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Simulated Impact of Intensification of Irrigation on Indian Monsoon Rainfall and Surface Fluxes

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Abstract

Using Bio-sphere Atmosphere Transfer scheme (BATS) coupled regional climate model (RegCM4) the impact of intensification of irrigation on Indian monsoon atmospheric circulations and surface fluxes is being studied. Land use/land cover change is performed in the model to study the design or sensitivity experiments. This is implemented by changing the vegetation/landuse type in the model. Impact of increase in irrigation activity over Central India and Northwestern region of India is still an open question and hence it is attempted to answer them in this research work. In the first irrigation sensitivity experiment, vegetation/land-use types have been modified to “irrigated crop” type along districts of Central India, Indo-Gangetic plain and northern parts of India, in the RegCM4 model to test the hypothesis that whether-“increase in irrigation decreases monsoon (JJAS) precipitation over certain regions of India and increases pre-monsoon (MAM) precipitation”. Simulations suggest that increase in irrigation over Indian monsoon domain has altered the Indian summer (JJAS) monsoon by weakening it at regional scale over various regions due to probable weakening of the temperature contrast between land and sea. Increase in irrigation over the central India causes a decrease (increase) in sensible heat flux (latent heat flux, surface pressure) in summer monsoon season. To further test the hypothesis that the northwestern region of India is a hotspot for land atmosphere interactions and to test the impact of irrigation intensification over northwestern region of Indian subcontinent, on Indian summer monsoon another sensitivity experiment with irrigation intensification over northwestern regions of India is performed using RegCM4. This experiment suggests that irrigation impact or sensitivity on soil moisture; surface fluxes are limited to northwestern region of Indian subcontinent. Simulations performed at higher (50 km) resolution shows increase in precipitation during pre-monsoon season over northwestern regions of India, too. The Indian monsoon circulations are a part of global general atmospheric circulations periodic in nature and any form of vegetation impact study is a complex process. Thus, from the irrigation sensitivity experiments (using a regional climate model) it can be concluded that due to increase in irrigated land over India, pre-monsoon (MAM) precipitation increase particularly over Central and northwestern regions of India, with the development of anomalous cyclonic circulations.

Keywords: Irrigation; Soil moisture; Precipitation; Latent heat flux; RegCM4.0 sensitivity experiments

Abbreviations

BATS: Biosphere Atmosphere Transfer Scheme; BOB: Bay of Bengal; BW: Bowen's ratio; CI: Central India; CORDEX: Coordinated Regional climate Downscaling Experiment; EF: Evaporative fraction; FAO: Food and Agriculture Organization of the United Nations; GLCC: Global Land Cover Characterization; GMT: Greenwich mean time; ICTP: International Centre for Theoretical Physics; ISMR: Indian summer Monsoon Rainfall; ISM: Indian summer Monsoon; IGP: Indo Gangetic plain; JJAS: June July August September; LCL: Lifting condensation level; LULCC: Land use/land cover change; LHF: Latent heat flux; NI: Northern India; NWP: North western part of India; RegCM4.0: ICTP version 4.0 of Regional Climate model; SHF: Sensible heat flux

Introduction

Agriculture, human health, major weather and climate phenomenon are impacted by climate change. Indian subcontinent is home to one-sixth of world population, where the Indian summer monsoon rainfall (ISMR) is important for irrigation activities. Within India, there is also evidence that intensive irrigation has led to changes in monsoon rainfall patterns with Lohar and Pal [1] reporting that doubling of the area covered by summer paddy crops in West Bengal is a possible cause for mean monthly rainfall from 1983-1992, less than half that observed from 1973-1982. The two-dimensional numerical simulations indicate that wetter soils along the coast reduce the temperature gradient between the land and the sea, hence reducing the intensity of sea breeze circulations and, therefore, lead to diminished pre-monsoon rainfall. Depending upon partitioning of the energy into latent (LHF) and sensible heat (SHF) fluxes, the role of soil wetness, vegetation in the land surface processes during monsoon season can be realized [2]. The vegetation dynamics of a climate system is composed of two major components: (a) the response of vegetation to changes in the environmental variable; and, (b) the response of the environmental variable to changes in vegetation cover. Vegetation and land surface processes effect weather (and climate) through the exchange of heat, moisture, and momentum between the earth's surface and the atmosphere at different timescales and hence is an important component of the climate system [3]. By affecting these fluxes, mesoscale circulations can potentially affect global atmospheric circulations. The vegetation appears to be the climatic response of inter-maintenance of soil moisture and precipitation and, in turn, becomes significantly active part of this inter-play. The vegetative control on the feedback between soil moisture and precipitation has been addressed across globe for model generated extreme anomalies [4-7].

In the last six decade, there is a substantial growth in gross irrigated areas over Indian subcontinent (particularly over north-western part of India due to canal irrigation) and the effects of irrigation can be large at a regional scale [8]. While the benefits of this expansion in agricultural productivity have been immediate, the environmental and social costs over the long term are becoming increasingly apparent as well. Most of the water used for irrigation in Central India is drawn from deep ground water bore wells. Human activities have modified the environment for thousands of years, more so in recent years. Significant population increase, migration and accelerated socioeconomic and agricultural activities have intensified these environmental changes over past decades of industrial and technological revolution. The climate impacts of these changes have been found in local, regional, and global trends in modern atmospheric temperature records and other relevant climatic indicators. An important human influence on atmospheric temperature trends is extensive land use/land cover change (LULCC) and its climate forcing. Studies using both model and observed data have documented these impacts [9]. Mabuchi et al. [10] using numerical simulations studies climatic impact of vegetation change in the tropics. Thus, it is essential for mitigation studies that some LULCC sensitivity experiments are performed using climate models, in a timely manner so as to better understand impacts caused by anthropogenic changes on climate and weather.

