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Research Paper

STUDYING HIMALAYAN SNOW - INDIAN MONSOON RELATIONSHIP BY SOME LULCC SENSITIVITY EXPERIMENTS IN REGCM4.0

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This study re-examines the relationship between Himalayan snow and Indian monsoon and impact of land surface degradation due to depletion of Himalayan glaciers on Indian monsoon precipitation and circulation patterns using land-use land-cover change (LULCC) sensitivity experiments. For performing the sensitivity experiments, simulations are done using Biosphere Atmosphere Transfer land Surface (BATS) scheme coupled regional climate model (RegCM4.0) simulations is done at 0.44° resolution using NNRP2 data as boundary forcings for evolution of meteorological variables. Results from sensitivity experiments (heavy snow and tundra) confirm that precipitation has decreased over whole Indian mainland (significant at 99% level of confidence) but increased over North India, Pakistan, Western Ghats, Arabian Sea and Bay of Bengal. From our analysis though strength of south-westerlies over Arabian Sea and easterlies over Bay of Bengal has increased but reduced mid-tropospheric north–south temperature gradient has actually weakened the Indian summer monsoon rainfall by not allowing the easterlies reach the land regions of Indian subcontinent. Results from second sensitivity experiment (representing land degradation over the Himalayan region) shows that over Indian subcontinent 2 metre-temperature, temperature upto 700 hPa increases. Runoff increases in the arid regions, whereas over Indo-Gangetic plains and east India runoff decreases.

Keywords: ReCM4.0, Indian monsoon rainfall, Himalayan glacier, Land degradation, Runoff

INTRODUCTION

The main source of energy at land surface is the incoming solar radiation but earth absorbs a fraction of it. Snow in the high altitude regions in the tropics (Himalayas) forms a part of the land surface system, substantially affecting the radiative and hydrological properties of the land surface and also interacts with the atmosphere. Hence, in weather models snow is assimilated for better representation of land surface in the model (Pullen *et al*., 2010). The land surface albedo in presence of snow increases from 0.05 - 0.4 (typical for bare soil and vegetation) to 0.9 for pure snow (Nolin and Liang, 2000), which impacts diabatic heating. The Gangotri glacier in the Himalayan is the source of the Ganges river and whereas Brahmaputra river originate from

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Mount Kailash. The recent concern about Himalayan snow / glaciers reported is that over the Indian region they are extremely vulnerable (Zaman et al. 2011, APN CAPaBLE Project: 2005-CRP1CMY-Khan) and is quickly depleting due to anthropogenic activities in the area affecting people at local scale. (http://e360.yale.edu/feature/as_himalayan_glaciers_melt_two_towns_face_ the_fallout/2858/). There are also reports, which says that glaciers in Karakoram Range are mysteriously expanding not receding representing glacial stability (http://www.livescience.com/48256-asia-karakoram-glaciers-stability.html). At present 10% of earth's landmass is covered with snow and out of the polar Artic and Antarctica regions, Himalayan region has the maximum concentration of glaciers (9%) with snow occupying approximately 30%. (www.navdanya.org/climate-change/in-the-himalayas). The major river system of Indian subcontinent originates from Himalayan region, but climate change has everlasting impact on glacial runoff, thus affecting the source of the rivers. As per Chapter 3 of IPCC AR5 report (Source: http://www.ipcc.ch/pdf/assessment-report/ar5/wg2/WGIIAR5-Chap3_FINAL.pdf, Jimeìnez Cisneros 2014) on fresh water resources, the Himalayan glacier mas change in future RCP scenarios are significant (Bolch *et al.,* 2012). In order to study the impacts of climate change on Himalayan glacier melting, we need to predict changes on much finer scales using state-of-art regional climate models, in hindcasting mode. Modeling techniques using the regional Climate Models (RCMs), have the potential to improve the representation of the climate information at higher resolution, important for vulnerability assessment studies and appropriate adaptation measures. Small-scale physical processes that drive the important local surface variables and forecast of these local variables, regional climate modelling for studying the inverse snow monsoon relationship is planned. General circulation models have been used to study inverse snow-monsoon relationship. Hahn and Shukla 1976 initially studied the relationship between Eurasian snow and Indian Summer Monsoon Rainfall (ISMR) using global climate simulations and found negative correlation between them. This was not a new result as paleoclimate studies also indicated reduced monsoon rainfall with more snow and ice (Bryson, 1975). Vernekar et al. 1994, Bamzai and Shukla 1999, Kripalani and Kulkarni, 1999 further used observed datasets suggest strong positive (negative) correlation of East (West) Eurasian snow depth with subsequent ISMR. Yim *et al*. 2010 studies the impact of Eurasian snow cover anomaly on East Asian summer monsoon and concluded that Eurasian snow can be used as a complementary precursor for East Asian summer monsoon rainfall.

Dash *et al*. 2005 studies the effect of remote Eurasian snow (using historical Soviet daily snow depth data) on Indian summer monsoon circulation and precipitation using IITD spectral GCM (Dash *et al*. 2006) at higher resolution T80L18. Shekhar and Dash (2005) used a regional climate model to see the effect of early April Tibetan snow on Indian summer monsoon (ISM) and found that Indian monsoon rainfall has significantly reduced. Mamgain et al, 2010 studied characteristics of Eurasian snow-depth and ISM onset. Dey et al 1983 studied the relationship between ISMR (IMD rainfall data) and Himalayan snow (satellite derived) and found that there is a negative correlation between the two. Further Turner and Slingo (2011) used climatological Sea-

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Surface temperature (SST) forced Hadley Centre model to understand the mechanism that communicates snow anomalies to monsoon rainfall and concluded that monsoon onset delays in the Tibetan heavy snow sensitivity experiment. Lodh 2015, (manuscript submitted to Journal of Hydrology, Elsevier) investigates the effects of Himalayan glaciers depletion along with extensive desertification of the Northwestern provinces (NWP) of India on precipitation and surface fluxes in the Indian summer monsoon regime.

All the above reports and previous studies make it curious to re-examine the relationship between Himalayan snow and Indian monsoon and provide some further insight into the impact of depletion of Himalayan glaciers on Indian monsoon precipitation and circulation patterns. Regional climate model (RegCM4.0) enabled simulations are planned for the purpose.

METHODOLOGY

Regional Climate Model: Dynamical Downscaling Approach

The three-dimensional, hydrostatic regional climate model (RCM) RegCM4.0 from ICTP (Elguindi 2010, Giorgi *et al.,* 2012, https://eforge.escience-lab.org/gf/project/regcm/wiki/) coupled with BATS land surface scheme is used in the present study the Himalayan snow-monsoon relationship. To study the impact of Himalayan glacier melting two sensitivity experiments are performed for four contrasting years (2001, 2002, 2009, 2010) of monsoon rainfall over Indian sub-continent. In the baseline and the design experiments the model installed in serial mode, domain is from 40°-130° East, 0°-40°North, where South Asian and Himalayas is properly represented, devoid of boundary effects. The lateral boundary condition scheme is relaxation exponential technique. For these experiments, the models were run at a horizontal resolution of 50 km or 0.44° resolution with 18 vertical levels in the atmosphere (sigma coordinate) and the central point of the model domain is located at 76°E and 22°N. There are 100 grid points in the latitudinal, North-South direction and 152 grid points in the longitudinal, East-West direction. Parameterization schemes employed are same as earlier studies (Lodh, 2011, Lodh and Raghava, 2013, Lodh *et al*., 2014 and Lodh 2015) as ISM is best well with these configuration parameterization schemes. The other inputs to the RCM were the Global Land Cover Characterisation (GLCC) data at a resolution of 10 min, GTOPO30 global Topography data with horizontal grid spacing of 30-arc sec (0.008 degree) and the globally interpolated (weekly) (1-degree resolution) Sea Surface Temperature (OISST) data. SST though prescribed is also allowed to evolve prognostically using the Zeng *et al*. (2005) scheme. The boundary layer scheme by Holtslag *et al.* (1990) and the cumulus cloud scheme Grell (1993) with Fritsch and Chappell (1980) closure, SUBEX moisture flux scheme by Pal *et al.* (2000) is also employed in the following design experiments. The radiation scheme used is the NCAR CCM3 (Kiehl *et al*., 1996).

Land Surface Model and Design Experiments

The regional climate model is coupled with BATS (Biosphere-Atmosphere Transfer Scheme) surface package (Dickinson *et al.,* 1993). The BATS model has a vegetation layer, a snow layer, a surface soil layer, root zone layer and a third deep soil layer. Surface fluxes, moisture and momentum fluxes are calculated using surface similarity theory. The various BATS vegetation calculation is encapsulated in the landuse map representing 20 vegetation types (For details refer RegCM4.0 manual by Elguindi Nellie, 2010). The baseline landuse map file can be modified to represent the land use change related design or sensitivity experiment. In the design experiments the aerosol chemical model (calculations based upon Marticorena and Bergametti (1995) and Alfaro and Gomes (2001)) is also activated with aerosol feedbacks on radiative, thermodynamic and dynamic fields (idirect=2 in namelist file). The aerosol types included in the model are anthropogenic, biomass, sulphur di-oxide, Black carbon and organic carbon, with dust and texture is also activated. See Figure 1 for details of the changed land use map for design experiments. More details about the RegCM4.0 model and its user guide can be found at the website: http://gforge.ictp.it/gf/project/regcm/frs/. See Figure 1 for changed land-use map for the DESIGN experiment 1 and DESGIN experiment 2. The DESIGN experiment 1, represents heavy snow experiment where all irrigated crop, forests type of vegetation in Himalayan mountain belt from North Kashmir to Sikkim is changed to *"Glaciers or ice class"* of vegetation. In the DESIGN experiment 2, everything is same as in DESIGN experiment 1 except *Tundra class* changes the *glacier or ice class* of vegetation over the Himalayas. Tundra is a specific type of biome or habitat where plants are short like small shrubs and grasses and hence Tundra region is characterized by freezing temperatures and treeless landscapes. The DESIGN experiment 2 represents land surface degradation in Himalayas due to Himalayan glacier depletion (Zaman *et al.*, 2011). Both the experiments are run from 00 GMT of January 1, 2001 to 24 GMT of December 31, 2002 and 00GMT of January 1, 2009 to 24 GMT of December 31, 2010 using NCEP/NCAR Reanalysis Project 2 data as boundary forcings (http://www.cpc.ncep.noaa.gov/products/wesley/reanalysis2/kana/reanl2-1.htm).

