Impact of Potential Large-scale and Medium-scale Irrigation on the West African Monsoon and its Dependence on Location of Irrigated Area

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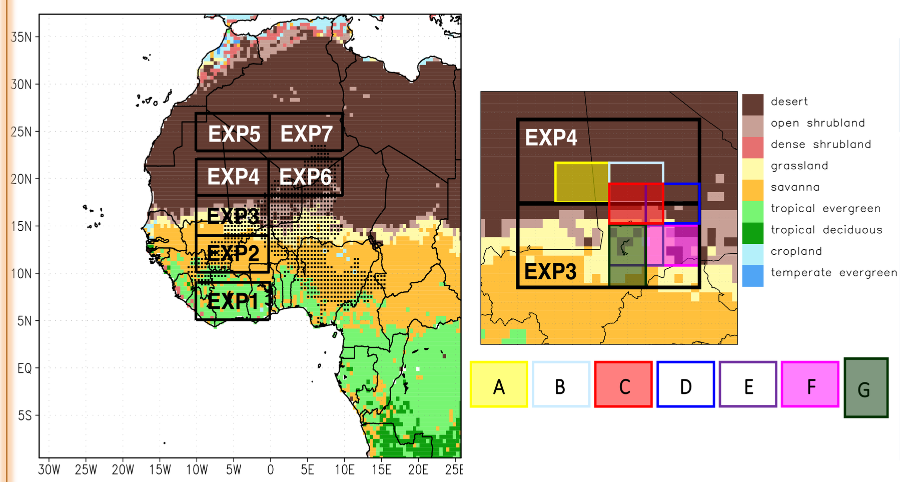
Abstract

This study investigates the impact of potential large-scale (about 400,000 km2) and medium-scale (about 60,000 km2) irrigation on the climate of West Africa using the MIT Regional Climate Model. A new irrigation module is implemented to assess the impact of location and scheduling of irrigation on rainfall distribution over West Africa. A control simulation (without irrigation) and various sensitivity experiments (with irrigation) are performed and compared to discern the effects of irrigation location, size and scheduling. In general, the irrigation-induced surface cooling due to anomalously wet soil tends to suppress moist convection and rainfall, which in turn induces local subsidence and low level anti-cyclonic circulation. These local effects are dominated by a consistent reduction of local rainfall over the irrigated land, irrespective of its location. However, the remote response of rainfall distribution to irrigation exhibits a significant sensitivity to the latitudinal position of irrigation. The low-level northeasterly flow associated with anti-cyclonic circulation centered over the irrigation area can enhance the extent of low level convergence through interaction with the prevailing monsoon flow, leading to significant increase in rainfall. Despite much reduced forcing of irrigation water, the medium-scale irrigation seems to draw the same response as large-scale irrigation, which supports the robustness of the response to irrigation in our modeling system. Both large-scale and medium-scale irrigation experiments show that an optimal irrigation location and scheduling exists that would lead to a more efficient use of irrigation water. The approach of using a regional climate model to investigate the impact of location and size of irrigation schemes may be the first step in incorporating land-atmosphere interactions in the design of location and size of irrigation projects. However, this theoretical approach is still in early stages of development and further research is needed before any practical application in water resources planning.

Experimental Design



- Model: MIT Regional Climate Model (MRCM)
- Initial and Boundary Conditions: ERAInterim Reanalysis data
- Simulation period: 1989.1.1- 2008.12.31 (20yr)
- Resolution: 50 km

	Name	Irrigation Period	Irrigated Water
Large-scale (4°x10° ≈ 400,000 km²)	EXP1	MJJAS	74 (km³/yr)
	EXP2	MJJAS	152 (km³/yr)
	EXP3	MJJAS	230 (km³/yr)
	EXP4	MJJAS	271 (km³/yr)
	EXP5	MJJAS	292 (km³/yr)
	EXP6	MJJAS	307 (km³/yr)
	EXP7	MJJAS	286 (km³/yr)

