

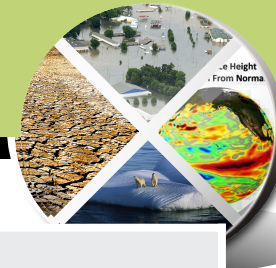
A study on the impact of irrigation on regional climate using the regional climate model

IM, Eun-Soon

Singapore-MIT Alliance for Research & Technology

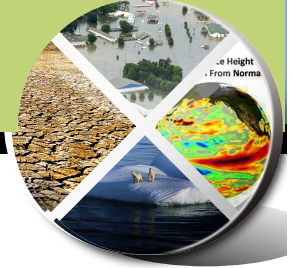


RegCM3 Upgraded by MIT Eltahir Group



Physics	New Features	Key References
Aerosols & Chemistry	New treatment of lateral boundary for mineral aerosol ♪	Marcella & Eltahir 2010
	Sub-grid variability of dust emission	Marcella & Eltahir 2011
Convective Cloud & Rainfall	New convective cloud fraction scheme	Gianotti & Eltahir 2014♪
	New convective rainfall autoconversion scheme	Gianotti & Eltahir 2014♪
	Modified boundary layer height & boundary layer cloud scheme♪	Gianotti 2012♪
Land Surface	Integrated Biosphere Simulator (IBIS) Land Surface Scheme	Winter et al. 2009
	New surface albedo assignment	Marcella & Eltahir 2012
	New irrigation module♪	Marcella & Eltahir 2014 Im & Eltahir 2014

SMART Regional Climate Modeling



MRCM Improvement

- Improvement of the Regional Climate Model (RCM)
 - : Implementing or modifying various physics schemes from the version of RegCM3 (e.g. convection cloud fraction and autoconversion scheme, land surface scheme irrigation module, boundary layer cloud , new albedo assignment)
- ➡ Im *et al.* 2014: Improving simulation of the West African monsoon using the MIT Regional Climate Model. [*J. Climate*]

MRCM Application

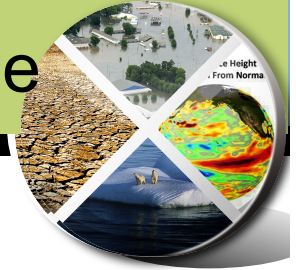
- Projection and understanding of anthropogenic impacts on regional climate system
 - ➡ Anthropogenic **greenhouse gases emission** (e.g. CO₂, CH₄) : Maritime Continent
 - ➡ Anthropogenic **land use change** (e.g. irrigation) : Africa

Significant Impact of Human-made Land-use Change

nature
geoscience

LETTERS

PUBLISHED ONLINE: 7 SEPTEMBER 2015 | DOI: 10.1038/NCEO2514



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. Eltahir¹

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 observations¹⁵. 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

interests²²; Sahel are irrigation easily dist climate; a rainfall en large-scal However at presen on a larg Gezira S confluen Fig. 1). I and con 1962 (th area. In to a ma from tl Fig. 1c, in Afri

The screenshot shows the Nature Geoscience journal homepage. The article title 'Rainfall consistently enhanced around the Gezira Scheme in East Africa due to irrigation' is highlighted in red. The authors listed are Ross E. Alter, Eun-Soon Im, and Elfatih A. B. Eltahir. The article is marked as 'FREE'. The abstract states: 'Land use changes can modify regional climate patterns. A comparison of climate simulations and observations show that a large-scale irrigation scheme in East Africa inhibits rainfall over the irrigation scheme, while enhancing it further away.' Links for 'Full text' and 'PDF (970 KB)' are provided. The website also features a 'Sustainability on Earth' section and various journal services like e-alerts and library recommendations.

What is Irrigation ?

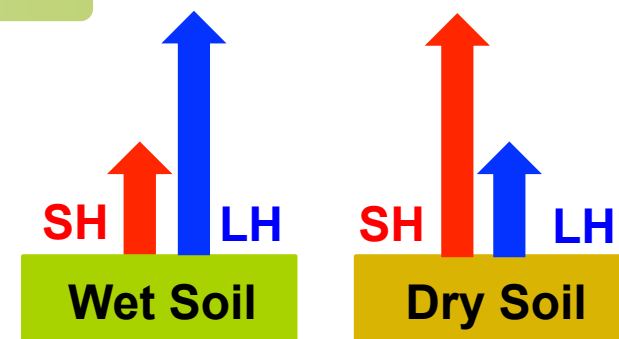
Definition of Irrigation

- 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



IBIS Irrigation Module within MRCM

Implementation of Irrigation Module

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

Here, ΔS : Changes in storage of soil moisture

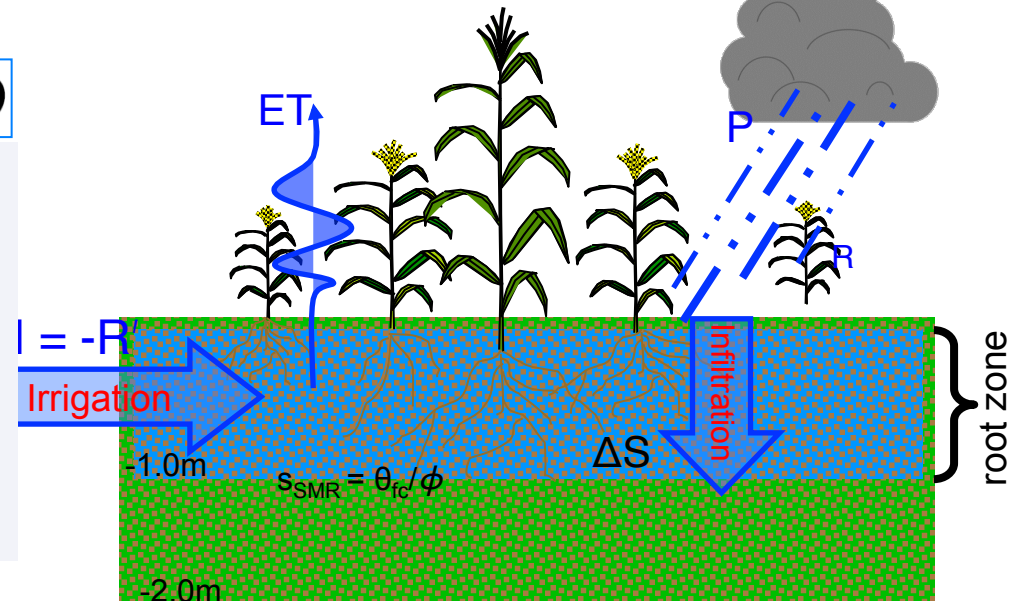
P: Precipitation

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

What is Irrigation ?

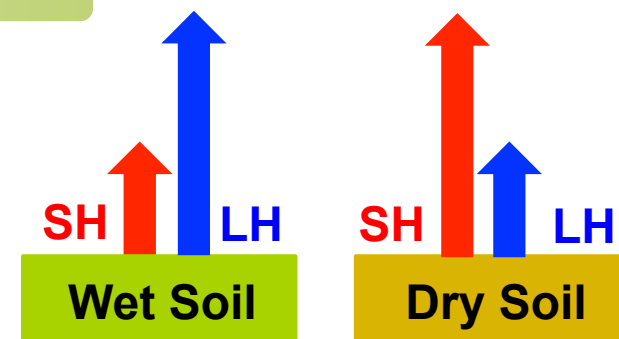
Definition of Irrigation

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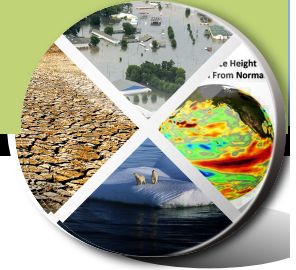


Irrigation-induced Changes

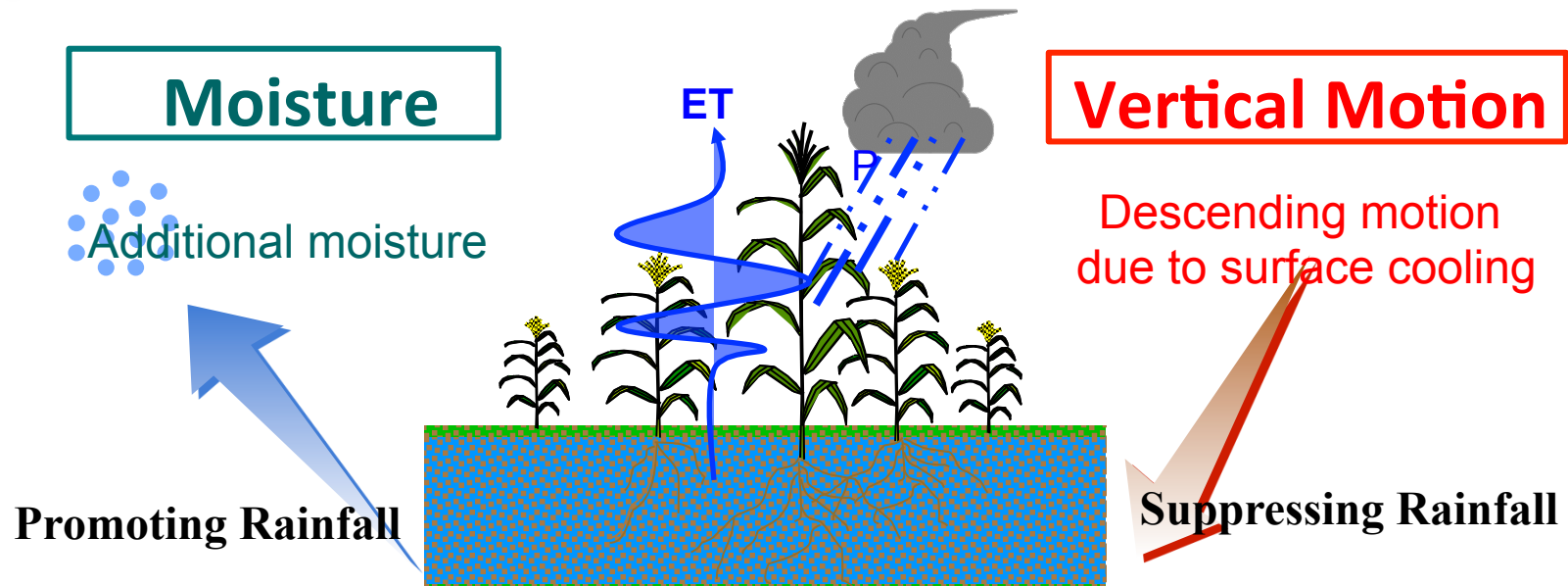
- Surface energy partitioning
- Water budgets
- Circulation pattern
- Local & remote rainfall



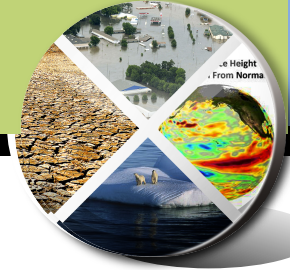
First-order Effect of Irrigation on Rainfall



Prerequisite Condition for Rainfall Formation



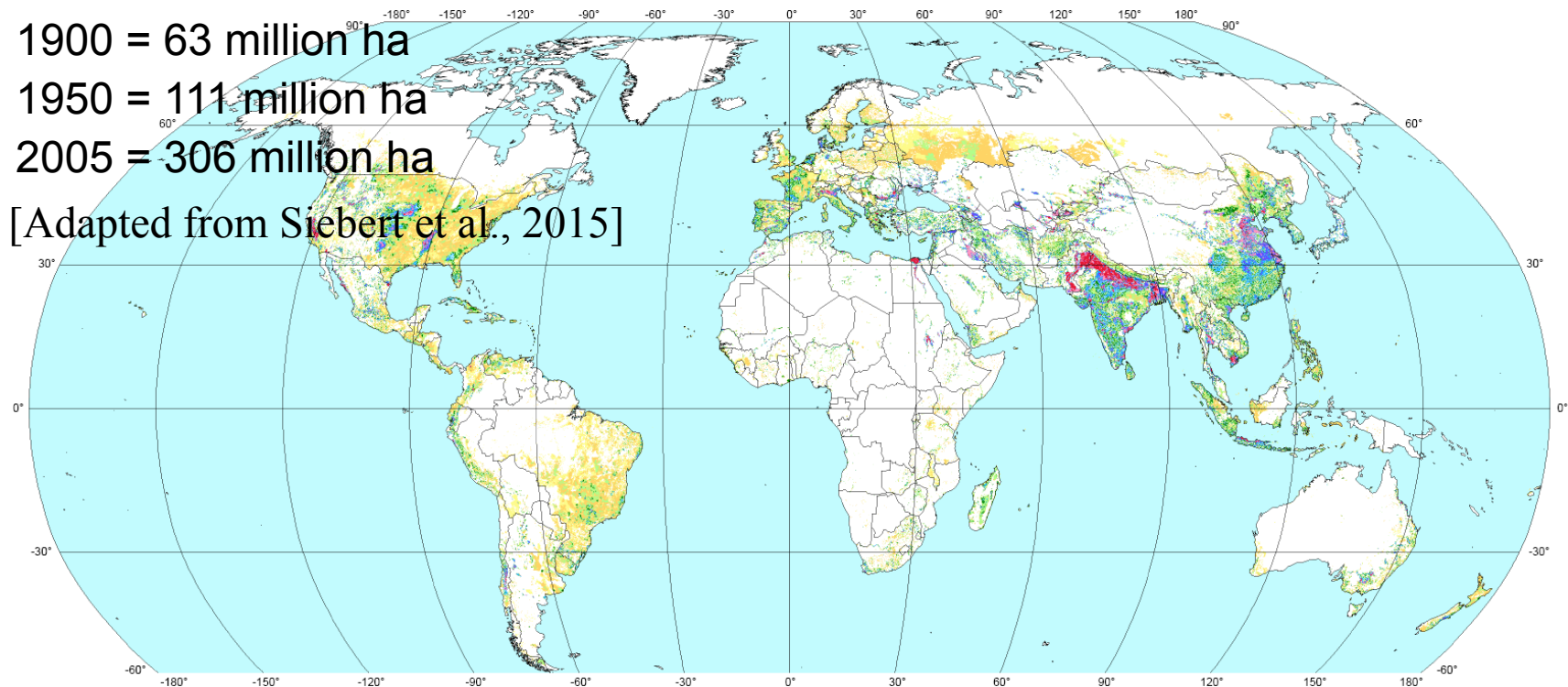
Digital Global Map of Irrigation Areas



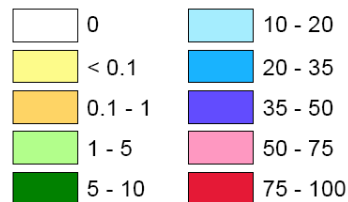
Rapid Extension of Irrigation Area

- 1900 = 63 million ha
- 1950 = 111 million ha
- 2005 = 306 million ha

[Adapted from Siebert et al., 2015]



**Area equipped for irrigation
in percentage of land area**



The map shows area equipped for irrigation in percentage of cell area.
For the majority of countries the base year of statistics is in the period
2000 - 2008.