RESULTS AND DISCUSSION

Analysis of Results from Design Experiment 1

The DESIGN experiment 1, representing heavy snow over the Himalayan region is performed to study the impact of snow on the Indian monsoon rainfall. The difference in simulated rainfall, snow-amount, surface pressure, wind at 850hPa, 200 hPa, temperature at 1000 hPa, 700 hPa and 500 hPa is examined. It is observed that snow amount increases during the JJAS, OND and January-February-March (JFM) months (See Figure 2). From Figure 3 to Figure 6 is observed that during pre-monsoon (MAM) season rainfall has decreased by -1 to -3 mm/day over northeast India (NEI), Myanmar whereas increased over Bay of Bengal (BOB) and Arabian Sea (AS) by the (also reported in Shekhar M.S. and Dash S.K. (2005), though the impact of Tibetan snow is reported here). During monsoon (JJAS) season of 2001, rainfall has reduced over whole Indian mainland Shekhar M.S. and Dash S.K. (2005), but increased over North India (NI) (Punjab, Uttarakhand, Jammu and Kashmir region), Pakistan, BOB, Western Ghats and southern AS by 3 mm/day. See Figure 20, 21 for grid cells, which are significant at 95% (green shaded) and 99% (blue shaded) level of confidence. During OND season also rainfall has increased over BOB, AS. Only during OND season of year 2002 there is increase in rainfall over West, North and some parts of Central India (Figure 5). During JFM months there is no change in rainfall over India. From Figure 7, westerly wind at 850 hPa is

Figure 1: (a) Landuse Map in the CONTROL or Baseline Experiment (b) Changed Landuse Map in the DESIGN Experiment 1 (Representing HEAVY SNOW Case) (c) Changed landuse Map in the DESIGN Experiment 2 (Representing TUNDRAVegetation Case)

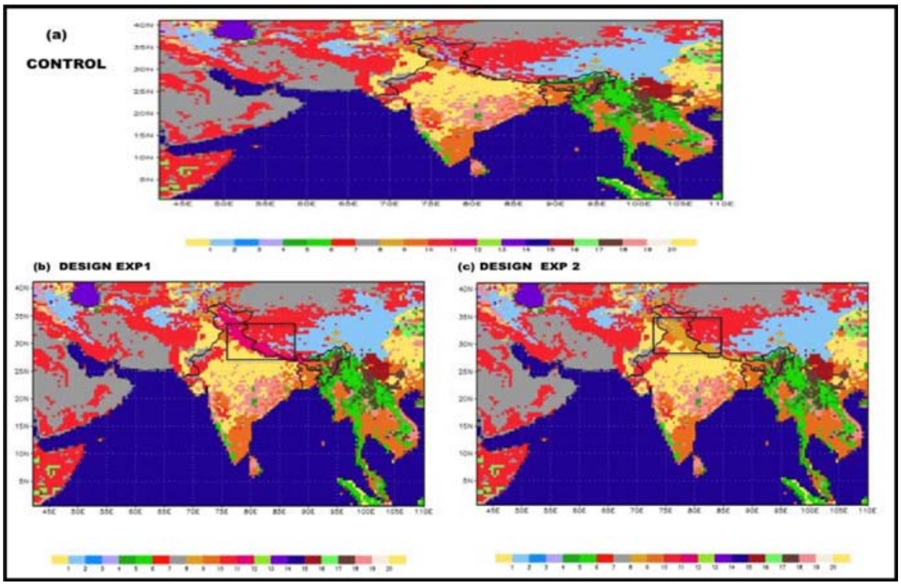

Figure 2: DESIGN EXP 1, Snow Amount Change (mm) for JJAS 2001, OND 2001, and JFM 2002, Compared with Baseline Experiment

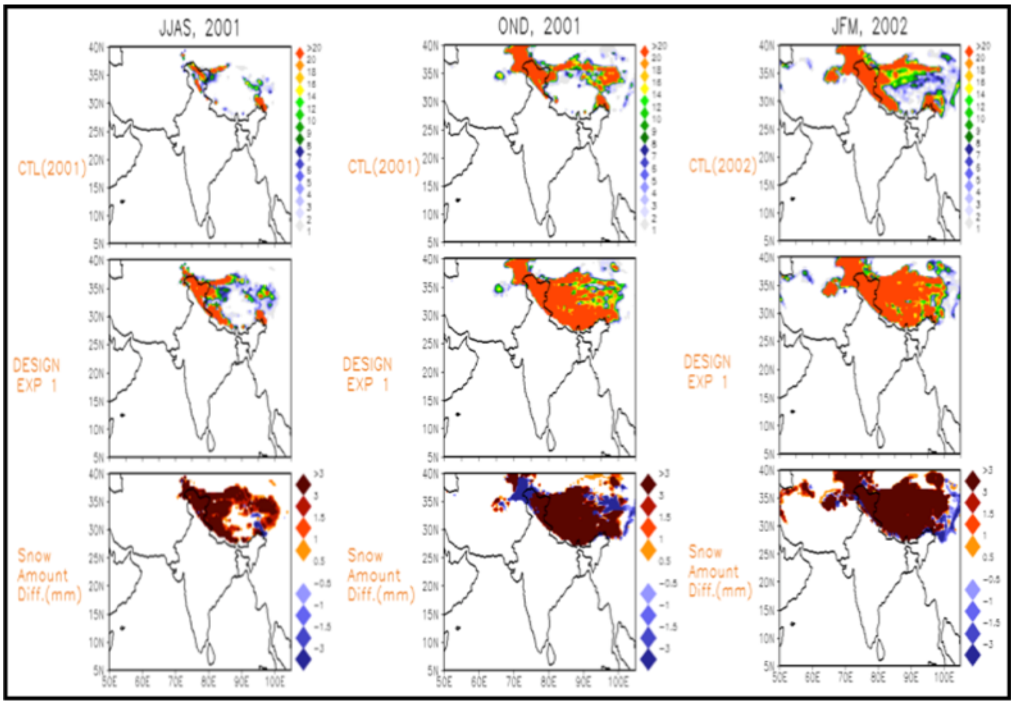

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Figure 3: DESIGN EXP 1, Precipitation Change (mm/day) for JFM 2001, MAM 2001, and JFM 2001, Compared with Baseline Experiment

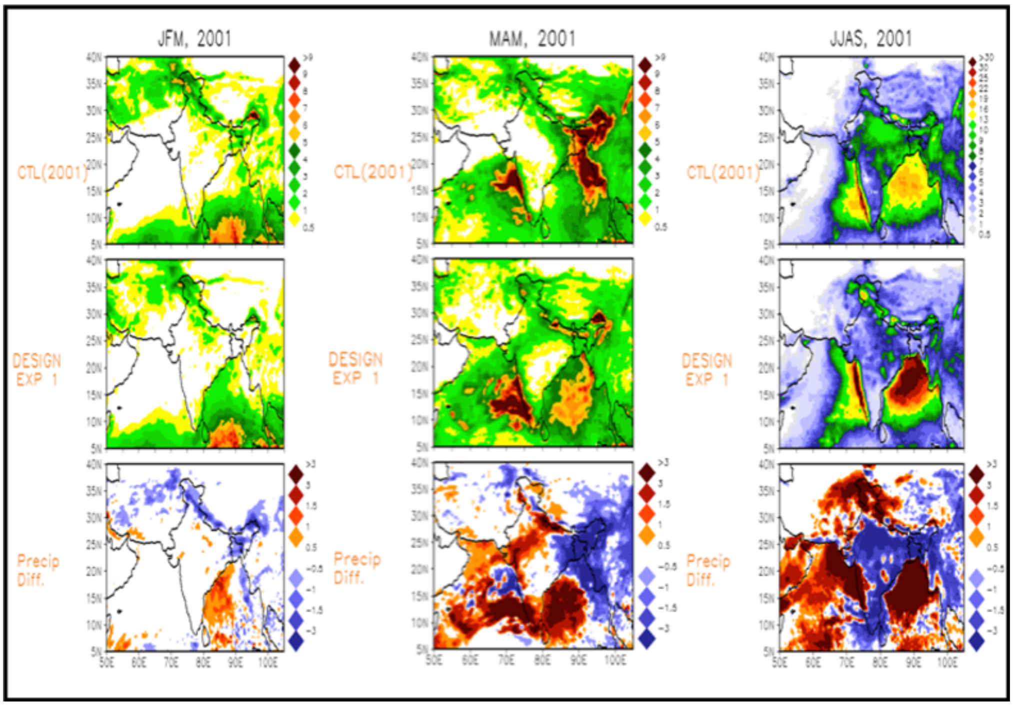


Figure 4: DESIGN EXP 1, Precipitation Change (mm/day) for OND 2001, JFM 2002, and MAM 2002, Compared with Baseline Experiment

