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Impact of irrigation on the South Asian summer monsoon

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[1] The Indian subcontinent is one of the most intensely irrigated regions of the world and state of the art climate models do not account for the representation of irrigation. Sensitivity studies with the regional climate model REMO show distinct feedbacks between the simulation of the monsoon circulation with and without irrigation processes. We find that the temperature and mean sea level pressure, where the standard REMO version without irrigation shows a significant bias over the areas of Indus basin, is highly sensitive to the water used for irrigation. In our sensitivity test we find that removal of this bias has caused less differential heating between land and sea masses. This in turns reduces the westerlies entering into land from Arabian Sea, hence creating conditions favorable for currents from Bay of Bengal to intrude deep into western India and Pakistan that have been unrealistically suppressed before. We conclude that the representation of irrigated water is unavoidable for realistic simulation of south Asian summer monsoon and its response under global warming.

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1. Introduction

[2] With dependence of 22% of world's population on its annual rainfall, South Asian Summer Monsoon (SASM) plays a crucial role by effecting water resources, agriculture, economics and human mortality of the region. Given the reliance of lives and economies of many countries in Asia on monsoon rainfall [*Cadet*, 1979], the understanding of processes affecting the monsoon is an issue of both scientific and societal importance.

[3] Since South Asia is one of the most intensely irrigated regions of the world [*Sacks et al.*, 2008], the role of irrigation in modifying the local climate through feed back mechanisms has been well recognized in earlier studies. *De Rosnay et al.* [2003] conducted a two year model simulation directed by the 1987–1988 International Satellite Land Surface Climatology Project data sets by coupling an irrigation module with a land surface model and compared the effects of irrigated against non-irrigated land over the subcontinent. *Douglas et al.* [2006] presented a conceptual approach and investigated the changes across India between a pre-agriculture and a contemporary agriculture land cover. Both of these studies deal with the irrigation effect on the atmospheric moisture and energy vertical fluxes, but do not take into account the effects on large-scale SASM circulations. More recently, *Lee et al.* [2009] highlighted the importance of irrigation over the India by statistically associating the changes of observed rainfall with irrigation. *Douglas et al.* [2009] simulated a five-day monsoon event using different crop scenarios and identified changes in circulation patterns and precipitation over India. Considering the complexity of processes and influence of different regions involved in the SASM phenomenon, there is a need of evaluation of irrigation affects over larger domain and longer time scale.

[4] Since more than a decade, the heat low over Pakistan and adjoining north-west India is used as an important predictor for SASM rainfall [*Singh et al.*, 1995]. The major part of this heat low region falls inside the densely irrigated Indus basin, which has been used for irrigation since ancient times (Figure S1 of the auxiliary material).[2] The Indus basin is the largest contiguous irrigation network in the world and its surface water is heavily manipulated by building large dams, link canals, watercourses etc. and hence resulting in modification of the amount of water in soil [*Khan et al.*, 2008]. It is estimated that the Indus River drains only one-eighth of the $\sim$400 km^3 water that annually falls on the basin in the form of rain and snow, with the remainder used mostly for irrigation and returned to the atmosphere by evapotranspiration (ET) [*Karim and Veizer*, 2002]. Therefore, it can be assumed that this huge manipulation of water for irrigation would modulate the local climate occurring in the heat low region and therefore may effect the large-scale SASM's circulations.

2. Methods

[5] In this study we have applied the Max Planck Institute's REgional Model (REMO) [*Jacob*, 2001; *Jacob et al.*, 2007] over South Asian domain, forced with so called "perfect" lateral boundary conditions obtained from the European Centre for Medium Range Weather Forecasts reanalysis (ERA40) [*Uppala et al.*, 2005]. REMO has been applied at a resolution of ½ degree ($\sim$55 km) over the South Asian domain which encompasses 12°S to 42°N and 35°E to 110°E with 109 grid points along the latitude and 151 grid points along the longitudinal direction. All the results presented are averaged over four monsoon months June, July, August and September.

