Diagnosing the characteristics of Sahel Drought in the Ensemble CAM 3.5 using Data Assimilation

Yu-Heng Tseng
Department of Atmospheric Sciences
National Taiwan University

Collaborators: Junjie Liu, Eugenia Kalnay, Inez Fung, Michael Wehner

2011 CESM-AMWG 14-16 Feb. at NCAR

Motivation & goals

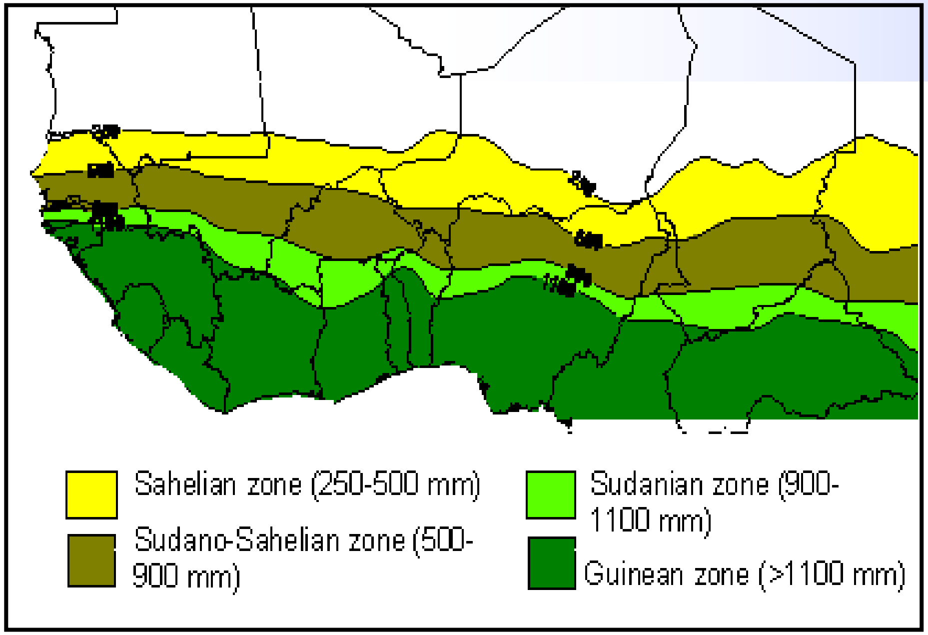
Motivation:

- Observation can be used to constrain uncertain parameters
- perturbed ensemble data-assimilated climate simulations can then be used to diagnose and quantify the uncertainty in climate projection
- Multi-model Ensembles (MME)???

Goals:

Through the Uncertainty Quantification (UQ), itentify the possible “missing” mechanism/dynamics controlling the Sahel precipitation in CAM3.5

The Sahel

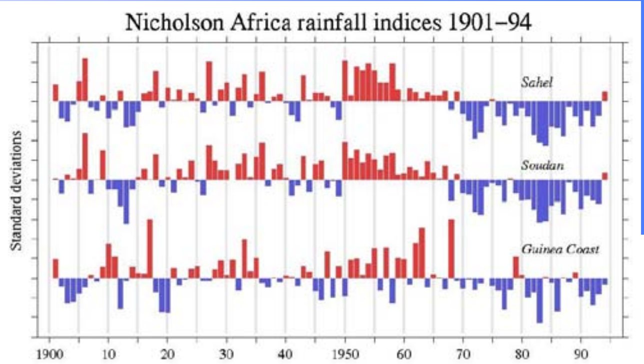


Agro-climatic Zones in the Sahel.
Source: http://www.fao.org/docrep/oo4

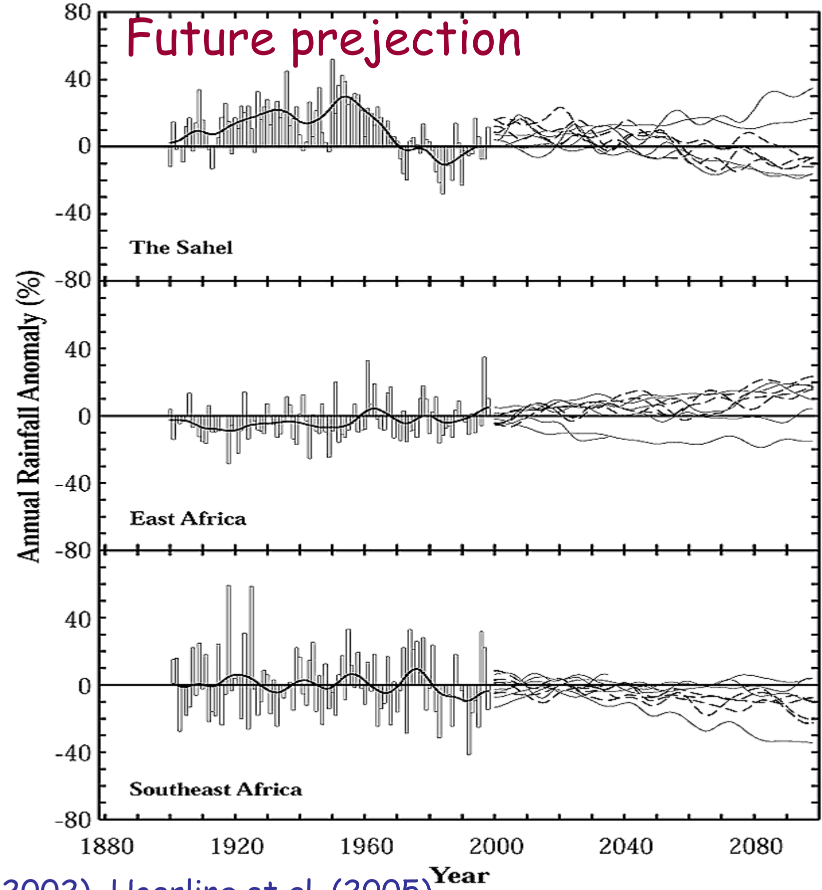
- Sahel –A transition between the southern margin of the Sahara desert and the savanna regions to the south.
- A bio-climatic zone of mainly annual grasses with a few shrubs and trees, that receives a mean annual rainfall of between 150 and 600mm
- A steep gradient of decreasing rainfall from south to north, with an increase in inter-annual and spatial variability.
- A zone of cultural transition where the Islamic culture from the north mingles with the traditional cultures of the south.
- North-south stratification of social systems, northerly cultures tend towards pastoralism, southerly cultures largely practice sedentary agriculture.

The Sahel drought: Historical hypotheses

- Local forcing: **(anthropogenic) deforestation/desertification cause enhanced albedo and subsidence.**
- Remote forcing: **Sea Surface Temperature (SST) anomalies change the tropical circulation and rainfall.**
- The climatic future of the Sahel remains uncertain. While some studies predict increased droughts, others suggest wetter conditions in parts of the Sahel, and an expansion of vegetation into the Sahara.



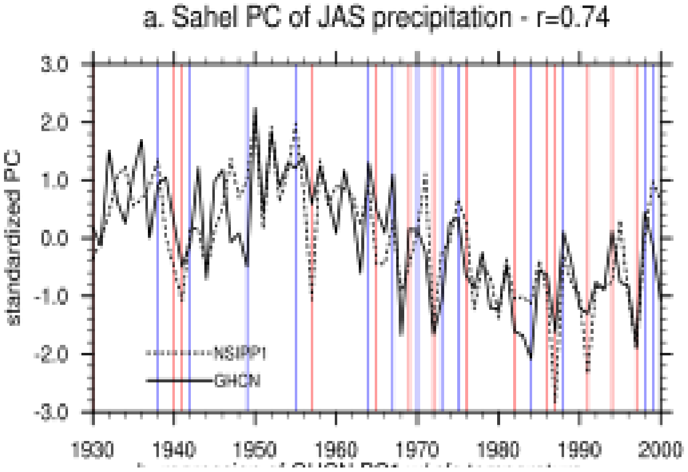
http://jisao.washington.edu/data/nicholson/


Future prejection

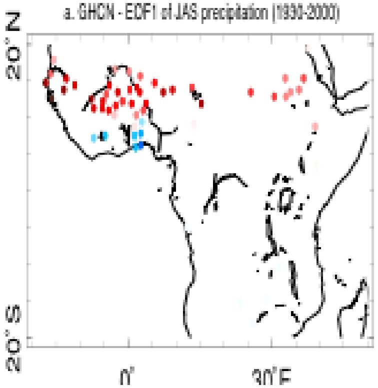
REF:e.g., Brovkin, (2002), Claussen *et al.* (2003), Maynard *et al.* (2002), Hoerling et al. (2005).