	Name	Irrigation Period	Irrigated Water
Medium-scale (2°x3° ≈ 60,000 km²)	EXPA/EXPA_S	MJJAS/First Week of JJA	45/12 (km³/yr)
	EXPB/EXPB_S	MJJAS/First Week of JJA	46/13 (km³/yr)
	EXPC/EXPC_S	MJJAS/First Week of JJA	46/13 (km³/yr)
	EXPD/EXPD_S	MJJAS/First Week of JJA	49/17 (km³/yr)
	EXPE/EXPE_S	MJJAS/First Week of JJA	50/20 (km³/yr)
	EXPF/EXPF_S	MJJAS/First Week of JJA	44/16 (km³/yr)
	EXPG/EXPG_S	MJJAS/First Week of JJA	49/21 (km³/yr)

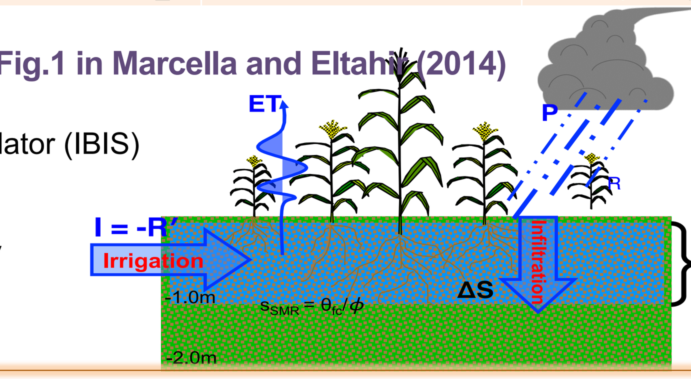
Irrigation Module within IBIS

$$\Delta S = P - R - ET + I - D$$

ΔS: Changes in storage of soil moisture
P: Precipitation
R: Runoff
ET: Evapotranspiration
I: Irrigation water
D: Drains into deeper layer

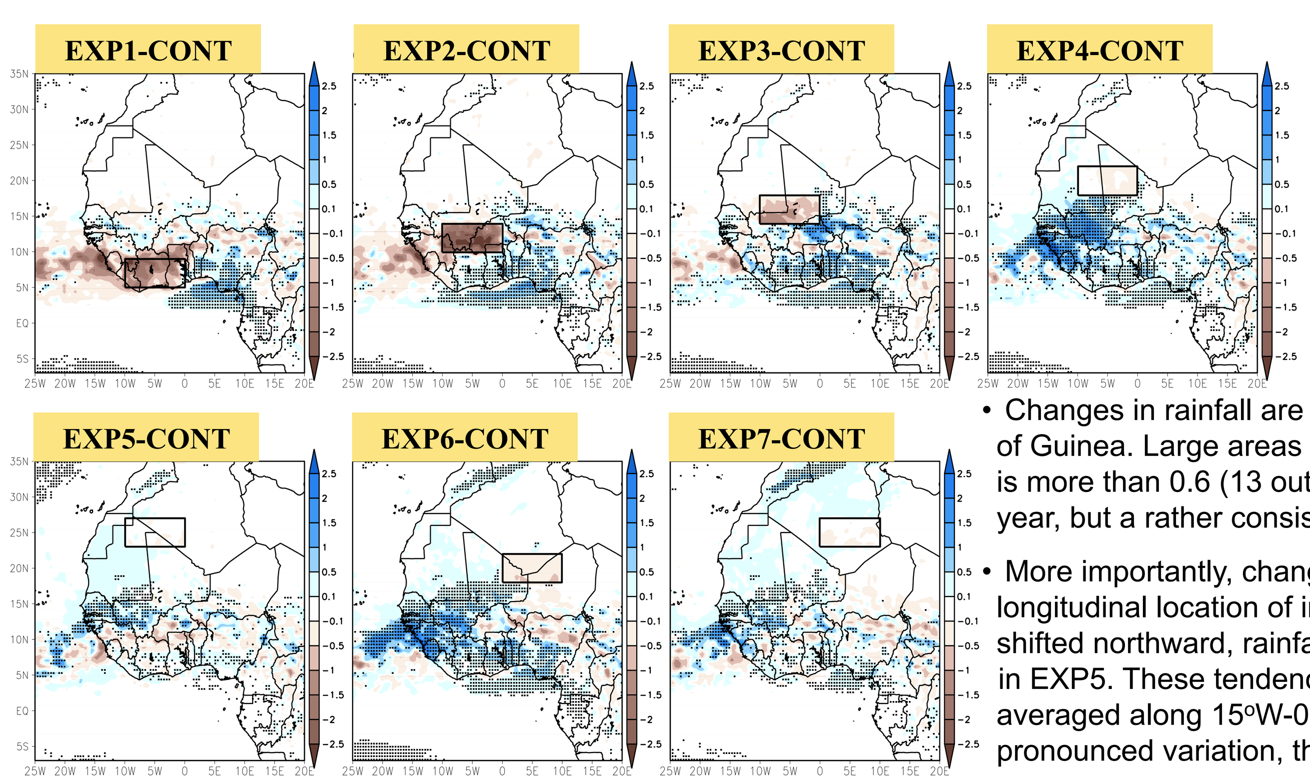
- Add anthropogenic land cover, irrigated cropland biome to the Integrated Biosphere Simulator (IBIS)
- Root zone soil moisture is forced to relative field capacity
- "Negative runoff" to supply water and conserve water balance
- Useful tool for the impact studies of anthropogenic land use change due to human activity
- Marcella and Eltahir, 2014: Introducing an Irrigation Scheme to a Regional Climate Model – A Case Study over West Africa. J. Climate, 27, 5708-5723.

