THE HONG KONG UNIVERSITY OF SCIENCE AND TECHNOLOGY

The impact of large-scale irrigation on rainfall in Africa using the regional climate model

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Significant Impact of Human-made Land-use Change

nature geoscience

LETTERS

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Rainfall consistently enhanced around the Gezira Scheme in East Africa due to irrigation

Ross E. Alter[1*†], Eun-Soon Im[2*†] and Elfatih A. B. Eltahir[1]

Land-use and land-cover changes have significantly modified regional climate patterns around the world[1,2]. In particular, the rapid development of large-scale cropland irrigation over the past century has been investigated in relation to possible modification of regional rainfall[3–14]. In regional climate simulations of the West African Sahel, hypothetical large-scale irrigation schemes inhibit rainfall over irrigated areas but enhance rainfall remotely[13,14]. However, the simulated influence of large-scale irrigation schemes on precipitation patterns cannot be substantiated without direct comparison to observations[15]. Here we present two complementary analyses: numerical simulations using a regional climate model over an actual, large-scale irrigation scheme in the East African Sahel—the Gezira Scheme—and observational analyses over the same area. The simulations suggest that irrigation inhibits rainfall over the Gezira Scheme and enhances rainfall to the east. Observational analyses of rainfall, temperature and streamflow in the same region support the simulated results. The findings are consistent with a mechanistic framework in which irrigation decreases surface air temperature, causing

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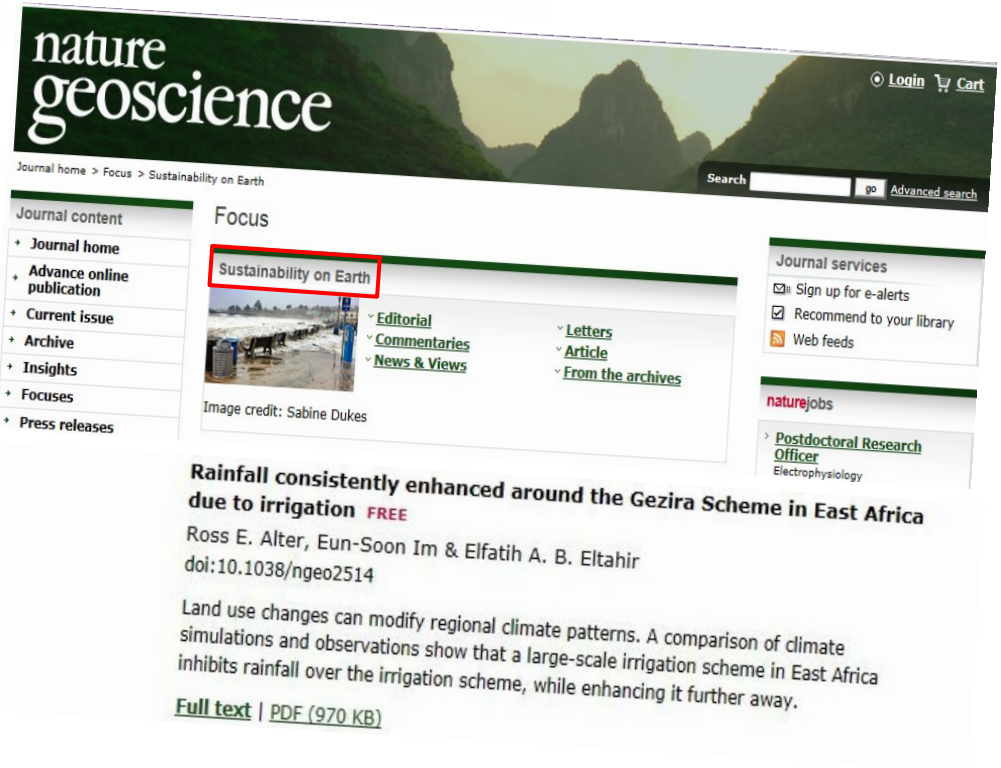


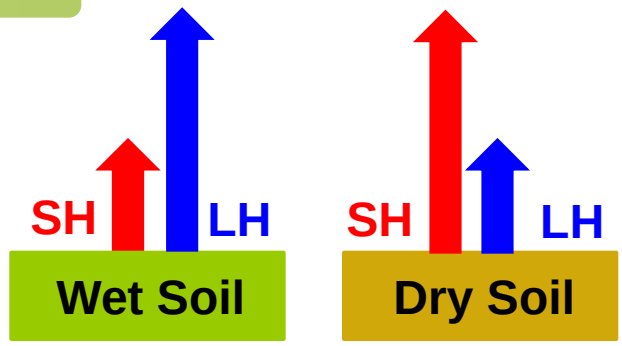
What is Irrigation ?

Definition of Irrigation

- Irrigation is the artificial application of water to the land or soil. It is used to assist in the growing of agricultural crops, maintenance of landscapes, and vegetation of disturbed soils in dry areas and during periods of inadequate rainfall [*Wikipedia*]

Irrigation-induced Changes

- Surface energy partitioning
- Water budgets
- Circulation pattern
- Local & remote rainfall



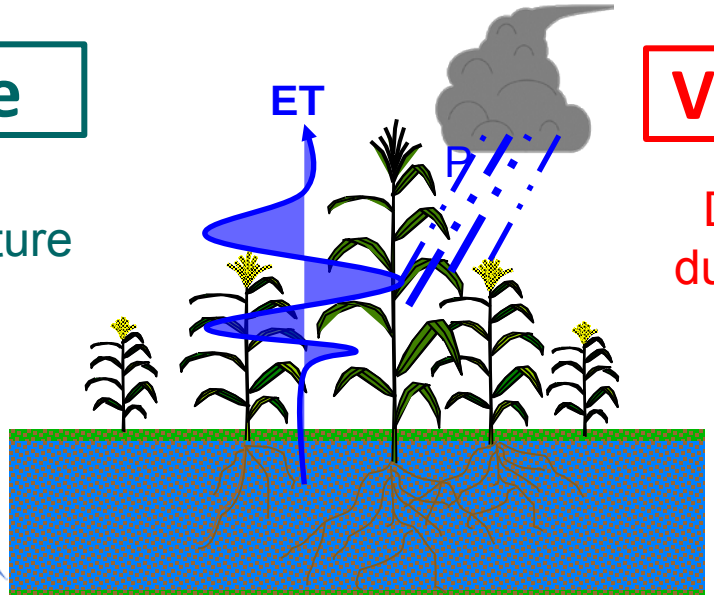
First-order Effect of Irrigation on Rainfall

Prerequisite Condition for Rainfall Formation

Moisture

Additional moisture

Promoting Rainfall



Vertical Motion

Descending motion due to surface cooling

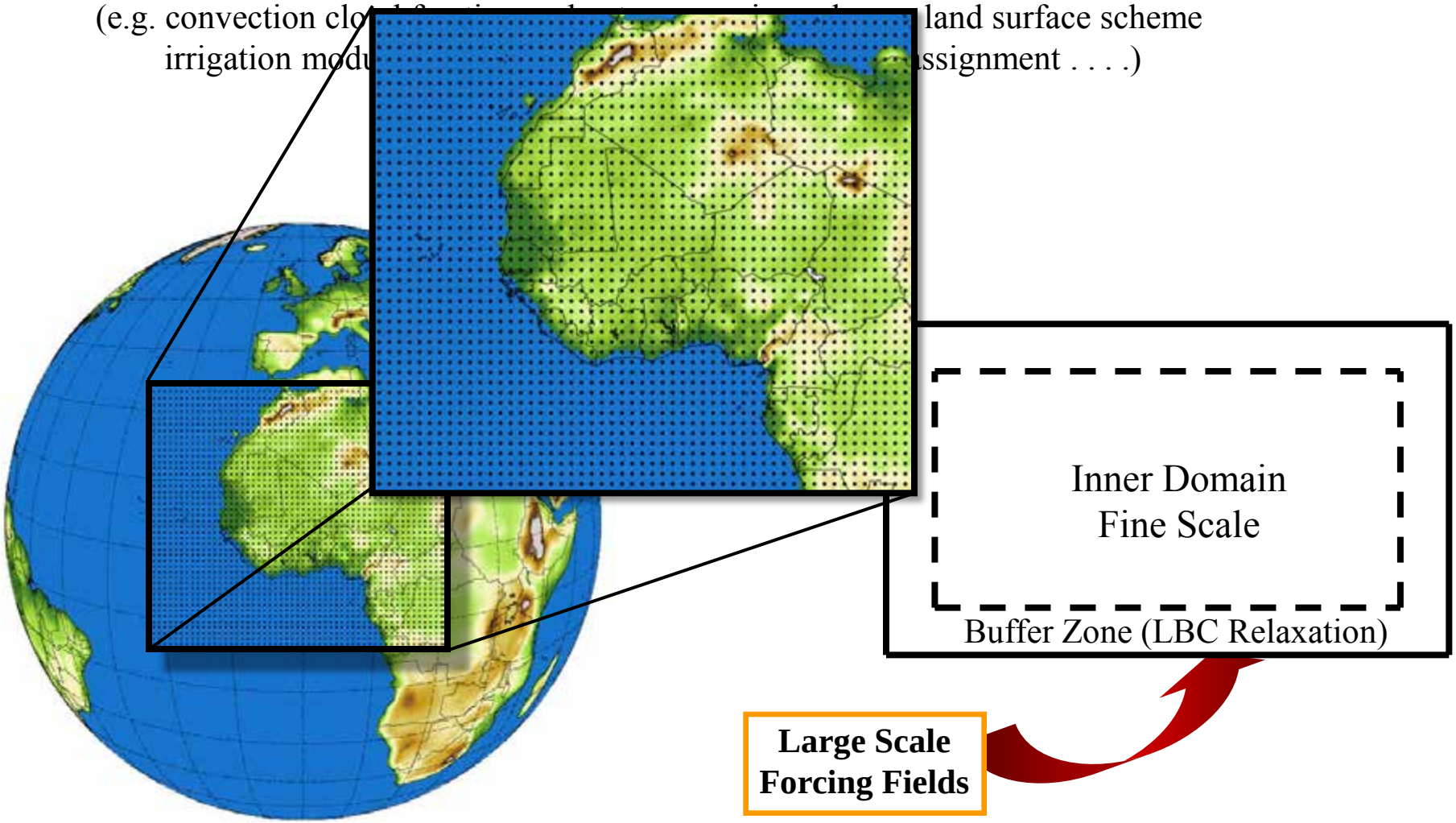
Suppressing Rainfall

MIT Regional Climate Model (MRCM)

MIT RCM Development

- Development and Improvement of the MIT Regional Climate Model (MRCM)

: Implementing or modifying various physics schemes from the version of RegCM3
(e.g. convection clo land surface scheme
irrigation modu ssignment . . . .)