[6] The first simulation comprises of 40 years from 1961 to 2000 (REMO-baseline), three years from 1958 to 1960 are considered as spin up. In the second simulation, in order to take into account the effect of irrigation, we conducted a sensitivity simulation using a map of irrigated areas as shown in Figure S2 [*Siebert et al.*, 2005]. This is then remapped to 0.5-degree resolution and brought to the REMO South Asian model domain. For the irrigated

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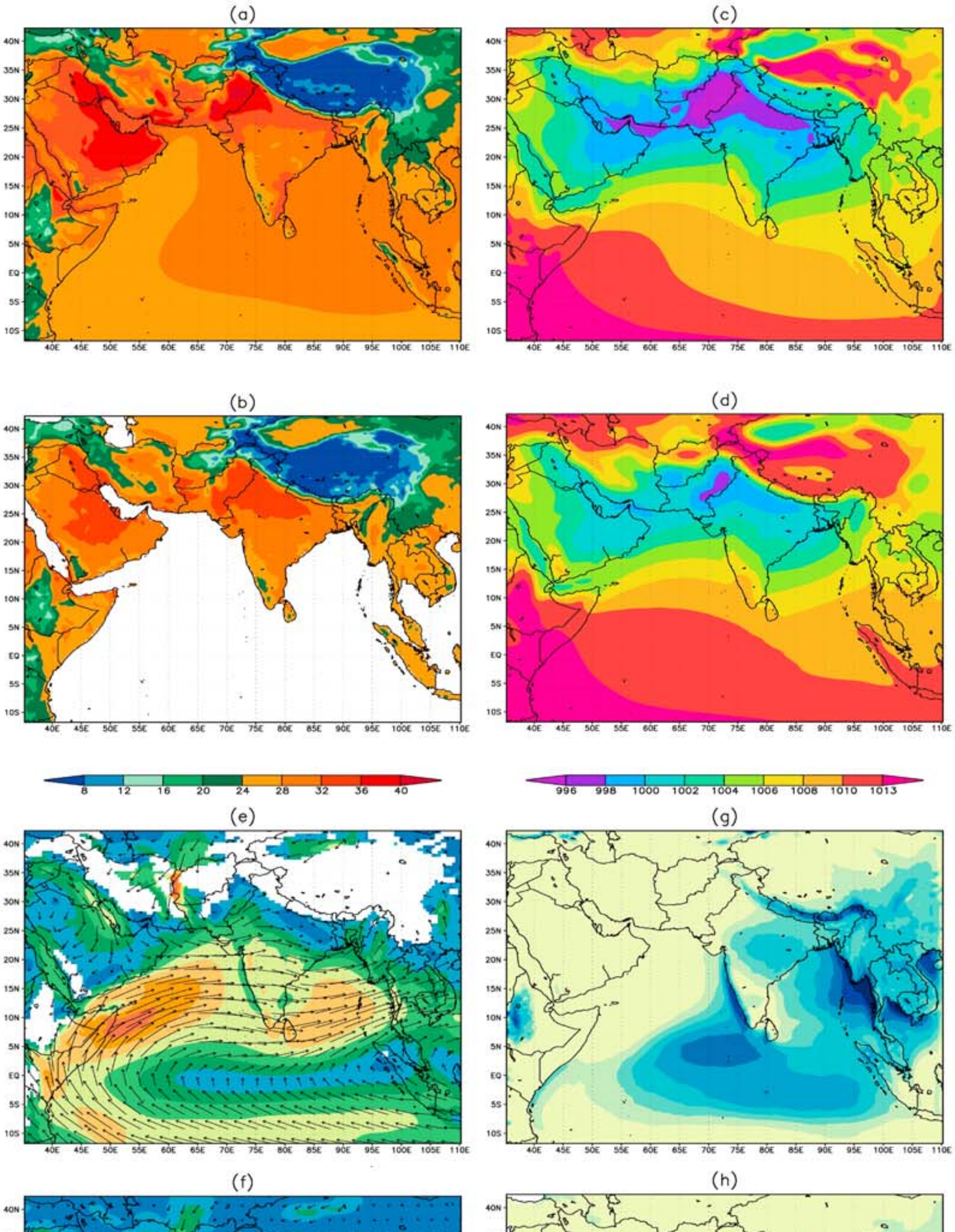

Figure 1. Summer (JJAS) climatologies (1961–2000) of 2m temperature (°C) (a) REMO, (b) CRU observations; mean sea level pressure (hPa) (c) REMO, (d) ERA40 reanalysis; 850 hPa winds (m/sec) (e) REMO, (f) ERA40 reanalysis; and precipitation (mm/day) (g) REMO, (h) *Willmott and Matsuura* [2009] observations.