Influences of SST:

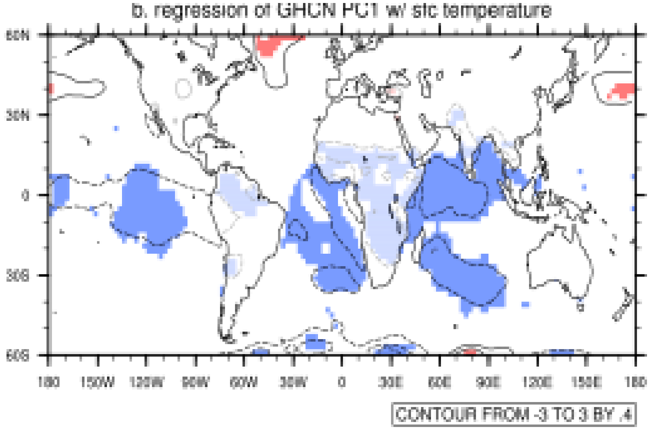
1. statistical association with WAM (West Africa Monsoon)



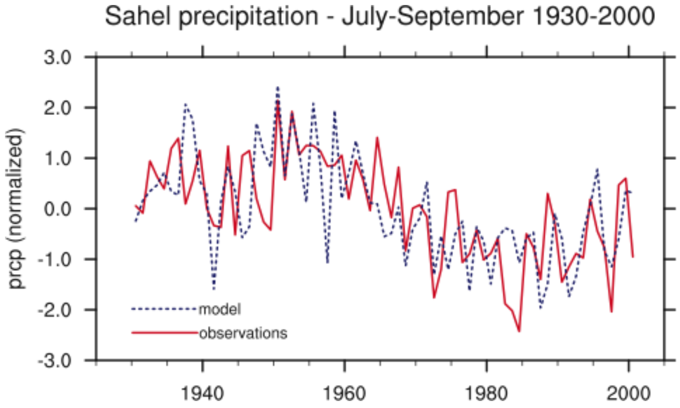
EOF1: Sahel rainfall

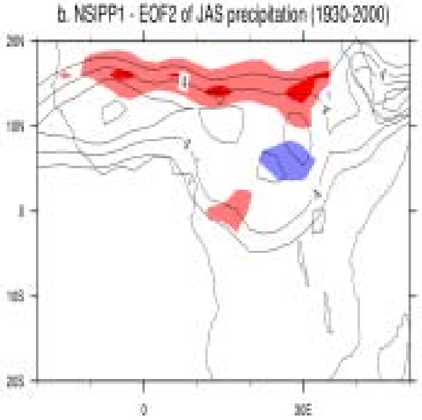


Associated SST



2. AGCMs forced with the historical SST reproduce the African summer rainfall modes





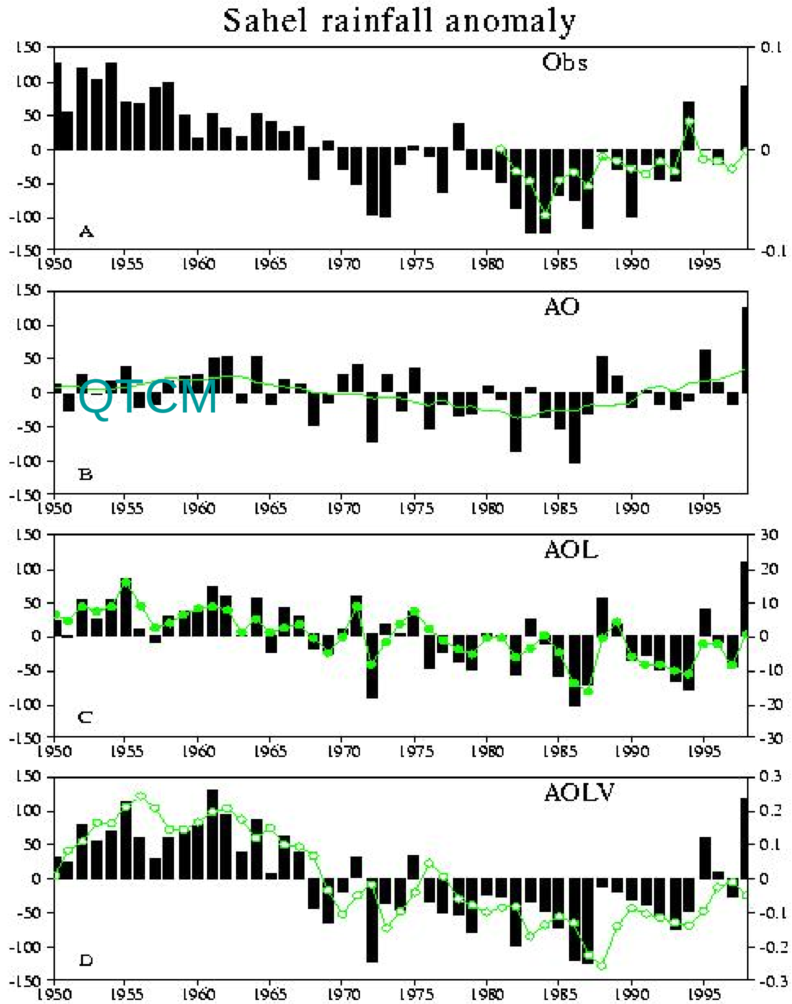
NSIPP
amip
ensemble

Giannini et al., 2003, 2005

The role of land surface processes: from forcing to feedback

- Observations:
    - vegetation follows rain
    - albedo changes unclear
- Model simulations:

  interactive surface processes and vegetation contribute to the strength and life span of rainfall anomalies.



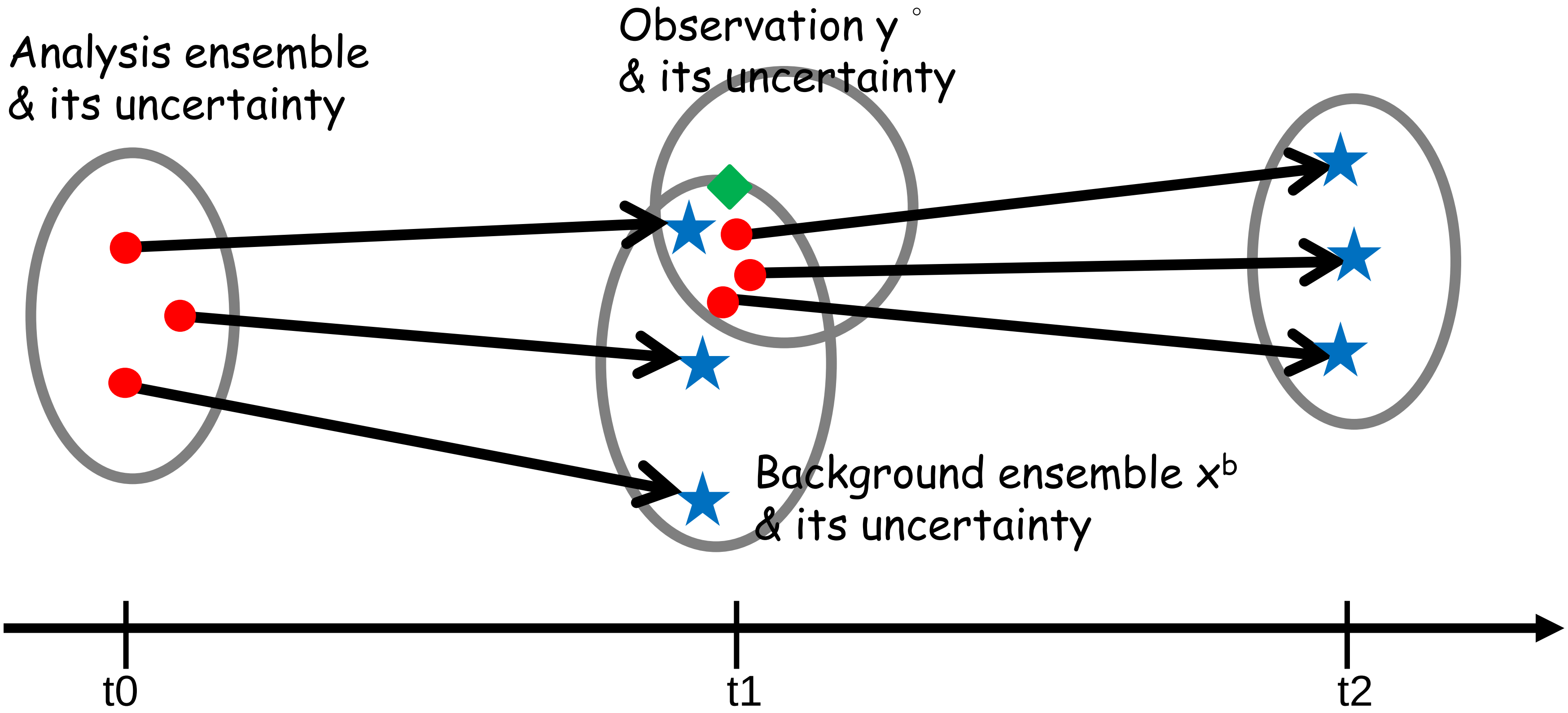
Nicholson et al, 1998; Zeng et al. 1999

Numerical Experiments

- Community Atmospheric Model 3.5 (CAM 3.5) coupled with Community Land Model 3.5 (CAM 3.5)
  - Finite Volume dynamical core
  - 2.5 ° x 1.9° horizontal resolution, with 26 vertical levels up to 3.5hPa.
- Four-year model integration started from 01 Jan 2000
- Focus on Aug 2000
- initialized with a random ensemble of global meteorol. status, equal to the randomly picked analysis increments of DOE/NCEP Reanalysis II