Adopted by Fig.1 in Marcella and Eltahir (2014)

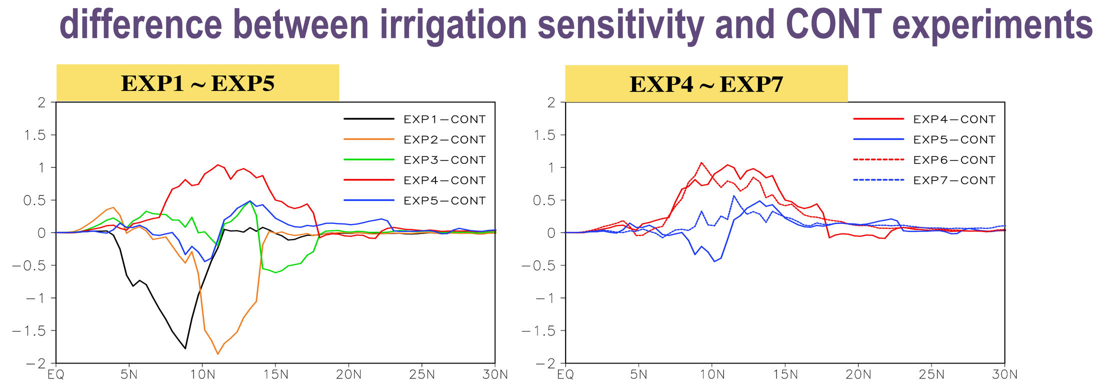


The Effect of Large-Scale Irrigation on Rainfall Change

✧ Spatial distribution of rainfall difference between Irrigation sensitivity and control (CONT) experiments averaged over May to September



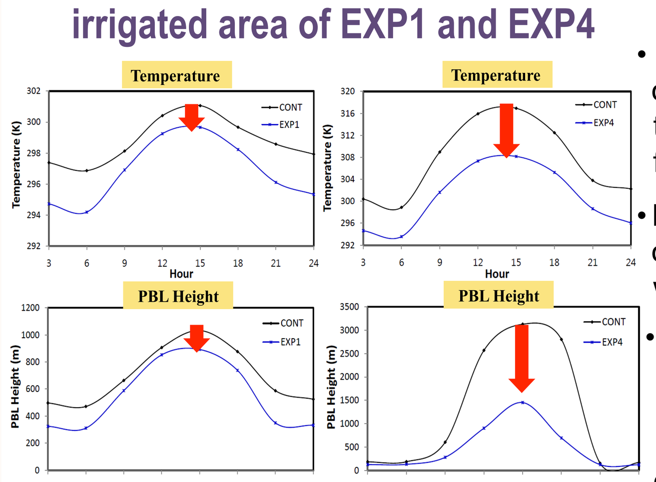
✧ Latitudinal distribution of zonally averaged (15W-0) rainfall difference between irrigation sensitivity and CONT experiments



- Changes in rainfall are simulated not only in and around the irrigated grid cells but across the Sahel and Gulf of Guinea. Large areas covered by dots indicate that the fraction of the simulation years with rainfall increase is more than 0.6 (13 out of a total of 20years), therefore, rainfall increase is not a random feature of of specific year, but a rather consistent pattern in different years.
- More importantly, changes in rainfall appear to be more sensitive to the latitudinal location rather than the longitudinal location of irrigation. A decrease in rainfall is well pronounced in EXP1, but as the irrigation is shifted northward, rainfall gradually increases and reaches a maximum in EXP4, and then decreases again in EXP5. These tendencies are clearly demonstrated in the latitudinal distribution of the rainfall, zonally-averaged along 15°W-0. While the differences between the CONT and EXP1 through EXP5 exhibit a pronounced variation, the comparison of EXP4 (EXP5) to EXP6 (EXP7) reveals similar patterns.