IBIS Irrigation Module within MRCM

Implementation of Irrigation Module

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

Here, ΔS: Changes in storage of soil moisture

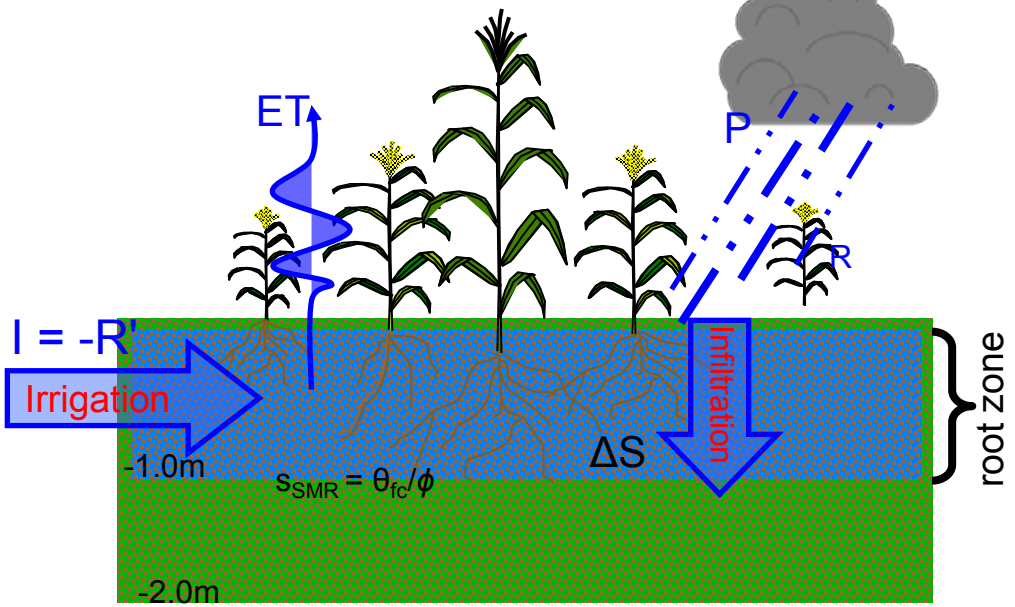
P: Precipitation

R: Runoff

ET: Evapotranspiration

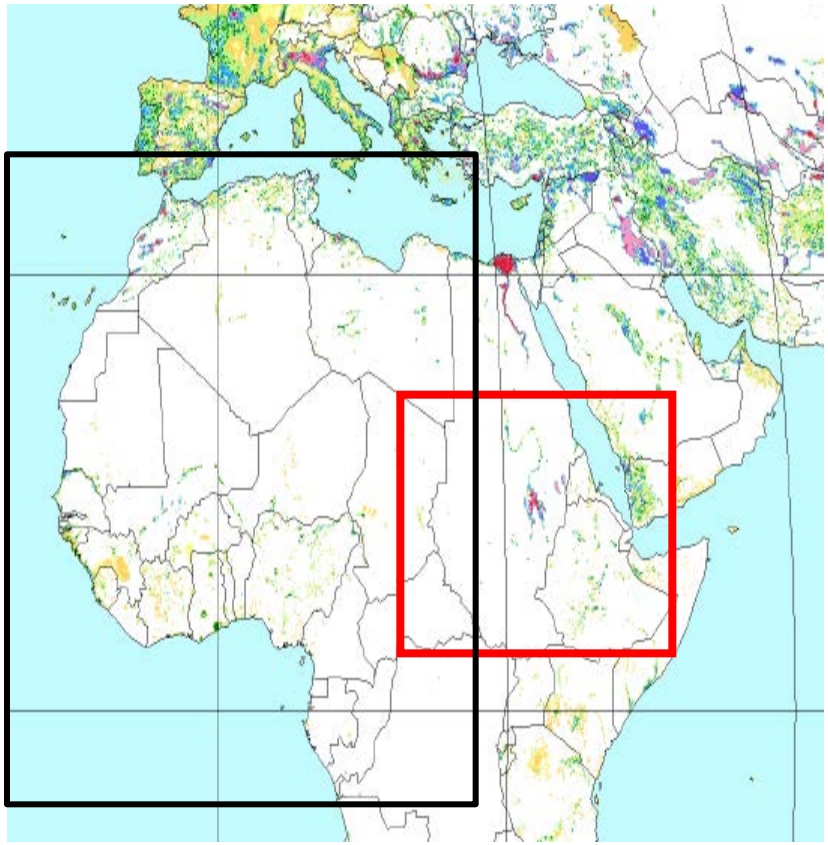
I: Irrigation water

D: Drains into deeper layer



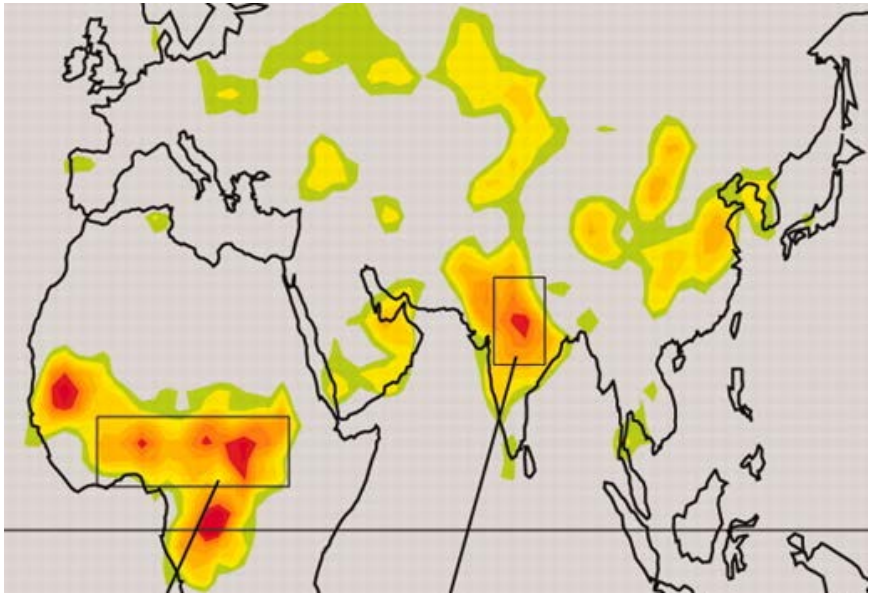
- Add anthropogenic land cover, irrigated cropland biome to IBIS
- Root zone soil moisture is forced to relative field capacity
- "Negative runoff" to supply water and conserve water balance
- Useful tool for the impact studies of anthropogenic land use change due to human activity

Study Area : West & East Africa



[Adapted from FAO, 2013]

Soil Moisture-Rainfall Feedbacks

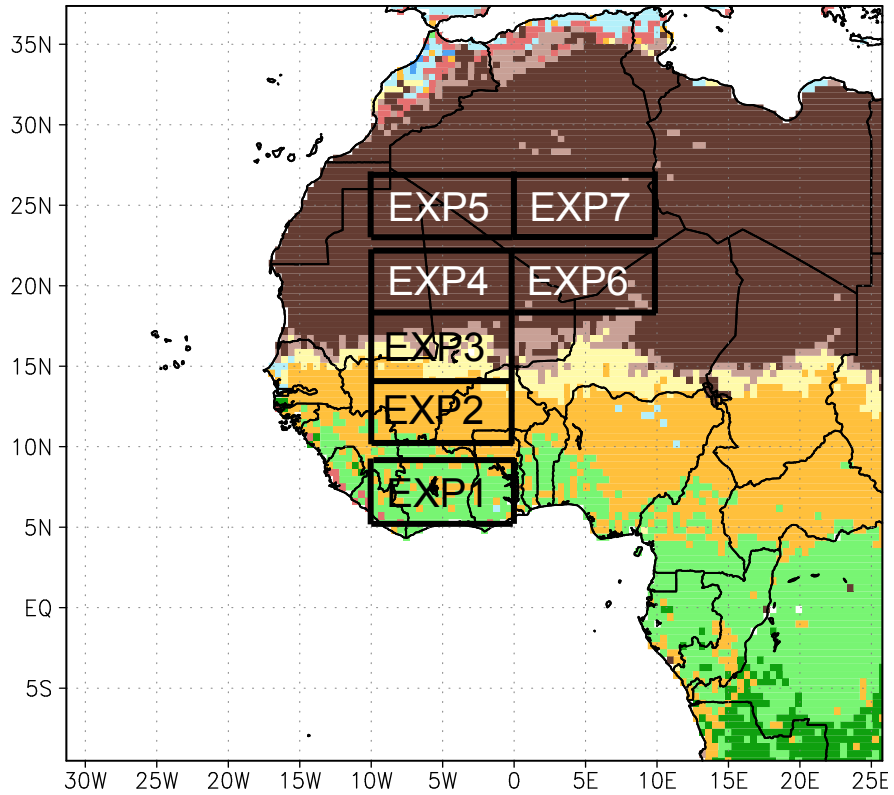


[Adapted from Koster et al., 2004]

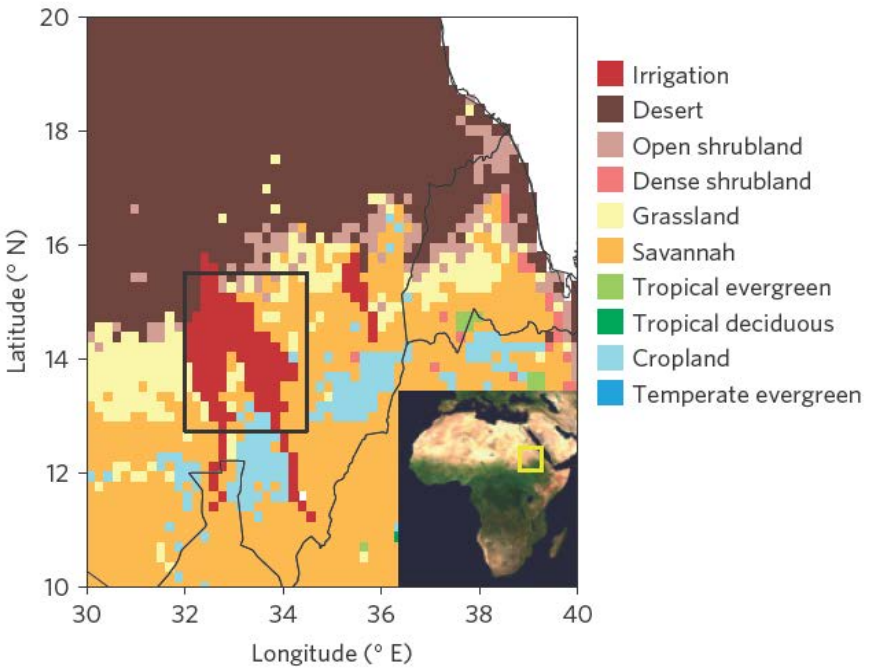
- West Africa is considered a “hot spot” for soil moisture-rainfall coupling. Therefore, anomalous soil moisture induced by irrigation can have significant impact on the West African Monsoon.

Irrigation Experimental Design

Step I: Theoretical & Conceptual EXP



Step II: Gezira Irrigation Scheme

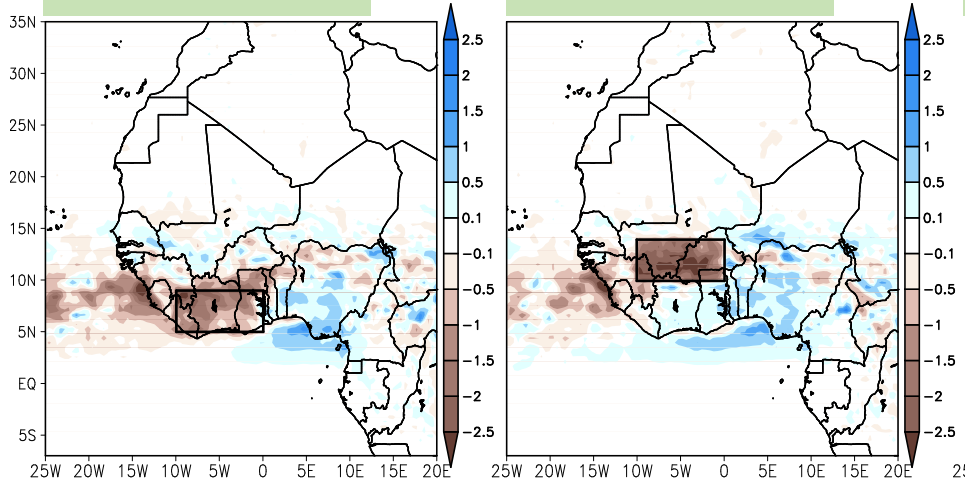


Large-scale Irrigation
: 4degX10deg~400,000 km^2

Medium-scale Irrigation
: 56,800 km^2

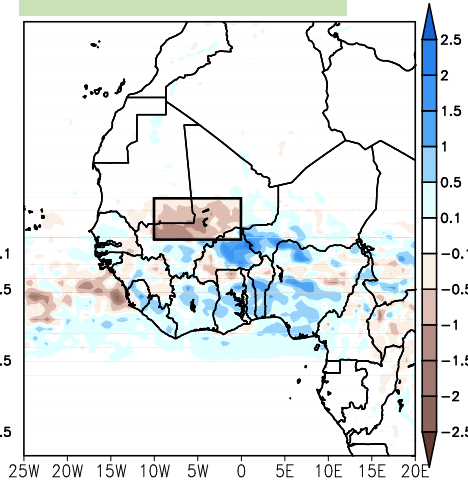
Irrigation Impact on Rainfall Changes (IRR-CONT)

EXP1-CONT



EXP2-CONT

EXP3-CONT



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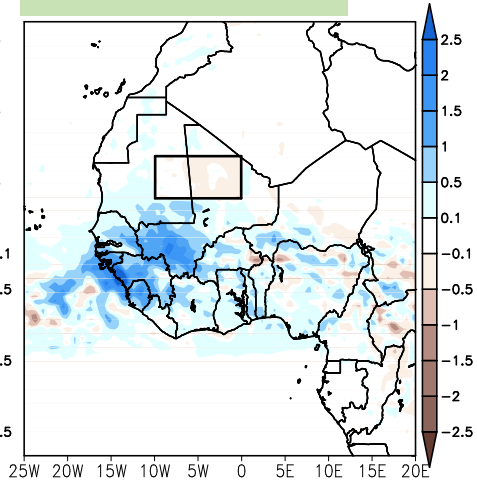
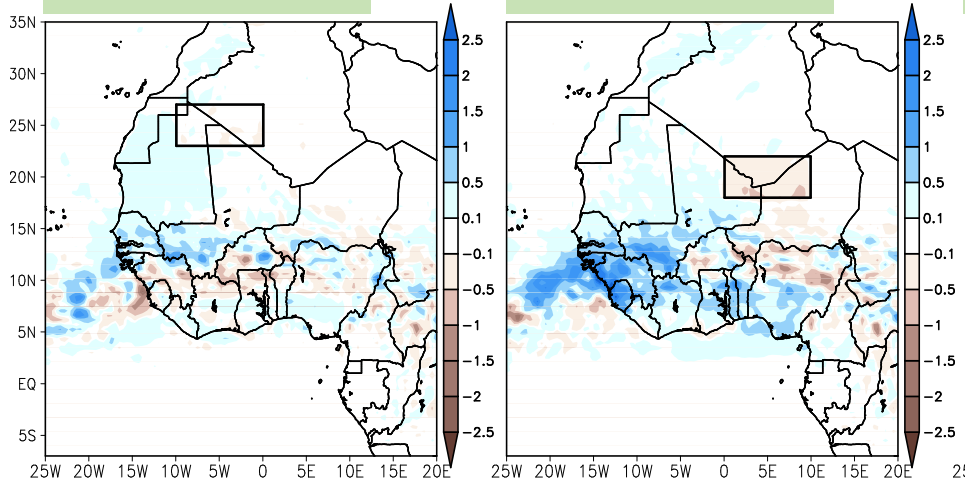
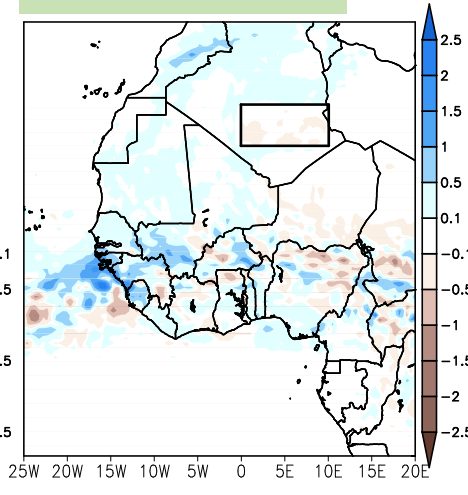