Although irrigated land is 17% of the 15×10^6 km^2 of world's agricultural land [11] the role of irrigation in observed temperature trends has been an understudied subject of investigation [12] moreover with regional climate modelling studies. Increase in irrigation activities of wasteland of India particularly located in Central India can be one way to restore the productivity and carbon storage in the soils [13]. It is also important to know the wasteland conversion potential of a developing country like India to reduce the cost for mitigating climate change. Jha [14] reports probable impact of afforestation (sensitivity experiment with deciduous type landuse change) of wastelands of India (particularly located over southern, west-central and north western regions of India) on rice yield of India using by feeding a climate model output to agricultural rice model. Increase in irrigation activities can be one of the ways to restore the productivity and carbon storage in the soils. But before doing irrigation induced carbon-credit related studies, it is important to understand how increasing the land under irrigation i.e., biosphere changes at vegetation surface also alter the surface energy balance. Hence, Indian subcontinent is an important region for studying irrigation and agricultural activities induced land-atmosphere interactions. These monsoonal circulations have their origin over oceans, and move towards the low-pressure system over the interior land regions of Indian subcontinent. Soil moisture, which is present in the layers of the soil, evaporates depending upon the amount of solar radiation incident on the land surface. The research question here is whether and how, increase in irrigated land impacts evapotranspiration, land surface temperature, soil moisture latent heat flux, and sensible heat flux. Douglas et al. [15] simulated and identified changes in circulation patterns and precipitation for a monsoon event over India in the year 2002 using different crop scenarios. Results from Niyogi et al. [16], though not unconditional, suggests that with agricultural intensification, early summer monsoon rainfall over certain regions of India could be reducing using a suite of statistical analysis involving empirical orthogonal functions and genetic algorithm. Hence, it is necessary to further analyse the open question that whether "increase in irrigation decreases monsoon (JJAS) monsoon precipitation and increases pre-monsoon (MAM) precipitation" Saeed et al. [17] with irrigation sensitivity experiment (1986 to 1992) simulations using REMO model finds out that increase in irrigated land over north-western regions of India removes the warm temperature bias over north-western regions of India and further allowing the currents from Bay Of Bengal to reach deep inside the lands. Moreover recently, Lodh [18] performed a sensitivity study using RegCM4 model and confirms that increase in afforestation over India results in increase in precipitation (statistically significant only during spring MAM season), soil moisture, convergence of vapor flux and reduced air temperature, 2-meter temperature, foliage temperature. With this evolving background of irrigation and Indian monsoon related studies, the objective and aim of this research paper is to address the change in climatic variables, particularly circulation features, surface fluxes and precipitation resulting due to increase in irrigation over Central and North-western regions of India in the Indian monsoon regime using downscaling tool of regional climate modeling.

Hence, in the present research paper the regional climate model description, experimental setup and data used, brief about the sensitivity experiments and their period of study is described in Section 2. "Result and Discussions" of the sensitivity experiment are described in Section 3, and the "Summary and Conclusions" are described in Section 4.

Methodology

Regional climate and vegetation model

A RCM (Regional Climate Model) version 4.0 of ICTP (RegCM4.0); http://portal.ictp.it/esp/research/esp-models/regcm4) has been used for the simulation of Indian monsoon [19,20]. The model is installed in "serial" mode at the central cloud-computing facility available at Computer Services Centre, IIT Delhi, over the Cordex South Asia domain (12°E to 138°E and 33°S to 55°N). Though not seamless model, RegCM4.0 model used in this study as in other studies reported [21-23]. More details about the model can be found at the website: http://www.ictp.it/research/esp/models/regcm4.aspx. The below mentioned combination of physical parameterization schemes employed in the RegCM4.0 simulations, meritoriously simulate Indian monsoon (IM) circulations and rainfall in control mode [24,25] include:

1) Radiative transfer package is of NCAR Community Climate Model version 3 (CCM3) by Kiehl et al. [26]

2) Scheme for boundary layer is Holtslag et al. [27]

3) Scheme for Cumulus cloud parameterization is Grell [28] with Fritsch and Chappell [29] closure,

4) Moisture flux scheme is SUBEX and

5) Ocean flux scheme by Zeng et al. [30].

6) Active aerosol chemistry model by Marticorena and Bergametti [31] and Alfaro and Gomes [32] is also activated during the model

simulation with no coupling between dynamic and thermodynamic variables. However, clear sky surface and top of atmosphere radiative forcings are diagnosed (idirect=1, in the namelist file). Active aerosol chemistry model is new scheme tested along with the combination of physical parameterization schemes. The types of aerosols included are anthropogenic, biomass, sulphur dioxide, black carbon and organic carbon along with dust. (In the model namelist file the aerosol type, aertyp = AER11D1). The texture dataset is also built. The aerosol chemistry module becomes effective in the model cells dominated by desert and semi-desert type of vegetation. Sensitivity experiments (explained in detail in Section 2.3) are performed with the set of physical parameterization schemes available within the RegCM4.0 suite that captures response of landuse change or sensitivity to IM circulations and rainfall meritoriously in previous studies [18,33,34].