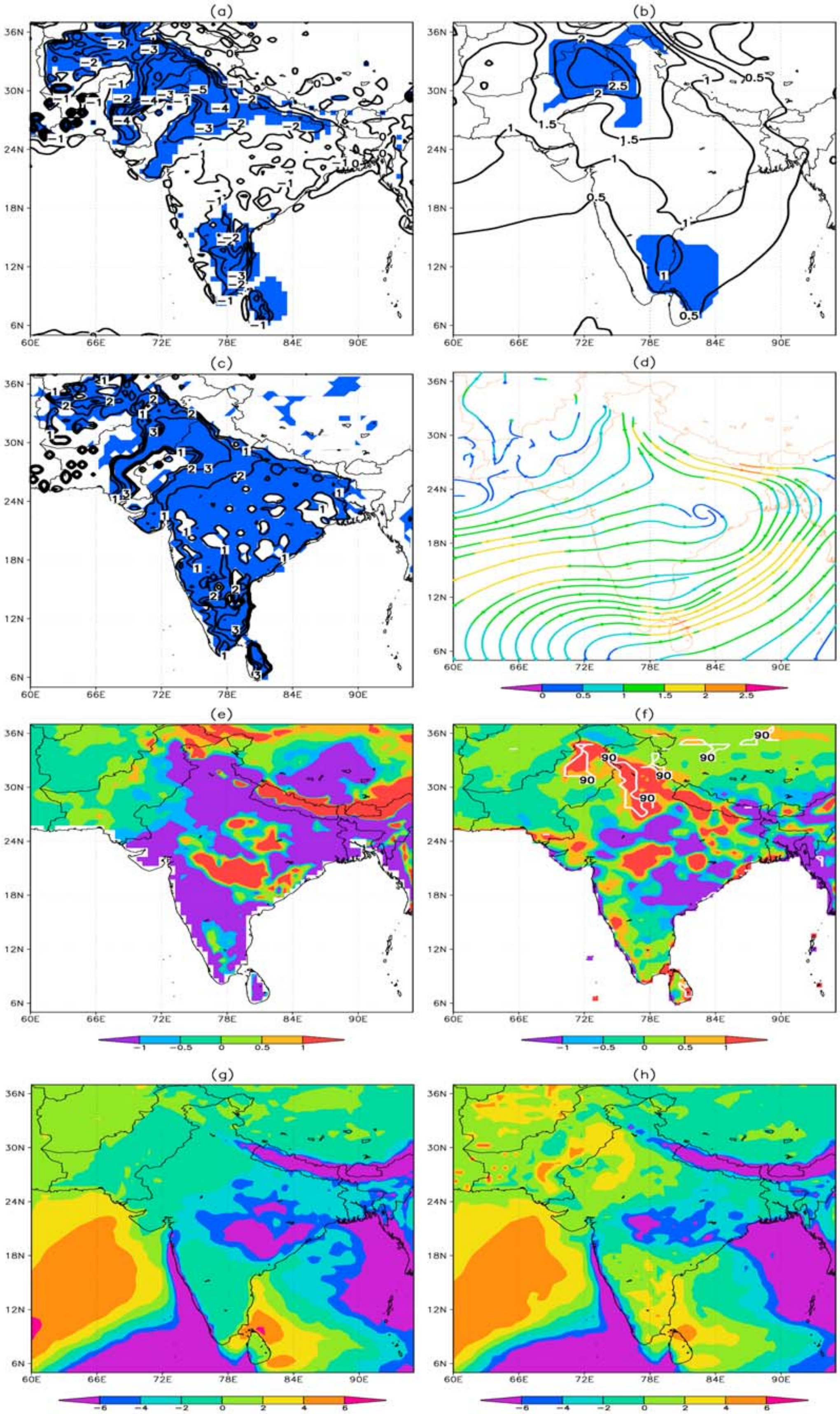

Figure 2

fraction of a grid box, we have increased the soil wetness to a critical value in each time step, so that potential ET can occur. In REMO, following *Roeckner et al.* [1996], this value is set to 75% of the soil water holding capacity by assuming that irrigation is conducted to fulfill optimal conditions for the vegetation/crops, so that they can transpire at a potential rate. The sensitivity experiment is conducted from 1986–1992 with the initial three years discarded as spin up for new soil moisture conditions (REMO-irrigation).