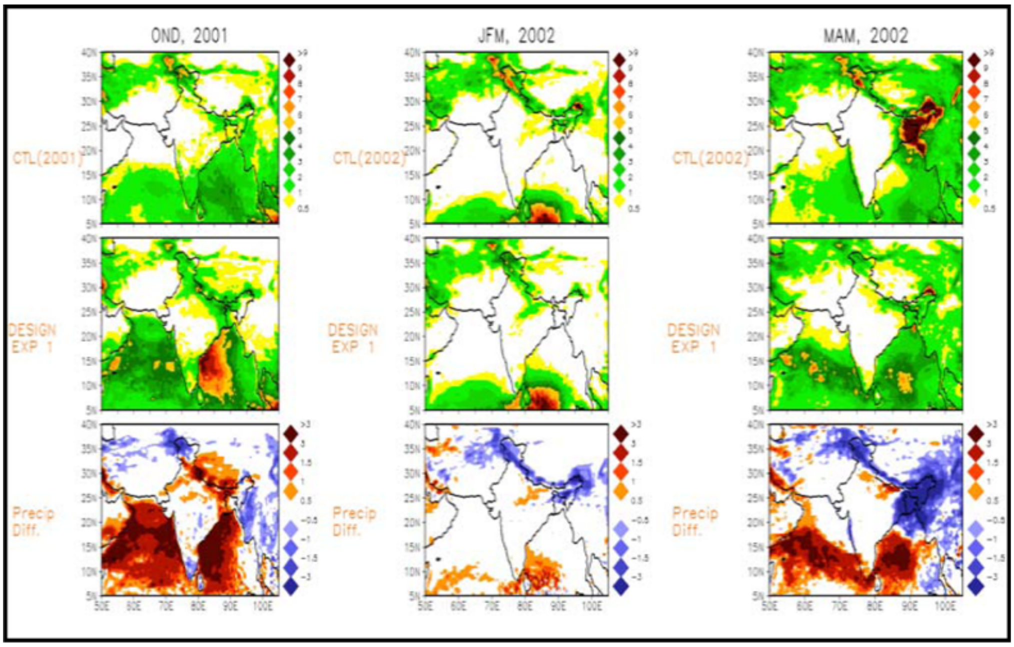


Figure 5: DESIGN EXP 1, Precipitation Change (mm/day) for JJAS 2002, OND 2002, and JJAS 2009, Compared with Baseline Experiment

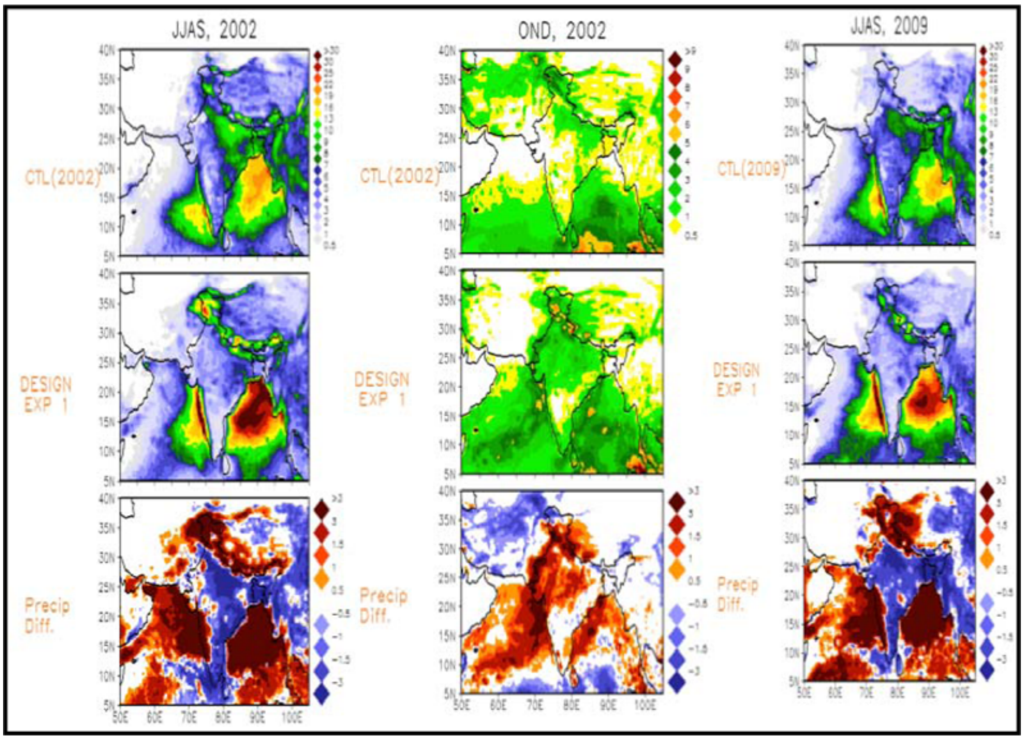
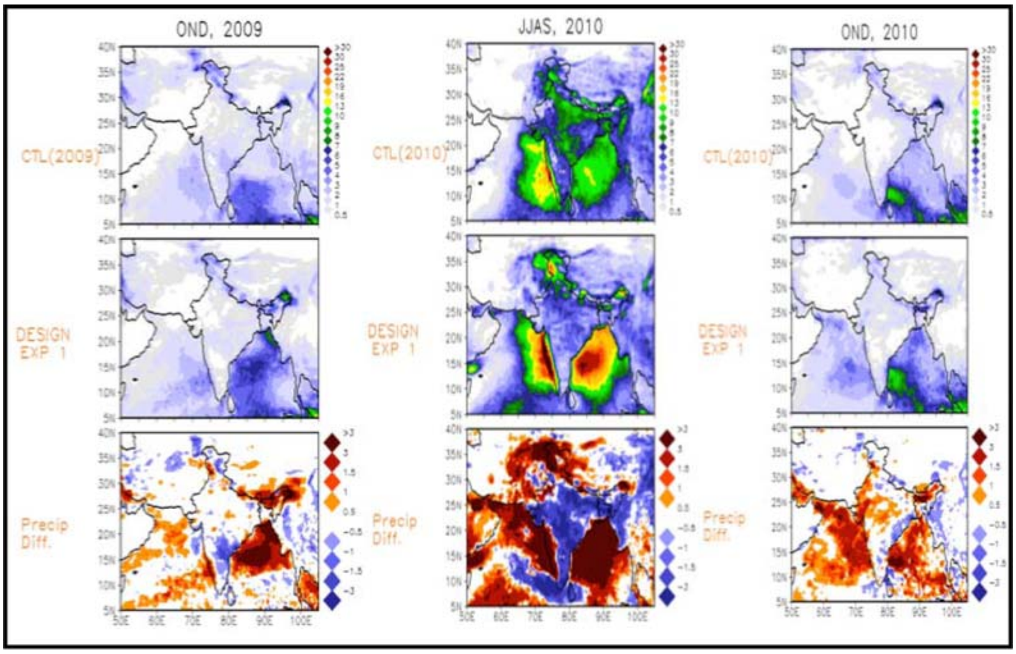


Figure 6: DESIGN EXP 1, Precipitation Change (mm/day) for OND 2009, JJAS 2010, and OND 2010, Compared with Baseline Experiment



stronger for JJAS season in the DESIGN experiment 1 compared with baseline control experiment. Cross-equatorial flow, southwesterly winds over AS, Indian peninsula (PI) has increased in the DESIGN experiment 1. Over head BOB there is a tendency to form cyclonic circulation resulting in more rainfall over BOB (See Figure 7). Though increase in wind magnitude and easterly flow is seen over Trans-Gangetic West Bengal but no increase in rainfall over land region due to decrease in mid-troposphere temperature gradient (See Figure 8). This decrease in temperature gradient exists at 15-40 °N and extends from 1000 hPa to 700 hPa but at 500 hPa there is shift in sign. Also surface pressure increase over NWP region of India, which is the monsoon low-pressure region. The substantial cooling (-1.5°C to -7.5° at 1000 hPa and -3°C at 700 hPa) (Turner and Slingo (2011) and warming (+2 °C) at 500 hPa persists during April to September month with increase in surface pressure result in decrease in JJAS monsoon rainfall in DESIGN experiment 1. From Figure 9 it is clear that tropospheric temperature gradient (DTT) changes sign from negative to positive late in the DESIGN experiment 1, hence monsoon onset is delayed (though not by 2 weeks as reported by Turner and Slingo (2011)) compared to control experiment. Tropospheric Temperature gradient (DTT) is computed as temperature difference over northern (5–35°N) minus southern (15°S–5°N) regions at 40–100°E (Xavier *et al.,* 2007). In the DESIGN experiment 1, tropospheric temperature gradient (DTT) reverses polarity from negative to positive sign and maintains positive sign from 27th of the May 2010 month, whereas in the baseline (CONTROL) experiment, DTT reverses polarity on 24th of the month.