Projection: Robinson
Resolution: 5 arc-minutes

<http://www.fao.org/nr/water/aquastat/irrigationmap/index.stm>

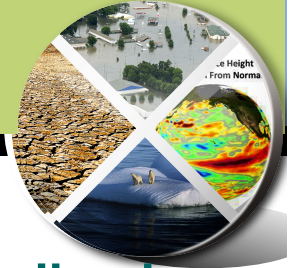
Stefan Siebert, Verena Henrich (Institute of Crop Science and Resource Conservation, University of Bonn, Germany) and
Karen Frenken, Jacob Burke (Land and Water Division, Food and Agriculture Organization of the United Nations, Rome, Italy)



universität**bonn**

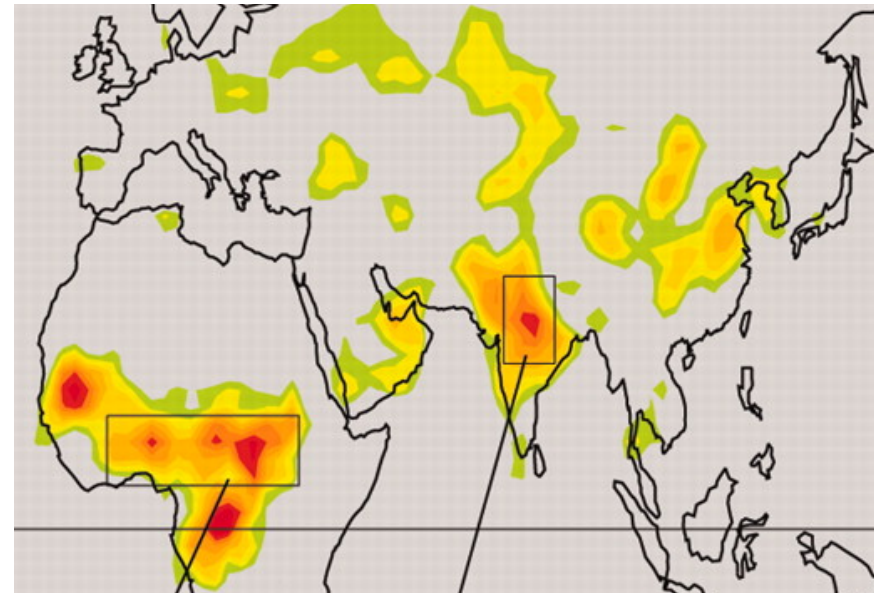
[Adapted from FAO, 2013]

Study Area : West & East Africa



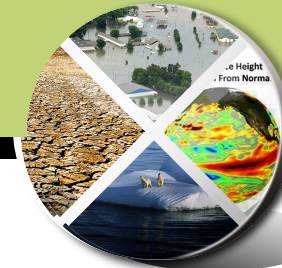
[Adapted from FAO, 2013]

Soil Moisture-Rainfall Feedbacks



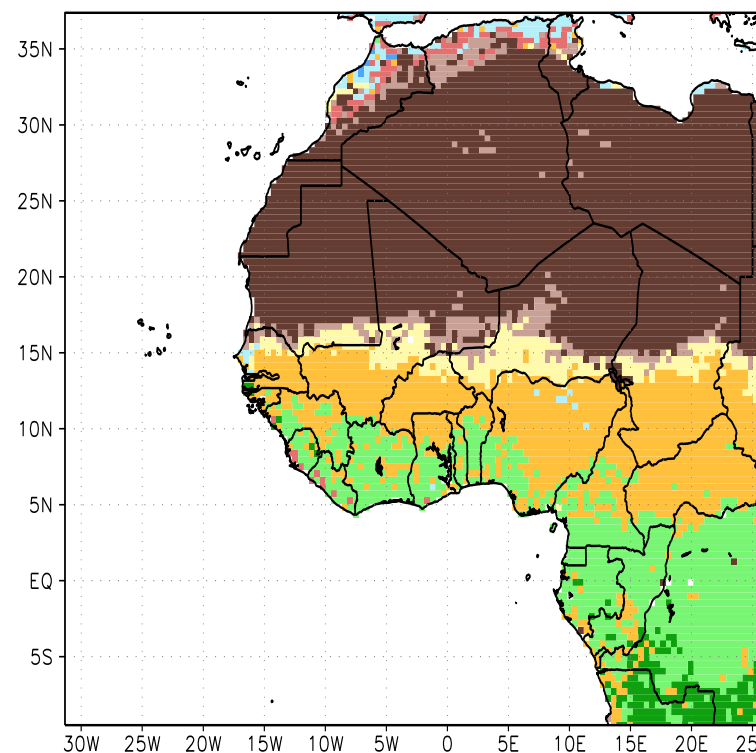
[Adapted from Koster et al., 2004]

- 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.

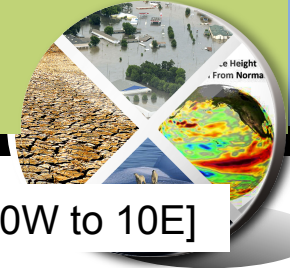


Validation of MRCM Control Simulation

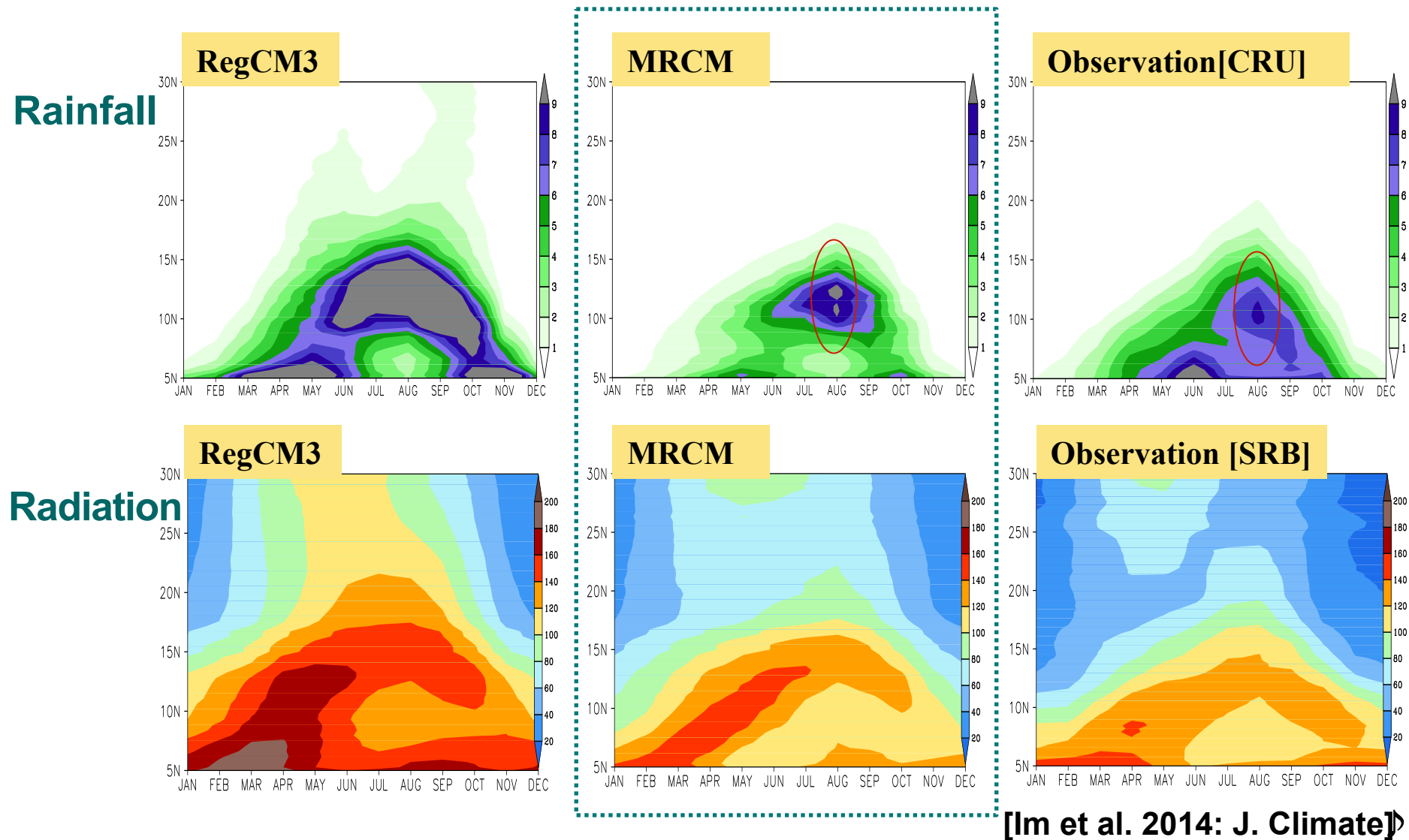
- Resolution: 50km
- Integration Period: 1989-2008 (20yr)
- Initial & Boundary Condition
: ERAInterim Reanalysis (1.5deg)



MRCM Improvement I : Annual Cycle

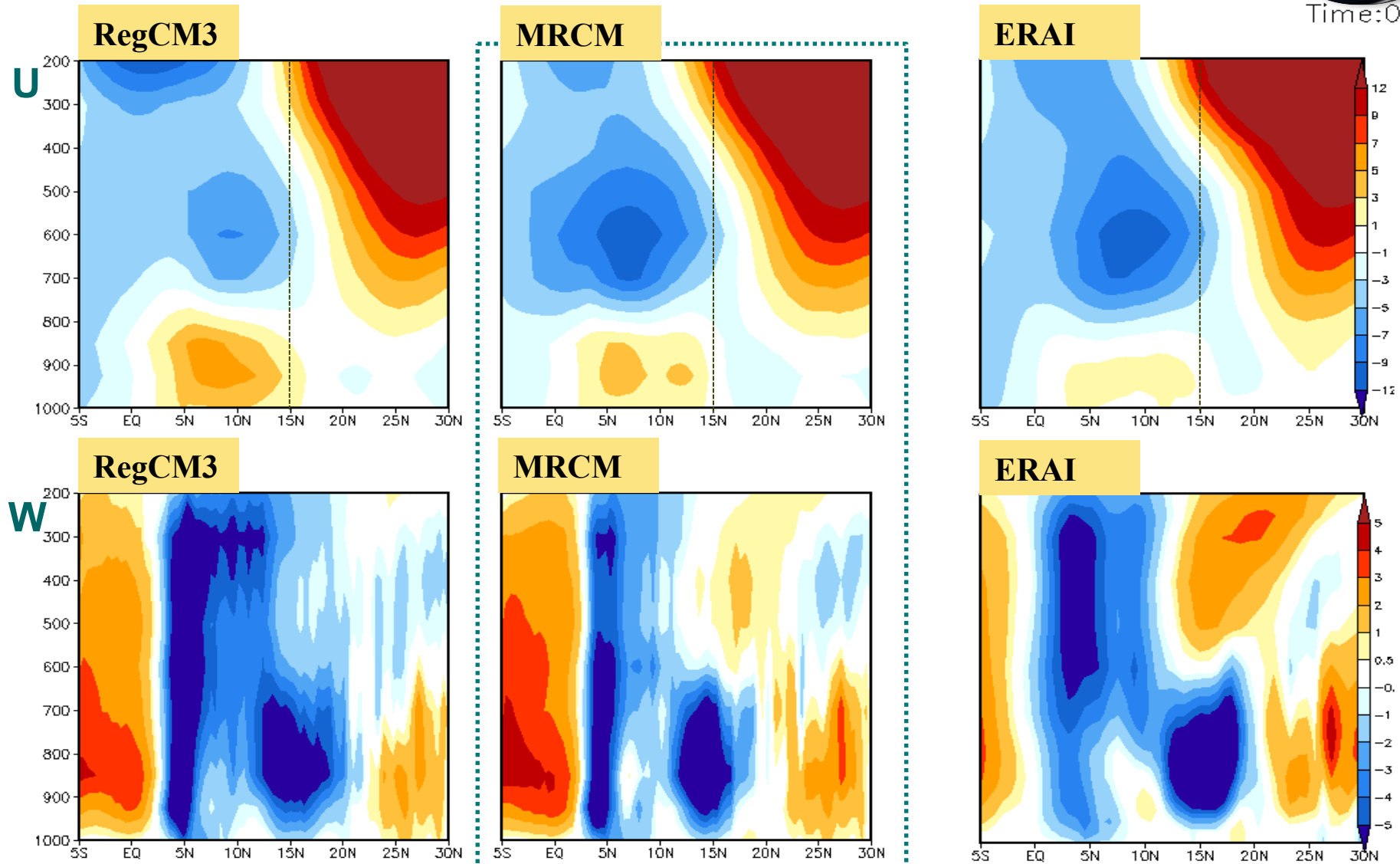
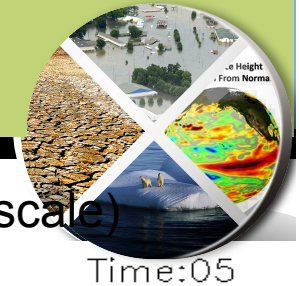