Mechanism of Local Response

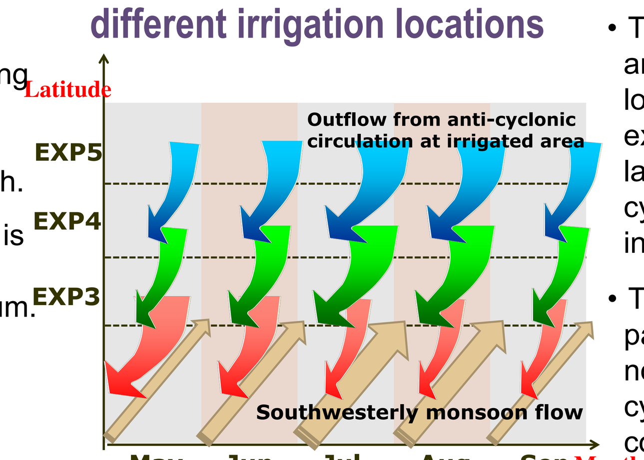
✧ Diurnal cycle of the temperature and PBL height averaged over irrigated area of EXP1 and EXP4



- Irrigation clearly leads to surface cooling over the corresponding areas. Lower temperature reduces the sensible heat flux, and restricts the PBL height growth.
- In fact, a large reduction of PBL height is observed in EXP4 during the daytime when the convection activity is maximum.
- The simulated reduction of the PBL height tends to inhibit convective triggering. In spite of the higher moist static energy, a significant increase in convective inhibition dominates and hinders the triggering of convection.
- This effect is independent of the location of the irrigation area

Mechanism of Remote Response

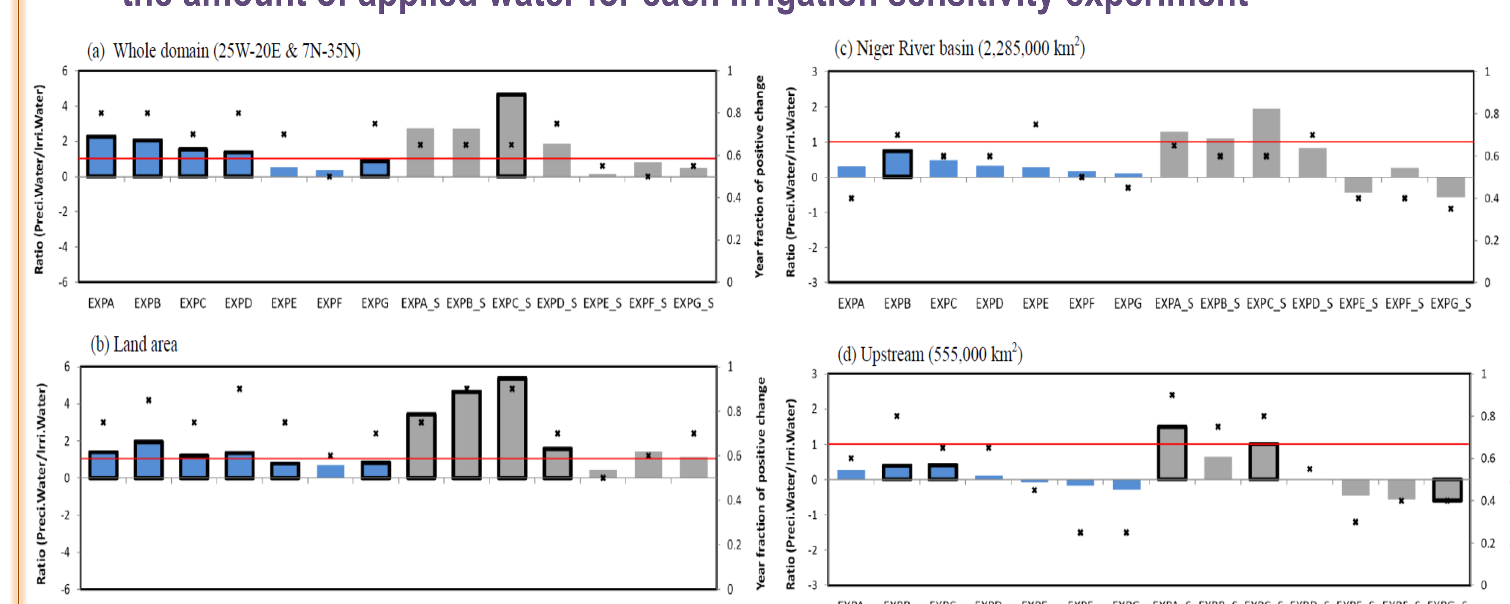
✧ Schematic diagram of remote effects leading to rainfall changes from different irrigation locations