Analysis of Results From Design Experiment 2

The DESIGN experiment 2 represents freezing temperatures and treeless landscapes over the Himalayan region, a proxy for landscape degradation over the Himalayas. The difference in simulated rainfall, snow-amount, surface pressure, wind at 850hPa, temperature at 1000 hPa, 700 hPa and 500 hPa, sensible heat flux, latent heat flux, Bowen's ration, planetary boundary layer height, runoff is examined. From Figure 10, it is observed that snow amount in DESIGN experiment 2 increases over the Himalayan region in the JJAS and OND season of year 2001. From Figure 11 it is observed that snow amount in DESIGN experiment 2 is less than DESIGN experiment 1, over the lower Himalayan regions of India during the JJAS 2001, OND 2001 and JJAS 2002. During OND season there is snow amount is reduced over the Tibetan plateau region lying between 30°N -35°N. From Figure 11 is observed that during pre-monsoon (MAM) season rainfall has decreased by -1 to -3 mm/day over northeast India (NEI), Myanmar whereas increased over Bay of Bengal (BOB), West India and Arabian Sea (AS) (Dash *et al.,* 2005). Similar to DESIGN EXP 1, precipitation again decreases over India (Dash *et al.,* 2005) during JJAS season of 2001, 2002, 2009 and 2010 but increased over NI (Punjab, Uttarakhand, Jammu and Kashmir region), Pakistan, BOB, Western Ghats and AS by 3 mm/day. See Figure 22, 23 for grid cells, which are significant at 95% (green) and 99% (blue) level of confidence. From Figure 12, increase in strength of westerlies during JJAS season is observed and tendency to form cyclonic circulation over head BOB resulting in more rainfall. But over Indian land region there is decrease in rainfall due to increase surface

Figure 7: DESIGN EXP 1, Surface Pressure (hPa) Change for JJAS, 2001 and Wind Magnitude (m/sec) and Direction Change for JJAS 2001 and 2002, Compared with Baseline Experiment

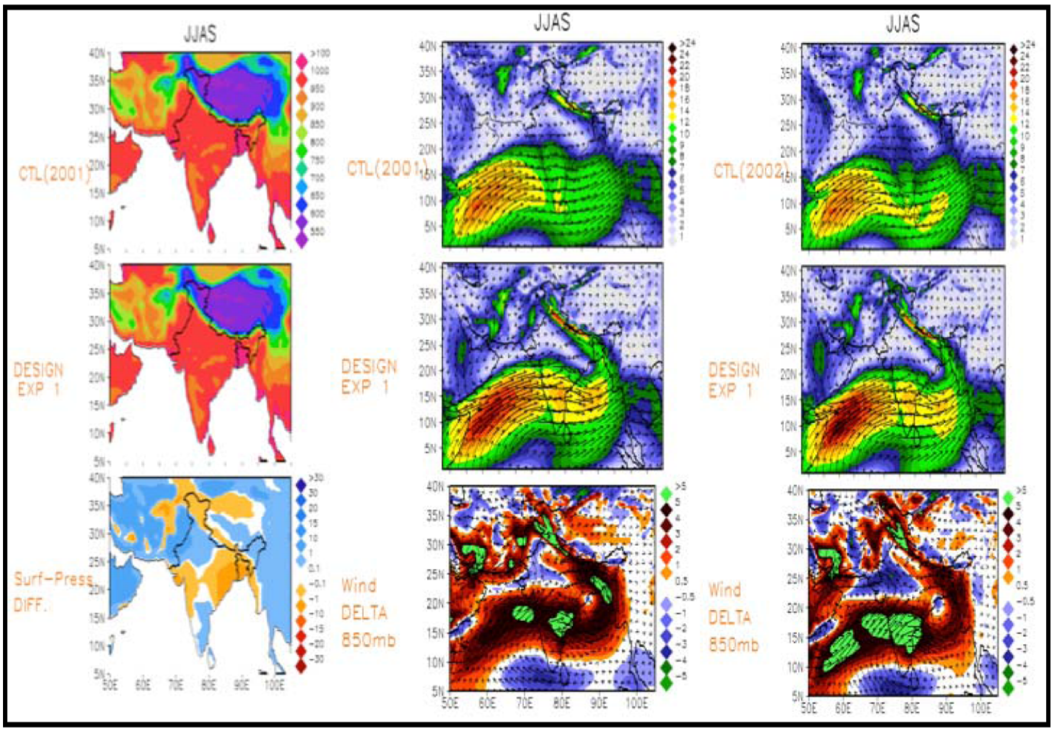


Figure 8: DESIGN EXP 1, Temperature Change (C) at 1000 hPa, 700 hPa and 500 hPa for JJAS, 2001, Compared with Baseline Experiment

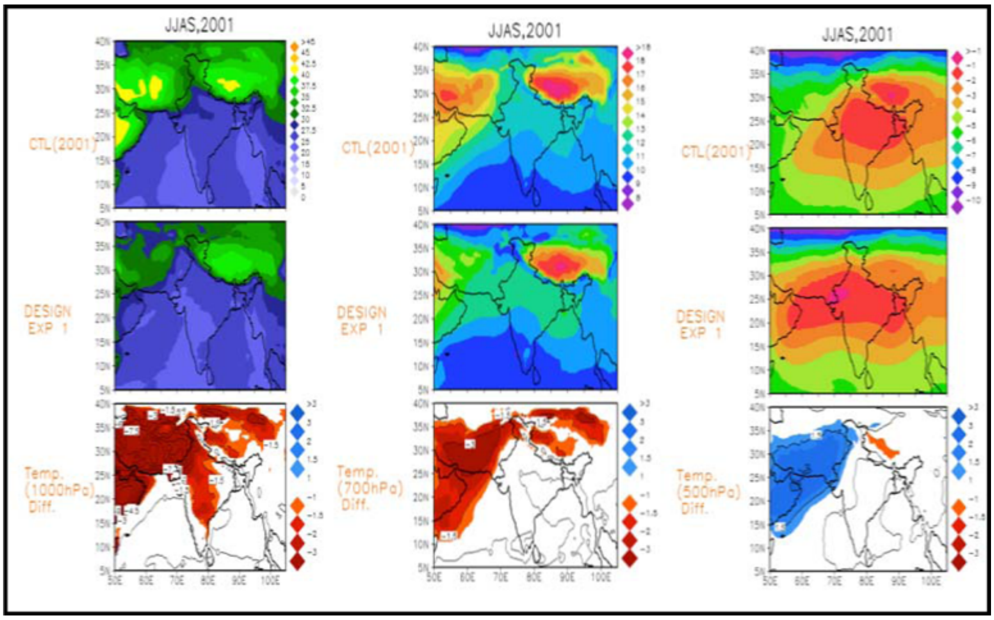


Figure 9: Tropospheric Temperature Gradient for DESIGN EXP 1 and Control Experiment for Month of May 2010

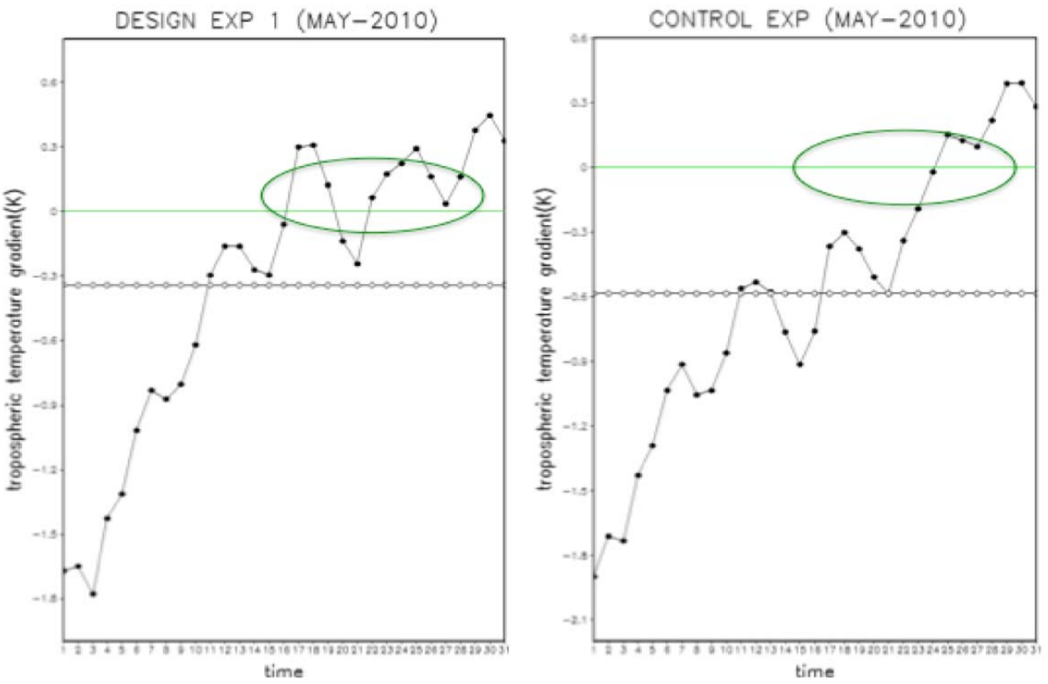


Figure 10: DESIGN EXP 2, Snow Amount Change (mm) for JFM 2001, JJAS 2001, and OND 2001, Compared with Baseline Experiment