EXP5-CONT



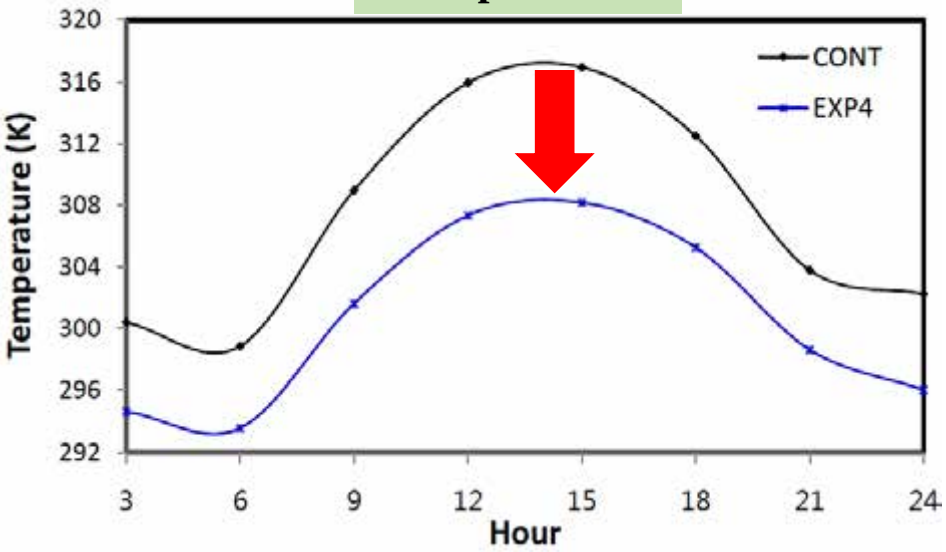
EXP6-CONT

EXP7-CONT

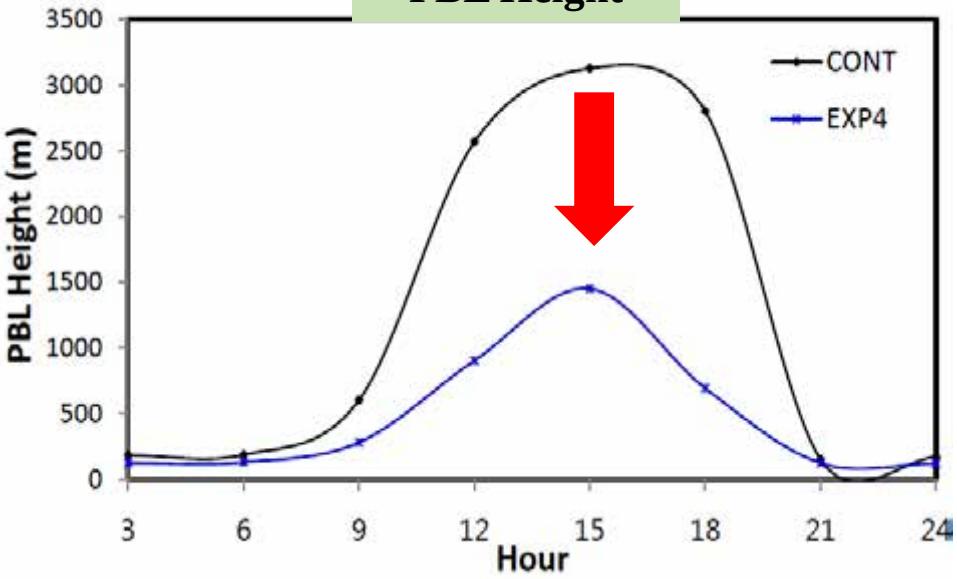


Mechanism of Local Response

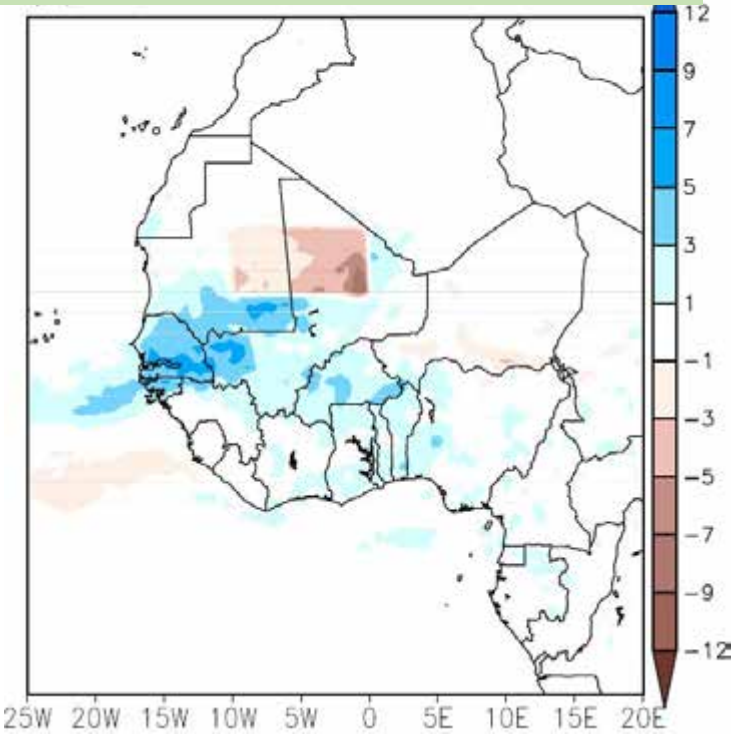
Temperature



PBL Height

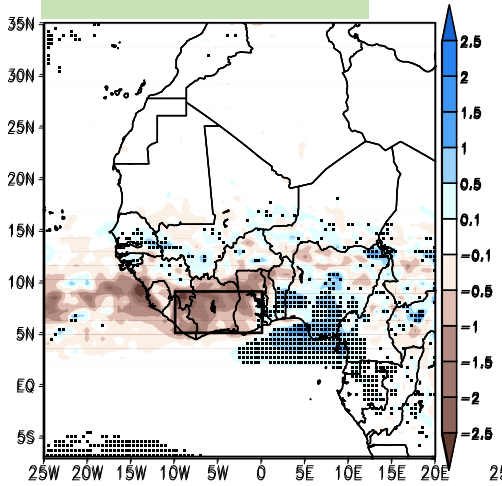


No of days with convective rainfall

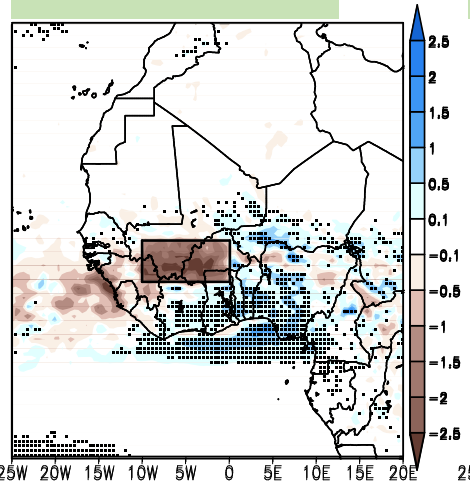


Irrigation Impact on Rainfall Changes (IRR-CONT)