- The EXP3, EXP4 and EXP5 all produce an anomalous anti-cyclonic circulation in the low level centered at the irrigated region due to excessive surface cooling. However, the different latitudinal location and magnitude of the anti-cyclonic circulation causes a marked difference in rainfall changes.
- The key determinants of the change of rainfall pattern is the timing and location of the northeasterly outflows derived from anti-cyclonic circulation. The northeasterly outflows collide with the prevailing (southwesterly) monsoonal flows causing additional convergence.
- Therefore, the optimal position and right timing of northeasterly outflows leads to favo rable condition for convergence consistent with prevailing monsoon flow, its latitudinal dependence and month to month variation.

The Effect of Medium-Scale Irrigation (location & scheduling) on Rainfall Change

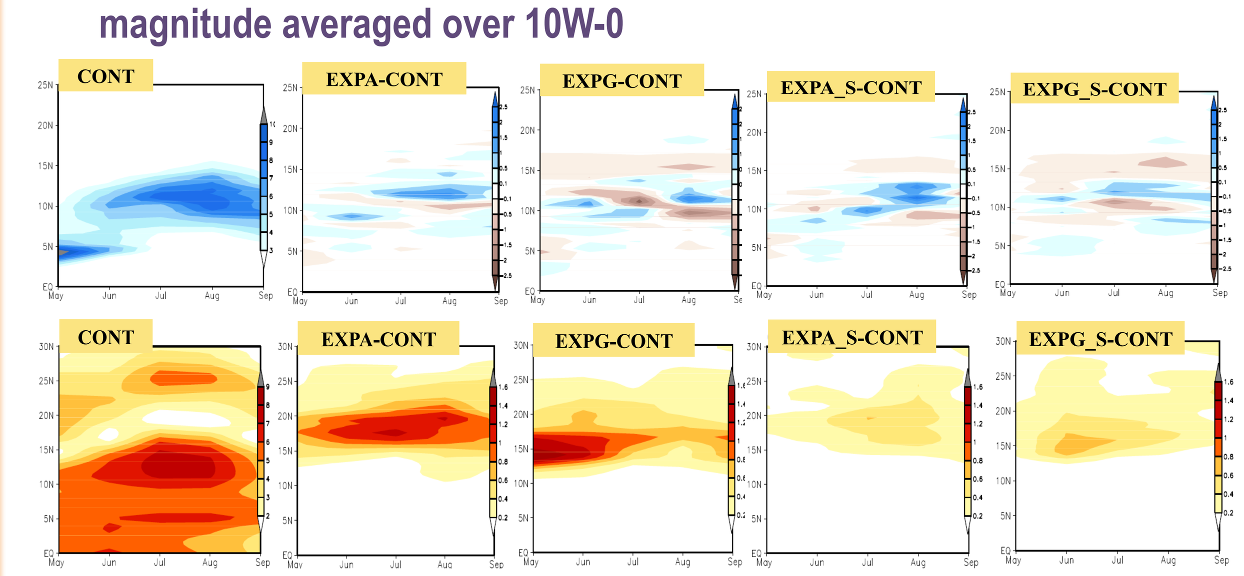
✧ The ratio between accumulated rainfall volume difference over whole domain, its land area, Niger River basin, and its upstream subbasin and the amount of applied water for each irrigation sensitivity experiment