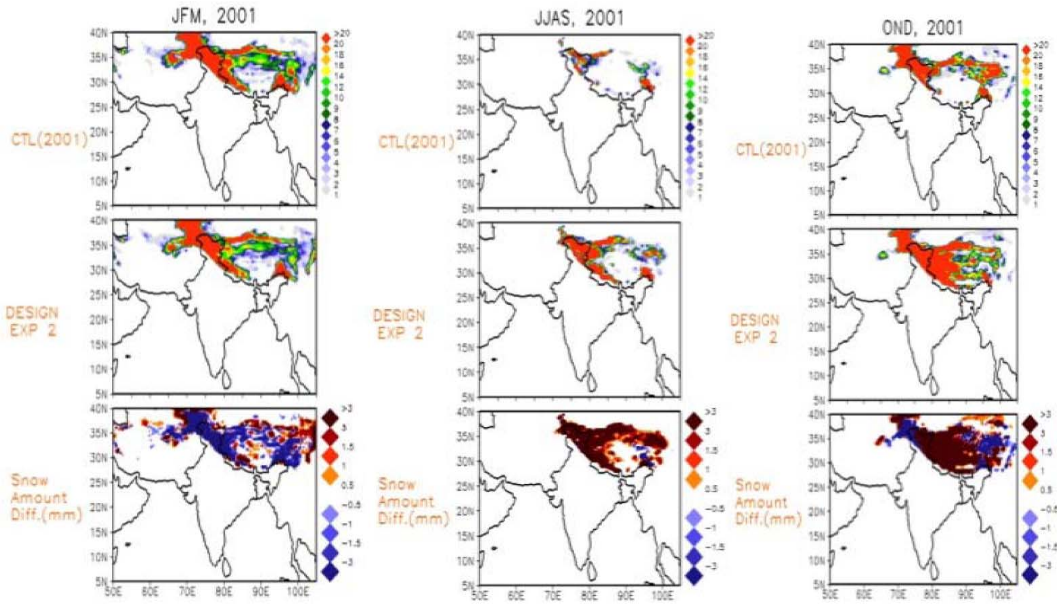


Figure 11:. DESIGN EXP 2, Snow Amount Change (mm) for JFM 2001, JJAS 2001, and OND 2001, Compared with DESIGN EXP 1

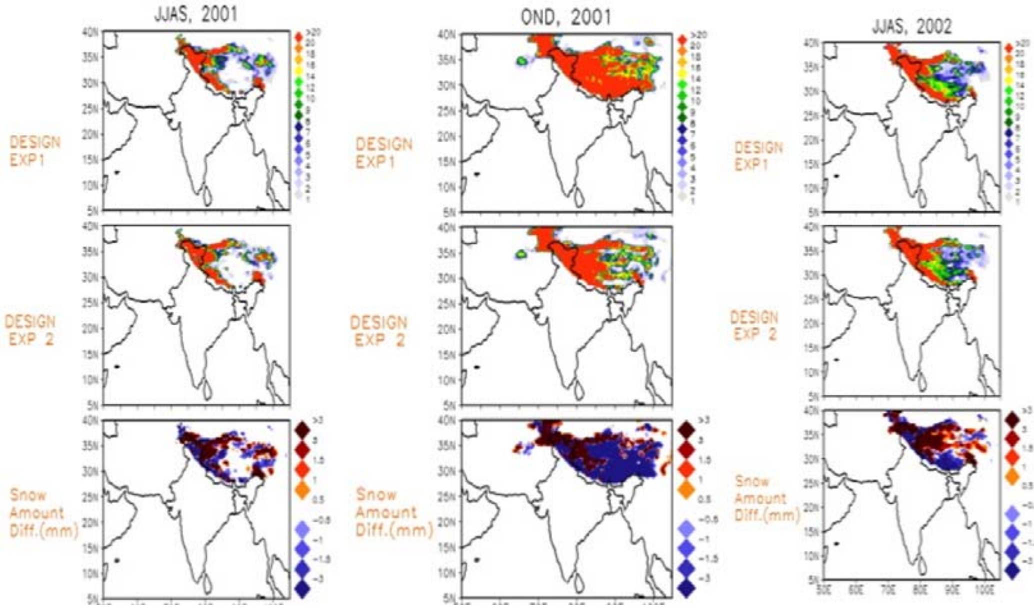


Figure 12: DESIGN EXP 2, Precipitation Change (mm/day) for MAM 2001, JJAS 2001, 2002, Compared with Baseline Experiment

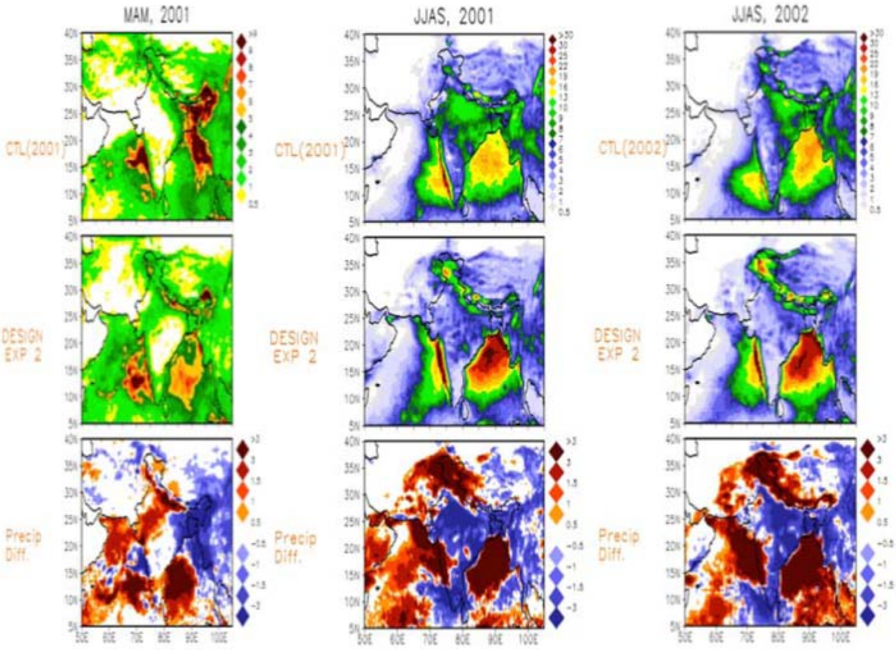


Figure 13: DESIGN EXP 2, Wind Magnitude (850 hPa) and Direction Change (mm/day) for JJAS 2001, 2002 and 2009, Compared with Baseline Experiment

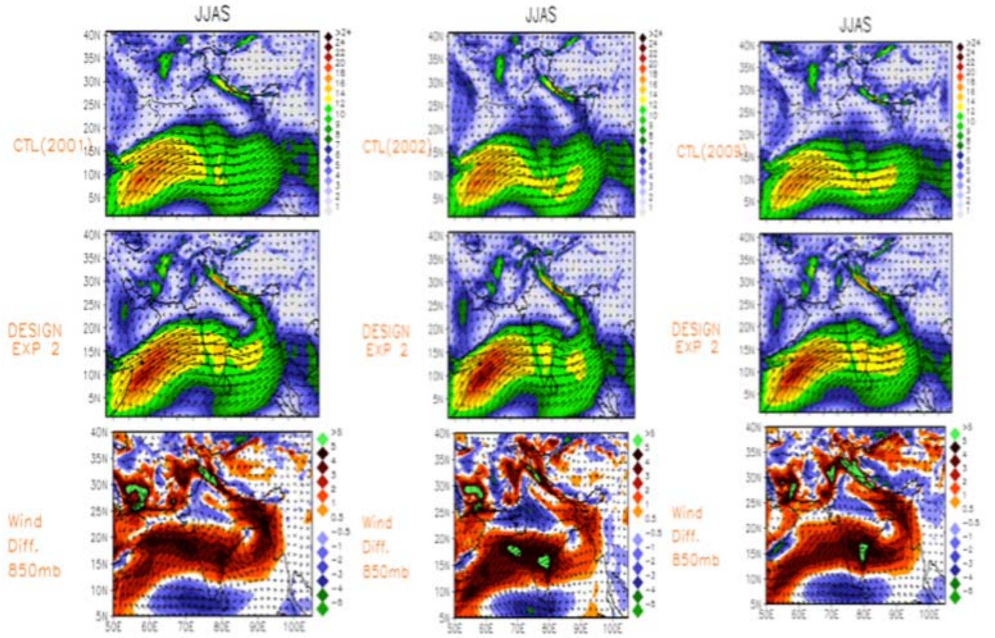


Figure 14: DESIGN EXP 2, Temperature Change (C) at 700 hPa, 500 hPa for JJAS 2001 and Surface Pressure (hPa) Change for JJAS 2001, Compared with Baseline Experiment

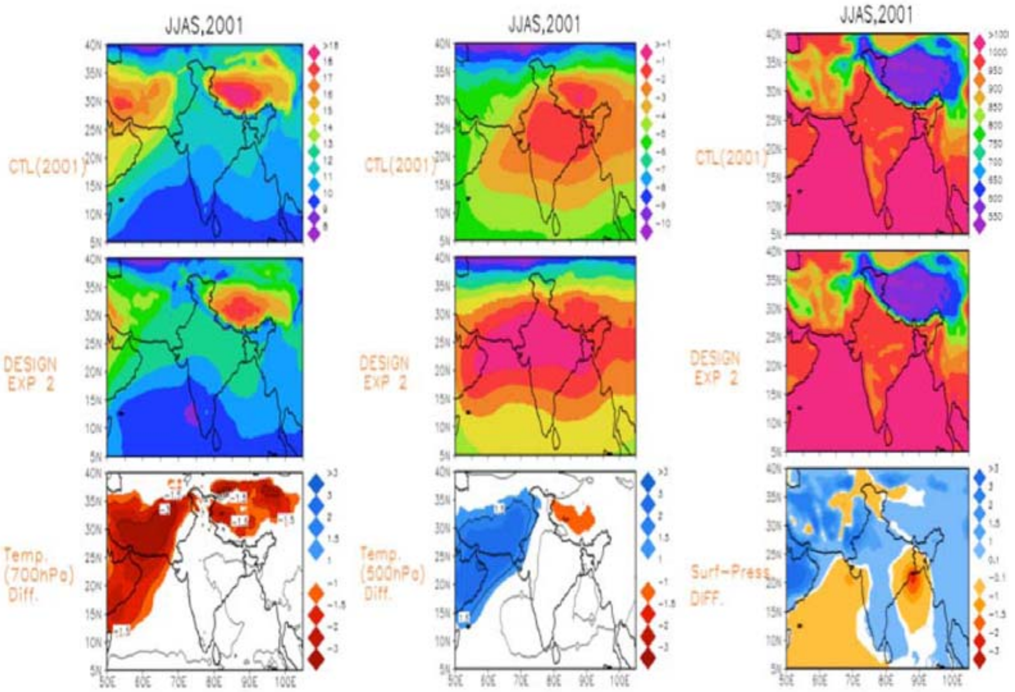


Figure 15: DESIGN EXP 2, Precipitation Change (mm/day) for JJAS 2001, 2002 and 2010, Compared with DESIGN EXP 1