Courtesy of Junjie Liu

Ensemble Kalman Filter



Analysis ensemble
& its uncertainty

Observation y^{o}
& its uncertainty

Background ensemble x^b
& its uncertainty

Analysis mean $\overline{X^a} = \overline{X^b} + K\left(y^0 - h\left(\overline{X^b}\right)\right)$,

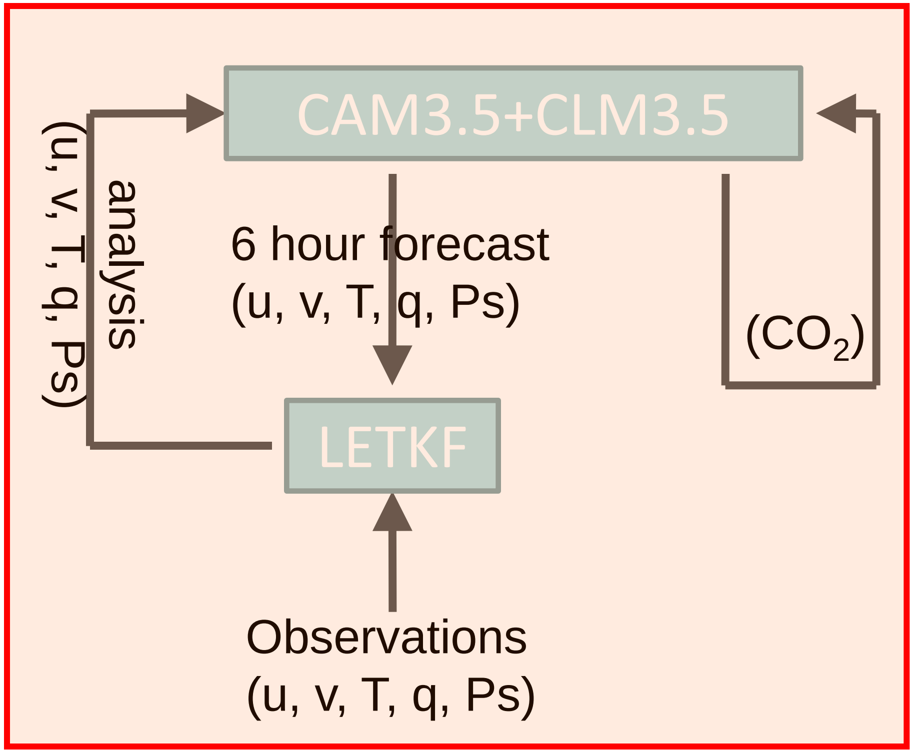
K is function of background error and observation error.

$h(\cdot)$ is the observation operator, which interpolates model forecast to observation space .

Two assimilation settings, with and without AIRS CO2

64 ensemble simulations-perturbed differences in initial fields only

Uncertainty estimation is superior to MMEs



CAM3.5+CLM3.5

analysis

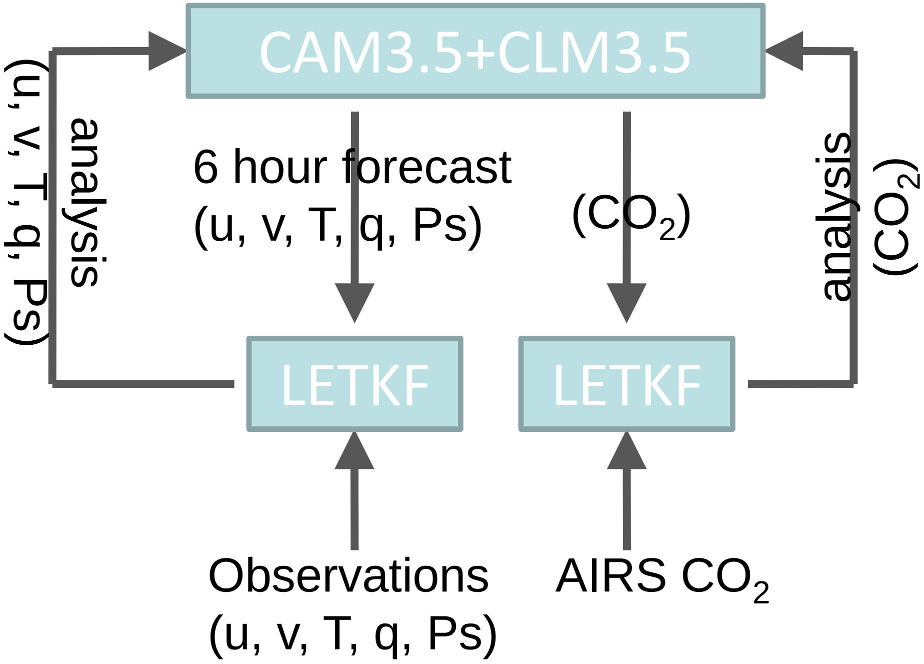
(u, v, T, q, Ps)

6 hour forecast
(u, v, T, q, Ps)

(CO_2)

LETKF

Observations
(u, v, T, q, Ps)



CAM3.5+CLM3.5

analysis

(u, v, T, q, Ps)

6 hour forecast
(u, v, T, q, Ps)

(CO_2)

analysis

(CO_2)

LETKF

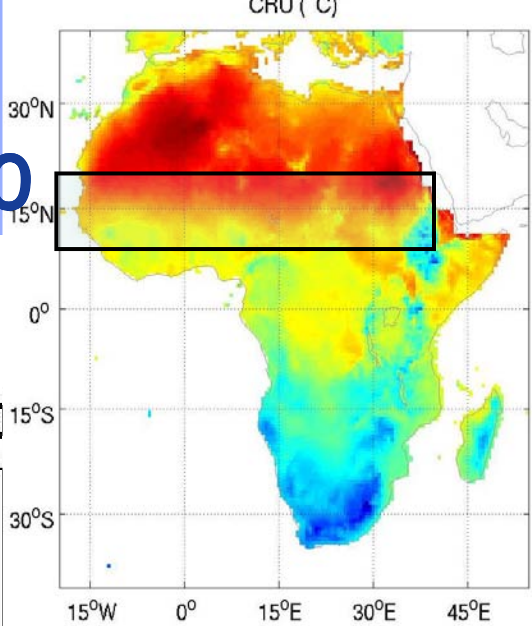
LETKF

Observations
(u, v, T, q, Ps)