3. REMO-Baseline

[7] Considering "notoriously difficult to predict" nature of SASM [*Jayaraman*, 2005], model has reproduced a number of important features satisfactorily in REMO-baseline experiment. It has simulated the characteristic wide range of 2m temperatures, ranging from more than 40°C in Pakistan, to less than 0°C over the Himalayas (Figures 1a and 1b). Over the Indian subcontinent, the model is characterized by a warm temperature bias of up to several degrees for most of the land areas. The largest deviation exceeding 5°C occurs over the heat low regions of the Indus basin as discussed above. The model simulates the location of heat low region, however the overestimation of temperature has caused an acute underestimation of sea level pressure (MSLP) (Figures 1c and 1d). This has resulted into increased differential heating between ocean and land, and therefore the overestimation of winds entering into the plains of the Indian subcontinent from the Arabian Sea (Figures 1e and 1f). In monsoon break periods, these winds play a passive role when monsoon currents from Bay of Bengal (BOB) are shifted towards northern India along the foothills of Himalaya and towards southern peninsula, allowing more westerlies to intrude inside the plains of central India [*Prasad and Hayashi*, 2007]. In our case however, the excess of differential heating between land and sea has given the active role to the westerlies to intrude inside the central India throughout the monsoon season. This causes a situation unfavorable for westward propagating currents from BOB to intrude deep into western India and Pakistan. Therefore, less moisture is advected causing an underestimation of precipitation over this area (Figures 1g and 1h).

[8] In his study of SASM with the General Circulation Model ECHAM4, *May* [2003] found a similar warm bias over Indus basin, and suggested that it was because of an unrealistic drying of the soil during the dry season (boreal winter and spring) due to the model's limited capacity of storing water in the ground. This leads to a reduction of evaporation and hence would reduce the local production of precipitation during the wet season. However in REMO, there is increased soil water storage capacity as compared to ECHAM4, and similar behavior of REMO leads to rejection of this hypothesis [*Hagemann et al.*, 1999]. Although REMO and ECHAM4 have different physics and dynamics than RegCM3, similar overestimation of temperature over the same region is found in the simulation of SASM using RegCM3 [*Ashfaq et al.*, 2009]. This similar bias in different models forces us to believe that a characteristic process of the region might be missing in all these models.

4. REMO-Irrigation

[9] As mentioned above, the largest positive temperature bias simulated by REMO is confined to highly irrigated basins of the Indian subcontinent. In the REMO-baseline experiment, simulated surface runoff and drainage account for 45% of the total precipitation falling over Indus basin, which is much larger than the observed value of 14% [*Karim and Veizer*, 2002]. This means that REMO simulates extra ∼30% of precipitation entering runoff instead of ET. This excess water is lost from the model, as in REMO and almost in all regional models, the lateral surface runoff and drainage generated in each time step are removed from the simulated water cycle due to the absence of any routing and irrigation schemes. The removal of this water in REMO results in the underestimation of ET that accounts for only 55% of total precipitation compared to the observed value of 84% [*Karim and Veizer*, 2002].Consequently, this leads to a reduction of local precipitation as proposed by *May* [2003].

[10] When irrigation is accounted for, a more realistic behavior of the simulated climate is yielded. Figure 2 compares the changes simulated by REMO-irrigation with the REMO-baseline run for the period 1989–1992. Improvement in temperature and MSLP can be seen all over the domain, but statistically significant and most pronounced changes are present over Indus, Ganges and southern India (Figures 2a and 2b). It can be noticed that these changes have occurred over the regions where there was an acute bias before (Figures 1a to 1d), hence showing better representation of these variables. Figure 2c indicates significant increase in ET over the whole subcontinent region, again with largest increase over Indus and southern India.. The ERA40 ET is also model generated; yet it shows realistic patterns with higher values over Indian subcontinent than over the drier region in the western part of the domain, whereas REMO-baseline does not show a realistic simulation of ET with very low values over the highly irrigated Indian subcontinent especially over the Indus basin (Figure S3). In our REMO-irrigation experiment, the introduction of water on the irrigated grids has caused the pattern of ET quite similar to that of ERA40, and over the four years period from 1989–1992 the correlation over land points between REMO-irrigation and ERA40 is increased to ∼0.88 as compared to the correlation between REMO-baseline and ERA40 of ∼0.83. REMO-baseline simulated ET is ∼52% of the total precipitation over the Indus basin, which was quite lower than the long term observed value of

Figure 2. Simulated summer (JJAS) averages for 1989–1992 zoomed over the Indian subcontinent. Difference (REMO-irrigation minus REMO-baseline) of (a) 2m temperature (°C), (b) Mean Sea Level Pressure (hPa), (c) Evapotranspiration (mm/day), (d) 850 hPa winds; shaded blue area represent significance at 90% from two tailed t-test. Precipitation (mm/day) differences of (e) REMO-baseline minus WM, and (f) REMO-irrigation minus REMO-baseline with areas significant at 90% level are shown by closed polygons. Simulated convergence (mm/day) of (g) REMO-baseline, and (h) REMO-irrigation.