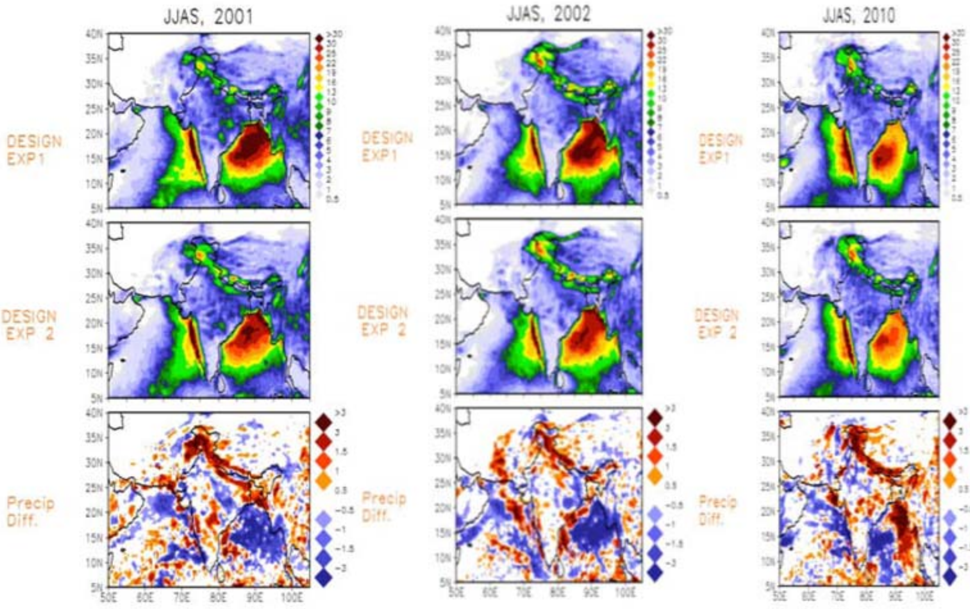


Figure 16: DESIGN EXP 2, wind Magnitude (850 hPa) and Direction Change for JJAS 2001, 2002 and 2010, Compared with DESIGN EXP 1

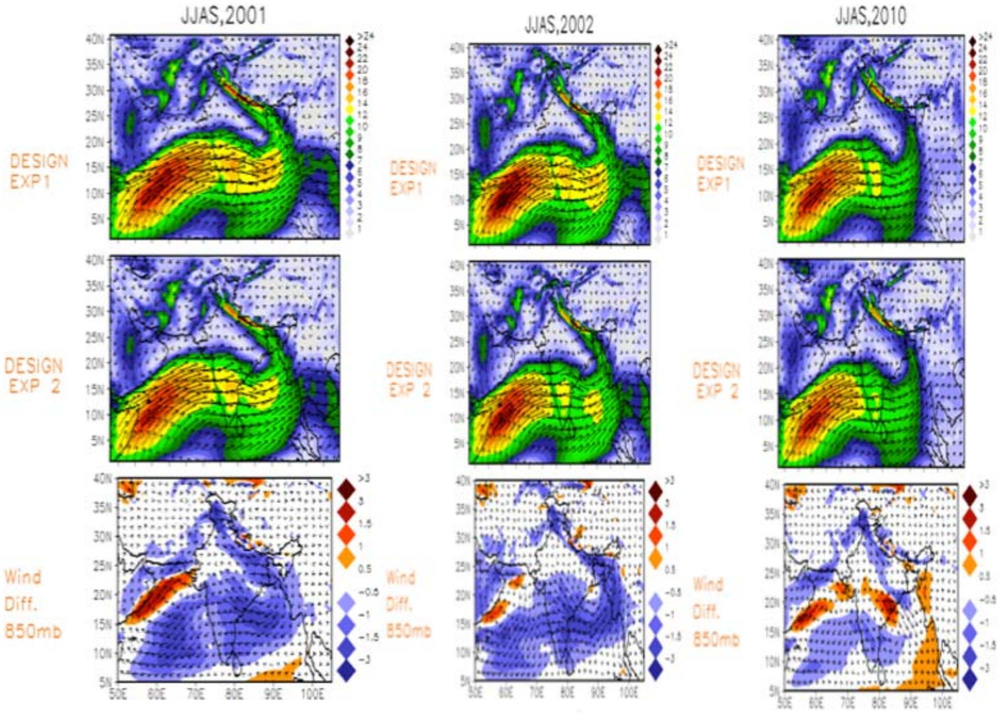


Figure 17: DESIGN EXP 2, 2 m-Temperature and Temperature Change at 1000 hPa and 700 hPa for JJAS 2001, Compared with DESIGN EXP 1

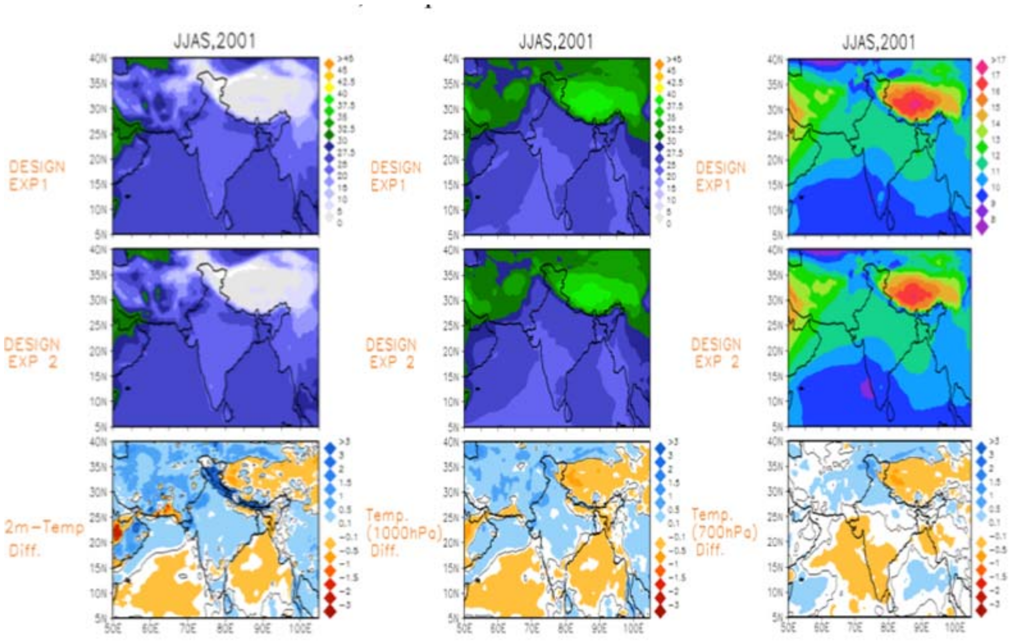


Figure 18: DESIGN EXP 2, Runoff Change (mm) for JJAS 2001, Compared with Baseline and DESIGN EXP1, Respectively and Planetary Boundary Layer Height (m) Change for JJAS 2001, Compared with DESIGN EXP 1

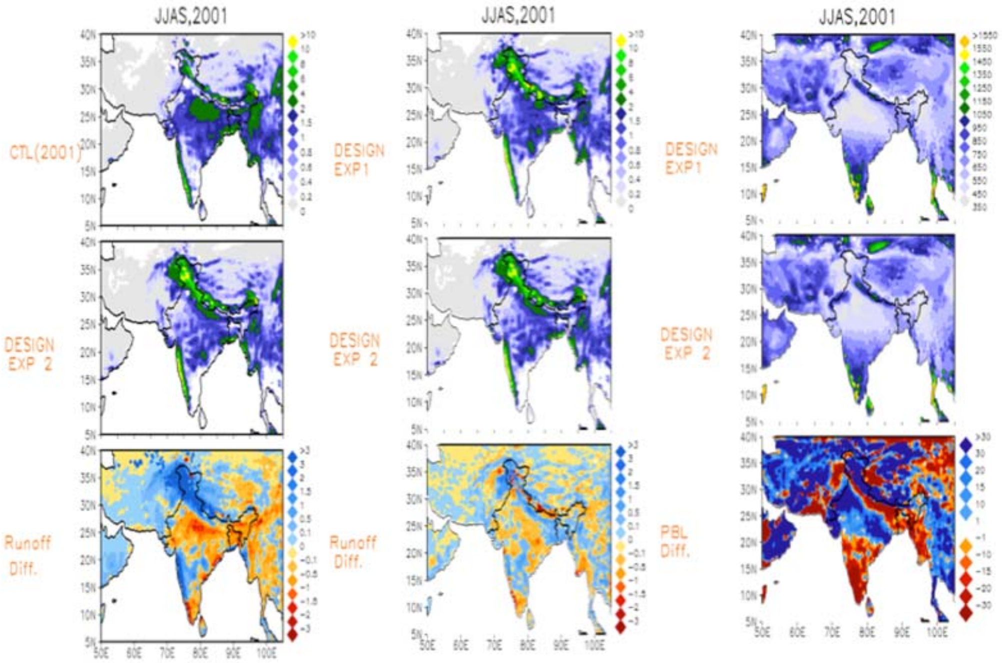


Figure 19: DESIGN EXP 2, Runoff Change (mm) for JJAS 2009 and 2010, Compared with Baseline and DESIGN EXP1, Respectively