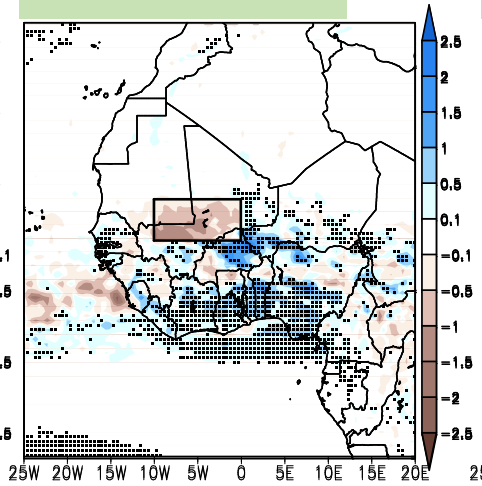
EXP1-CONT



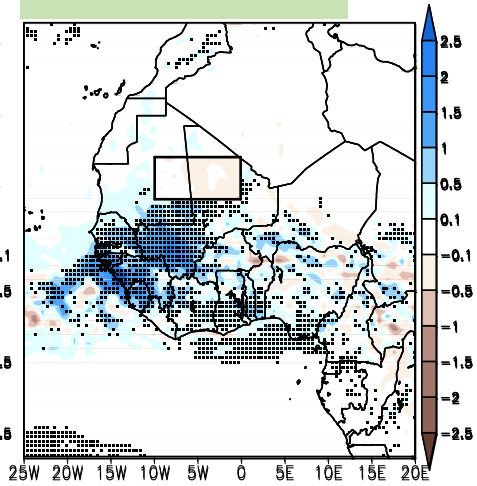
EXP2-CONT



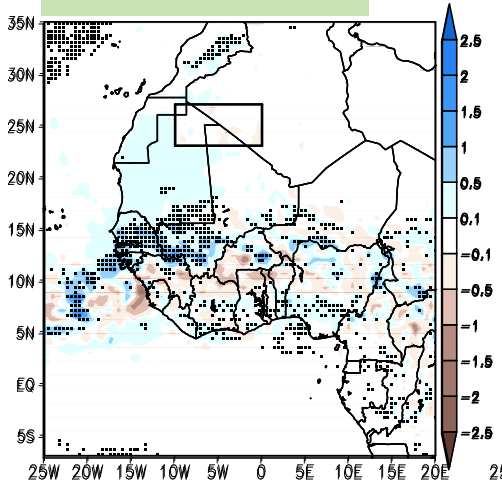
EXP3-CONT



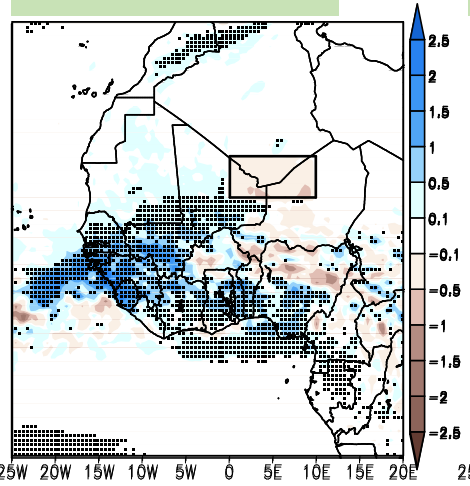
EXP4-CONT



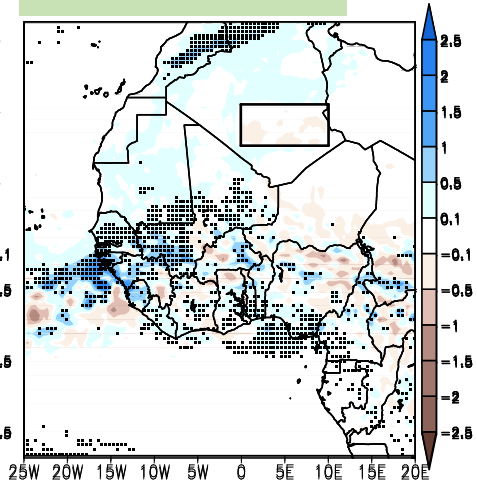
EXP5-CONT



EXP6-CONT



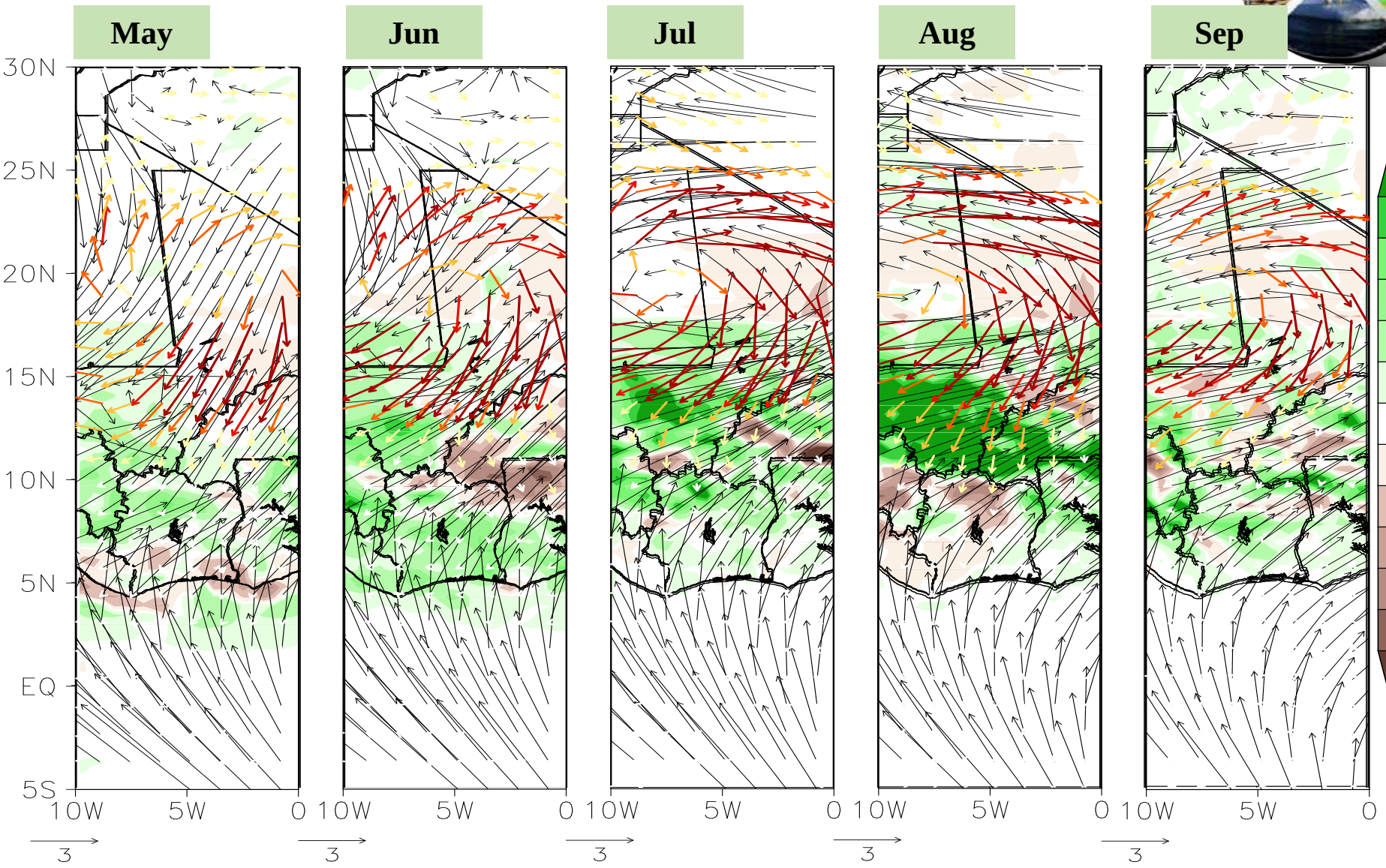
EXP7-CONT



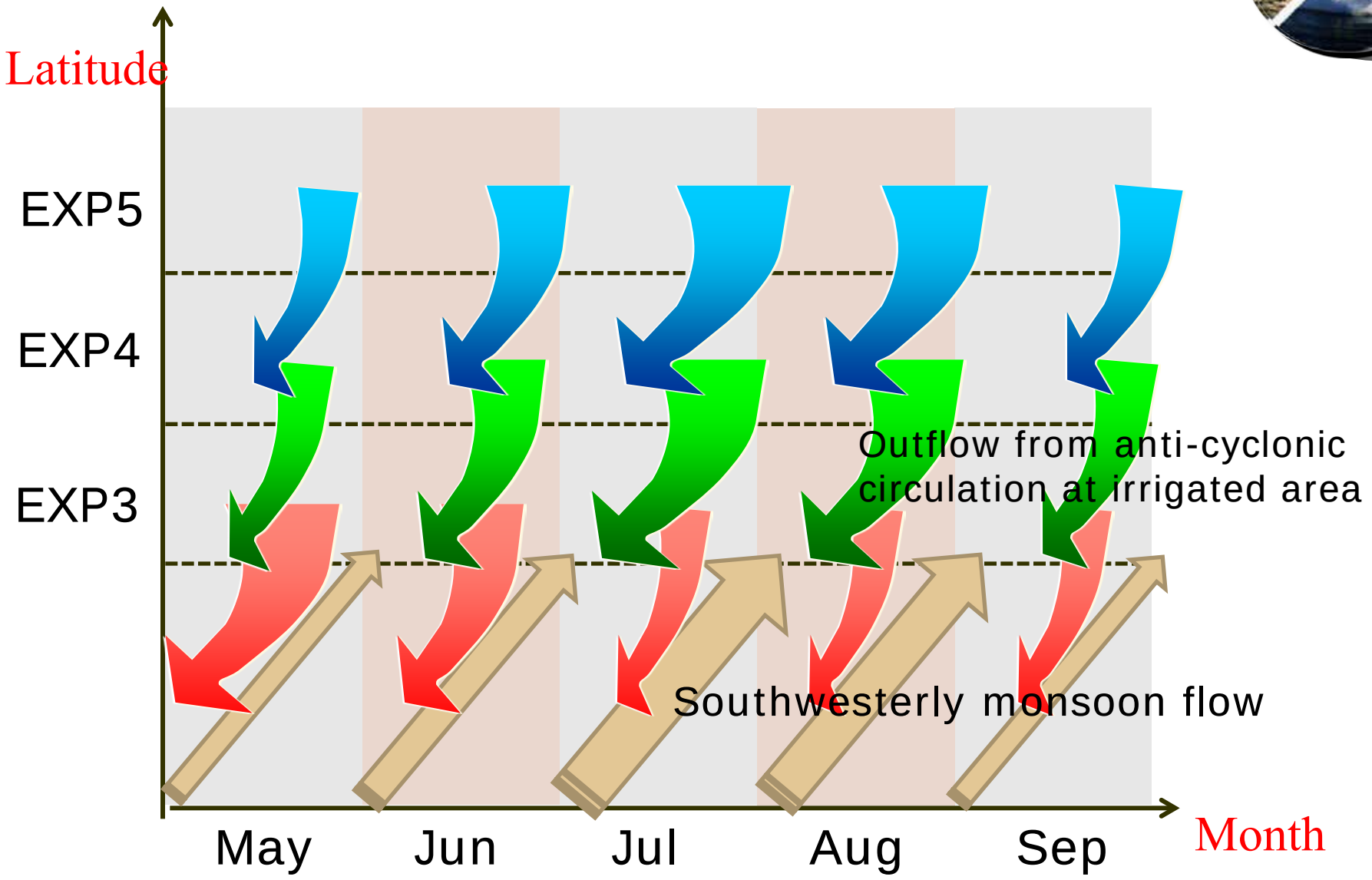
- Dotted area
: Significance of rainfall increase

Remote Response

- Black arrow : CONT monsoon flow
- Red gradient arrow: Anomalous flow

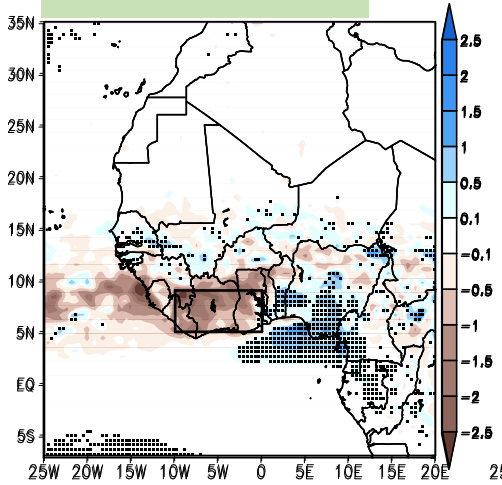


Schematic Diagram of Remote Mechansim

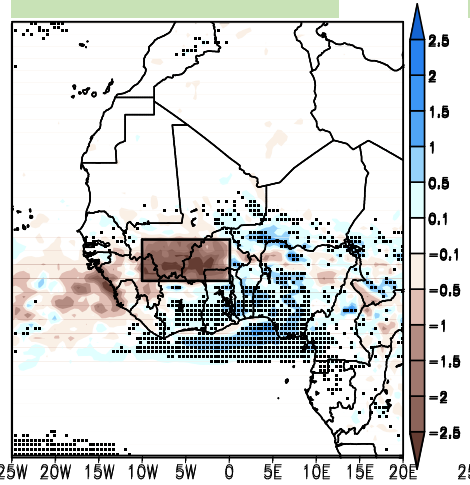


Irrigation Impact on Rainfall Changes (IRR-CONT)