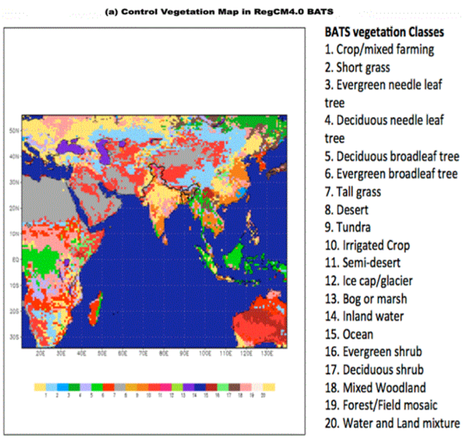

Figure 1a: Biosphere-Atmosphere-Transfer Scheme (BATS) land use map of 20 vegetation classes in the baseline run of RegCM4.0 – BATS model. Land use changed map.

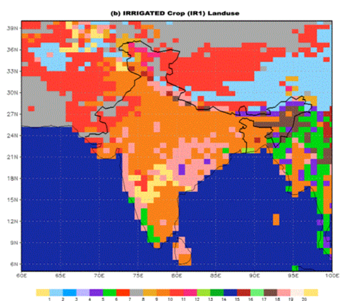

Figure 1b: Irrigation experiment IR1, sensitivity experiment "irrigated crop" over Central India, and Indo-Gangetic plain and northern parts of India.

For this study, the land surface scheme utilized within the RegCM4.0 model is, the Bio-sphere Atmosphere Transfer scheme (BATS) [35]. BATS is a state of the art land-surface scheme designed to describe the role of vegetation and interactive soil moisture in modifying the surface-atmosphere exchanges of momentum, energy and water vapor. BATS have 20 vegetation types [36]. Figure 1a shows the contemporary state of land cover in India as represented by the Global Land Cover Characterization (GLCC) datasets. The landuse data can be found at: http://users.ictp.it/~pubregcm/RegCM3/globedat.htm#part5.

Experimental setup and data used

For the sensitivity experiments the model is integrated over the CORDEX South Asia domain from 12°E - 138°E, 33°S-55°N, at 90 km horizontal resolution, the central point is located at 75°E and 15°N and there are 130 grid points along the latitude circle (N-S direction) and 160 grid points along the longitude circle (E-W direction). The time step of model integration is 30 seconds. The time interval at which solar radiation is calculated is 30 minutes; absorption-emission is calculated is 18 hours. The time interval at which BATS is incorporated is 600 seconds. The lateral and lower boundary conditions for ground temperature (Tg), surface pressure (ps), sea surface temperature (SST) (except for soil moisture) were provided by the National Center for Environmental Prediction, NCEP-DOE AMIP-II Reanalysis (R-2) [37] 6-hourly data and Reynolds weekly sea surface temperature (SST) [38] respectively. OISST CAC Weekly Optimal Interpolation dataset in the original NetCDF format is used at the SST boundary forcing. RegCM4.0 was run at approximately 90 km horizontal resolution (baseline and sensitivity experiments) with Normal Mercator map projection with 18 vertical levels in the atmosphere (sigma coordinate), with finer resolution than previous vegetation impact studies [10,39]. The lateral boundary conditions were updated every 6 hours. The output files are written 6 hourly in "grads" compatible binary format.

Description about the Sensitivity experiments and their period of study

Land-Use-Land-Cover changes and its impact on the atmosphere over the domain have been considered as a proxy to the biosphere-atmosphere interaction over the Indian monsoon domain. The analysis is done over Indian monsoon domain for pre-monsoon (March-April-May i.e., MAM), monsoon (June-July-August-September i.e., JJAS) and post monsoon (October-November-December i.e., OND) period. The irrigation sensitivity experiments are performed to study the impact of various landuse and land cover changes on Indian summer monsoon precipitation and circulation pattern (Figure 1b). The changes are implemented by changing the vegetation type correspondingly other parameters like roughness length; vegetation albedo, maximum fractional vegetation cover etc. get modified (Table 1a). For more details about the modification to the vegetation change formulation in the regional climate model refer Section 6.1.4 [19]. The irrigation sensitivity experiment details (Table 1b) are as follows:

(a) For the first irrigation sensitivity (IR1) experiment the RegCM4.0 model coupled with the BATS scheme over the CORDEX (South Asia) domain is run continuously around the year from 00GMT 1st November 1981 to 24 GMT 31st December 1988 and from 1st April 2009 to 31st December 2010. In the model's standard vegetation map, central India and north-western region of India are selected to represent increase in irrigation activities. Thus, RegCM4.0 model vegetation/land-use types have been modified to irrigate crop (IR1) category in the model and an experiment has been set up with the changed land-use cover into irrigated crop, which resembles the intensified irrigation activity over Central India (CI), Indo-Gangetic plain (IGP) and northern India (NI).

(b) The second sensitivity experiment to test the hypothesis that the north-western region of India is a hotspot for potential land atmosphere interactions [16], a second (IR 2) irrigation sensitivity experiment is planned and executed (using regional climate model RegCM4.0) to test intensive irrigation over north-western region of Indian subcontinent. The RegCM4.0 model coupled with the BATS scheme over the CORDEX domain is run around the year from 00GMT 1st November 1986 to 24 GMT 31st December 1988 and from 00GMT 1st November 1996 to 24 GMT 31st December 1998, separately (Figure 11). (Sensitivity experiment is done for two time periods for robustness of results and to get the correct signal during different SST epochs).