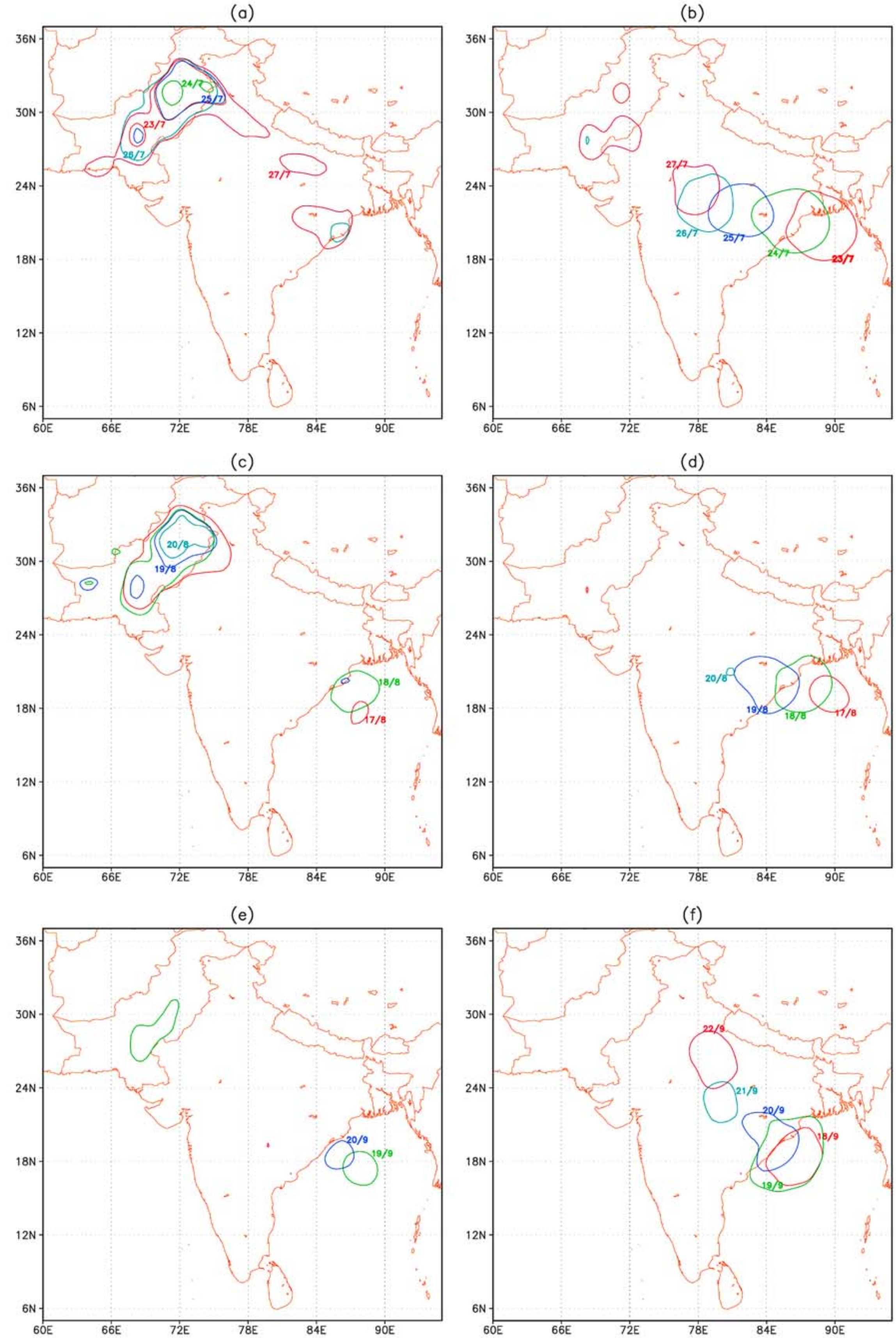

Figure 3. Monsoon depressions/lows development and movement: July 23–27, 1991 at 993 hPa MSLP (a) REMO-baseline (b) REMO-irrigation; Aug 17–20, 1990 at 996 hPa MSLP (c) REMO-baseline (d) REMO-irrigation; and Sep 18–22, 1991 at 999 hPa MSLP (e) REMO-baseline (f) REMO-irrigation.