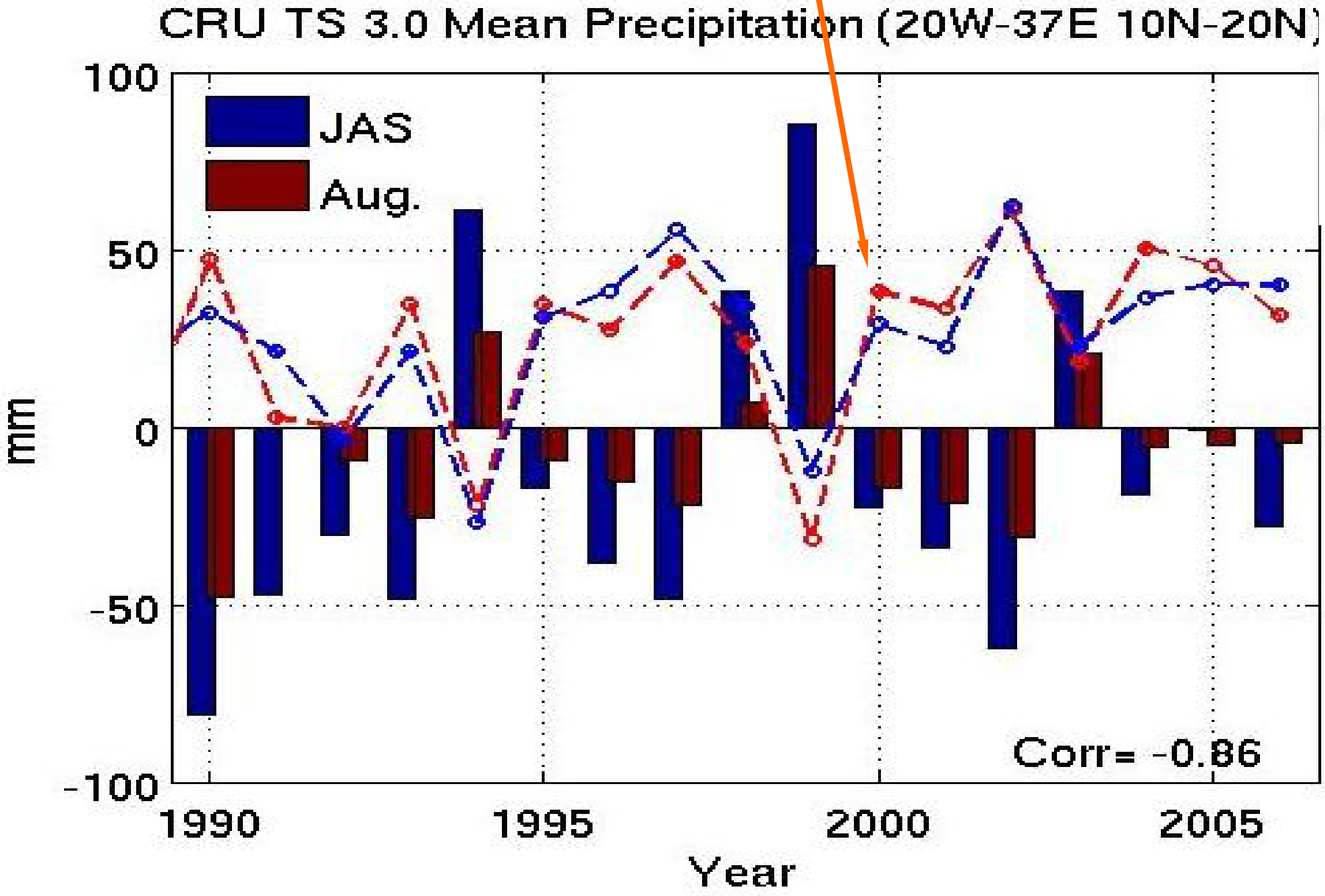
AIRS CO_2

- In Meteo run we assimilate u, v, T, q, Ps: no constraints on model CO_2 (here)
- In AIRS run we also assimilate AIRS CO_2 (Junjie)

Observed rainfall and temperature anomaly from the mean of 1950-1990

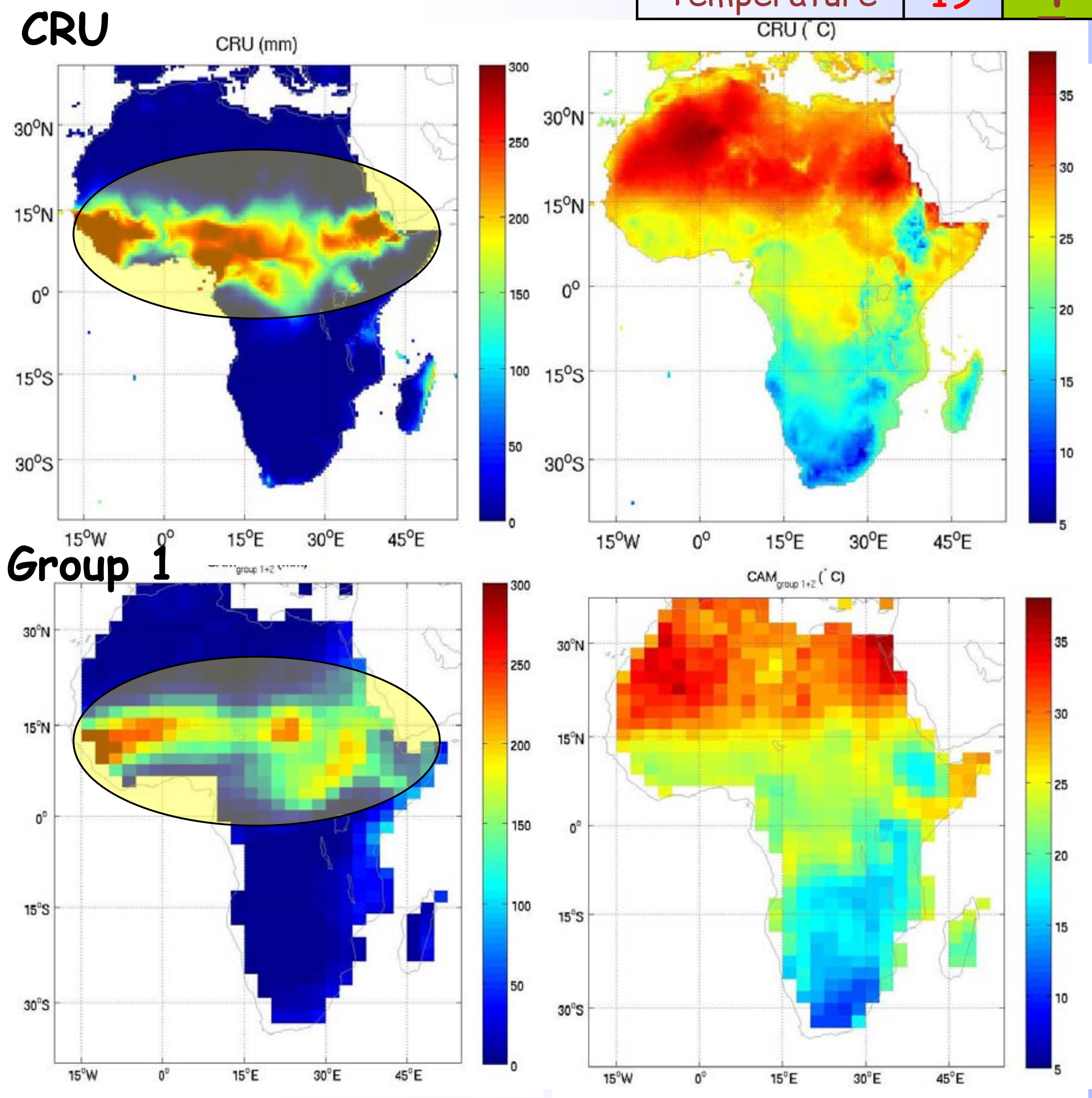


Pick year 2000



No clear drying trend

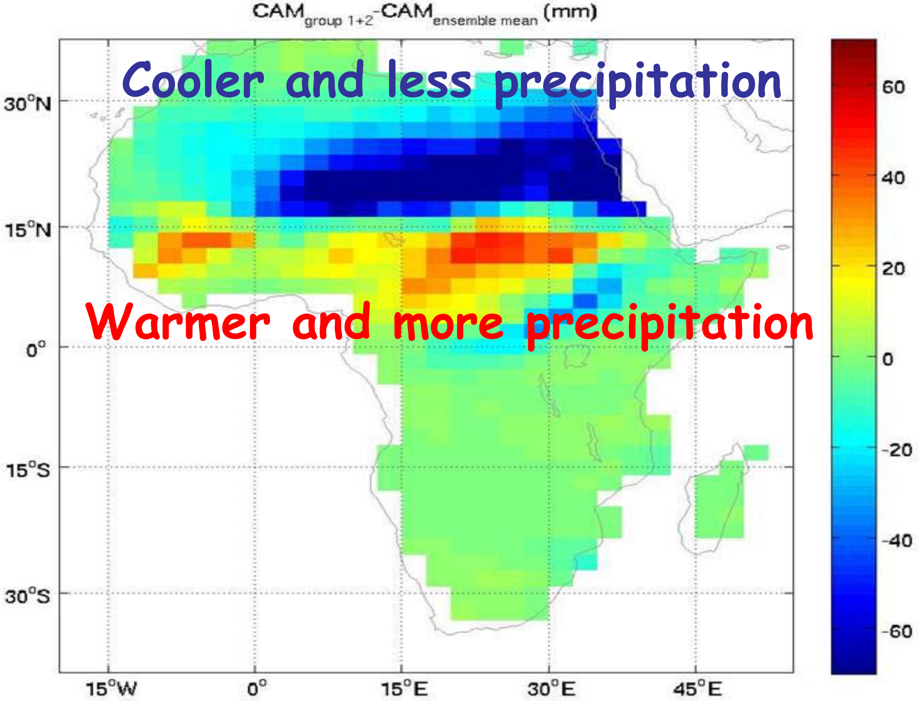
	Group 1				Group 2			
Precipitation	34	19	61	60	4	42	43	48
Temperature	19	4	34	43	32	21	62	56



Divide the ensemble members into 16 groups
Group 1: minimal error
Group16:maximal error