(c) For the IR2-50 km sensitivity experiment case, the experiments are performed with chemistry off (chem=0), chemistry on (chem=1, idirect=1) at 50 km resolution (100 x 152 grid points in x-y direction) and the model domain is from 40°E-130°E, 0°-40°N, where South Asian properly represented with no boundary effects. For performing the IR2-50 km sensitivity experiment, the domain of the model is smaller in comparison to IR1 and IR2 experiments. Thus, performing this experiment with reduced model domain, the model noise is reduced too (Section 6.3 of Giorgi et al. [16]). The model run is from 1st January 1987 to 31st December 1988. The types of aerosols included are anthropogenic, biomass, sulphur dioxide, black carbon and organic carbon along with dust. The model run is done two times for the year 1987 and 1988. When chemistry is off there is no coupling, aerosol are only transported and don't interact with radiation scheme. However, when chemistry is on (i.e., chem=1 and idirect =1), there is no coupling between dynamic and thermodynamic variables. However, clear sky surface and top of atmosphere aerosol radiative forcings are diagnosed.

So for each of the sensitivity (IR1, IR2 and IR2-50 km) experiments, we have it's corresponding baseline or control experiment. Thus, for two different set of simulations the "anomaly" between control and sensitivity experiment is calculated. The increase or decrease of precipitation (and other meteorological variables) due to the increase of irrigation is measured quantitatively. Also Student's t-test is used to judge the significance of the sensitivity experiments to provide an estimate of the probability that a given sensitivity experiment result is attributed to a cause not merely random noise fluctuations [40]. It is also important to mention here that neither the absence of significant response in a sensitivity experiment has to indicate that climate change mechanism is not happening in nature (in the present study case increase in irrigation).

The information about BATS vegetation landcover data for irrigated crop is available in Table 1a (Source: ICTP RegCM Version 4.0 Core Description Manual). In the baseline or standard vegetation map of BATS coupled RegCM4.0, "crop and mixed farming" class of vegetation is available over Central India (CI), Indo-Gangetic plain (IGP) and north India (NI). In the irrigation sensitivity experiments, the vegetation over the above-mentioned regions is changed to "irrigated crop". From Table 1b, it is to be noted that roughness length, vegetation albedo and maximum fractional vegetation cover of "irrigated crop" is less than "crop and mixed farming" in the original control land use map.

	Roughness length	Vegetation albedo for Wavelengths < 0.7 μ m	Vegetation albedo for Wavelengths > 0.7 μ m	Maximum fractional vegetation cover
Irrigated Crop	0.06	0.08	0.28	0.8

Table 1a: BATS vegetation landcover table (Source: ICTP RegCM Version 4.0 Core Description Manual [36]).

Experiment name and its acronym	Domain and Resolution	Land-surface condition and duration of simulation run	Details of Parameterization schemes used
RegCM4.0-BATS-IR1 (chem = true, idirect=1)	11°E-139°E, 34°S- 55°N (Cordex South Asia), ~ 90 km (160 × 130 × 18, Normal Mercator map projection). The central point is located at 75°E and 15°N (approx.)	Irrigation sensitivity experiment with increase in irrigated 00GMT 1st November 1981 to 24 GMT 31st December 1988 1st April 2009 to 31st December 2010	a) Grell scheme with Fritsch and Chappell closure and Holstag PBL scheme. (b) Original ASCII text landuse map in the RegCM4 model altered to incorporate the design experiments. (c) The years of hind casting simulations are: 1982 (El Niño + drought), 1983 (weal La Niña + flood), 1984 (normal), 1985 (drought) and, 1986 (drought), 1987(El Niño+ drought), 1988 (La Niña + flood), 2009 (El Niño and drought) and 2010 (La Niña + normal)
RegCM4.0-BATS-IR 2 (chem = false)	-	Irrigation sensitivity experiment with increase in irrigation over north-western 00GMT 1st November 1986 to 24 GMT 31st December 1988 00GMT 1st November 1996 to 24 GMT 31st December 1998	
RegCM4.0-BATS-IR 2 (chemistry = false and chemistry =true and idirect=1)	40°E-130°E, 0°-40°N, 50 km grid resolution (100 × 152 grid points in x-y direction	1st January 1987 to 31st December 1988	

Table 1b: List of irrigation sensitivity experiments using Regional Climate model.

The perturbations in the land use/land cover change impacts both near surface meteorological and atmospheric variables. Change in precipitation, wind magnitude and direction (both at 850 hPa and 200 hPa), latent heat flux (LHF), sensible heat flux (SHF), Bowen's ratio (BW), evaporative fraction, surface layer soil moisture were studied. Over arid regions the land surface variable, Bowen ratio doesn't provide correct information about surface fluxes. Hence, in this study for analysing surface fluxes over arid regions, evaporative fraction (EF)

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is used for representing relative contributions of the turbulent energy fluxes to the surface energy budget. The Bowen ratio is related to the evaporative fraction by the equation

EF = LHF/SHF+LHF =1/(1+BW)

The Bowen ratio is an indicator of the type of surface. Their value is less than one over surfaces with abundant water. Over deserts its value is greater than 10.