84% [*Karim and Veizer*, 2002]. However in the REMO-irrigation experiment, the value of ET is ∼92% of the total precipitation which is not unrealistic as compared to 84% of the observed value. Here, an overestimation could be expected as the REMO-irrigation experiment assumes optimal irrigation conditions. The wind pattern shows complex behavior with less flow towards the foothills of Himalaya and into Ganges and Indus basin. However, from central India downwards, the decrease in westerly winds from the Arabian Sea into the Indian plains is also reduced due to the reduction of land sea differential heating (Figure 2d).

[11] The only significant change in precipitation is the increase in the western-northwestern India and Pakistan (Indus and Ganges basins), which is attributed to the local recycling of water, also shown in the convergence plot (Figures 2g and 2h). Convergence C of vertically integrated water vapor flux in a grid box is calculated from the water vapor conservation equation [*Peixoto and Oort*, 1992].

$$C = ET - P - \Delta S,$$

where ET and P are evapotranspiration and precipitation respectively, and ΔS is the change of vertically integrated specific humidity during each 6 hourly time step. Here the positive values will represent divergence and negative values will show convergence of water vapor in a grid box.

[12] From Figures 2g and 2h, the net divergence of moisture from western India and Pakistan area in REMO-irrigation as opposed to net convergence in REMO-baseline can be noticed. This indicates the increased contribution of evapotranspiration in providing increased amount of moisture for precipitation, hence causing local recycling. In central India, the REMO-irrigation has reduced the precipitation's wet bias near the BOB coast and is producing more precipitation further inland. This behavior can also be seen in convergence plots where the convergence is reduced in the region near the BOB and a convergence maximum is formed west of 78°E. As mentioned before that due to the reduced westerlies (Figure 2d) there is more chance for the monsoon currents, in the form of depressions/lows (Ds/Ls) and cyclones originating from BOB, to intrude deep into land in REMO-irrigation. Under normal circumstances, these currents play a vital role in distribution of rainfall during SASM. Whereas in REMO-baseline, the precipitation wet bias near BOB over central India is because of the blocking effect of westerlies, limiting the movement of westward propagating monsoon currents. This leads Ds/Ls and cyclones to deposit their moisture over coastal areas without intruding deep inside the land.

[13] To further ascertain our findings, examples of the development and movement of monsoon Ds/Ls are also considered (Figure 3). The criteria for selecting these examples is their occurrence in different months, should be captured by either of the simulation during the period 1989–1992 and discussed in earlier published literature [*Mahajan et al.*, 1995; *Narkhedkar et al.*, 2007; *Seetaramayya et al.*, 1993]. It is evident that the development of monsoon Ds/Ls is more pronounced in REMO-irrigation and travels deep into land towards western India and Pakistan in all events as compared to REMO-baseline. Moreover, in 23–27 July 1991, REMO-irrigation shows the development and inland movement of a depression, which is not even captured in the case of REMO-baseline. Therefore, the increase in precipitation in central/western India and Pakistan is not only attributed to the local recycling of moisture, but also to the currents from BOB penetrating into these areas.

5. Conclusions

[14] The present study signifies the role of irrigation in effecting the local temperature, which in turn effects large-scale circulations and precipitation. It is also mandatory to consider the irrigation over Indus Basin while analyzing effects of irrigation on SASM, which was missing in earlier studies. It may be concluded that representation of water used for irrigation is unavoidable for the realistic simulation of SASM circulation and associated rainfall in climate models. This study has also pointed out the conclusion of *May* [2002], which criticizes the use of the simple so-called bucket scheme and highlights a need for more sophisticated parameterization of land-surface hydrology of the model, in order to remove the temperature bias. In contrast, it has been shown that the non-representation of irrigation water is the root cause of this overestimation rather than the simple treatment of soil hydrology in the model.

[15] Results indicate that representation of irrigation has caused the removal of the warm bias and overestimation of the monsoon heat low. This has not only resulted in increased evapotranspiration effecting vertical exchanges and causing local production of precipitation, but also the reduction of the heat low has caused less westerlies to enter into land from Arabian Sea. This reduction of westerlies over land has created favorable conditions for currents from BOB to intrude deep into land, thereby removing the precipitation wet bias near BOB coastal area and dry bias over central/western India and Pakistan.

[16] 80% of Indus basin river flows are attributed to the melt of snow and glacier. Considering the large impact of irrigation on SASM behavior, one can assume that under global warming the changes in the timings of water inflows would shift towards earlier months, hence causing changes in cropping patterns and subsequently irrigation. It may also be concluded that the changes in irrigation patterns over the Indus basin may have a substantial effect on SASM circulation and associated rainfall under climate change.

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