kendall statistic for test of significance of trend at α=0.05 where n.s., ‘*’, ‘**’ and ‘***’ implies non-significant, poorly significant (P ≤ 0.05), moderately significant (P ≤ 0.01) and strongly significant (P ≤ 0.001) respectively. ‘s.s’ is the Theil-Sen slope parameter.
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Karakoram Region
Study Area

Topography (m) over Indus Basin (as per Rajbhandari et al. 2015)
Changes in surface air temperature (°C)  
A). Near future (2020-49) minus Present (1970-2005) and 
B). Far Future (2070-2099) minus present for **RCP2.6** over Indus Basin from REMO regional 
model forced with MPI-ESM-LR global model for DJF (December, January February) season (a), 
MAM (March, April, May) season (b), JJAS (June, July, August, September) season (c) and for ON 
(October, November) season (d).
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Time series of near surface air temperature (°C) averaged over the Indus basin for the period 1970-2099 for DJF (December, January February) season (a), MAM (March, April, May) season (b), JJAS (June, July, August, September) season (c) and for ON (October, November ) season (d) from REMO regional model forced with MPI-ESM-LR global model. The series in grey, green, dark blue and red corresponds to Present, RCP2.6, RCP4.5 and RCP8.5 warming scenarios respectively.
Percentage change in total annual precipitation over Indus Basin from REMO regional model forced with MPI-ESM-LR global model. (A) Near future (2020-49) minus Present (1970-2005) and B) Far Future (2070-2099) minus present (1970-2005) for (a) RCP2.6 (b) RCP4.5 and (c) RCP8.5.
Time series of total annual precipitation (mm) averaged over the Indus basin for the period 1970-2099 from REMO regional model forced with MPI-ESM-LR global model. The series in grey, green, dark blue and red corresponds to Present, RCP2.6, RCP4.5 and RCP8.5 warming scenarios respectively. The dashed grey horizontal lines represent the ±1 standard deviation from present mean climate (1970-2005) to represent the baseline variability.
Conclusions

• In the upper Indus basin the temperature changes are more prominent especially in wintertime under all the future scenarios.

• The magnitude of changes are very high under the strongest warming scenario i.e. RCP8.5.

• In the later half of all the warming scenarios, the rate of warming accelerates considerably in all the respective seasons.

• In far future, the percentage of area facing the decrease in precipitation gradually increases with increased radiative forcing under the various warming scenarios.

• In the strongest warming scenario, the decrease in precipitation in the basin may range up to greater than 30 %.

• In the later half of the 21st century, a decreasing trend in the total annual precipitation is seen under the strongest warming case.