Results and Discussion

Effect of irrigation - land cover change on precipitation, circulation features and surface fluxes

Model had simulated significant change in total precipitation during the JJAS season in the irrigation (IR1) sensitivity experiments. The main discussion points are as follows:

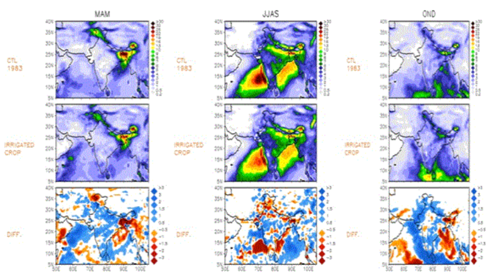

Figure 2: IR 1, sensitivity experiment precipitation change for year 1983 (weak La Niña + flood) season (a) MAM (b) JJAS (c) OND. (For all the meteorological variables the difference or change is calculated by doing difference of irrigation sensitivity experiments ("IR1" or"IR2" or "IR 2 - 50 km") minus RegCM4.0 baseline experiment (CTL). The top panel represents the CONTROL or baseline experiment, the second panel represents the irrigation sensitivity experiment and the third panel represents the "difference").

1) Precipitation change for MAM, JJAS and OND season year 1983 is shown in Figure 2. For the year 1983 precipitation is seen to increase over CI, IGP and north Western Ghats during pre-monsoon (MAM), monsoon (JJAS) and post-monsoon (OND) season and decrease over Trans-Gangetic region in all the three seasons of 1983. Correspondingly, JJAS wind magnitude and direction change for year 1983 at 850 hPa, 700 hPa and 500 hPa is seen to increase over these regions at 850 hPa, 700 hPa.

2) The Figure 3 depicts simulated 1982, 1984, 1986 seasonal (JJAS) precipitation for baseline, sensitivity experiment (IR1) and change in precipitation due to IR 1 sensitivity experiment. Mean observed seasonal (JJAS) precipitation pattern has been properly captured by RegCM4.0 simulation (both with and without sensitivity); it has properly captured the high precipitation along the Western Ghats and north eastern regions of India and the overall precipitation distribution pattern. Also it is important to inform that irrigation intensification over India is not altering and effecting the global atmospheric circulations, significantly and important precipitation features like high precipitation over Western Ghats and north-eastern regions of India is observed both in baseline and sensitivity experiment. Cross equatorial flow and Somali jet is also well observed, both in baseline and sensitivity experiment. But changes are there at regional scales.

3) In the IR 1 type sensitivity run, the difference in JJAS precipitation is observed over mainland of India (Figure 3). During the years of study, in the JJAS season for the year 1982 there is decrease in precipitation over the northern Western Ghats, parts of NI (Punjab), eastern region of India by 1 mm/day to 2 mm/day. There is increase in precipitation over Bay of Bengal (BOB) by 1 mm/day to 2 mm/day. But in the JJAS season of year 1984, over the inlands of India i.e., over Central India (CI), Orissa and peninsular India (PI) there is increase in precipitation by 2 mm/day to 3 mm/day (Figure 3). Observing the circulation pattern at 850 hPa for JJAS season of year 1982, 1984, 1986 shows increase in wind magnitude by +2 m/sec to -3 m/sec over BOB, peninsular India and north Western Ghats (Figure 4). For the year 1986, during MAM season precipitation is seen to increase over west Madhya Pradesh and peninsular India and decrease over IGP, increase over Western Ghats and CI during JJAS-1986 season. The circulation pattern at 850 hPa and 700 hPa during 1986 JJAS season shows increase in wind magnitude (by +1.5 m/sec) over north Western Ghats and tendency to form anomalous cyclonic circulation over western and north western region of India extending upto 700 hPa (Figure 5). Over BOB, winds tend to increase in opposite direction, away from Indian (land) region at 850 hPa. Also at 200 hPa there is increase in magnitude of wind over BOB, Western Ghats and western regions of India (Figure 5).

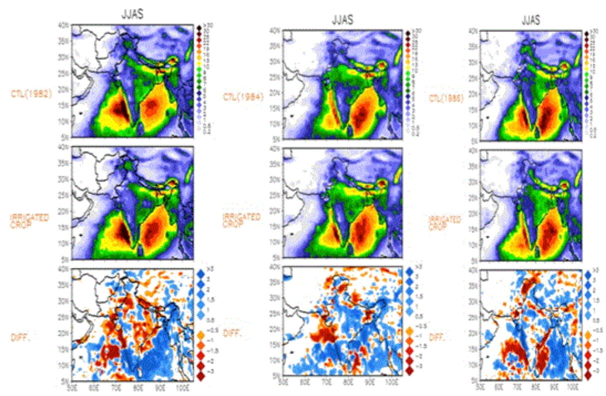

Figure 3: IR 1, sensitivity experiment precipitation change (mm/day) of JJAS season for year (a) 1982 (El Niño + drought year) (b) 1984 (normal year) and, (c) 1986 (drought year).

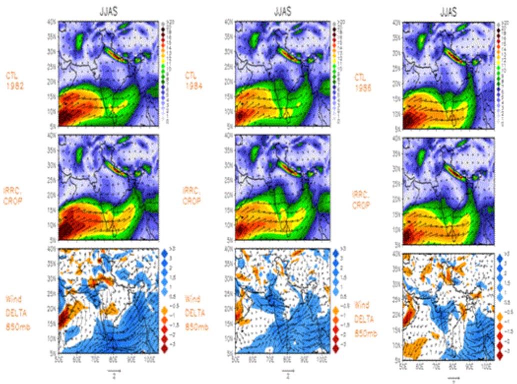

Figure 4: IR 1, sensitivity experiment JJAS wind magnitude and direction change at 850 hPa of JJAS season for year (a) 1982 (El Niño + drought year) (b) 1984 (normal year) and, (c) 1986 (drought year).