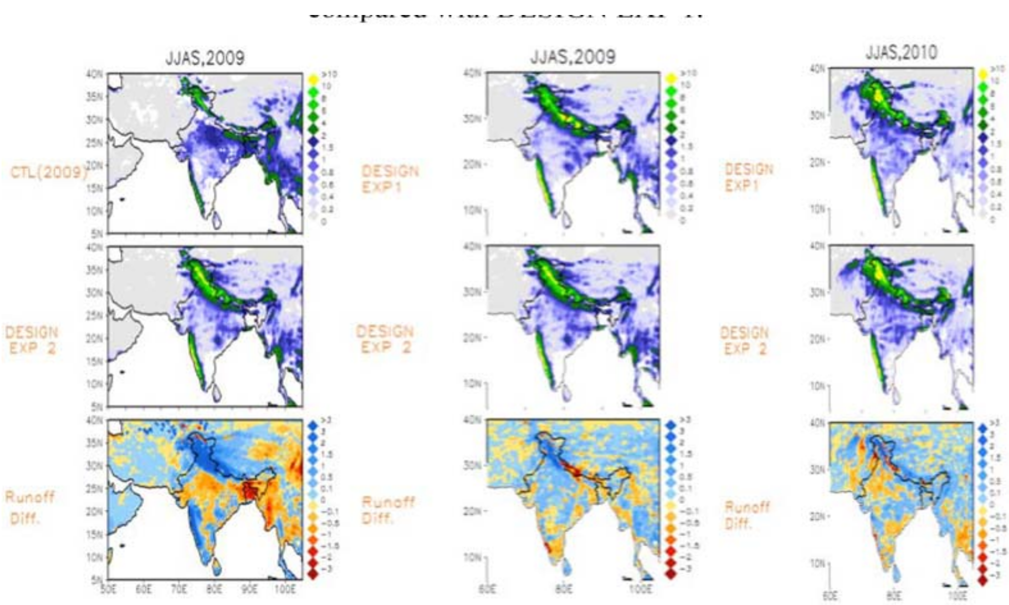


Figure 20: DESIGN EXP 1 (Heavy Snow), Precipitation Change (mm) for May and July 2001 Respectively, with Grid Cells Significant at 95% (Green) and 99% (Blue) Level of Confidence

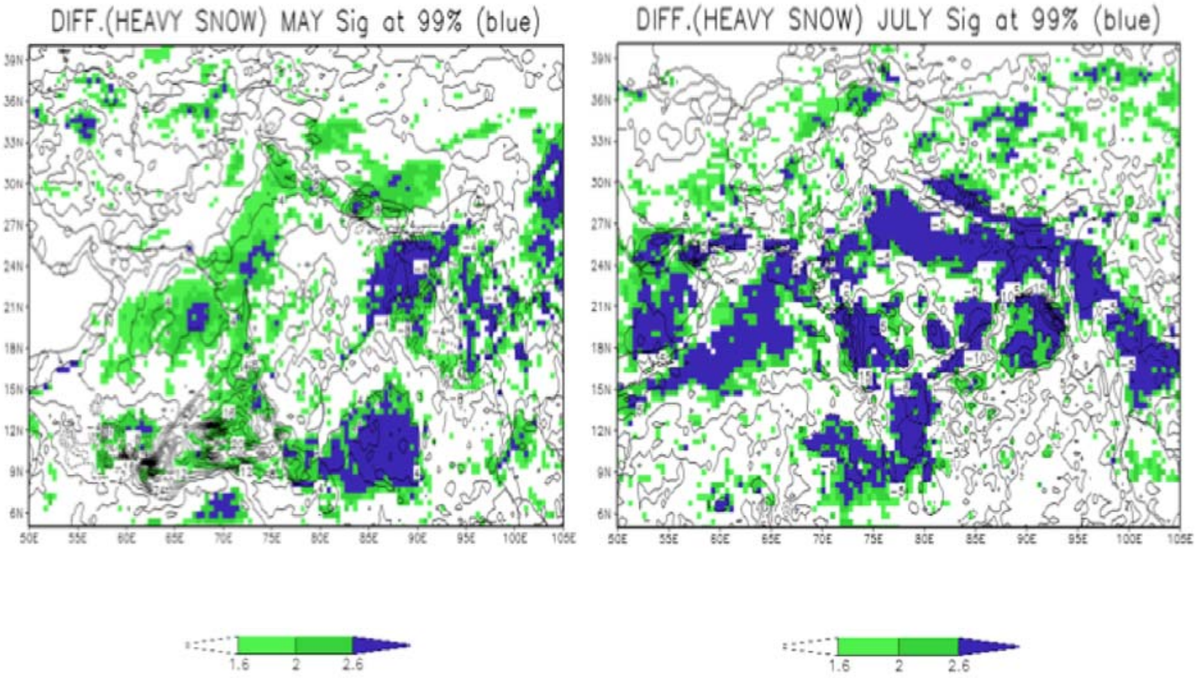


Figure 21: DESIGN EXP 1 (Heavy Snow), Precipitation Change (mm) for August and September 2001 respectively, with Grid Cells Significant at 95% (Green) and 99% (Blue) Level of Confidence

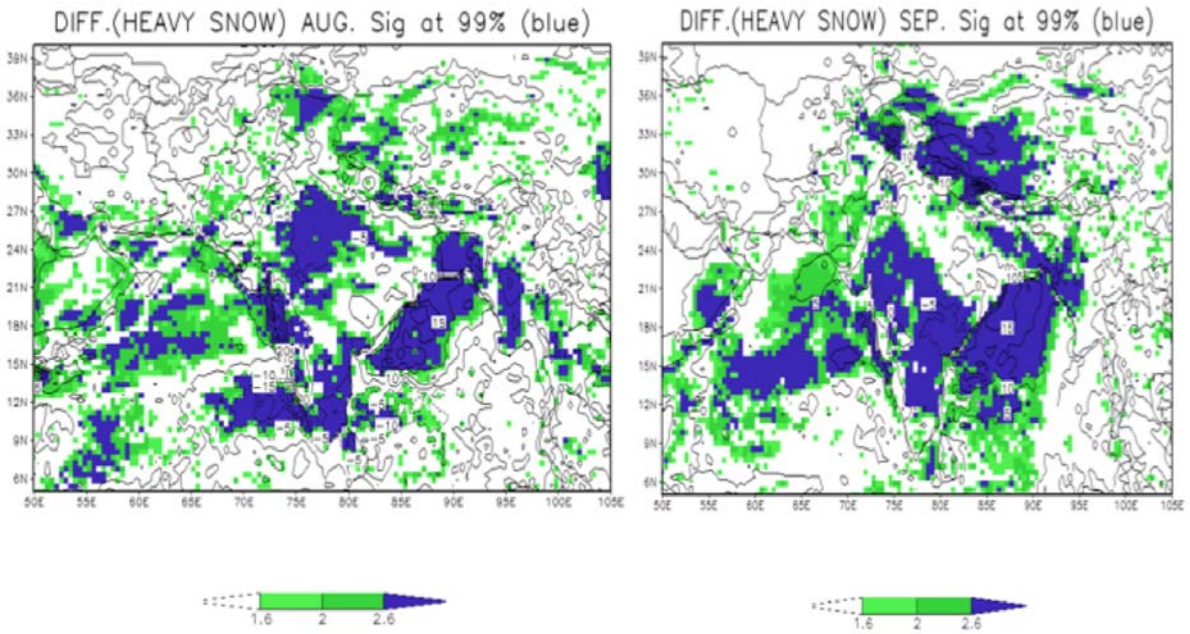


Figure 22: DESIGN EXP 2 (TUNDRA), Precipitation Change (mm) for May and July 2001 Respectively, with Grid Cells Significant at 95% (Green) and 99% (Blue) Level of Confidence