❖ Latitude-Time Cross-section of Rainfall & Net Radiation [averaged from 10W to 10E]



MRCM Improvement II : Vertical Structure

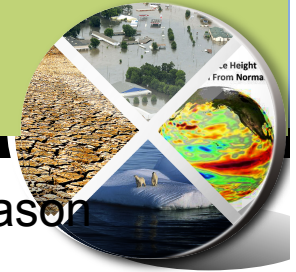
❖ Vertical Cross-section of Zonal Wind & Omega (May to Oct: monthly scale)



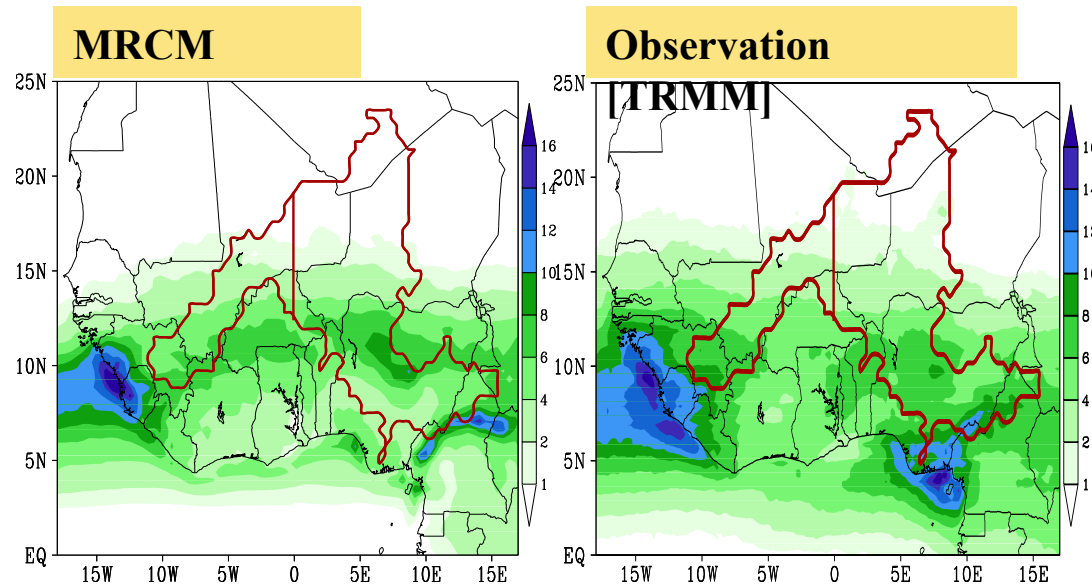
[Im et al. 2014: J. Climate]

Rainfall & Runoff over the Niger River Basin

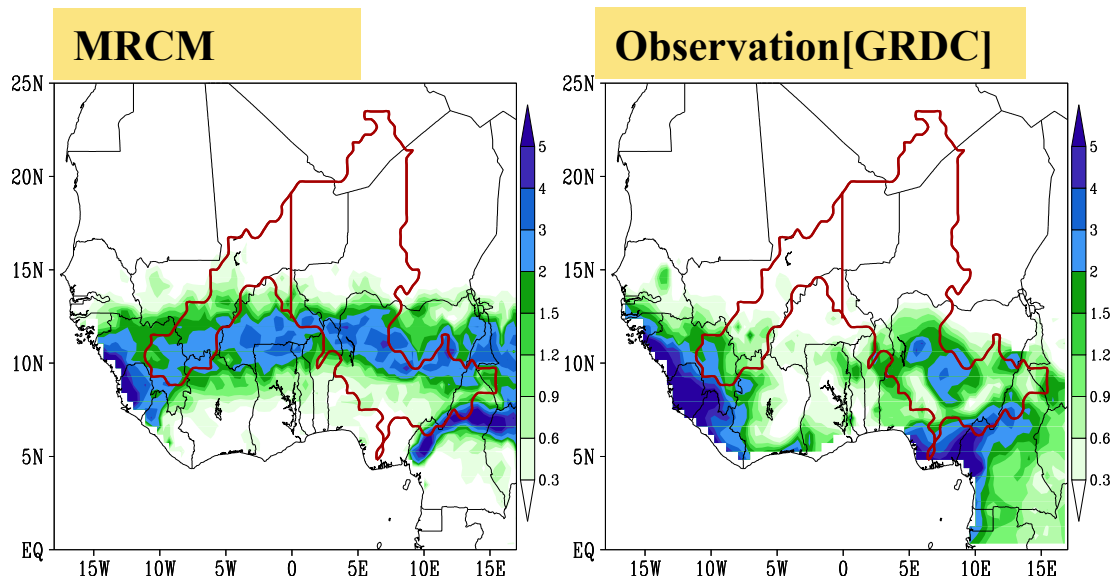
❖ Spatial Distribution of Climatological Rainfall & Runoff for Summer Season



Rainfall

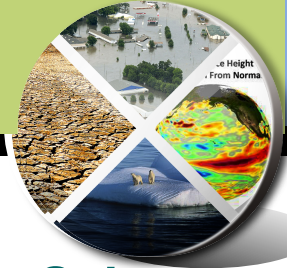


Runoff

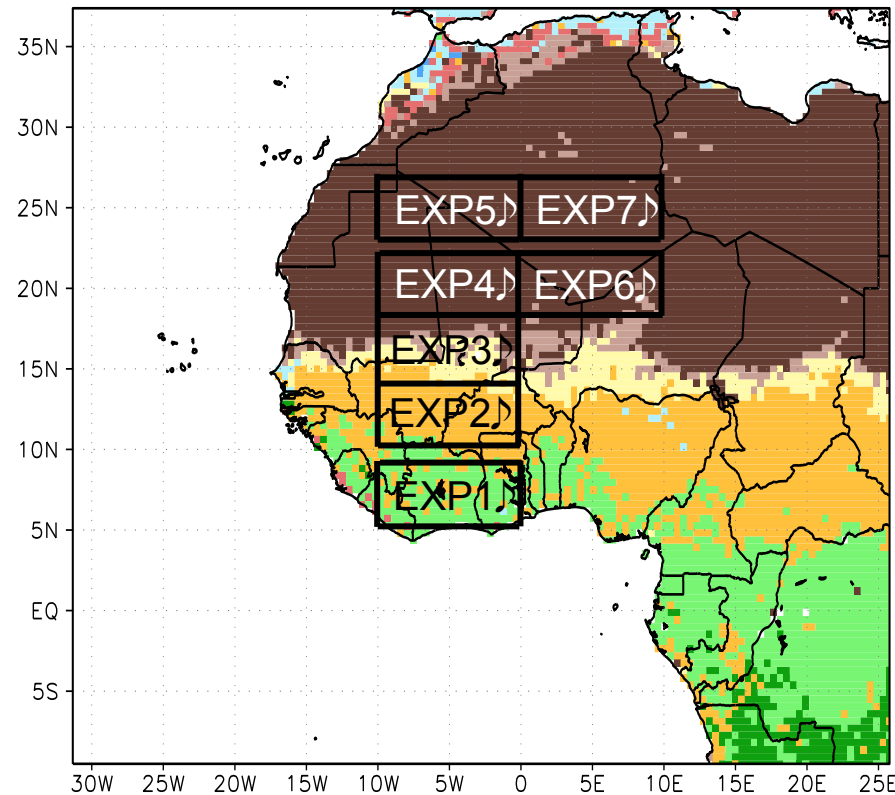


[Im & Eltahir 2014: WRR]

Irrigation Experimental Design

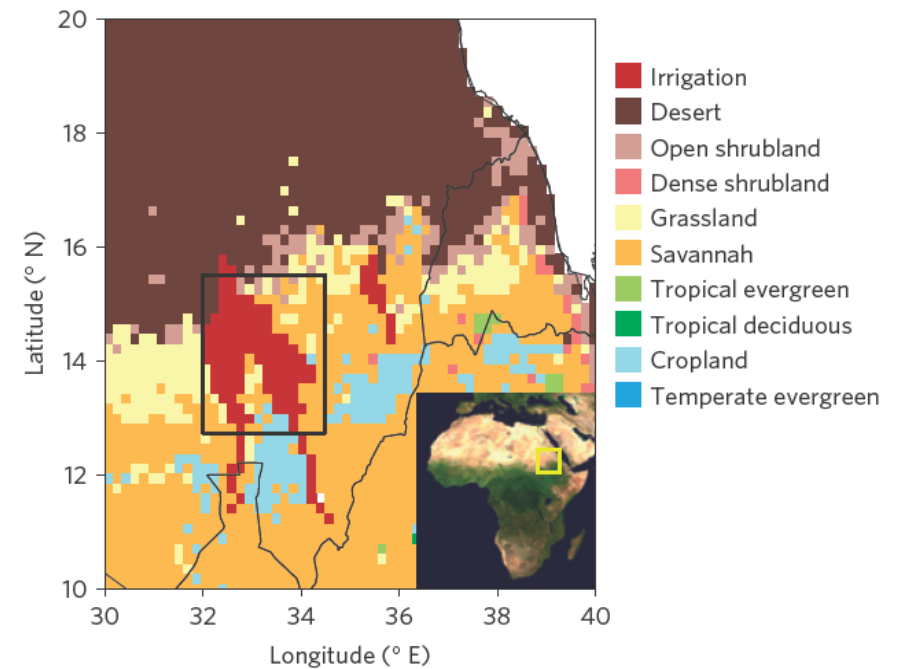


Step I: Theoretical & Conceptual EXP



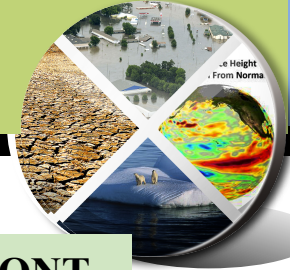
Large-scale Irrigation
: 4degX10deg~400,000 km²

Step II: Gezira Irrigation Scheme

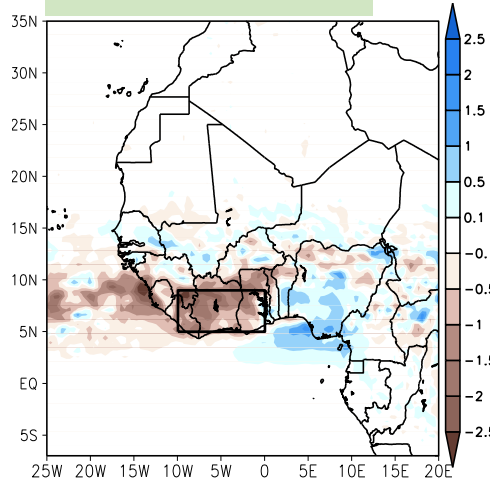


Medium-scale Irrigation
: 56,800 km²

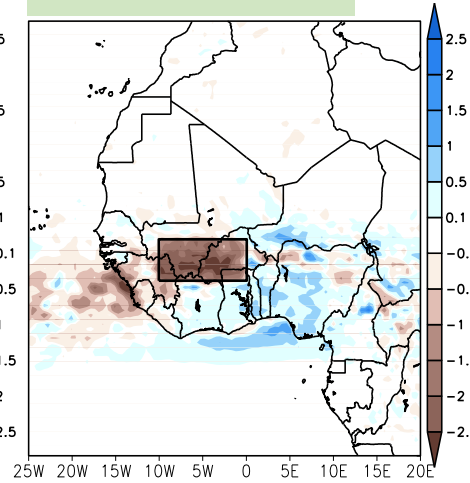
Irrigation Impact on Rainfall Changes (IRR-CONT)