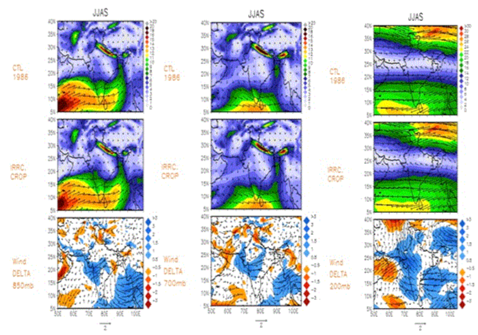

Figure 5: IR 1, sensitivity experiment JJAS wind magnitude and direction change for year 1986 (drought year) (a) 850 hPa (b) 700 hPa (c) 200 hPa.

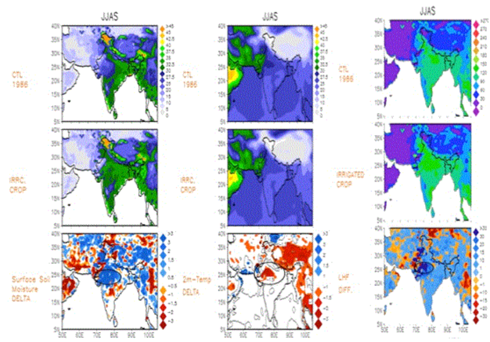

Figure 6: IR 1, sensitivity experiment JJAS change for year 1986 (drought year) (a) surface soil moisture (b) 2 metre temperature (c) Latent heat Flux.

4) Though in the IR1 sensitivity experiment increase in irrigation activity in the model is over CI, IGP and NI. Simultaneously, increase in surface soil moisture is seen over CI, IGP and NI extending upto north-western part (NWP) of Indian sub-continent (Figure 6). Though over CI and NWP region it is observed that there is increase in evapotranspiration and LHF (Figure 6) but decrease in 2 metre temperature, sensible heat flux, Bowen's ratio and evaporative fraction (Figure 7). Also run off decrease over CI and NWP region. The air temperature is also decreasing over the monsoon low region (CI, NWP) at 925 hPa and 850 hPa (Figure 8). Hence, mid-tropospheric temperature gradient is altered due to intensification of irrigation activities over CI and NWP region in the model. Statistical significant grid cells for precipitation differences (at 5% and 1% level of significance) between the baseline and sensitivity experiment IR 1, is also shown in Figure 9 for months of June and July 1986. It is again observed that decrease in precipitation over the northern Western Ghats and increase in precipitation over BOB is statistically significant at 5% level of confidence.

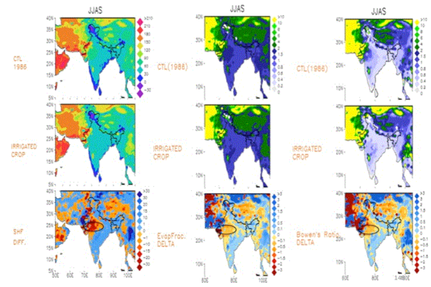

Figure 7: IR 1, sensitivity experiment JJAS change for year 1986 (drought year) (a) Sensible Heat Flux (b) Evaporative fraction (c) Bowen's ratio.

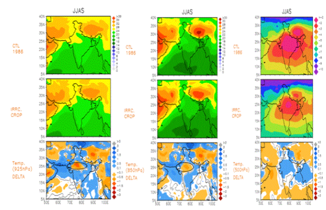

Figure 8: IR 1, sensitivity experiment JJAS change for year 1986 (drought year) (a) 925 hPa temperature (b) 850 hPa temperature (c) 500 hPa temperature.

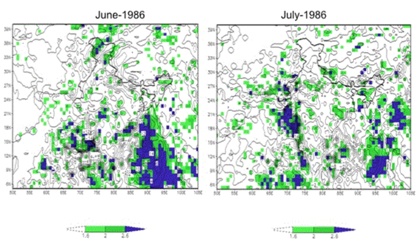

Figure 9: Precipitation change (mm/day) in IR-1 sensitivity experiment, for June and July 1986 significant at 5% (grid cells are shaded with green color) and 1% level of significance (grid cells are shaded with blue color).

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5) From Figure 10 it is observed that there is increase in LHF over Central India, but decrease precipitation over Arabian sea (AS) and eastern regions of India for both JJAS season of 2009, 2010. Though there is increase in wind magnitude at 850 hPa over Central India, but precipitation has also increased at few locations over central and north-western regions of India.

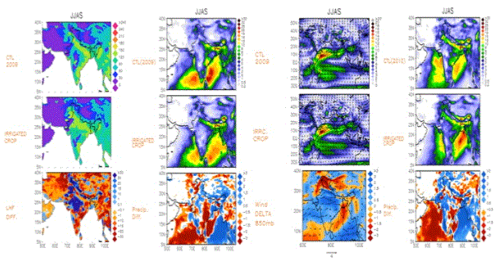

Figure 10: IR 1, sensitivity experiment (a) latent heat flux (b) precipitation change (c) 850 hPa wind, change for JJAS 2009 (El Niño+ drought year) and (d) JJAS 2010 (La Niña + normal) precipitation change.