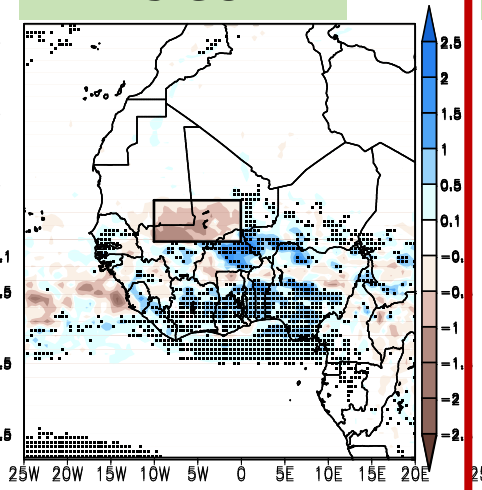
EXP1-CONT



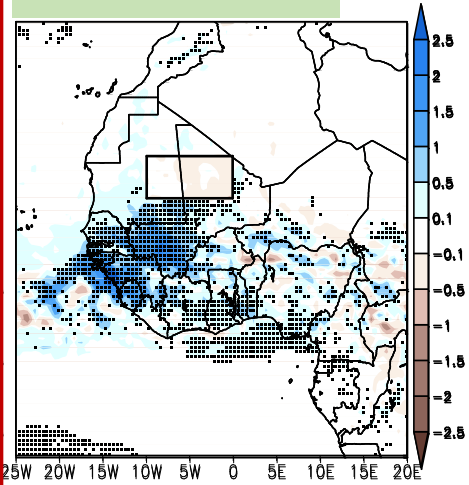
EXP2-CONT



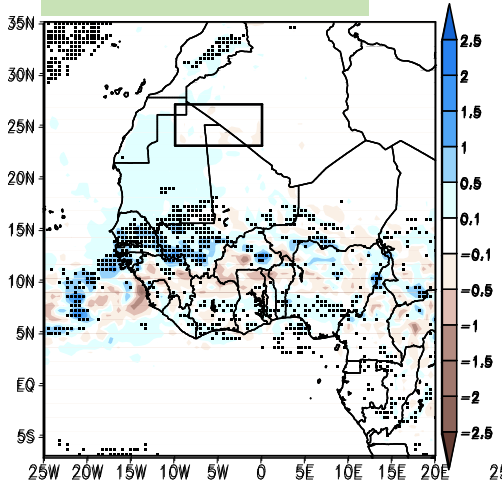
EXP3-CONT



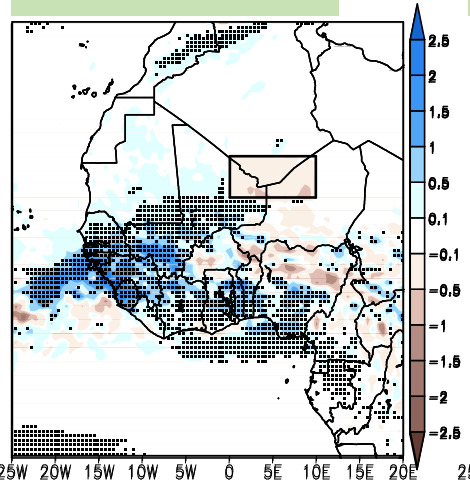
EXP4-CONT



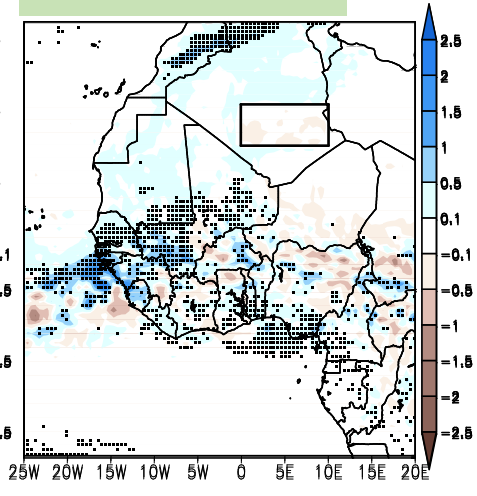
EXP5-CONT



EXP6-CONT



EXP7-CONT

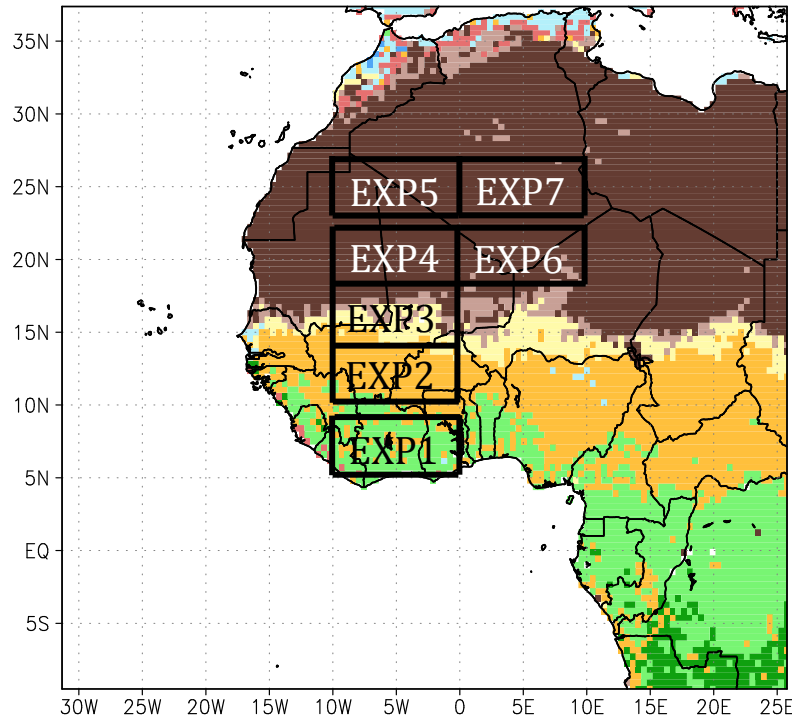


- Dotted area

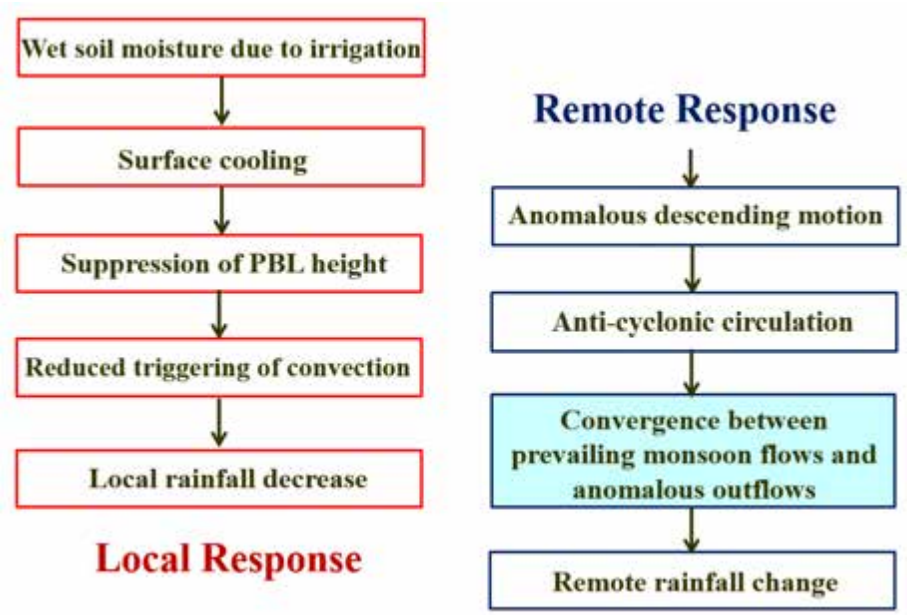
: Significance of rainfall increase

Reliability of Methodology

Theoretical & Conceptual Experiments

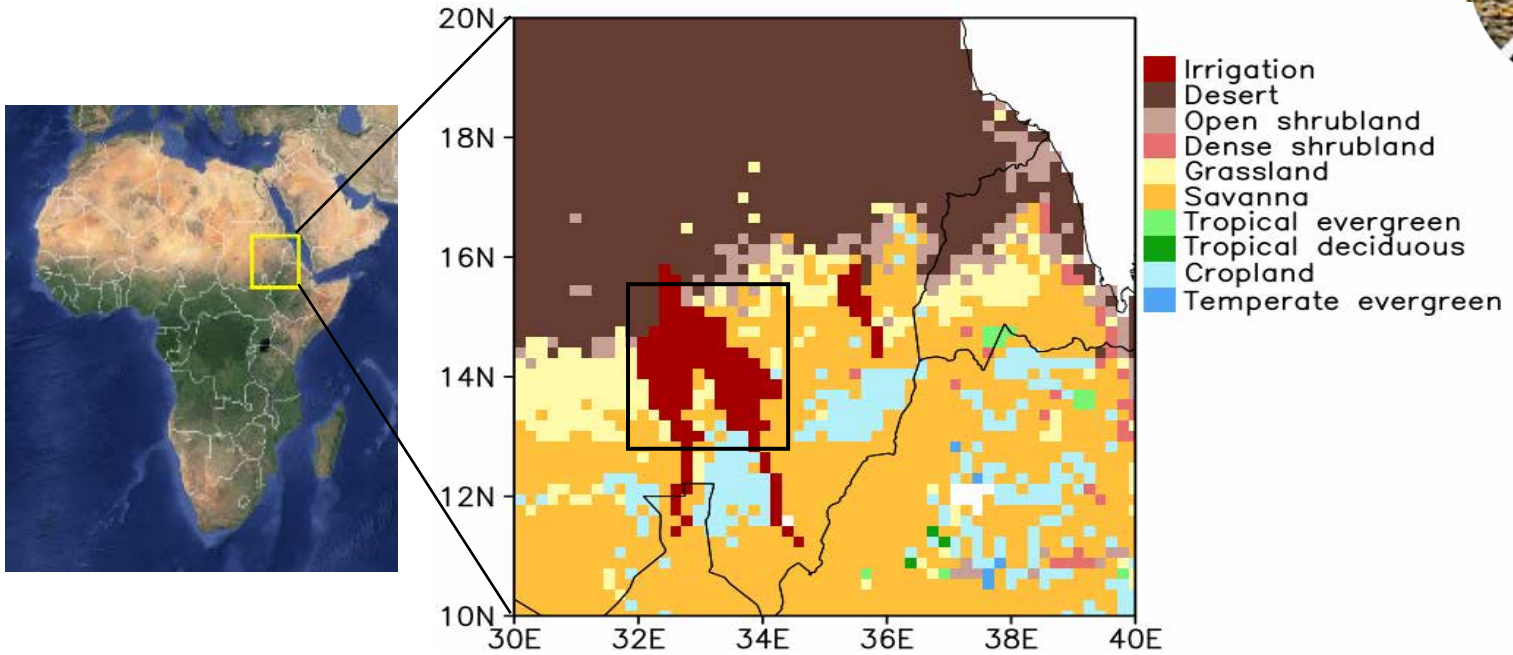


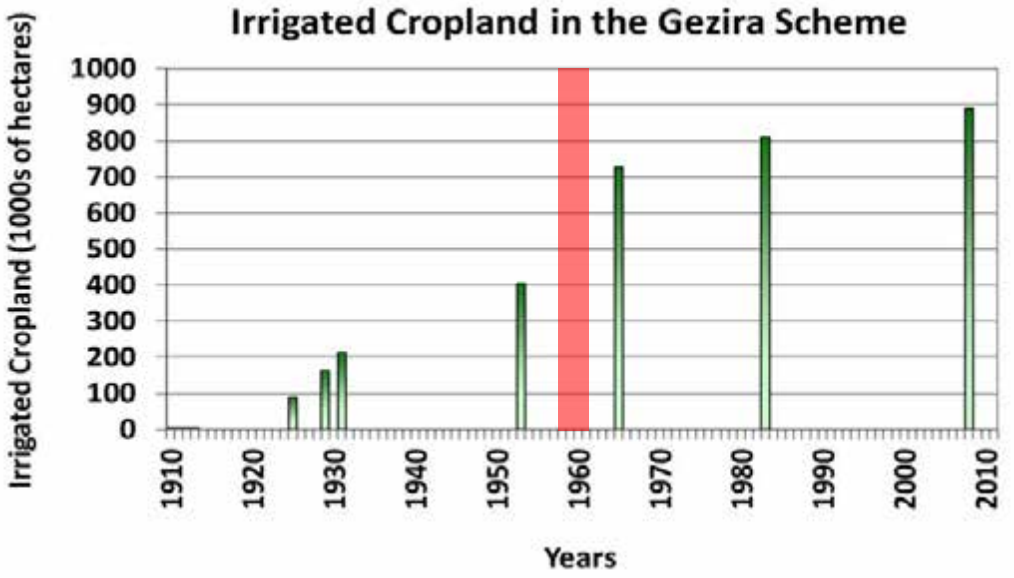
Physical Mechanism



- **Im, E.-S.**, M. 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, 994-1099.
- **Im, E.-S.**, and E. A. B. Eltahir (2014), Enhancement of rainfall and runoff upstream from irrigation location in a climate model of West Africa. ***Water Resources Research***, 50, 8651-8674.