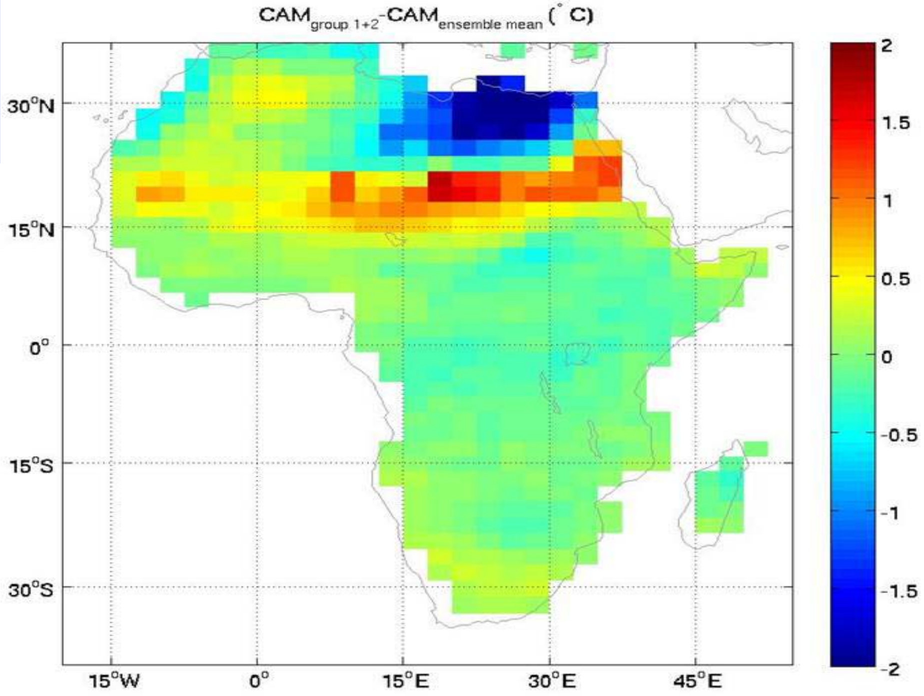
- quite consistent rainbelt location and temperature distribution
- magnitude is different (microphysics and others)