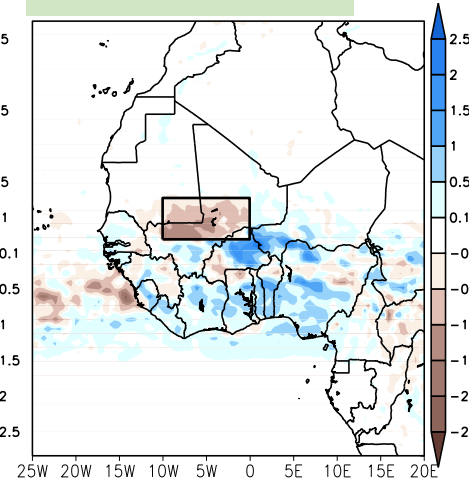
EXP1-CONT



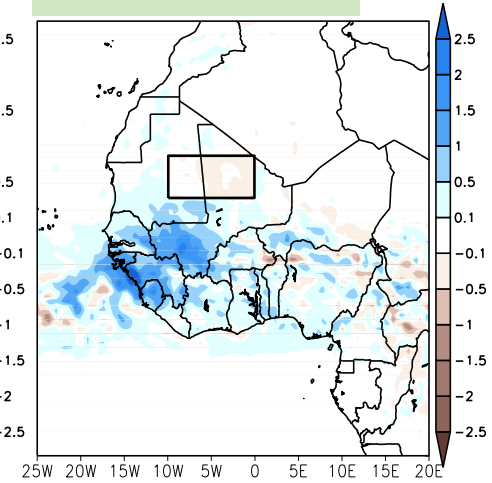
EXP2-CONT



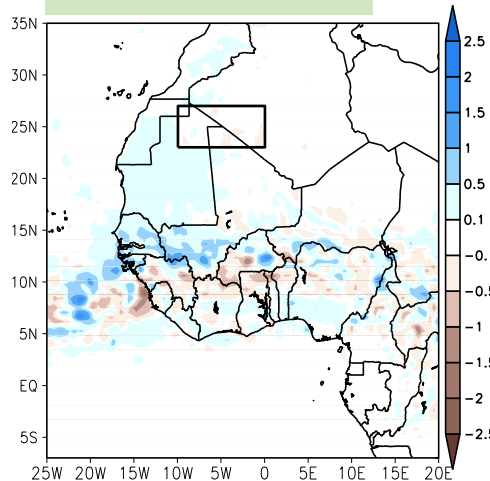
EXP3-CONT



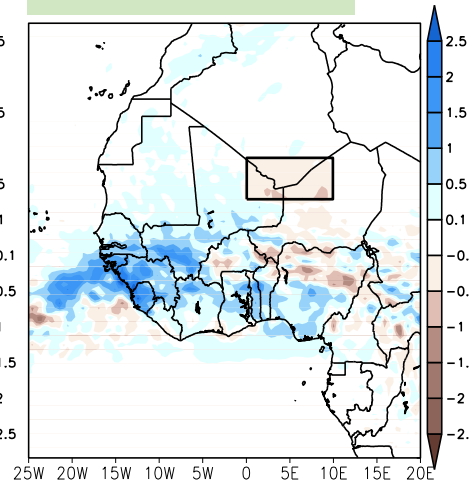
EXP4-CONT



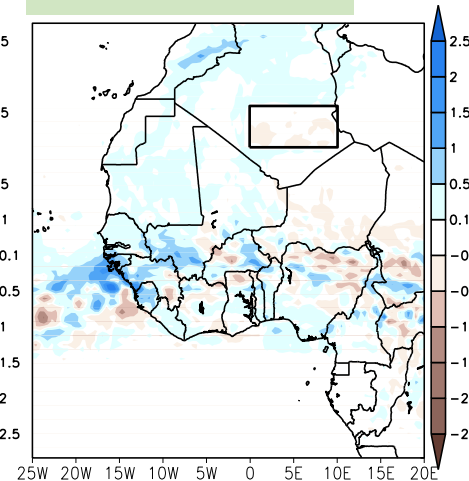
EXP5-CONT



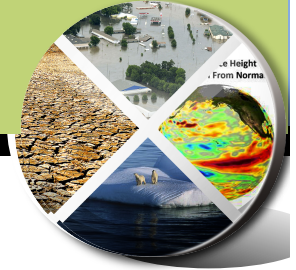
EXP6-CONT



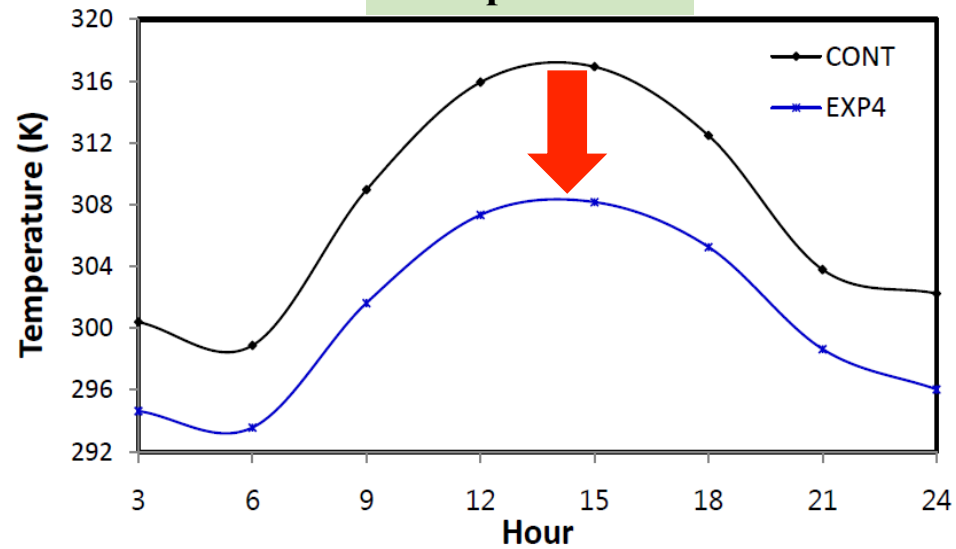
EXP7-CONT



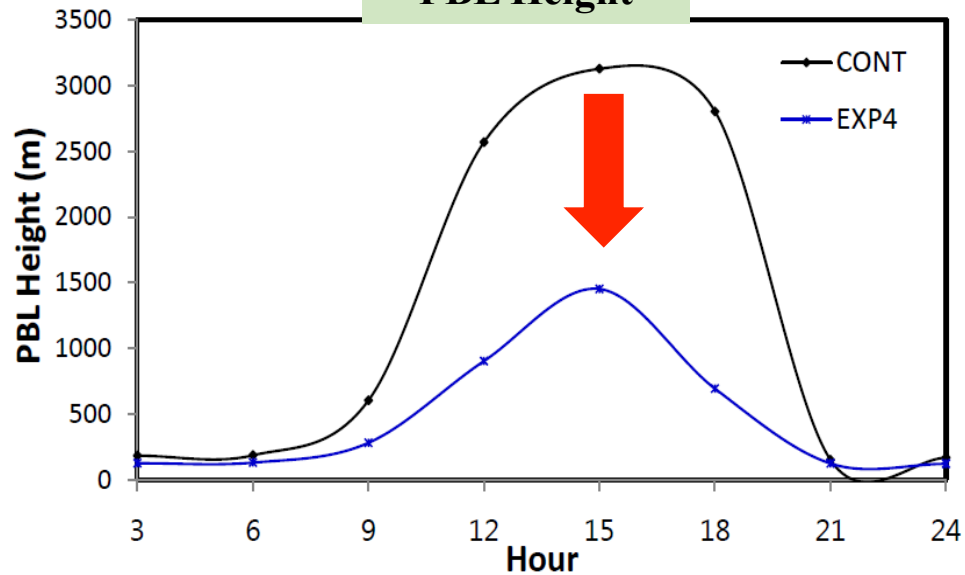
Mechanism of Local Response



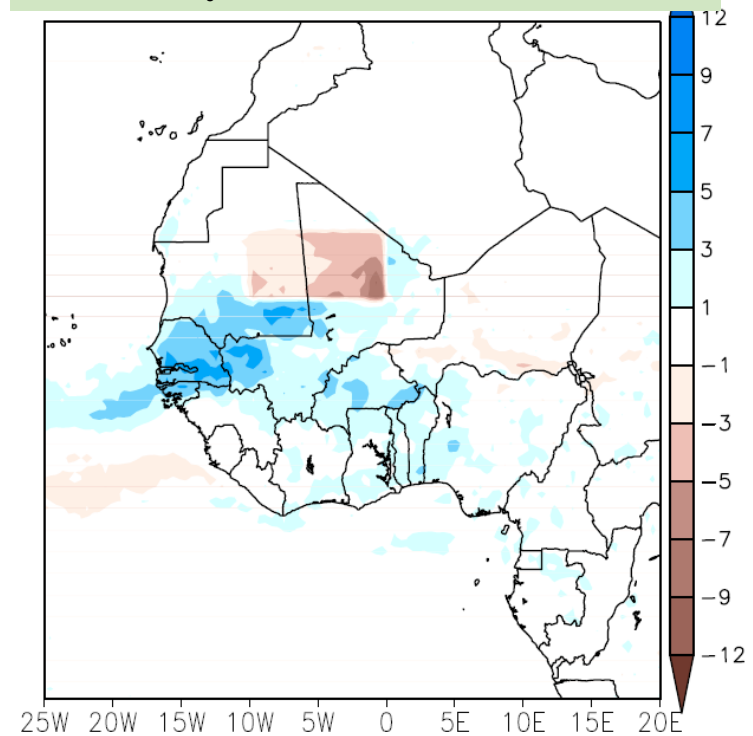
Temperature



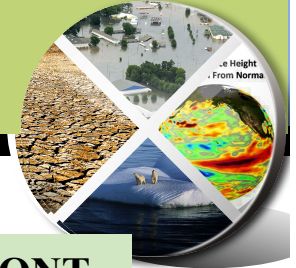
PBL Height



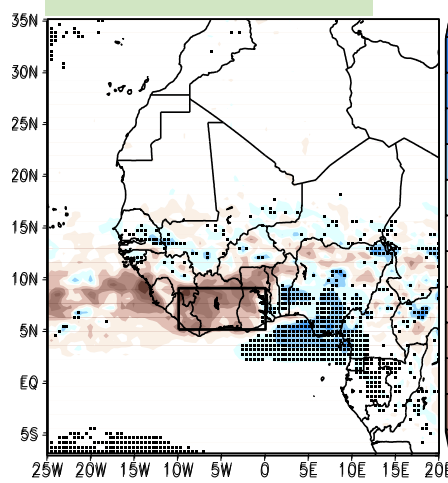
No of days with convective rainfall



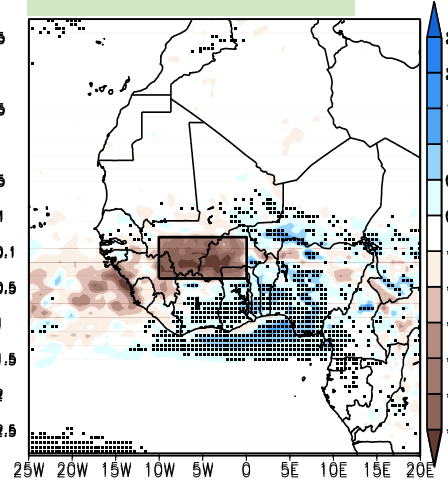
Irrigation Impact on Rainfall Changes (IRR-CONT)