Gezira Irrigation Scheme in East Africa

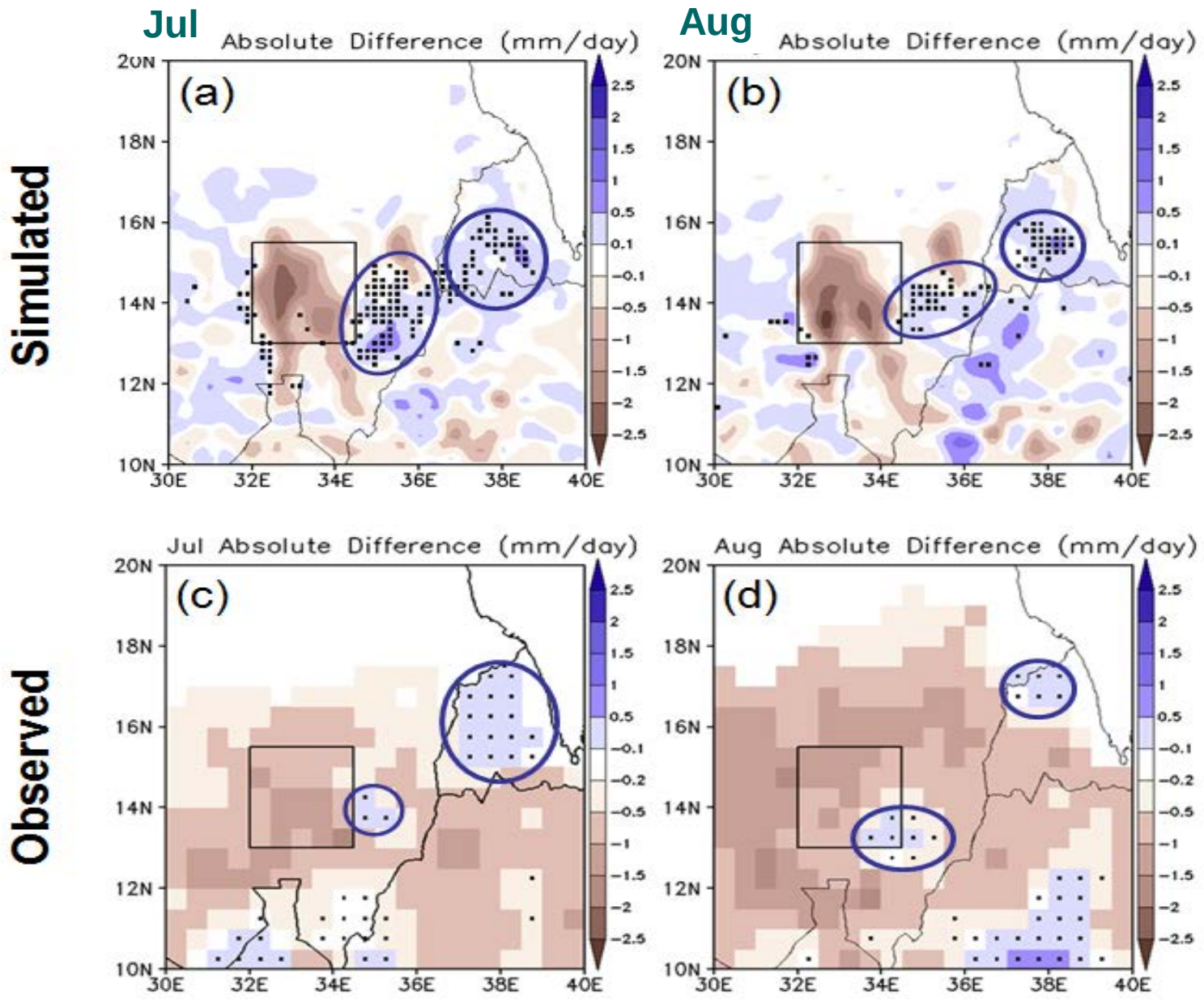




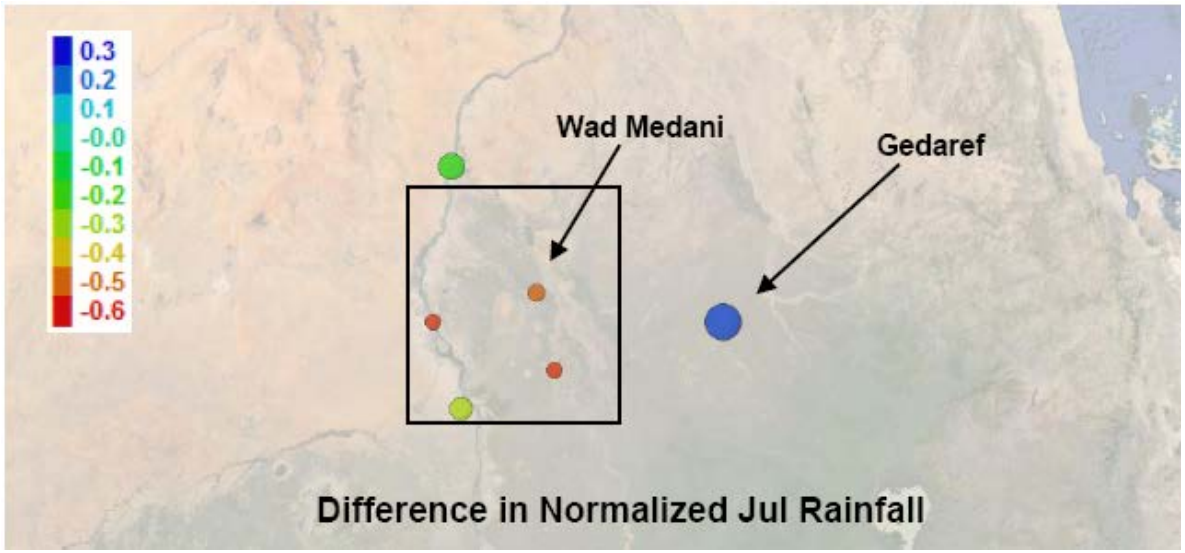
Manaqil Extension (MEX)

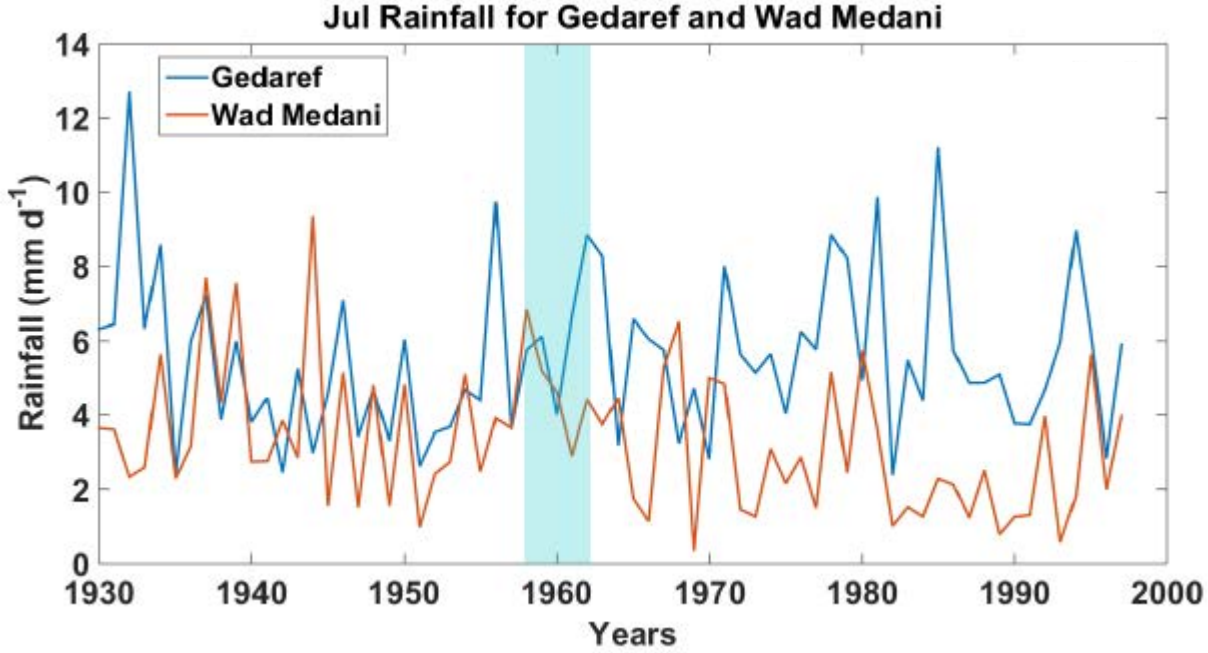
- Period of intense irrigation development between 1958 and 1962
  - pre-MEX: 1930-1959
  - post-MEX: 1970-1999

Simulated & Observed Changes in Rainfall



Temporal & Spatial Changes in Rainfall





Potential Mechanism

Wet soil moisture due to irrigation

↓

Surface cooling

↓

Suppression of PBL height

↓

Reduced triggering of convection

↓

Local rainfall decrease

↓

Anomalous descending motion

↓

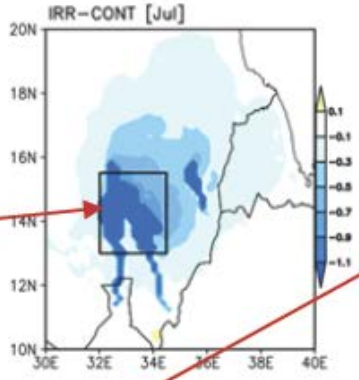
Anti-cyclonic circulation

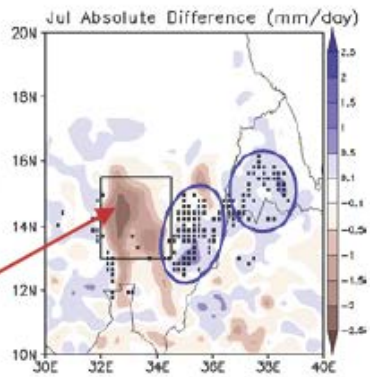
↓

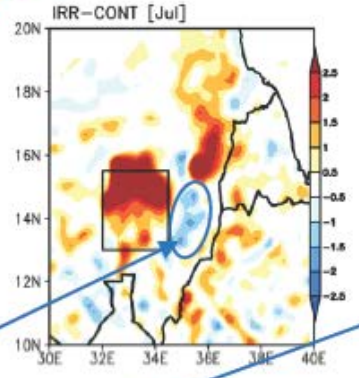
Convergence between anomalous outflows and prevailing monsoon flows

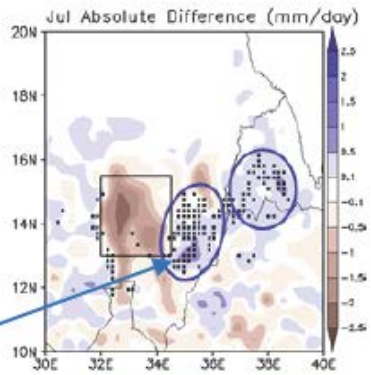
↓

Remote rainfall change



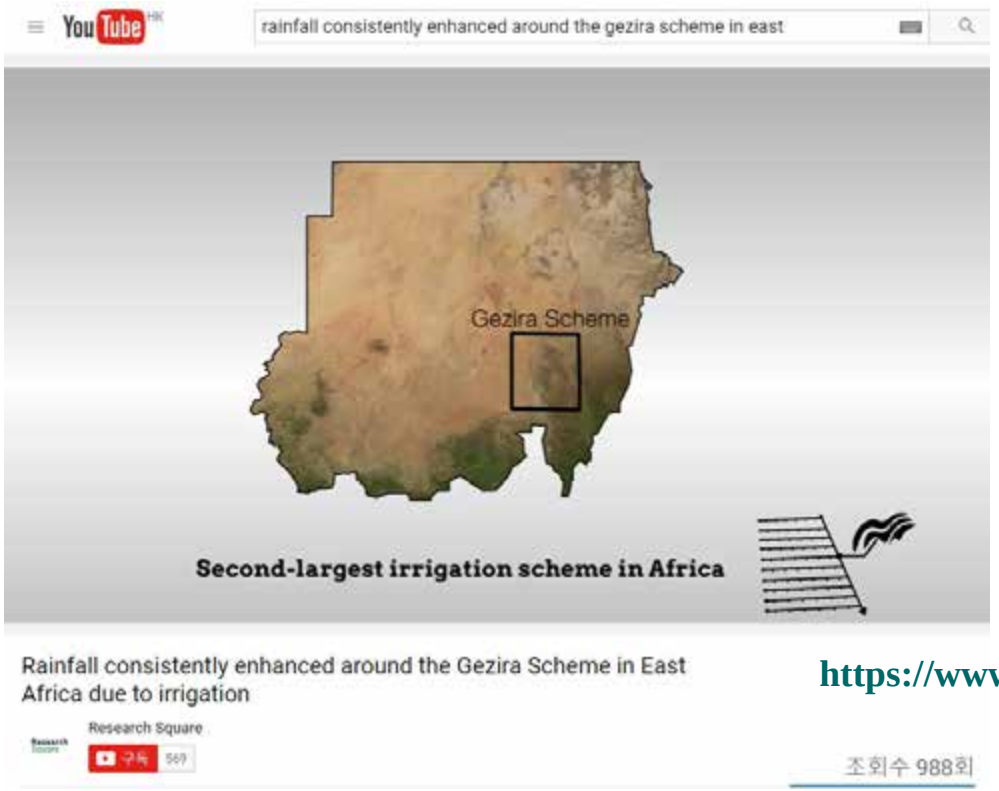






Take Home Messages

1. MRCM is a useful scientific tool for climate study
2. Irrigation has a significant impact on regional climate
3. Optimal irrigation planning is important for sustainability



https://www.youtube.com/watch?v=3O-BGdHbS6Q

Thank you for your attention!