The difference between Group 1&2 and the mean

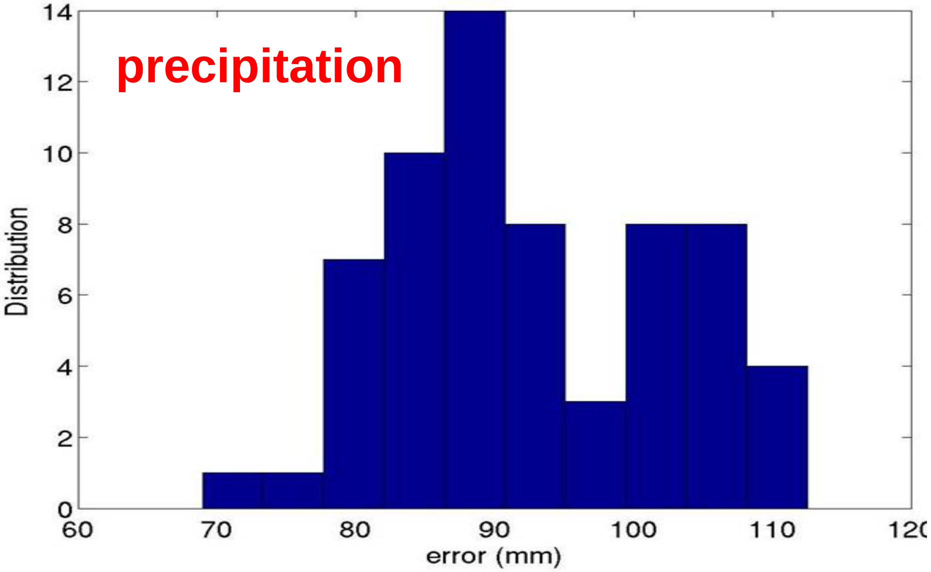


Cooler and less precipitation

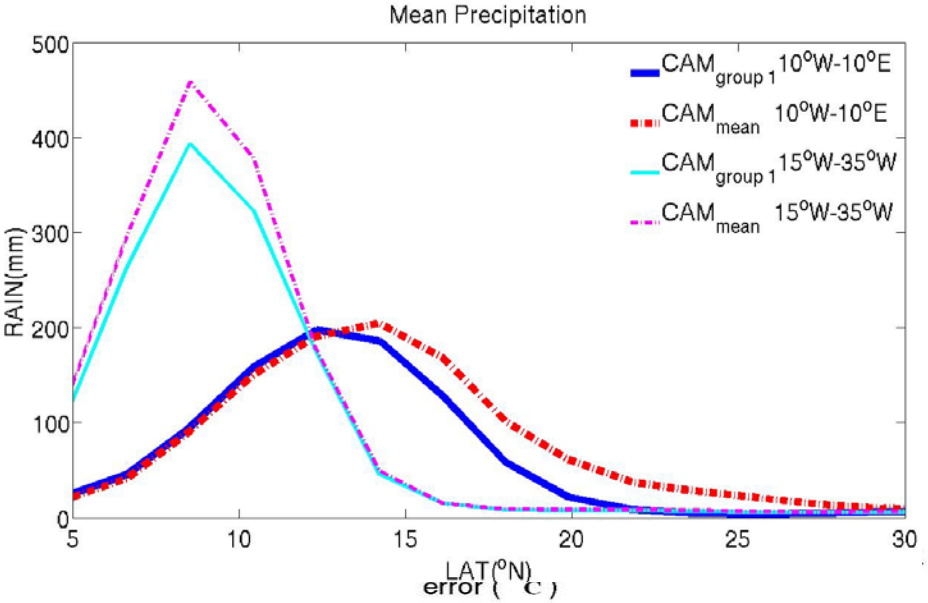
Warmer and more precipitation



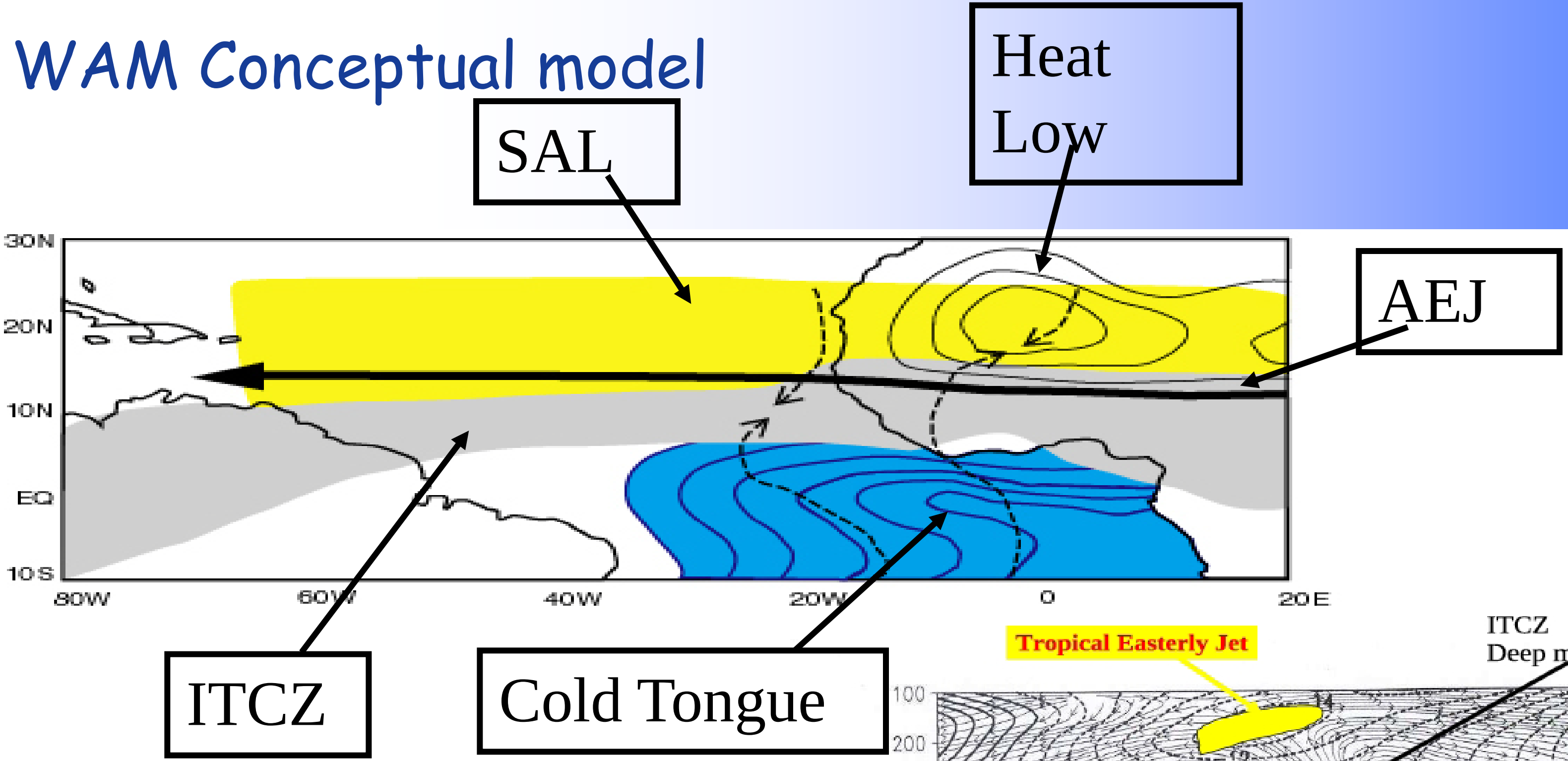
Error distribution



precipitation



WAM Conceptual model



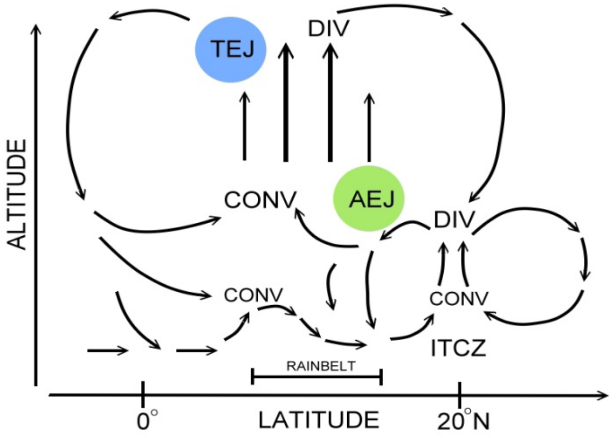
SAL

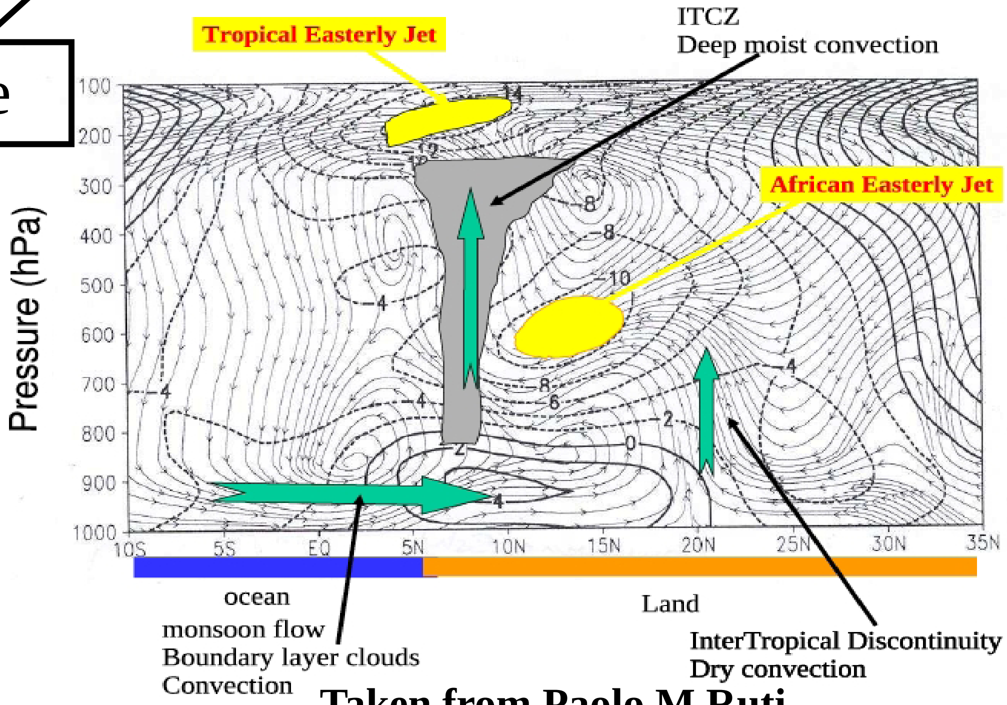
Heat Low

AEJ

ITCZ

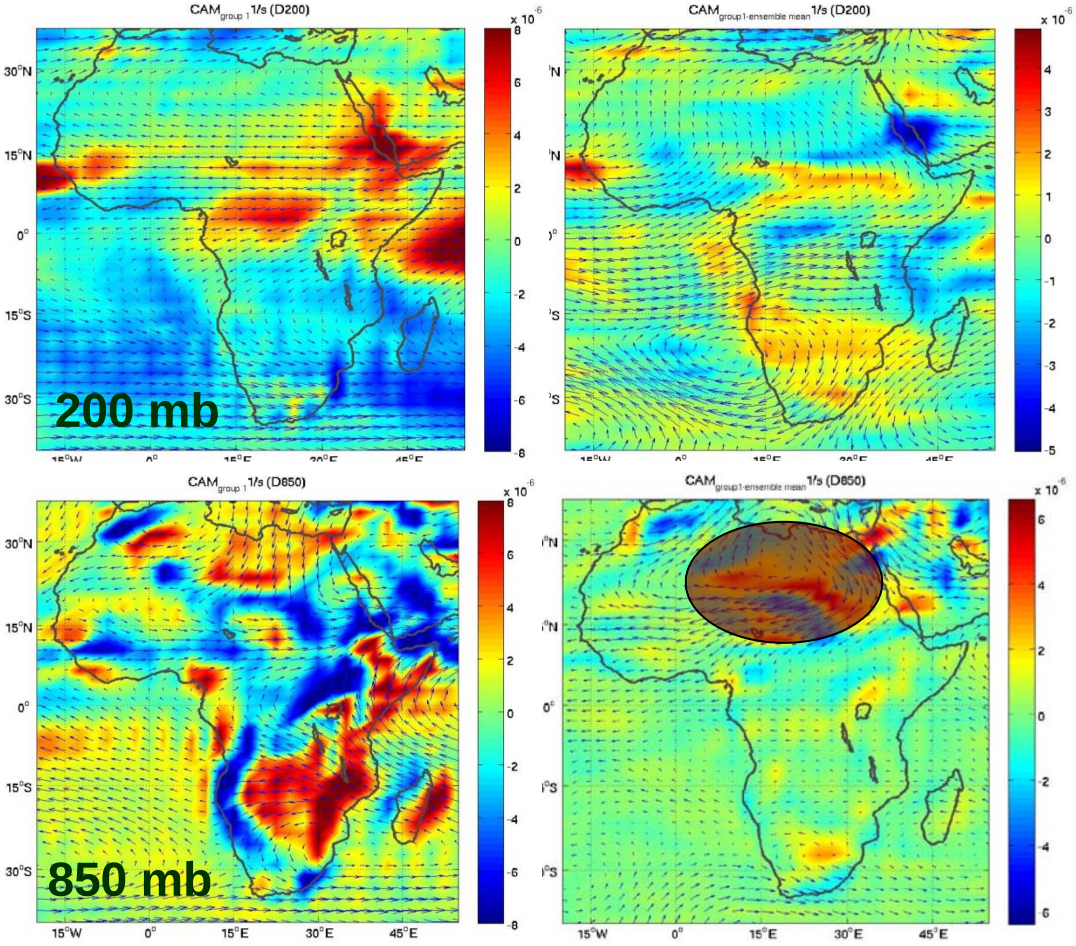
Cold Tongue