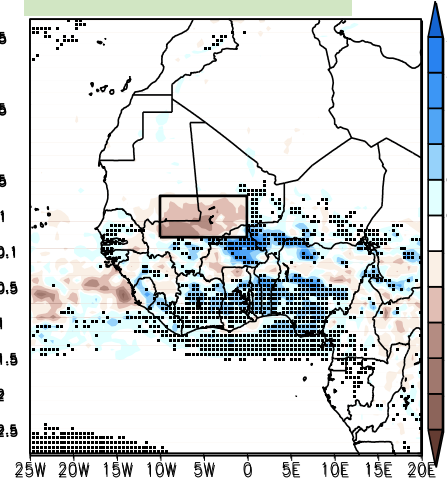
EXP1-CONT



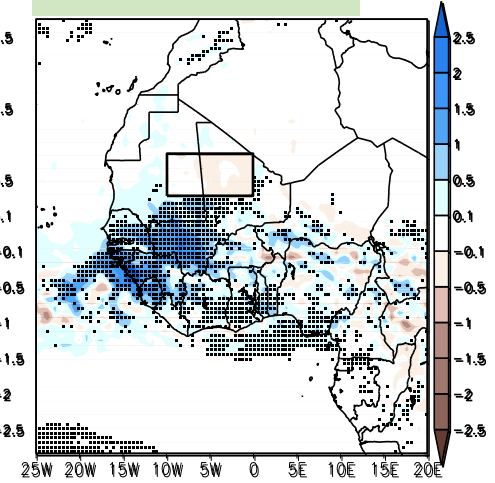
EXP2-CONT



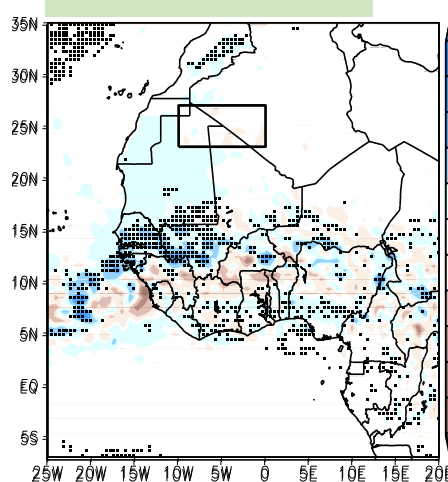
EXP3-CONT



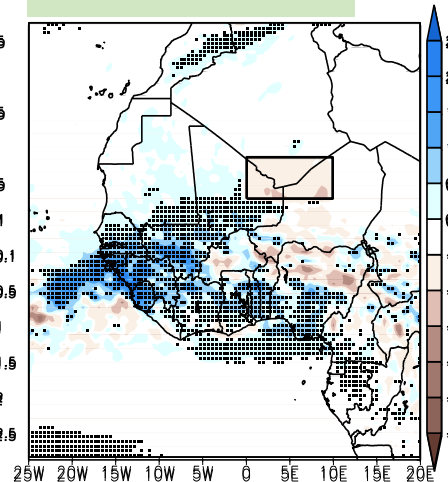
EXP4-CONT



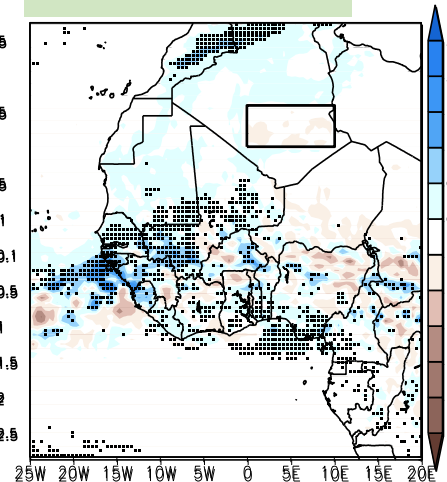
EXP5-CONT



EXP6-CONT



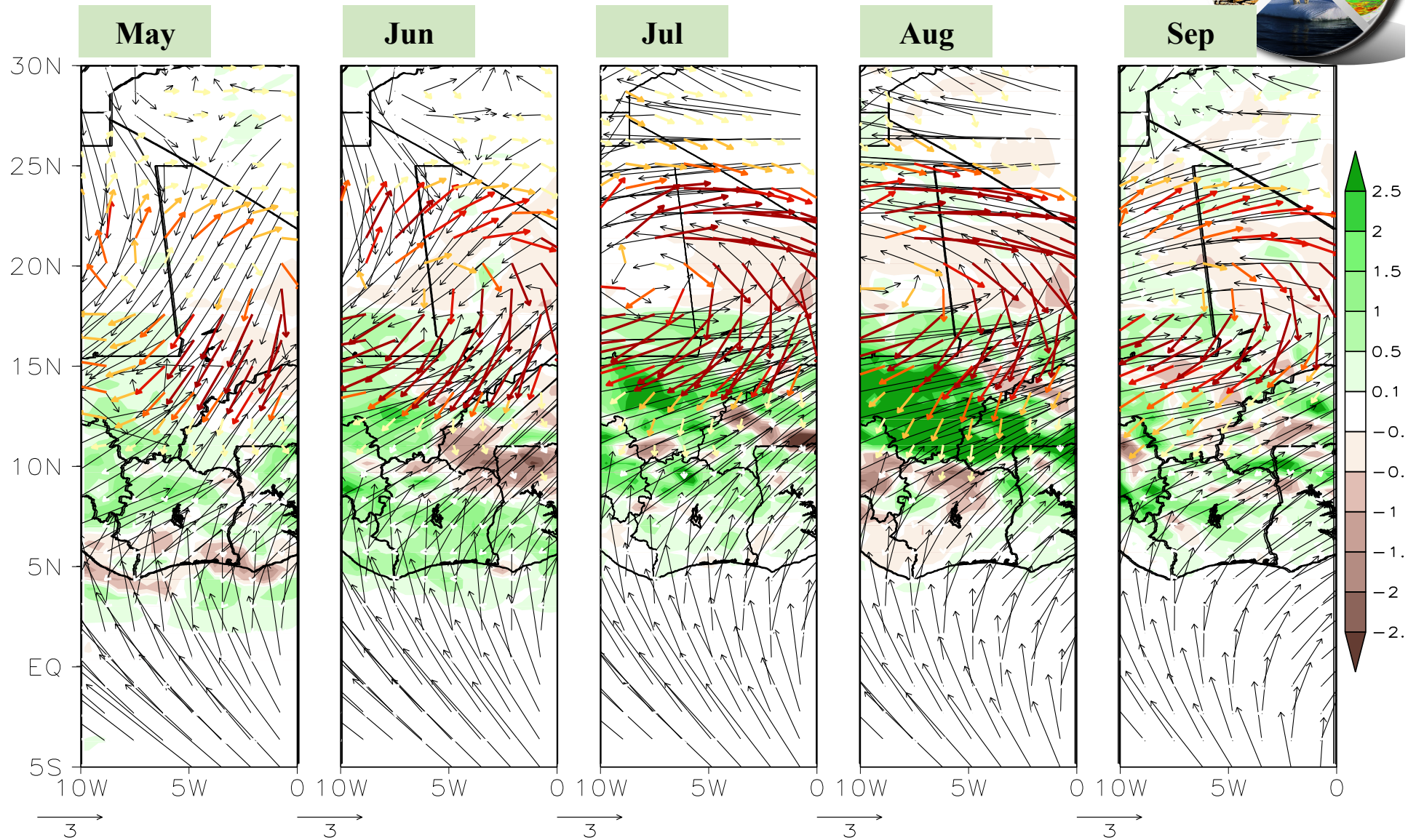
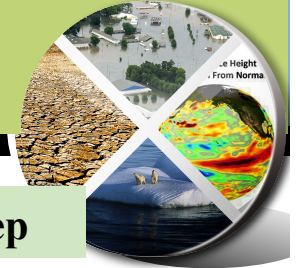
EXP7-CONT



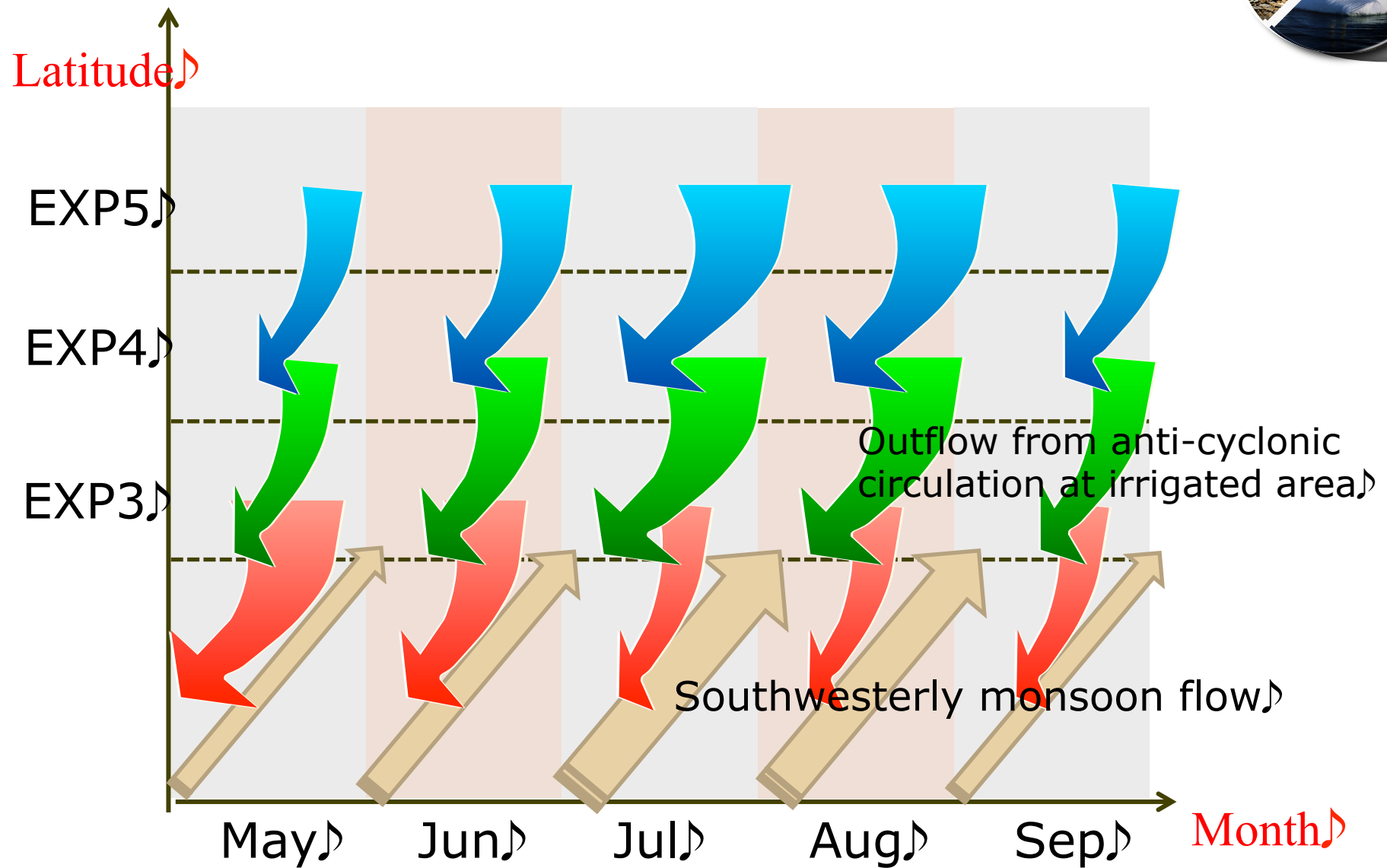
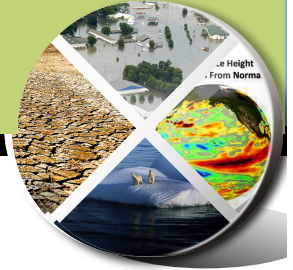
- Dotted area : Significance of rainfall increase

Remote Response

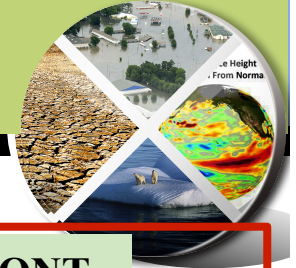
- Black arrow : CONT monsoon flow
- Red gradient arrow: Anomalous flow



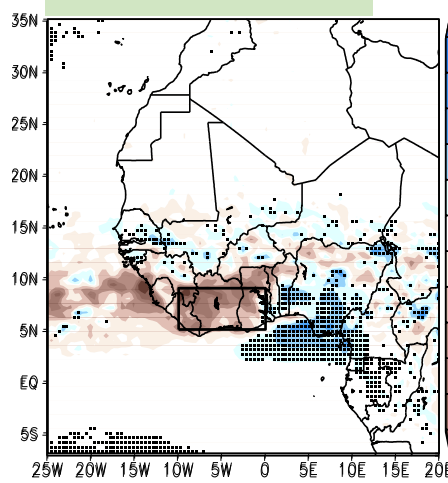
Schematic Diagram of Remote Mechanism



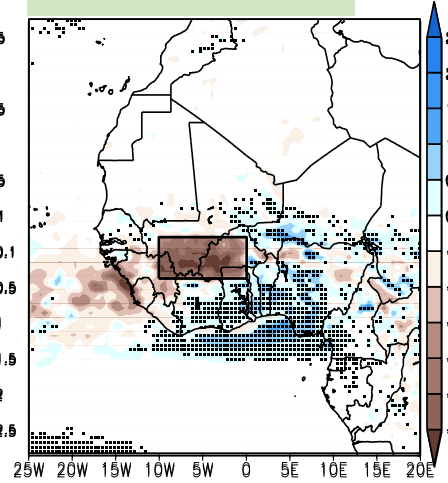
Irrigation Impact on Rainfall Changes (IRR-CONT)