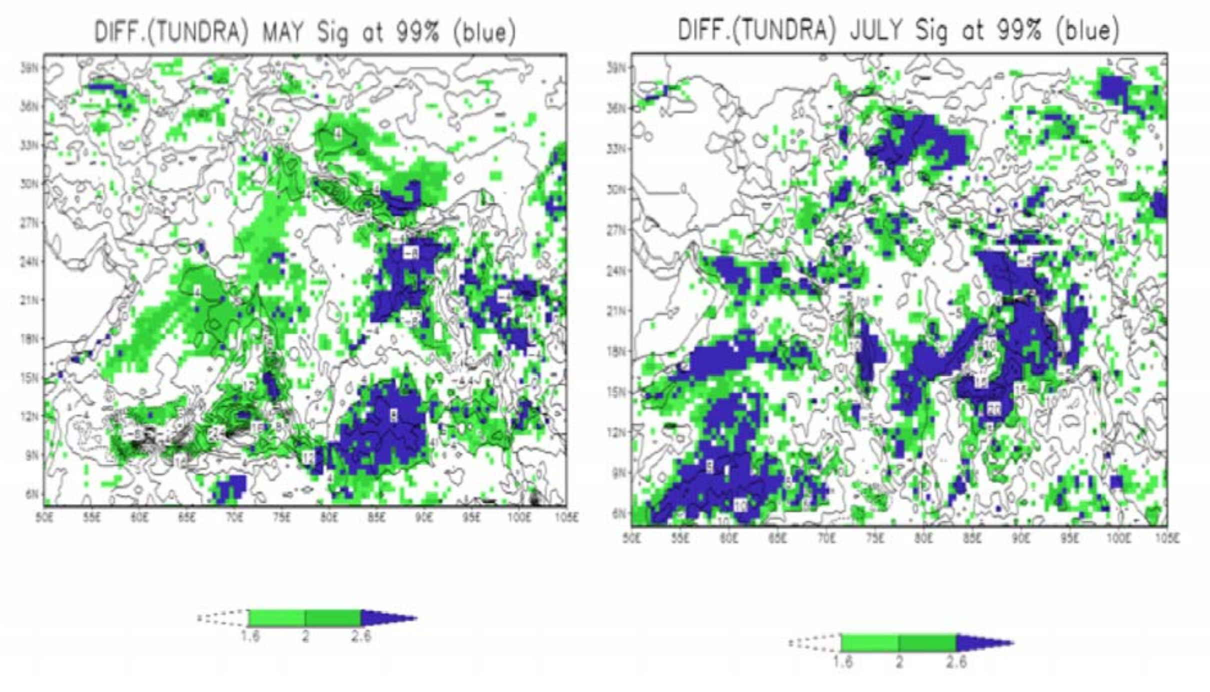
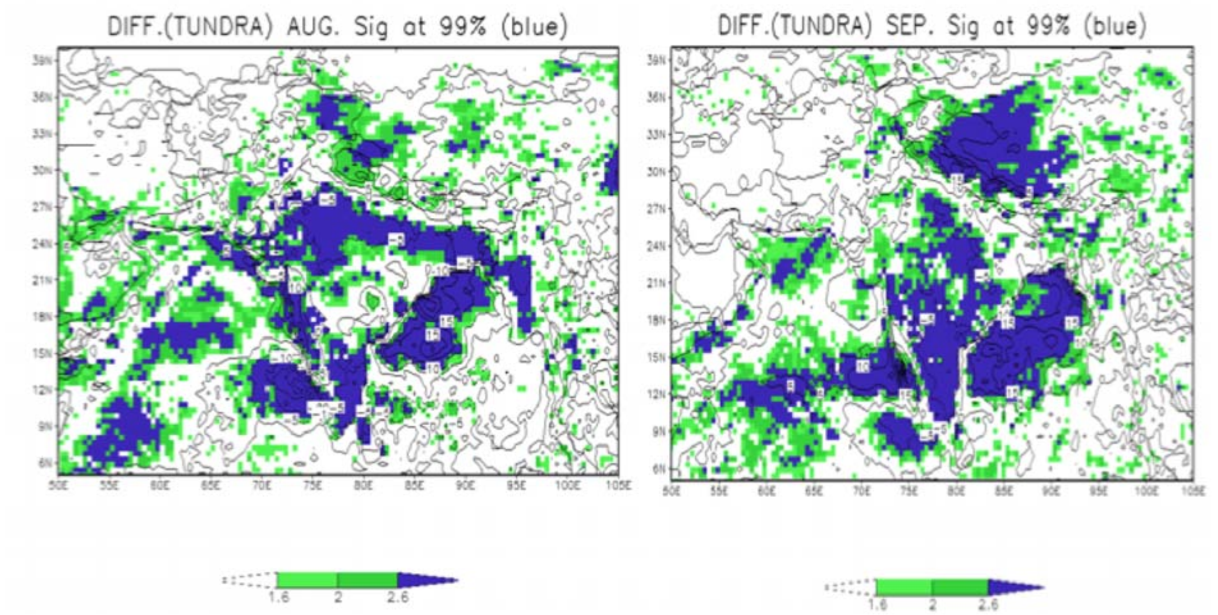


Figure 23: DESIGN EXP 2 (TUNDRA), Precipitation Change (mm) for August and September 2001 Respectively, with Grid Cells Significant at 95% (Green) and 99% (Blue) Level of Confidence



pressure and decrease in mid-troposphere temperature gradient extending upto 700 hPa (See Figure 14). The decrease in tropospheric temperature gradient is lower because of reduction in sensible heat flux from the surface (figure not shown).

Further, to analyze the impact land degradation over the Himalayan region, DESIGN experiment 2 is compared with DESIGN experiment 1. From Figure 15 it is observed that over the Himalayan and Indo-Gangetic plains there is increase in precipitation but over BOB there is reduced precipitation. Figure 16 shows the formation of anti-cyclone over Head BOB, resulting in less rainfall. From Figure 17 it is observed that 2 m-temperature, temperature extending upto 700 hPa increase over Indian subcontinent by 2-3°C. Collins *et al*. (2013) reports that May-June-July-August-September (MJJAS) air temperature in Central Himalayas is rising rapidly from the mid-1970s to 2000's reaching levels achieved in earlier warmer periods. As seen from Figure 18, it is seen that runoff increase in North Himalayan region and West India, i.e., arid regions, whereas over Indo-Gangetic plains and east India runoff decreases. Kaser *et al.* (2010) also reports that due to Himalayan glacier-melting water decreases downstream and becoming negligible in the monsoon-dominated east, whereas increases in the west where the runoff enters dry regions. Planetary boundary layer height increases over Central India and West India. From Figure 19, it is observed that during JJAS season of 2009, runoff decrease over Central India and East India.

CONCLUSION

Past studies have studied have indicated the inverse Eurasian snow-ISMR relationship (Kripalani and Kulkarni, 1999; Dash *et al*. 2006) and Tibetan snow – ISMR relationship (Shekhar

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and Dash, 2005). In this paper a modest attempt has been made to re-examine the relationship between Himalayan snow and Indian monsoon and provide some further insight. Two sets of design experiments using the regional climate model RegCM4.0 is run at 50 km resolution to study the impact of snow and land surface degradation in Himalayas due to glacier depletion on ISMR. The BATS land surface and aerosol chemistry scheme coupled RegCM4.0 model is able to capture Indian monsoon features. Though snow data is not assimilated in the model, but by doing LULCC change DESIGN experiment 1 ("heavy snow") and DESIGN experiment 2 ("tundra") sensitivity experiments are performed. The Results from DESIGN experiment 1 and 2 compared with baseline experiment confirm that rainfall has reduced over whole Indian mainland (grid cells are significant at 99% level of confidence) but few locations of precipitation maximum exits over NI (Punjab, Uttarakhand, Jammu and Kashmir region), Pakistan, Bay of Bengal, Western Ghats and Arabian Sea. This decrease in mid-troposphere north-south temperature gradient or cooling of the troposphere exists at 15-40 °N during JJAS period and extends from 1000 hPa to 700 hPa. This cooling of the landmasses impacts the establishment of large-scale monsoon flow. Also surface pressure increase over NWP region of India, which is the monsoon low-pressure region. Also the surface fluxes, Bowen's ratio, evaporative fraction are reduced considerably (Figures not shown). Hence, Blanford hypothesis (Blanford, 1884) is supported from our analysis, which states reduced mid-troposphere temperature gradient (though along Tibetan plateau), reduced sensible and latent heat flux weakens the summer monsoon rainfall. Turner and Slingo (2011) also confirm substantial mid-troposphere cooling over 600-200hPa at 15-40 °N by performing AGCM sensitivity experiments.

Results from comparing DESIGN experiment 2 with DESIGN experiment 1, designed to study impact of land surface degradation due to Himalayan glacier melting, shows that over Indian subcontinent 2 metre-temperature, temperature extending upto 700 hPa increase by 2-3°C confirming Collins *et al*., 2013. Further runoff increase in North Himalayan region and West India i.e. arid regions, whereas over Indo-Gangetic plains and east India runoff decreases, confirming Kaser *et al*., 2010, WGI AR5 Chapter 3 and/or Jimenez Cisneros 2014. Also, snow amount in DESIGN experiment 2 is less than DESIGN experiment 1, showing that snow depth also decreases due to landscape degradation of Himalayas. This result shows the importance of trees and vegetation to persist in the Himalayan region. The present analysis is based upon regional climate model runs, which allows feedback from radiative, thermodynamic and dynamic fields. Some additional regional climate model runs are necessary with slightly perturbed initial conditions and radiation scheme off to obtain a confirmed mechanism. Secondly, clear sky surface and top of atmosphere forcings are diagnosed in the radiation scheme, but no coupling between dynamic and thermodynamic fields. Snow analysis, as a part of land surface processed fields for weather models is operational at major weather modelling research centres of the world (Pullen *et al*. 2010). Similarly attempts should be made to prepare snow analysis to initiate climate models for correct data representation for land surface processes calculations in numerical models. Hence, significant influence of landuse change especially land degradation and treeless landscape due to deglaciation of Himalayan glaciers on the climatic features of the Indian subcontinent is observed and much government policies while clearing deforestation or mining projects in the eco-sensitive Himalayan region must take into account the adverse future consequences. This research work thus emphasizes need of the concerned authorities to take into account risks due to global climate change, glacier melting on water security in Indian subcontinent.

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LIST OF ABBREVIATIONS

AGCM	Atmospheric General Circulation model
AS	Arabian Sea
BATS	Biosphere-Atmosphere Transfer Scheme
BOB	Bay of Bengal
CI	Central India
GLCC	Global Land Cover Characterization
GMT	Greenwich mean time
ICTP	International Centre for Theoretical Physics
ISMR	Indian summer Monsoon Rainfall
ISM	Indian summer Monsoon
JJAS	June-July-August-September
LULCC	Land-Use Land-Cover Change
MJJAS	May-June-July-August-September
NWP	Northwestern part of India
NEI	North-east India
NI	North India
NNRP2	NCEP/NCAR Reanalysis Project 2
PI	Peninsular India
RegCM4.0	ICTP version 4.0 of Regional Climate model
DTT	Tropospheric temperature gradient

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