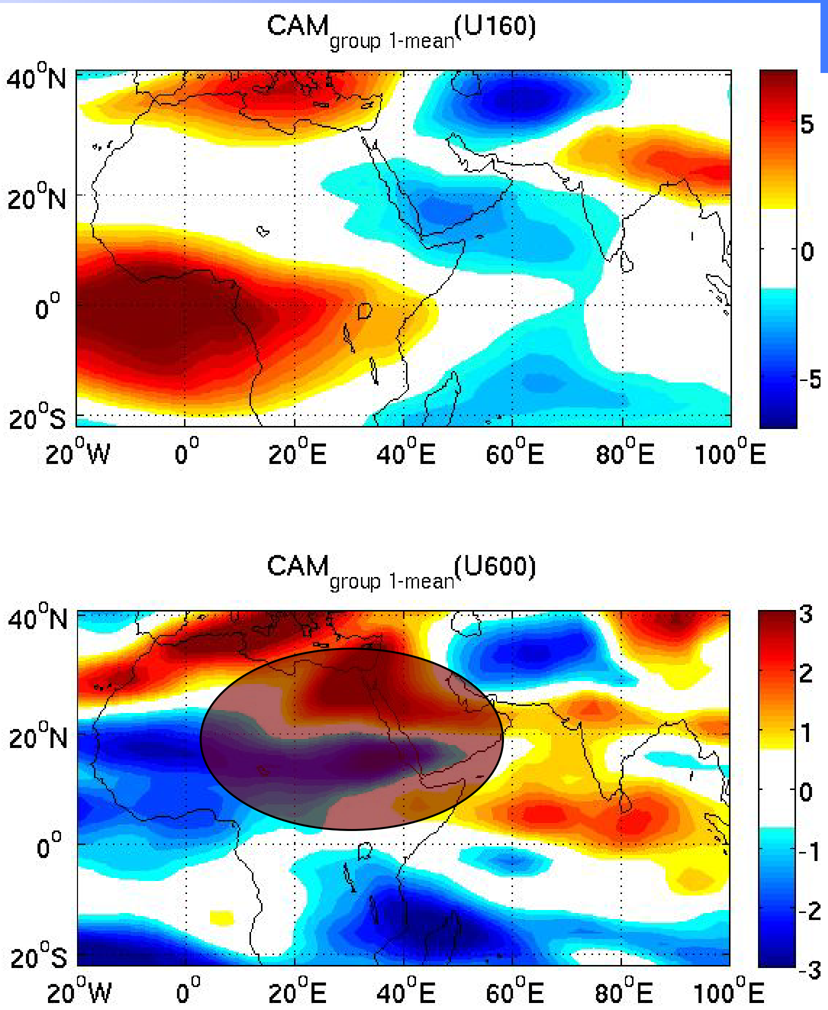




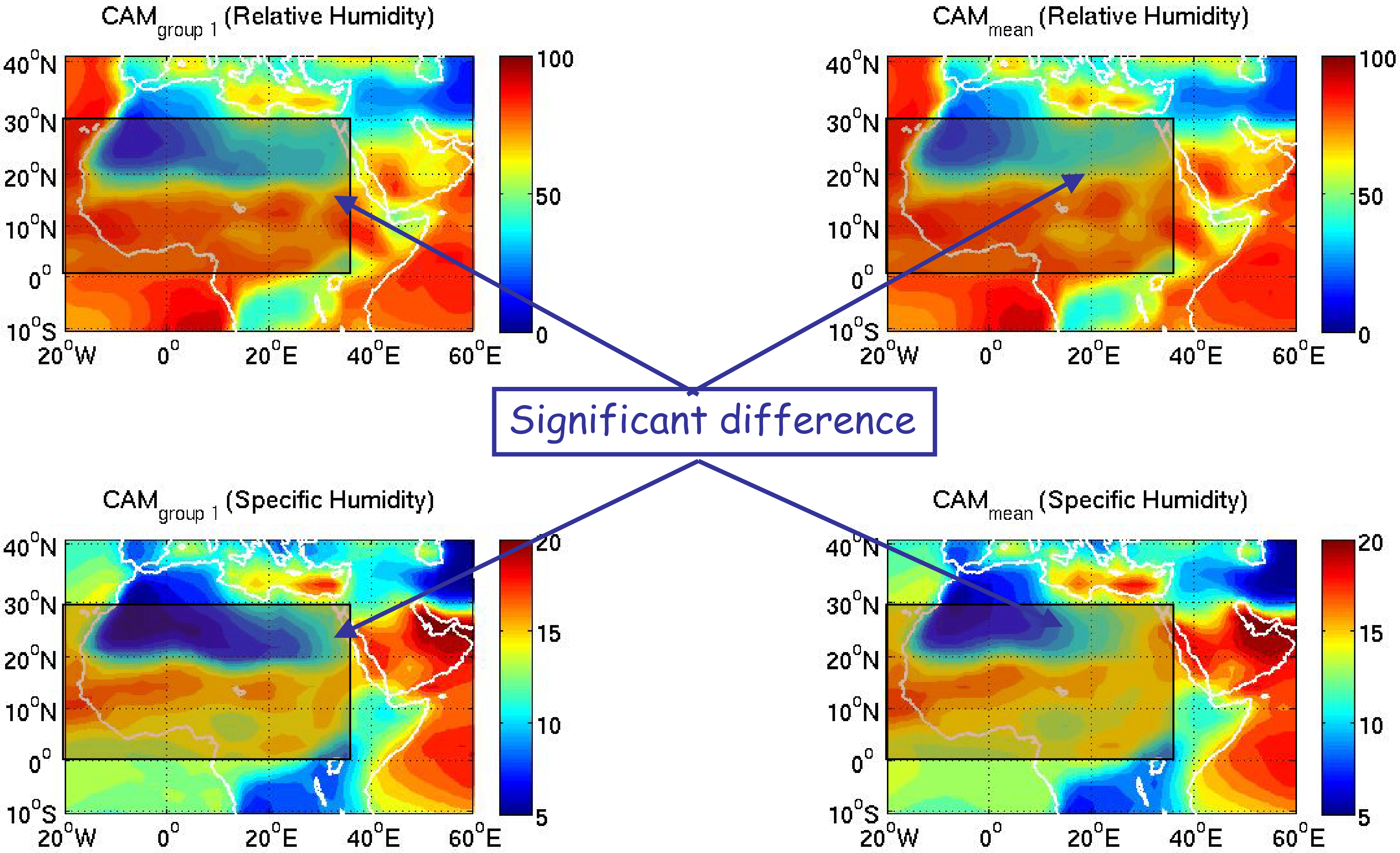
Taken from Paolo M Ruti

divergence superimposed by wind field





Comparison of the Humidity

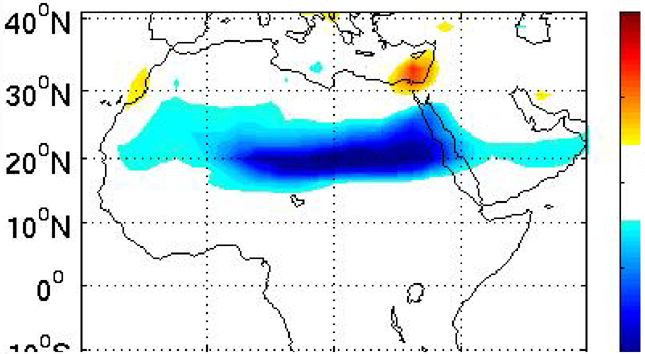

$\text{CAM}_{\text{group 1}}$ (Relative Humidity)

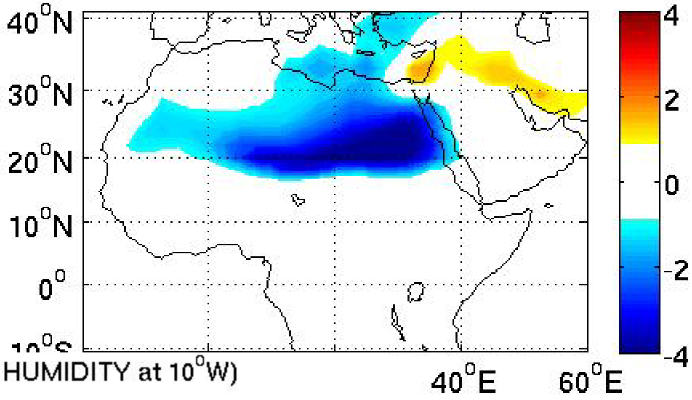
CAM_{mean} (Relative Humidity)

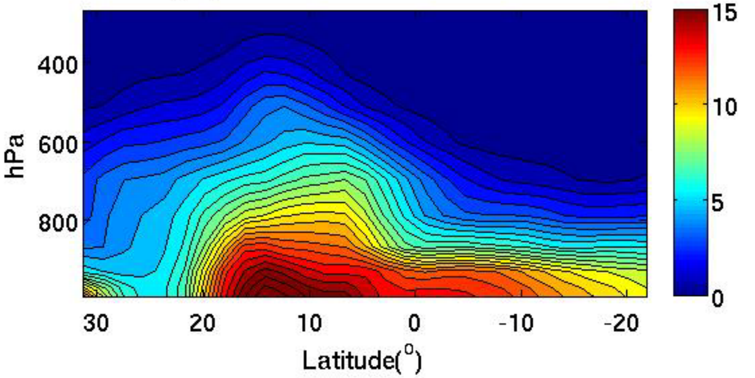
Significant difference

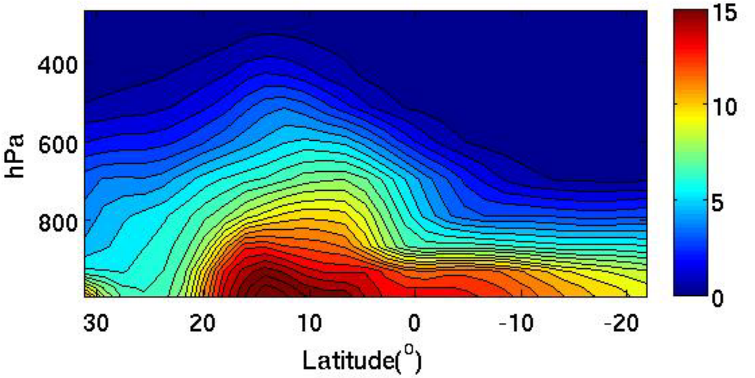
$\text{CAM}_{\text{group 1}}$ (Specific Humidity)