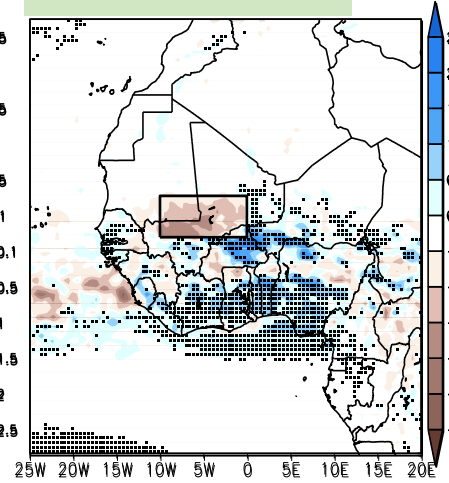
EXP1-CONT



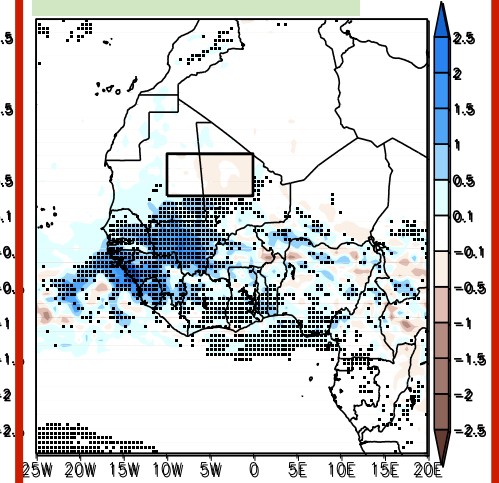
EXP2-CONT



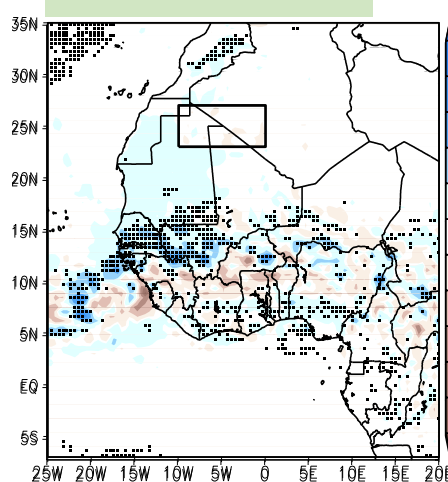
EXP3-CONT



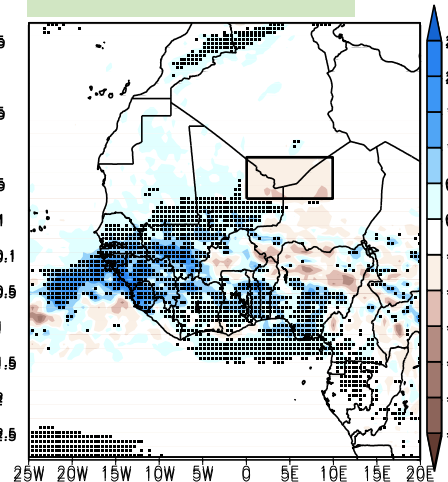
EXP4-CONT



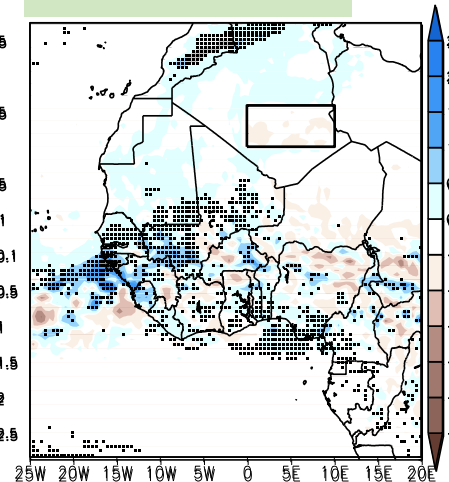
EXP5-CONT



EXP6-CONT



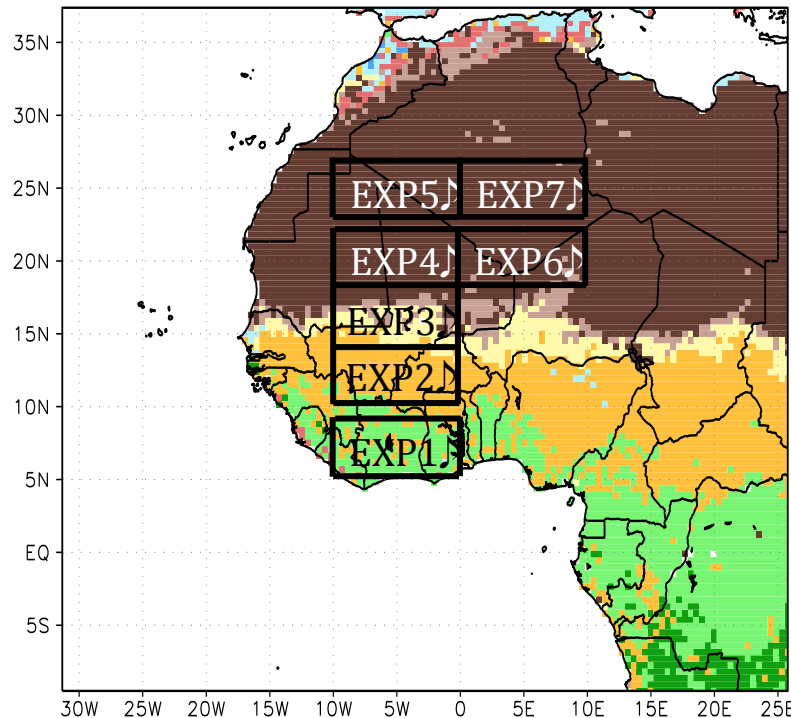
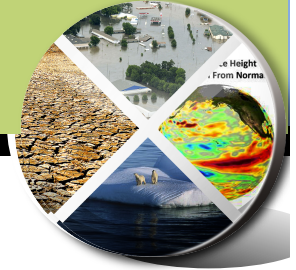
EXP7-CONT



- Dotted area
- : Significance of rainfall increase

Reliability of Methodology

Theoretical & Conceptual Experiments



Physical Mechanism

Wet soil moisture due to irrigation

Surface cooling

Suppression of PBL height

Reduced triggering of convection

Local rainfall decrease

Local Response

Remote Response

Anomalous descending motion

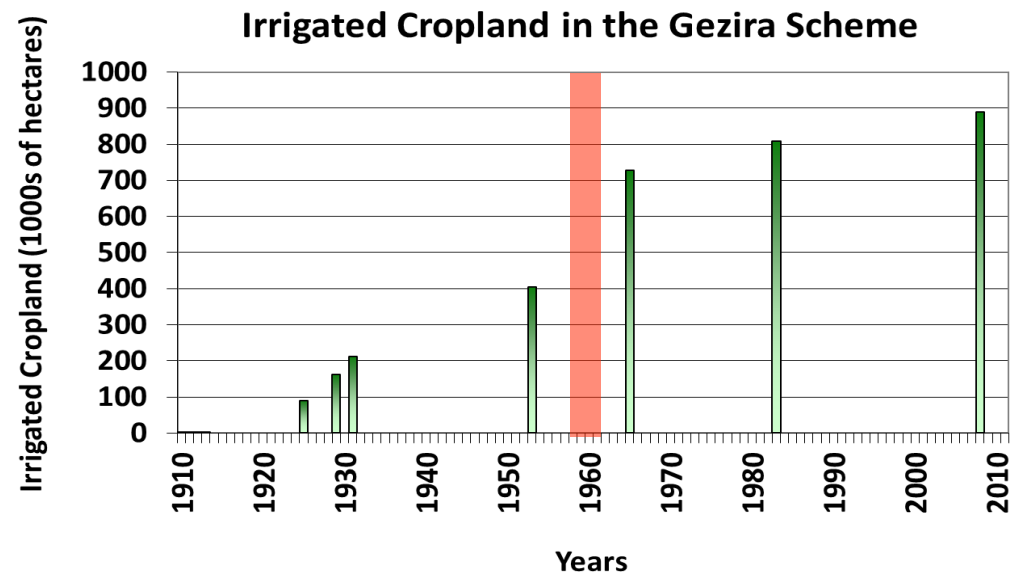
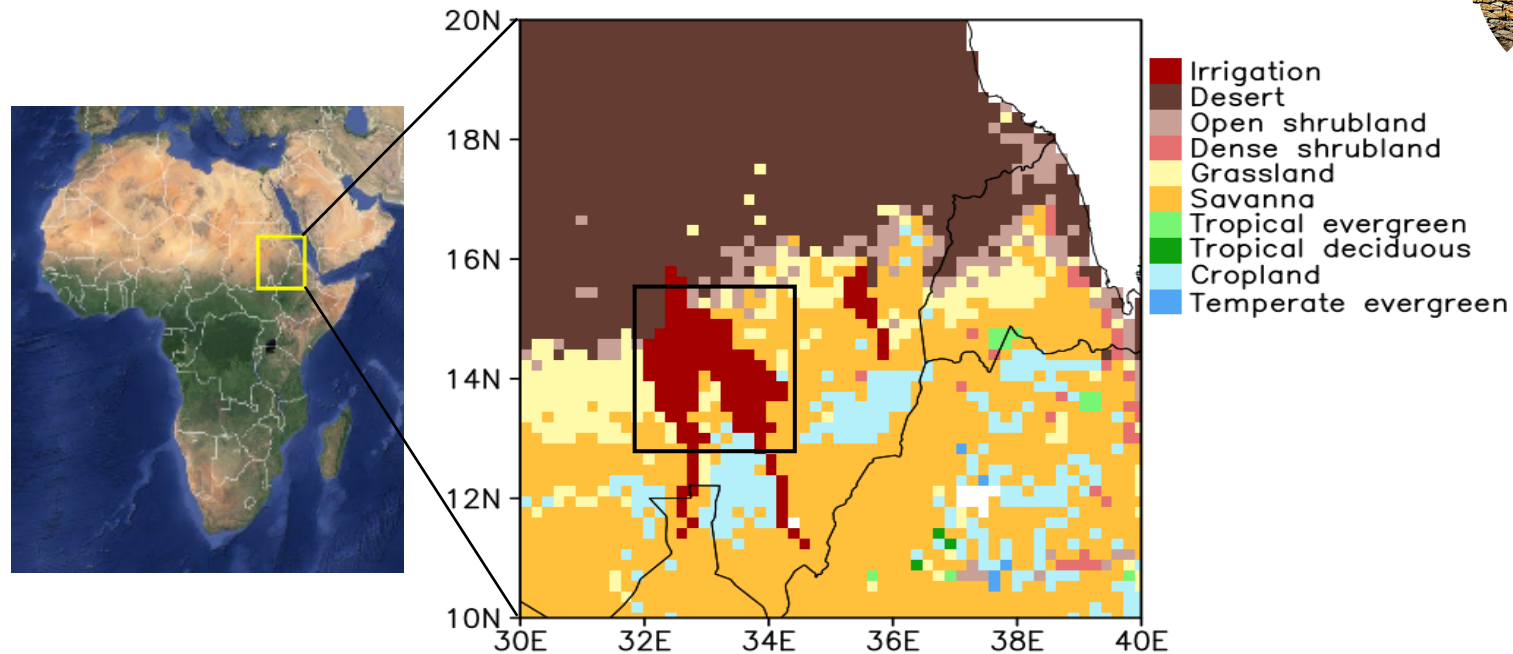
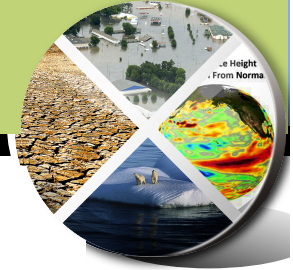
Anti-cyclonic circulation