ceim@ust.hk

- Im, E.-S., R. L. Gianotti, and E. A. B. Eltahir (2014) Improving simulation of the West African monsoon using the MIT Regional Climate Model. ***J. Climate***, 27, 2209-2229.
- Im, E.-S., M. 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, 994-1099.
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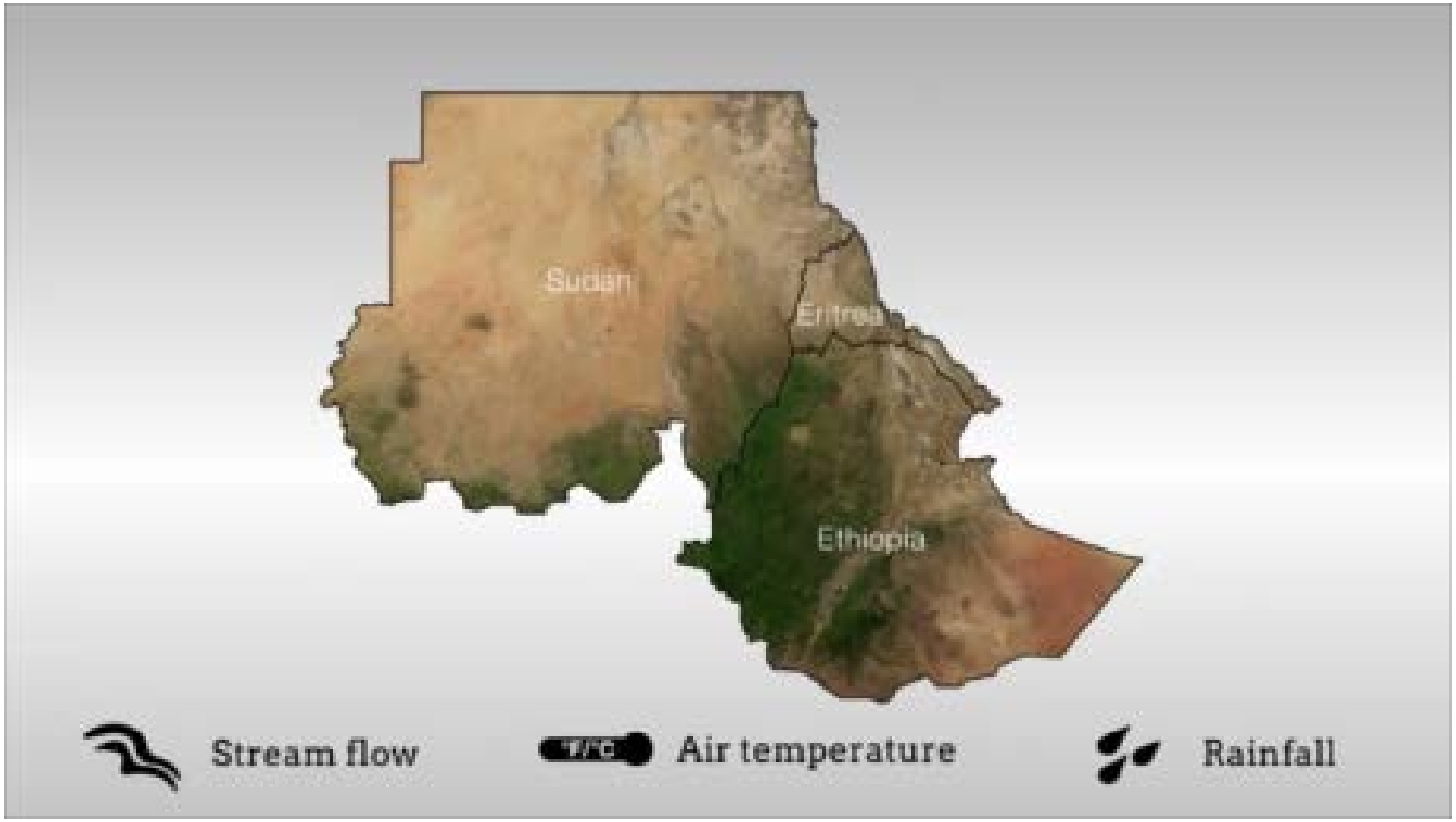
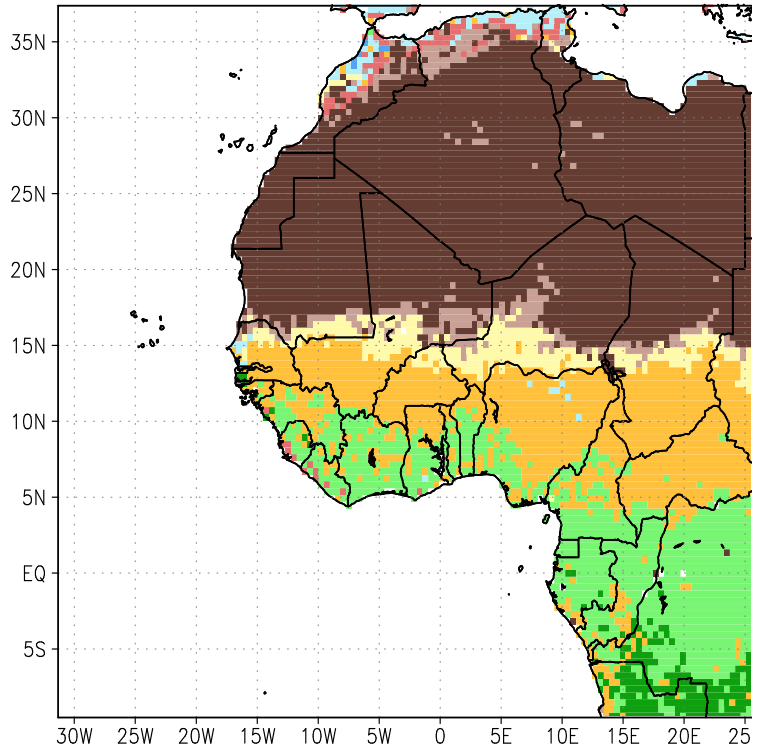
- Alter, R. E., E.-S. Im, and E. A. B. Eltahir (2015) Rainfall consistently enhanced around the Gezira Scheme in East Africa due to irrigation. ***Nature Geoscience***, 8, 763-767.
- Im, E.-S., and E. A. B. Eltahir (2017) Simulations of the observed "jump" in the West African monsoon and its underlying dynamics using the MIT Regional Climate Model. ***Int. J. Climatology***, Provisionally Accepted.

Potential Mechanism



Validation of MRCM Control Simulation

- Resolution: 50km
- Integration Period: 1989-2008 (20yr)
- Initial & Boundary Condition
  : ERAInterim Reanalysis (1.5deg)

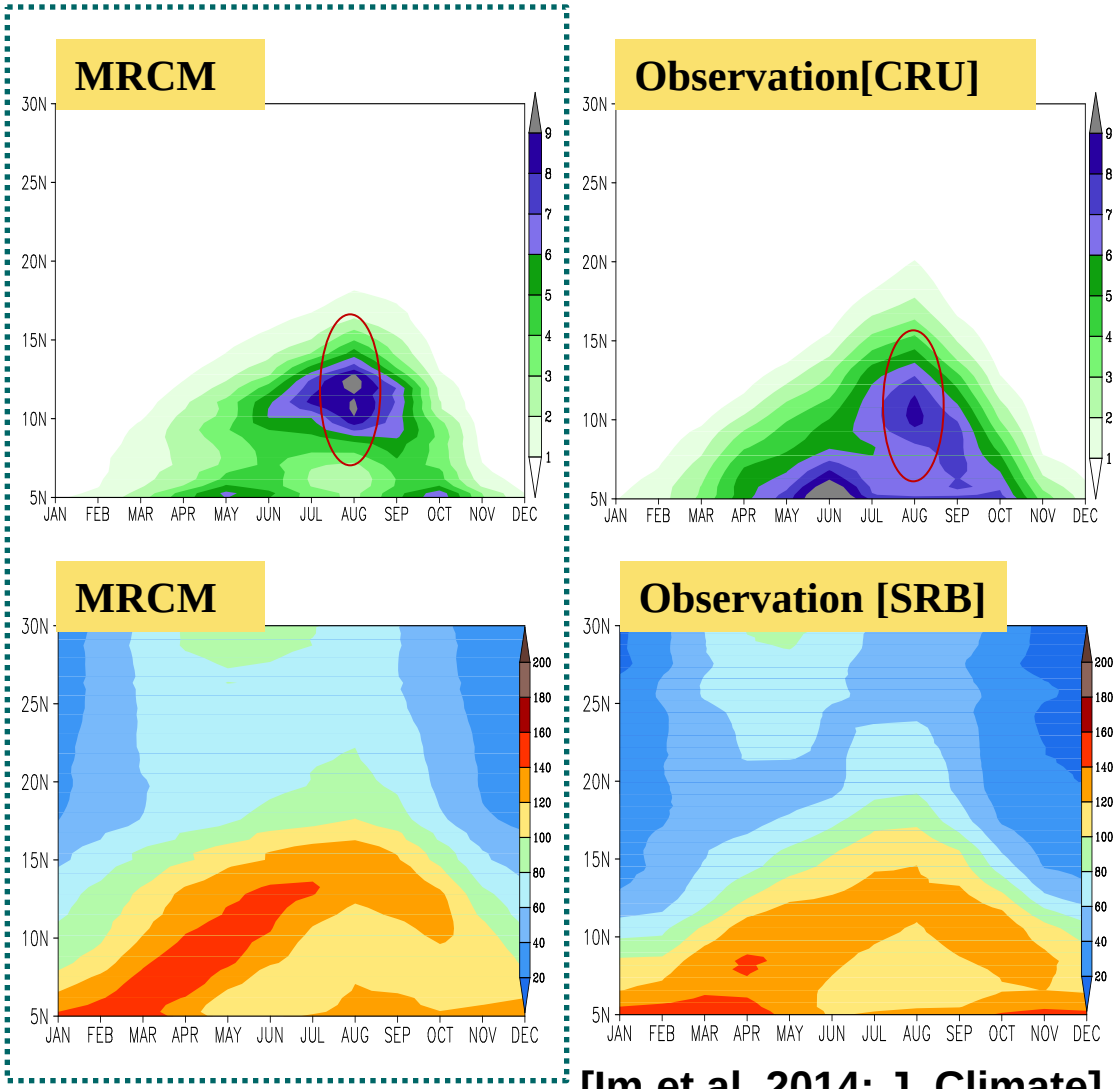


MRCM Improvement I : Annual Cycle

❖ Latitude-Time Cross-section of Rainfall & Net Radiation [averaged from 10W to 10E]

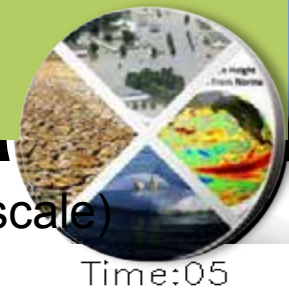
Rainfall

Radiation

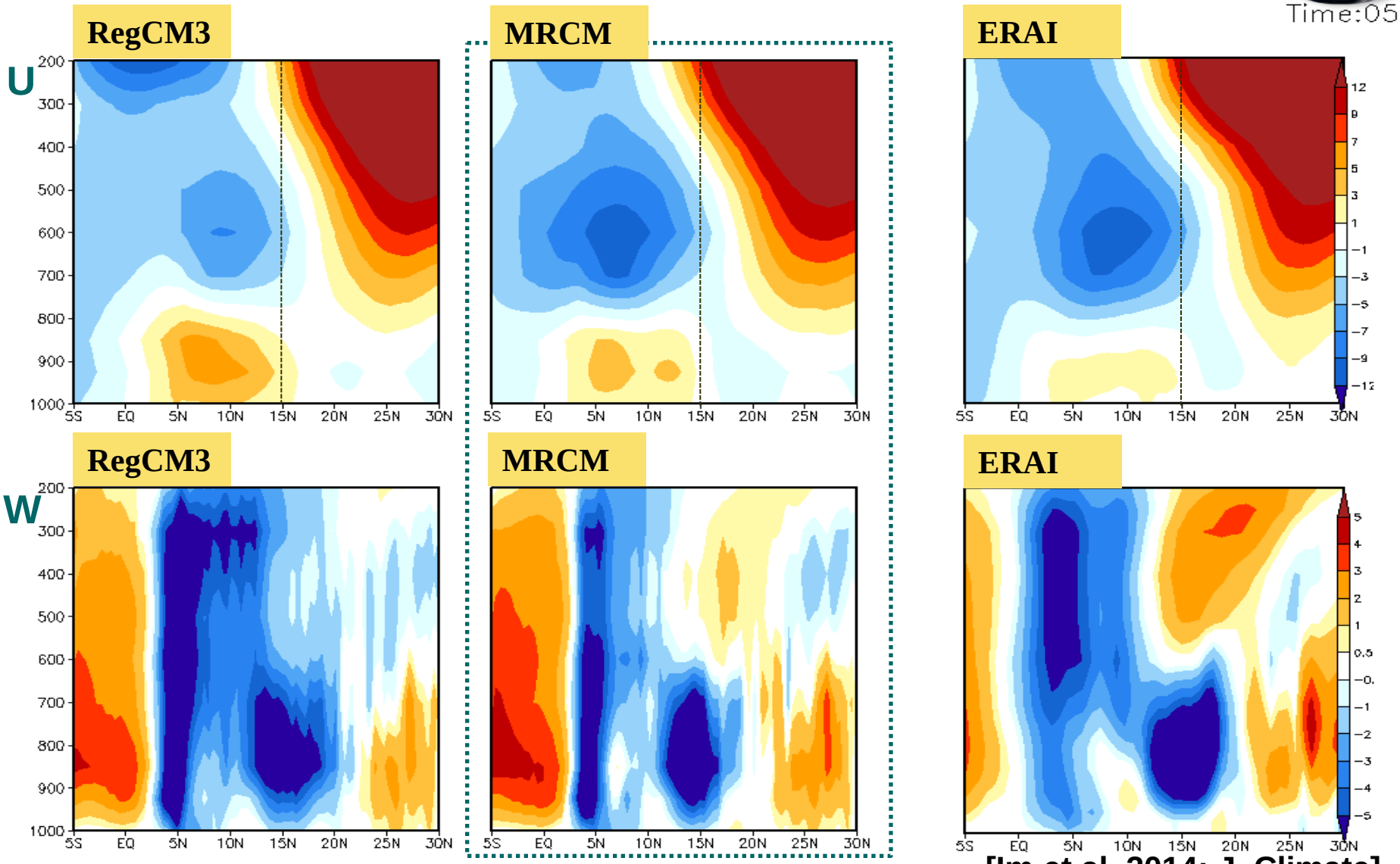


[Im et al. 2014: J. Climate]

MRCM Improvement II : Vertical Structure



- Vertical Cross-section of Zonal Wind & Omega (May to Oct: monthly scale)



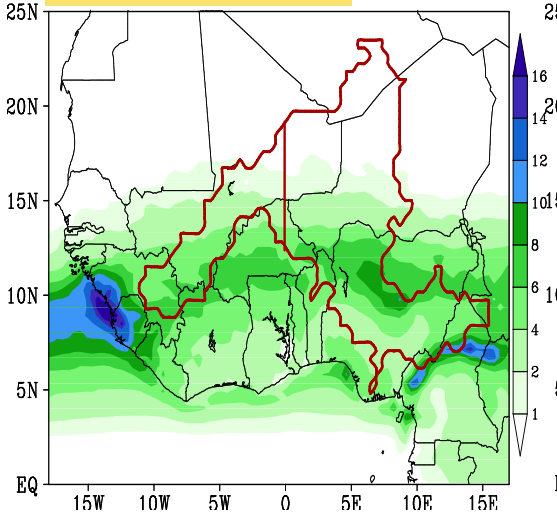
[Im et al. 2014: J. Climate]