6) The mechanism of precipitation increase or decrease due to increase in irrigation activity is dependent on season or time scale in the Indian monsoon domain and regime. As pointed out by previous studies [40,41], the negative feedback effect of soil moisture variability can arise by increased soil moisture leading to increased evaporation which can cool the surface temperature and thereby decreasing the temperature contrast that drives the mean monsoon. In our study it is also found that though there is increase (decrease) in soil moisture, evapotranspiration, latent heat flux (2 m-temperature, runoff) over CI, but precipitation (JJAS) is not increasing particularly over the regions where there is maximum increase in LHF. It is also curious to note that evaporative fraction and Bowen's ratio in decreasing over these regions though latent heat flux has increased over whole of the country. During the pre-monsoon season (MAM) precipitation has increased over PI and some parts of NWP.

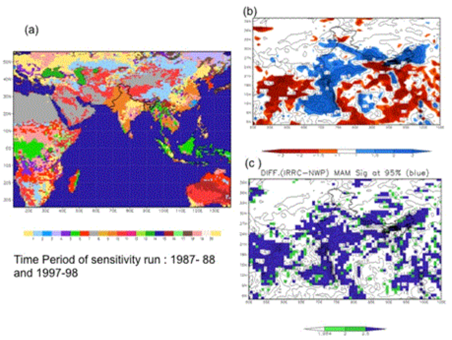

Figure 11: Irrigation experiment 2 (IR 2) (a) sensitivity vegetation map of IR 2. (b) Pre-monsoon (MAM) precipitation changes for year 1987 ((El Niño+ drought year) and (c) precipitation change (mm/day) for MAM-1987 significant at 95% (95% significant grid cells are shaded with green color) and 99% level of significance (99% significant grid cells are shaded with blue color).

7) Second sensitivity experiment (IG 2) is done to perform increase in irrigation activity over NWP region of Indian subcontinent (Figure 11). Precipitation is significantly increased during pre-monsoon season (MAM) over CI and west India (Figure 11). During winter season (JFM, DJF) there is no precipitation difference over CI. During JJAS season there is decrease in precipitation over Indian (land) region, with increase only over Himalayan region (Figure 12). A decreased land-sea temperature contrast (Figure 13) and hence, a weakened Indian summer monsoon is consistent with Meehl [41,42], Lee et al. [43,44] There is increase in surface pressure over NWP region by 1 to 1.5 hPa in the IR2 experiment [45]. Thus, the decrease in early Indian summer monsoon (ISM) rainfall over the Indian subcontinent appears partially related to the decreased land-sea heat contrast and decrease in wind magnitude over Western Ghats, due to increase in irrigated regions over land. The decrease in wind magnitude and reversed direction is observed at 850 hPa and 500 hPa and correspondingly slight increase in wind magnitude at 200 hPa (Figure 15a). Related increase in pre-monsoon (MAM) precipitation and hence vegetation, both of which correspond to an increase in the root zone and surface soil moisture, LHF, evaporative fraction and a decrease in the SHF during the monsoon (JJAS) season (Figures 13 and 14). The results from irrigation (IG1 and IG2) sensitivity experiment performed at 90 km are similar but the difference is that Bowen's ratio over NWP, CI has decreased more in IG2 than in IG1 experiment (Figures 7 and 13). In the IG 2 sensitivity experiment the areas of decreased rainfall during JJAS season coincided with the areas of increased rainfall during pre-monsoon (MAM) season (Figure 12).

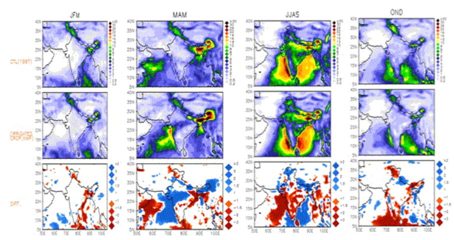

Figure 12: IR 2, sensitivity experiment JJAS precipitation change for year 1987 (El Niño+ drought year) season (a) JFM (b) MAM (c) JJAS (d) OND.

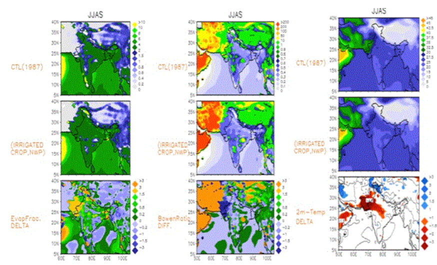

Figure 13: IR 2, sensitivity experiment changes for year 1987 (El Niño+ drought year) (JJAS season) (a) evaporative fraction (b) Bowen's ratio (c) 2 metre-Temperature.

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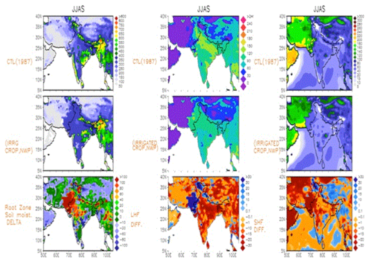

Figure 14: IR 2, sensitivity experiment changes for year 1987 (El Niño+ drought year) (JJAS season) (a) root zone soil moisture (b) Latent heat flux (c) Sensible heat flux.