Convergence between prevailing monsoon flows and anomalous outflows

Remote rainfall change

- **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



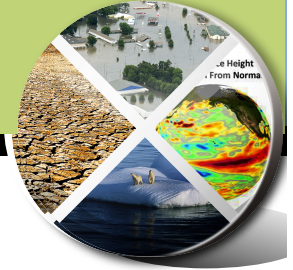
Manaqil Extension (MEX) ♪

➤ Period of intense irrigation development between 1958 and 1962♪

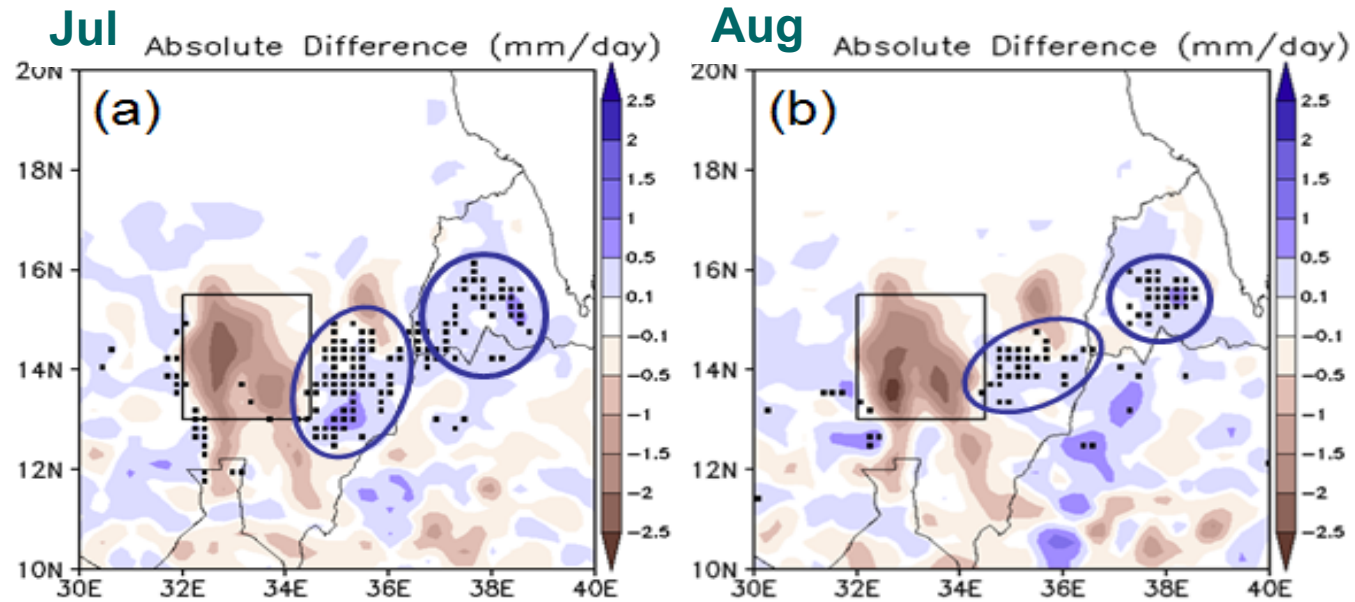
- pre-MEX: 1930-1959

- post-MEX: 1970-1999♪

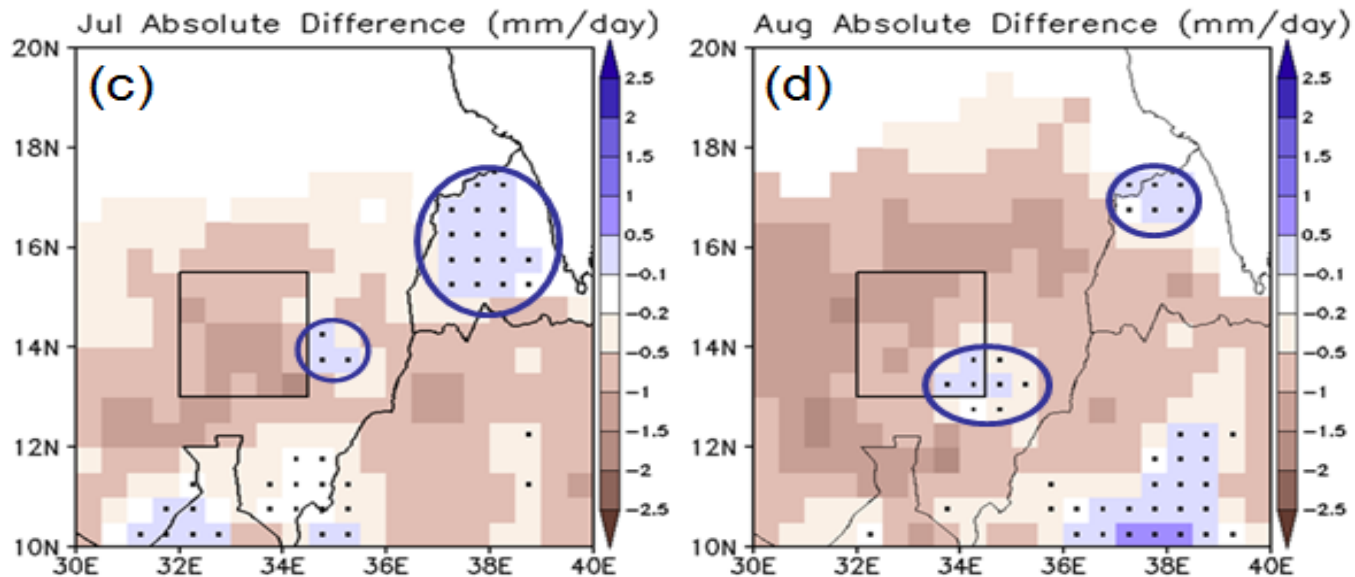
Simulated & Observed Changes in Rainfall



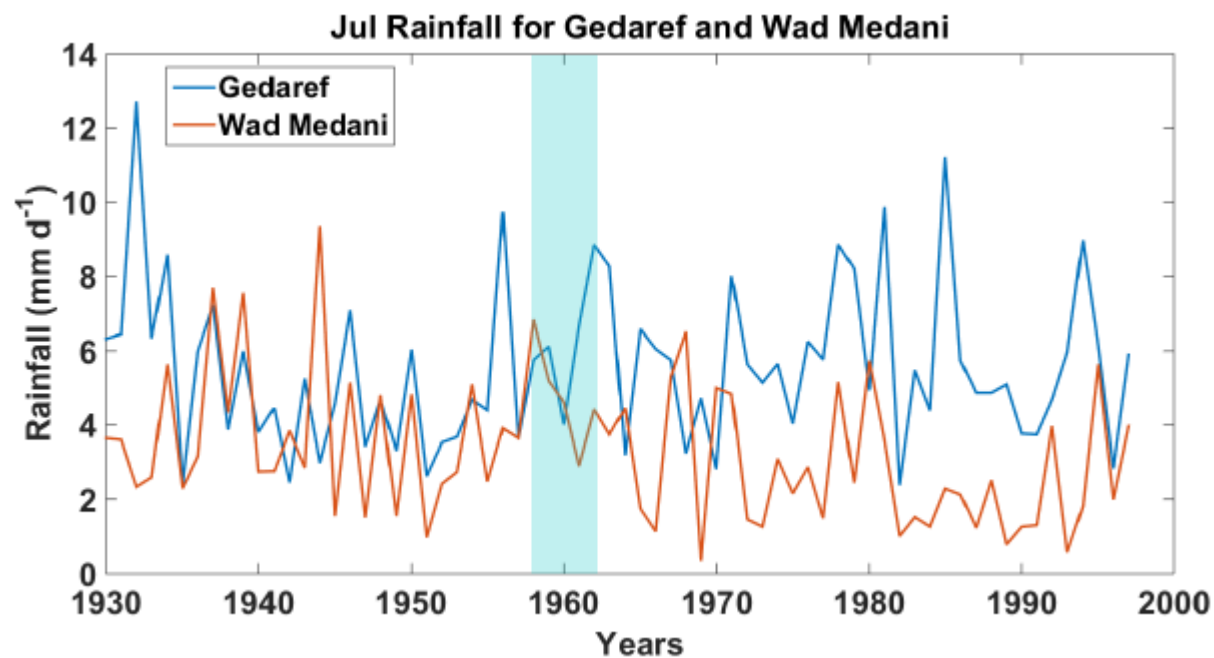
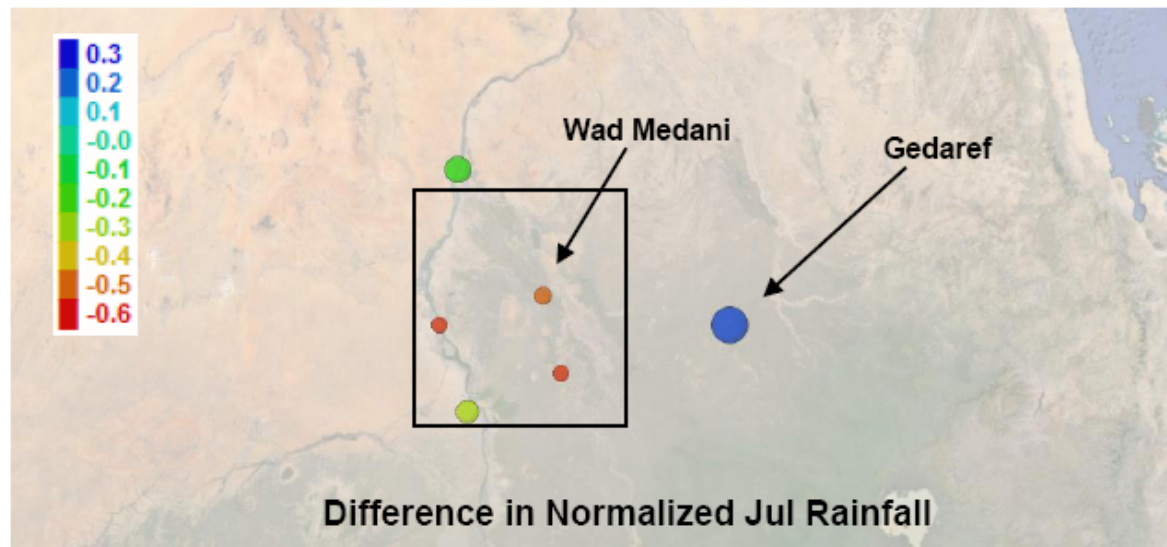
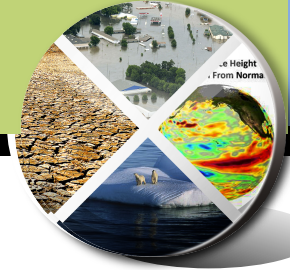
Simulated



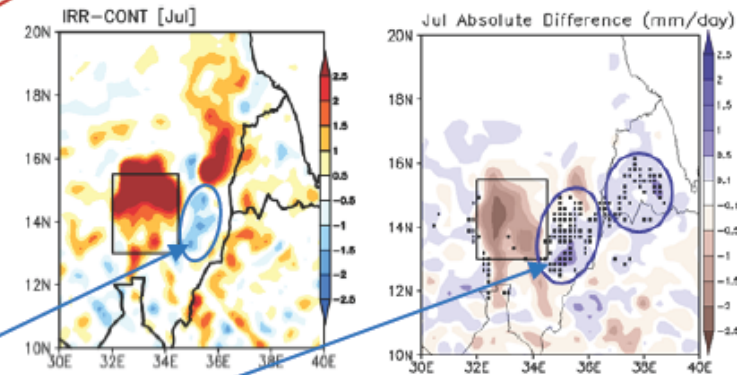
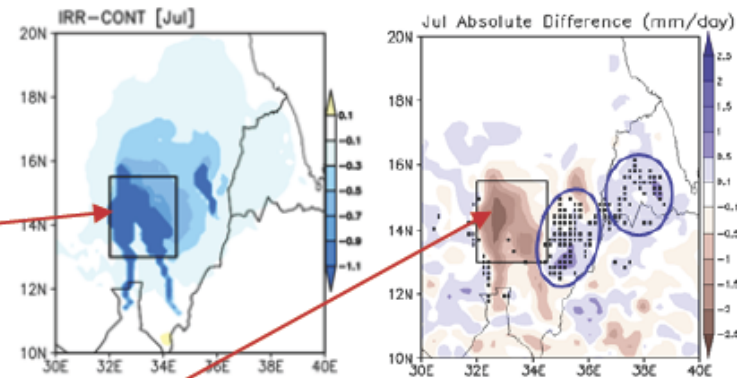
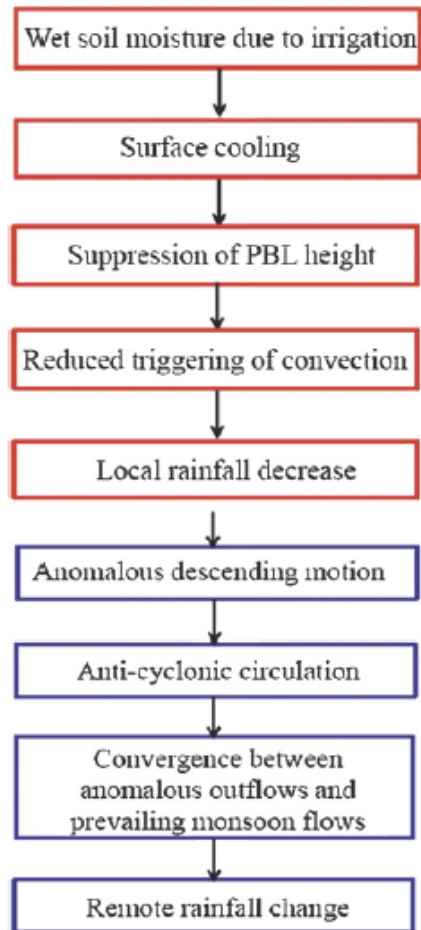
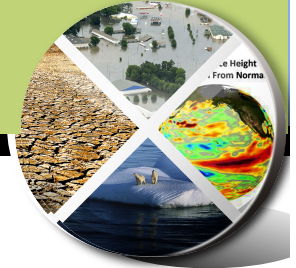
Observed



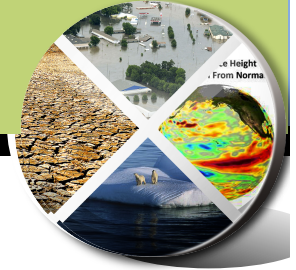
Temporal & Spatial Changes in Rainfall



Potential Mechanism



Take Home Messages



1

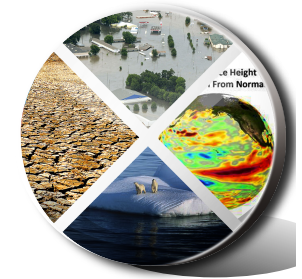
MRCM is a useful scientific tool for climate study

2

Irrigation has a significant impact on regional climate

3

Optimal irrigation planning is important for sustainability

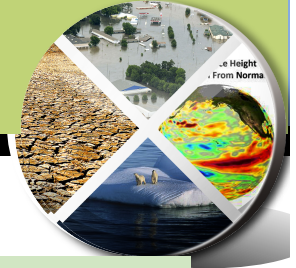


Thank you for your attention!