Rainfall & Runoff over the Niger River Basin

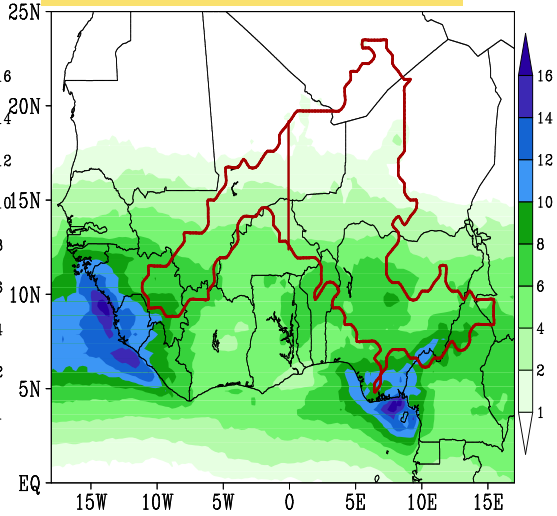
❖ Spatial Distribution of Climatological Rainfall & Runoff for Summer Season

Rainfall

MRCM

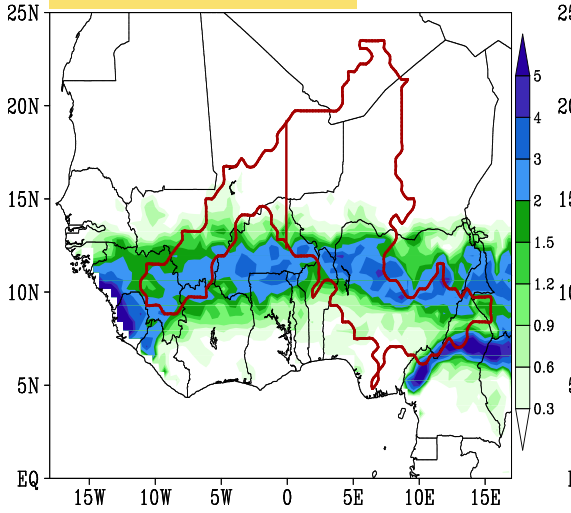


Observation[TRMM]

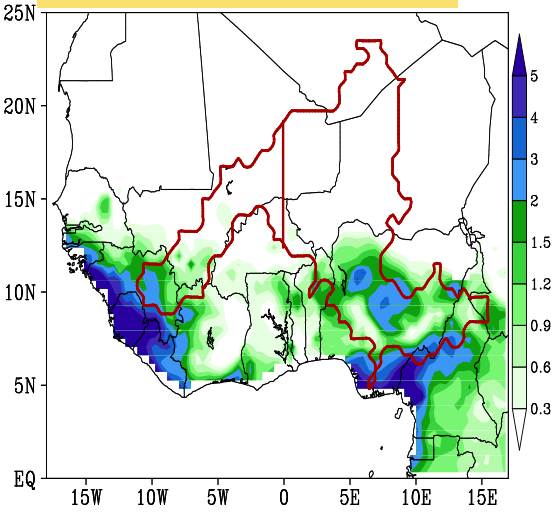


Runoff

MRCM



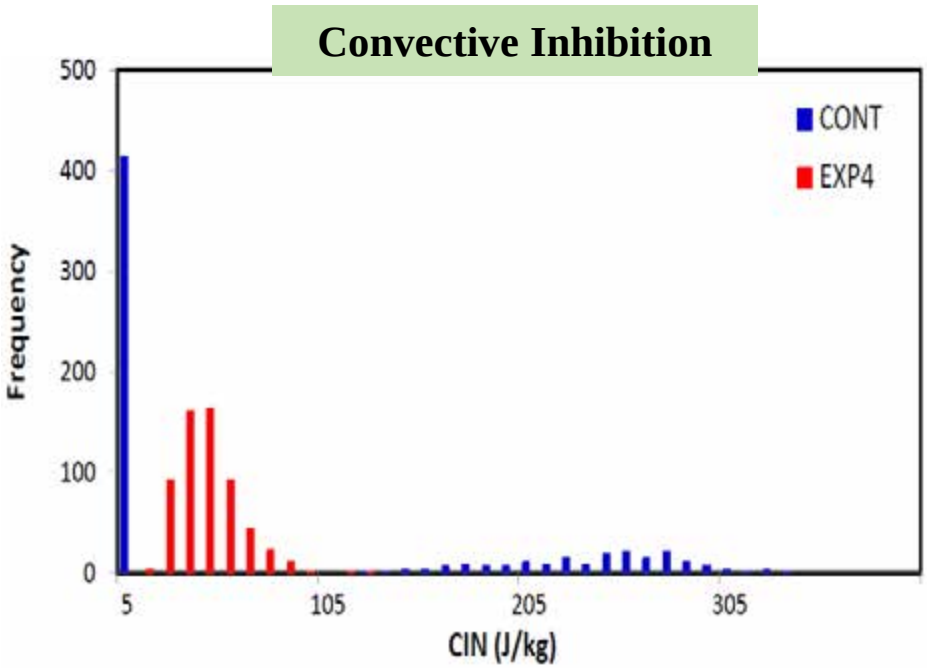
Observation[GRDC]

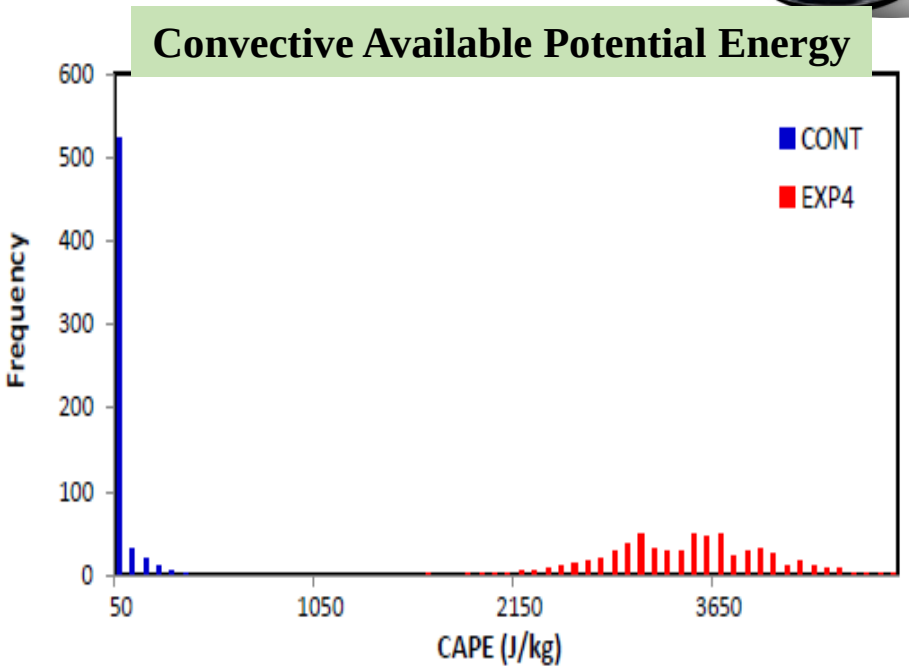


[Im & Eltahir 2014: WRR]

Irrigation Impact on Atmospheric Instability

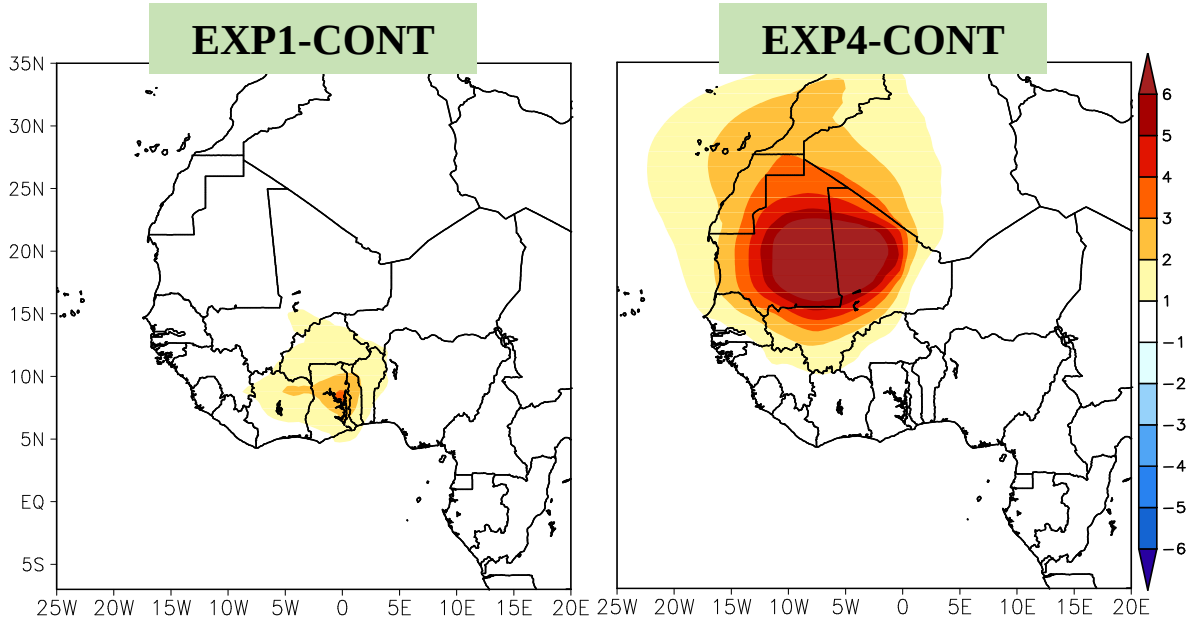
❖ Frequency Distribution of CIN & CAPE

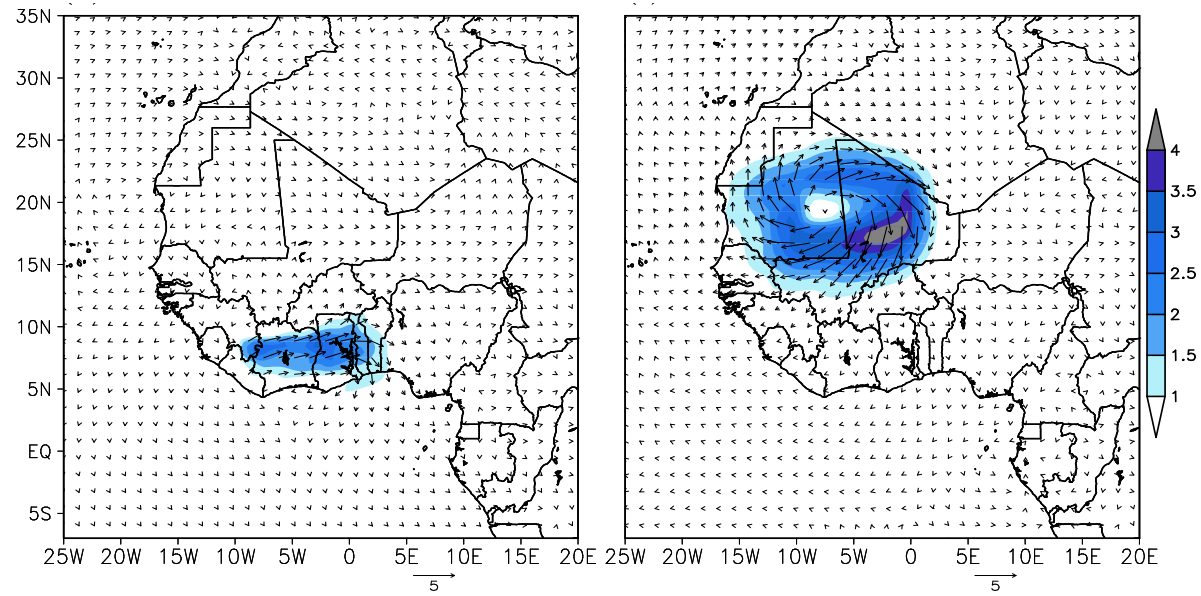




- Convective inhibition (CIN) indicates a negative buoyant energy needed to overcome the free ascent of an air parcel while Convective Available Potential Energy (CAPE) is a positive buoyancy of a rising air parcel.
- The increase in CAPE due to higher surface moisture seems to be dominated and overwhelmed by the decrease in frequency of convective triggering owing to enhanced convective inhibition.

Geopotential Height & Wind at 925 hPa





- Higher pressure centered at irrigated area is associated with anomalous descending motion, leading to low-level divergence over the irrigated region. Theses low-level outflows result in anomalous anti-cyclonic circulation.