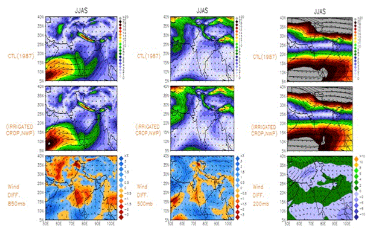

Figure 15: IR 2, sensitivity experiment JJAS wind magnitude and direction change for year 1987 (El Niño+ drought year) (a) 850 hPa (b) 500 hPa (c) 200 hPa.

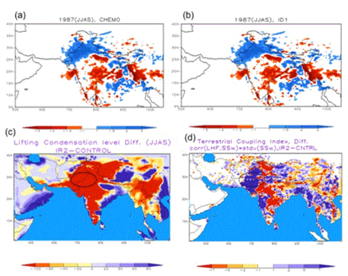

Figure 16: IR 2-50 km, sensitivity experiment (50 km) JJAS precipitation changes for 1987 (El Niño+ drought year) (a) with chemistry aerosol module OFF (b) with chemistry aerosol module ON (c) difference in lifting condensation level (d) difference in terrestrial coupling index, between IR2-50 km and control experiment.

8) In the IR2 sensitivity experiment when the model is run at 50 km, (without and with chemistry aerosol module) it is observed that due to intensification of irrigation activities over north-western regions of India there is increase in JJAS precipitation there (Figure 16, significant at 1% level of significance). It is also observed that over north-western regions of India latent heat flux, evaporation, terrestrial coupling index (45, Figure 16) increases whereas sensible heat flux, 2 metre temperature, temperature at 850 hPa, 700 hPa, lifting condensation level(LCL) (Figure 16) decreases. The decrease in land-ocean temperature gradient coupled with formation of anomalous anticyclonic circulation over India is preventing the moisture-laden easterlies over Bay of Bengal (BOB) to move towards land during monsoon season. Hence, the increase in precipitation during monsoon season over north-western regions of India can be attributed to decrease in LCL and increase in terrestrial coupling index.

Summary and Conclusions

Firstly, it is important to mention that the results and conclusion drawn are based on sensitivity experiments using regional climate model, RegCM4.0 simulations. All the sensitivity experiments performed show that model has sensitivity to land surface changes. In this irrigation study we have investigated the influence of intensive irrigation on surface fluxes, atmospheric circulation and the importance of surface soil moisture over north-western regions of India. Douglas et al. [46], Lee et al. [43] examined the effects of land cover change particularly enhanced irrigation activity on Indian summer monsoon (ISM) rainfall. With our study we have tried to answer the following questions: 1) Do increase in irrigation activity effect monsoon precipitation (2) Do soil moisture variability arising due to increased soil moisture leads to increased evaporation and hence precipitation. This study supports the conclusion that increase in irrigated area and vegetation activity during the ISM season promotes an increase in latent heat flux and decrease in sensible heat flux thereby favouring a reduced horizontal temperature gradient. Also, there is decrease in 2 metre temperature, maximum and minimum ground temperature. Therefore, increase in agricultural activity (irrigation) appears to be a significant factor affecting the ISM. The proposed mechanism offered based upon irrigation sensitivity simulations is given below:

1) Increase in irrigation → Increase in LHF and decrease in SHF→ Decrease in 2-metre surface temperature/ground temperature (Kueppers et al. [7] → Decrease in land–sea temperature contrast → Decrease in summer monsoon precipitation(JJAS) over the Indian (land) region [43], but increase in March-April-May precipitation over CI (statistically significant at 99% level of confidence). This increase in pre monsoon rainfall is also reported in Lodh [18].

The irrigation sensitivity simulations performed at 90 km resolution shows increase in pre-monsoon (MAM) precipitation. Though the signals are subtle but over CI, summer (JJAS) precipitation is not affected by increase in soil moisture and latent hat flux due to increased irrigation activity. Evaporative fraction has decreased over CI region. Understanding the mechanisms of the change in precipitation due to soil moisture is difficult because of complex relationship existing between soil moisture, evaporation from surface and moisture flux convergence. Thus, by using land use change irrigation sensitivity experiments forced over major part of north India including IGP (in IG 1) and over NWP (in IG 2) experiment, it is observed that the sensitivity in soil moisture and land surface fluxes changes is limited to north-western part of India.

When the model is run at 50 km resolution, there is increase in precipitation over north-western region of India during monsoon (JJAS) season. The increase in precipitation during monsoon season over north-western regions of India can be attributed to land atmosphere interactions, as there is decrease in LCL and increase in Dirmeyer's terrestrial coupling index. Though previous studies like Niyogi et al. [16] suggests that with agricultural intensification, pre-monsoon precipitation over peninsular and northern India could be reducing. However, from our modelling study it is observed that both pre-monsoon and monsoon precipitation has increased (decreased) particularly over NWP (CI, Eastern) parts of India. Rai et al. [47] also conclude from their study that pre-onset rainfall anomaly over north-western regions of India is associated with decrease in ISMR. The increase in precipitation during monsoon season over NWP can be attributed to possible land-atmosphere interactions happening there in the model, as it is observed that terrestrial coupling index is increasing and LCL is decreasing over north-western regions of Indian subcontinent. In all the irrigation sensitivity experiments performed it is observed that soil wetness (runoff) increases (decreases) over north-western regions of Indian subcontinent. Hence, wastelands over north-western and central Indian regions can be made arable through increase in irrigation activities there. The conclusions rose by Saeed et al. [17] that the actual representation of irrigation activities over north-western regions of India is valid and important for realistic simulation of India summer monsoon and its response under global warming.

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