- Irrigation has a strong impact on, rainfall and sign and magnitude of their change depend on the irrigation location and scheduling. Overall, there seem to be two groups: one group (EXPA, EXPB, EXPC, and EXPD, hereafter Group 1) shows a high ratio of rainfall increase to irrigation water and the other group (EXPE, EXPF, and EXPG, hereafter Group 2) shows a relatively low ratio. Such distinction becomes clearer in the scheduling experiments. The results from the two-tailed t-test also support the different behavior between Group 1 and Group 2. Rainfall increases in Group 1 are more statistically significant at the 95% confidence level (bar with black outline). In addition, the fraction of years with rainfall increase is generally higher in Group 1 than in Group 2.
- The reason that scheduling experiments, particularly with Group 1, show a much higher ratio is the reduction in the water supplied for irrigation, not any enhancement of the rainfall. Once scheduling is applied, generally less than one-third of irrigation water is required. Therefore, the ratio of rainfall increase to irrigation water is significantly higher even though the rainfall increase is similar or even less compared to that from the experiment without scheduling. This means that the additional water used for irrigation is not compensated enough by increases in rainfall.

Physical Mechanism behind Remote Rainfall Change

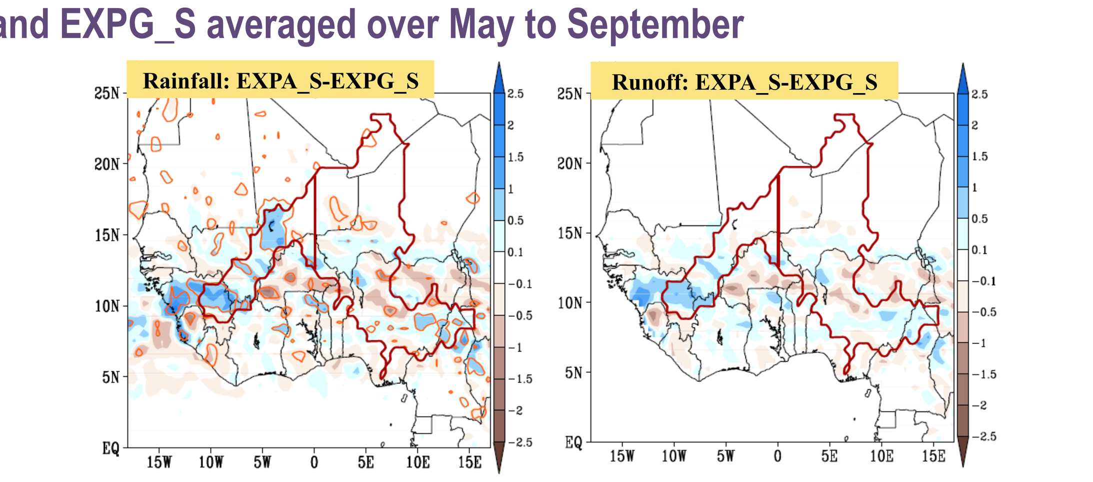
✧ Latitude-time cross section of monthly mean rainfall and wind magnitude averaged over 10W-0



- The climatological aspect of wind magnitude is well correlated with rainfall climatology, thus the changes of wind and resultant circulation can be strongly related to the change in the rainfall distribution. The key for explaining the remote impact is related to modification of the WAM circulation. Since the anomalous low-level outflows blowing from anticyclonic circulation associate with the distribution of the areas with low-level convergence through interaction with the prevailing monsoon flow, the position and timing of this flow in the control climate play an important role in remotely modulating the rainfall.

Enhancement of Rainfall &Runoff Upstream

✧ Spatial distribution of rainfall and runoff difference between EXPA_S and EXPG_S averaged over May to September



- The results of this study suggest that irrigation north of the Niger River basin (EXPA_S and EXPC_S) combined with draining of the swamps of the Inland Delta can improve the level of water availability significantly in this region. We regard this conclusion as preliminary and we plan to pursue future studies using different models to address this hypothesis further. The swamps of the Niger inner delta are of economic and ecological significance. In practical planning of future irrigation in the region those two sets of factors should be taken seriously. We are not proposing any specific drastic changes without consideration for the ecology.

References

Im, E.-S., M. P. Marcella, and E.A.B. Eltahir, 2014: Impact of potential large-scale irrigation on the West African Monsoon and its dependence on location of irrigated area. J. Climate, 27, 994-1009.

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