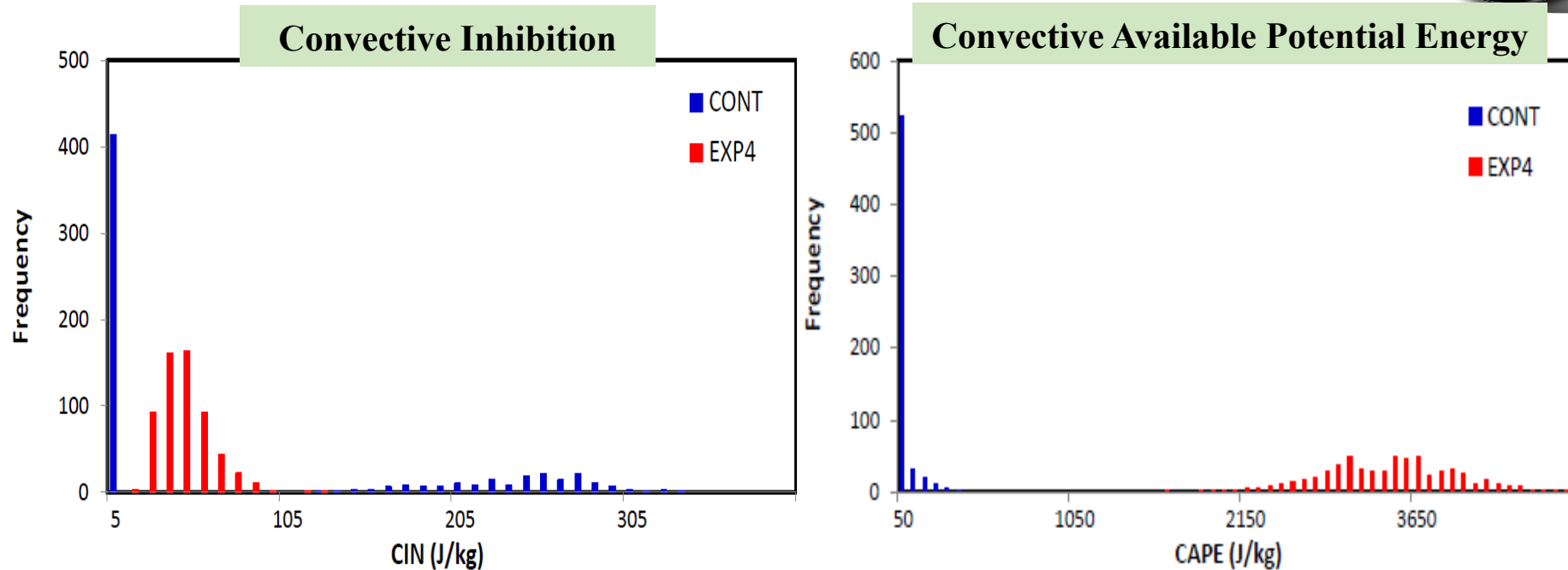
eunsoon@smart.mit.edu

- **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 (2016) Simulations of the observed “jump” in the West African monsoon and its underlying dynamics using the MIT Regional Climate Model. *Int. J. Climatology*, In revision.

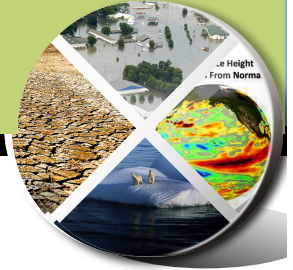
Irrigation Impact on Atmospheric Instability



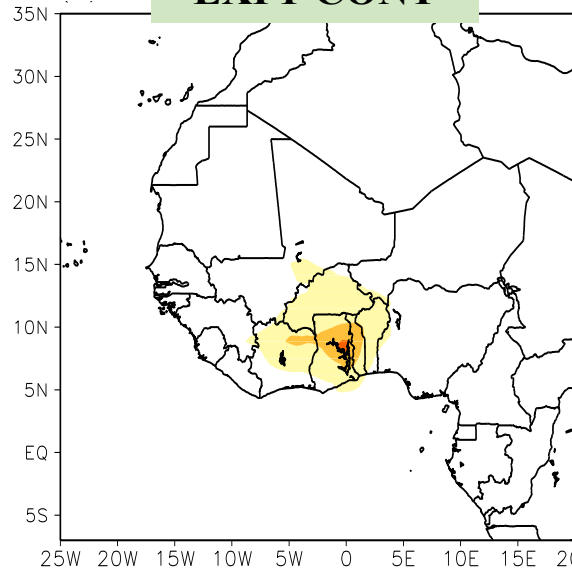
❖ Frequency Distribution of CIN & CAPE



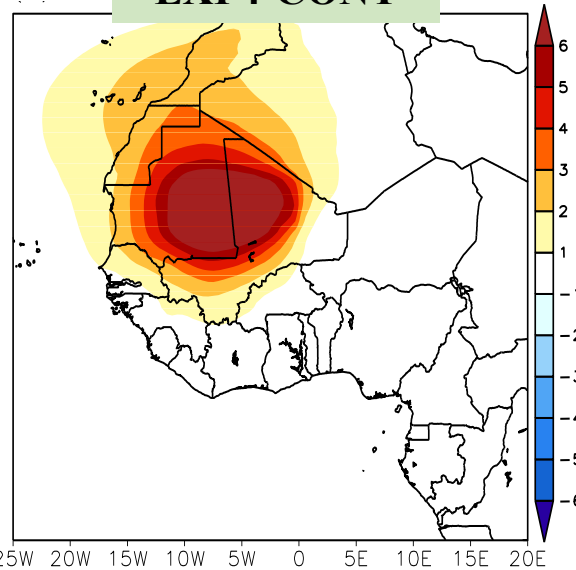
Geopotential Height & Wind at 925 hPa



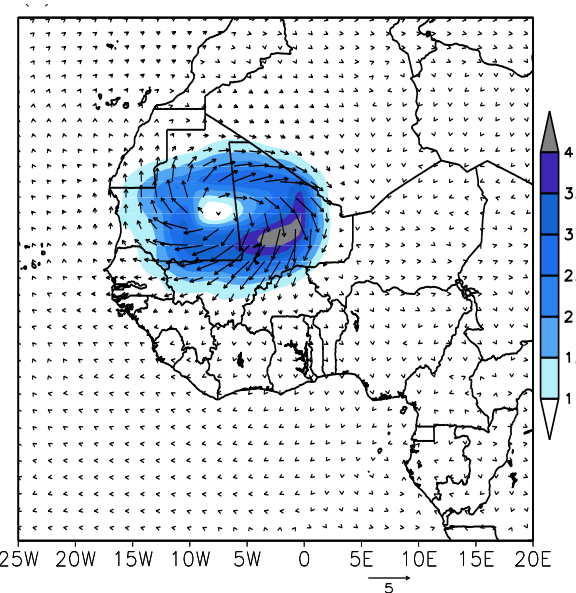
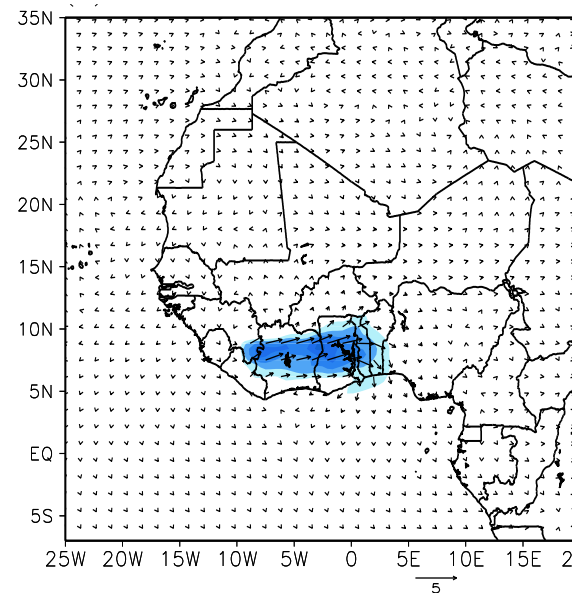
EXP1-CONT



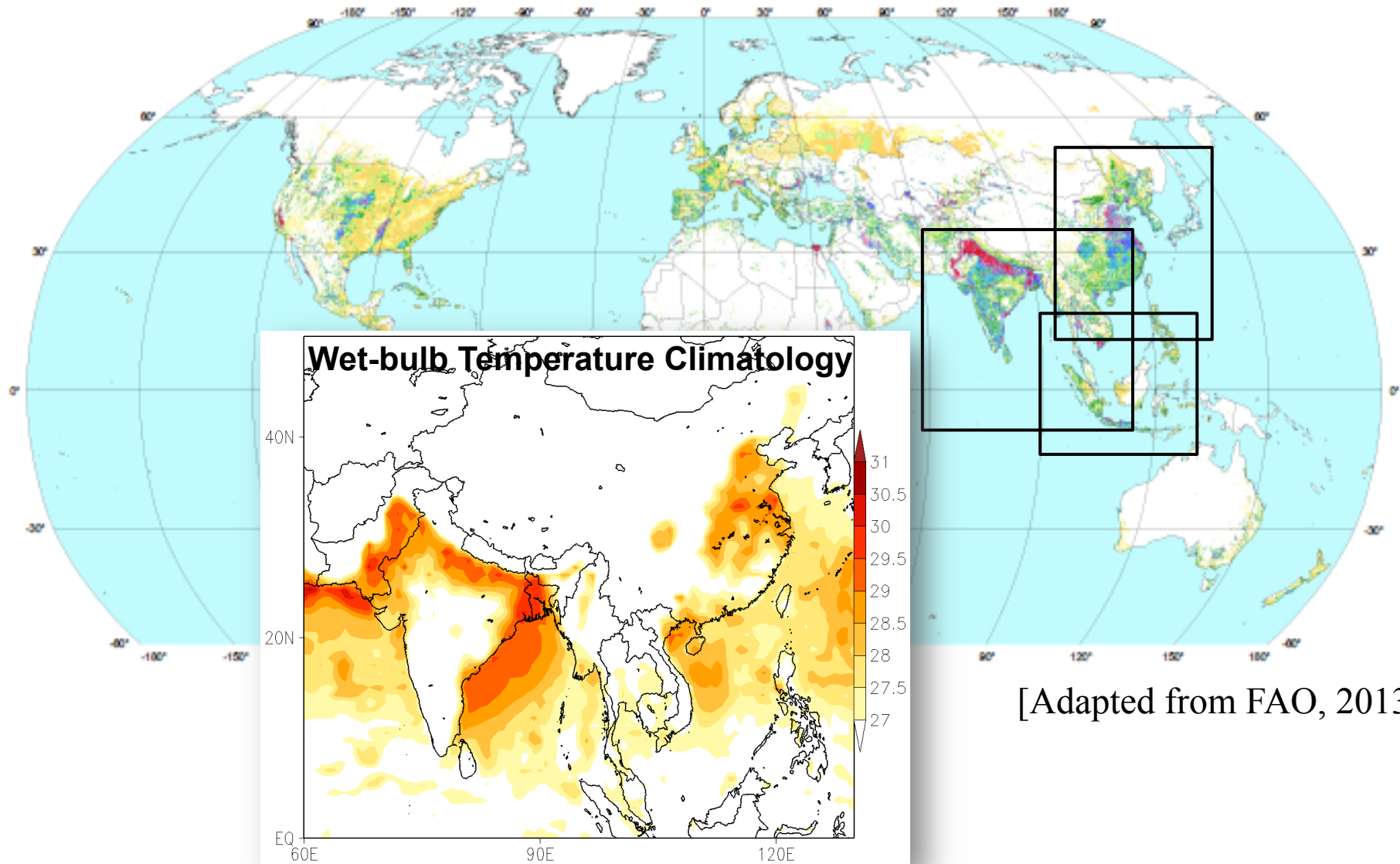
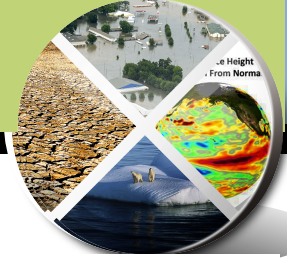
EXP4-CONT



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

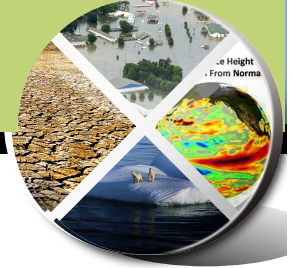


Future Study



[Adapted from FAO, 2013]

SMART Regional Climate Modeling



MRCM 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 cloud fraction and autoconversion scheme, land surface scheme irrigation module, boundary layer cloud , new albedo assignment)
- ➡ Im *et al.* 2014: Improving simulation of the West African monsoon using the **MIT Regional Climate Model**. [*J. Climate*]

MRCM Application

- Projection and understanding of anthropogenic impacts on regional climate system
- ➡ Anthropogenic **greenhouse gases emission** (e.g. CO₂, CH₄) : **Maritime Continent**
- ➡ Anthropogenic **land use change** (e.g. irrigation) : **Africa**

Potential Mechanism