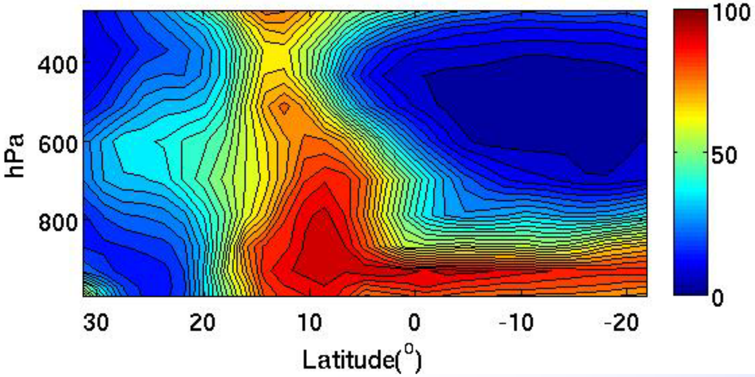
CAM_{mean} (Specific Humidity)

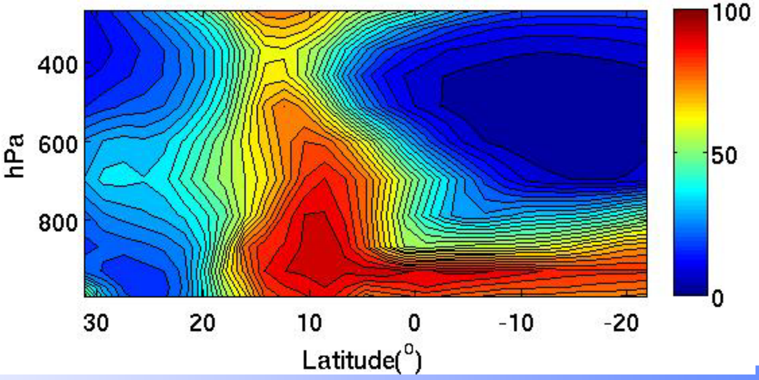

CAM$_{\text{group 1-mean}}$ (Relative Humidity)


CAM$_{\text{group 1-mean}}$ (Specific Humidity)

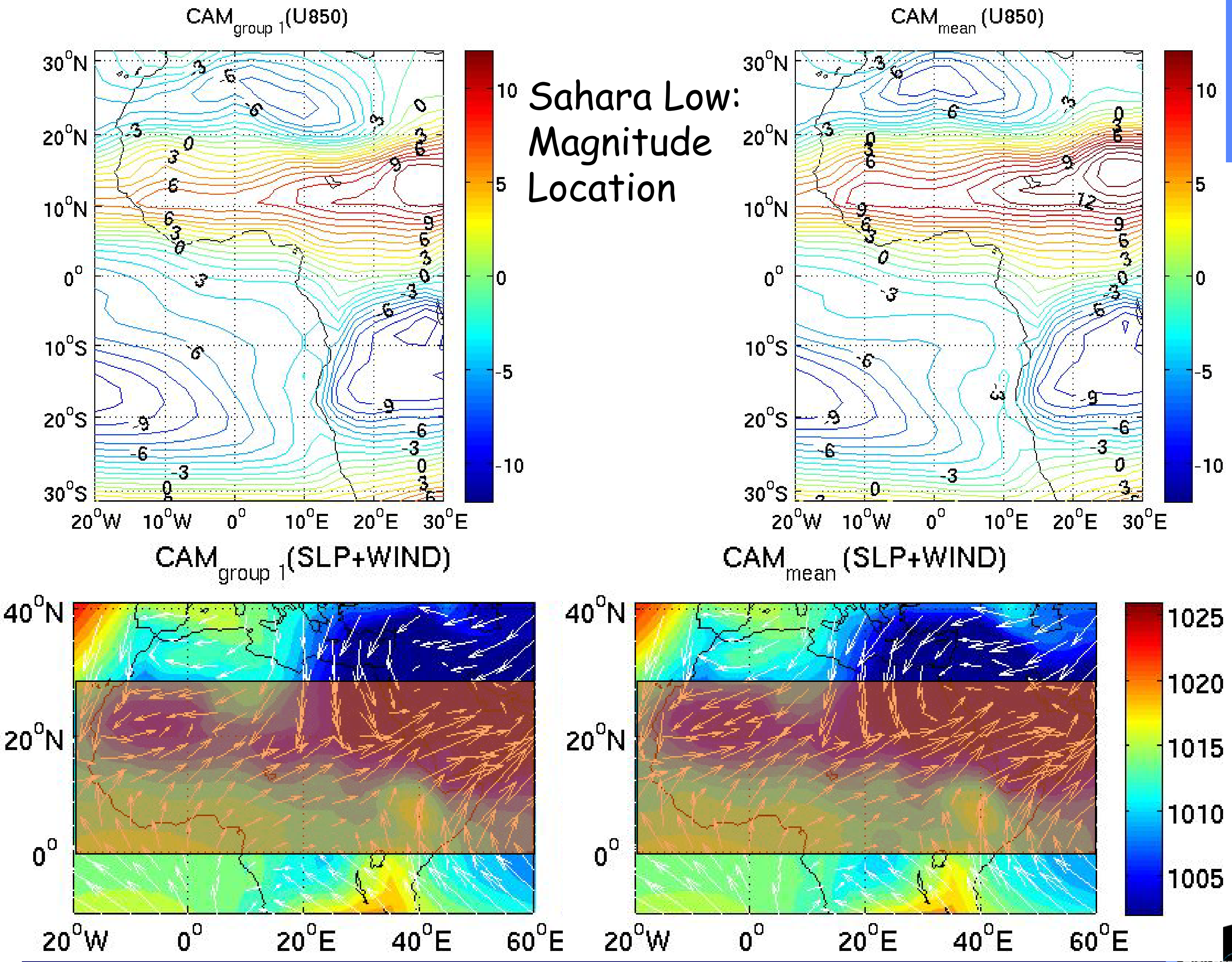

CAM$_{\text{group 1}}$ (SPECIFIC HUMIDITY at 10°W)


CAM$_{\text{mean}}$ (SPECIFIC HUMIDITY at 10°W)


CAM$_{\text{group 1}}$ (RELATIVE HUMIDITY at 10°W)


CAM$_{\text{mean}}$ (RELATIVE HUMIDITY at 10°W)

Sahara Low:
Magnitude
Location



Summary

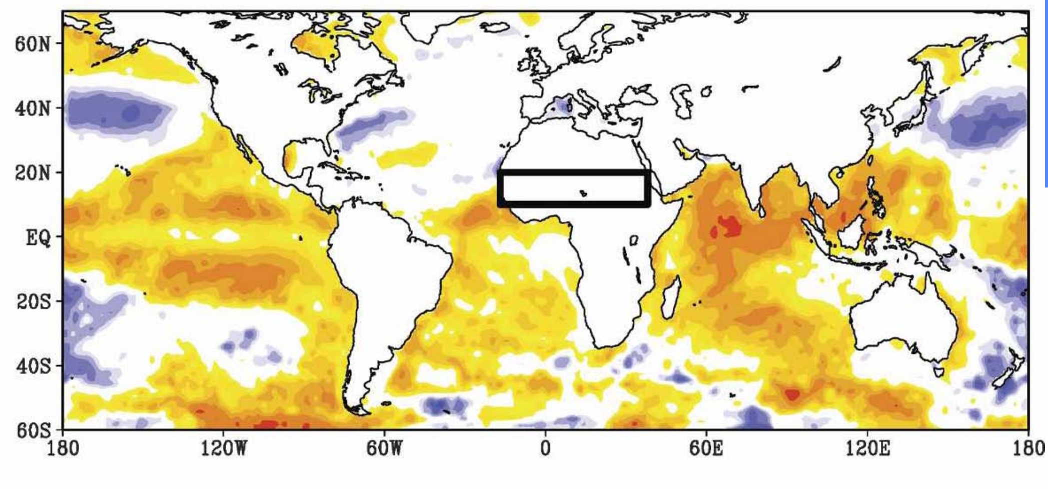
- The spread of modeled Sahel precipitation and temperature in CAM3.5/CLM3.5 is still large
- LETKF provides a unique way to quantify the model uncertainty without the structural errors in MMEs
- The only difference among ensembles is the initial perturbations
- The best group (4/64=1/16) reduces systematic error by up to 25%
- model bias may result from the modeled location and magnitude of low-level Sahara low
- Where and what is the missing error source (may be AEW -> AEJ)?

The Atlantic and Indian Oceans may also play a role in interannual variability

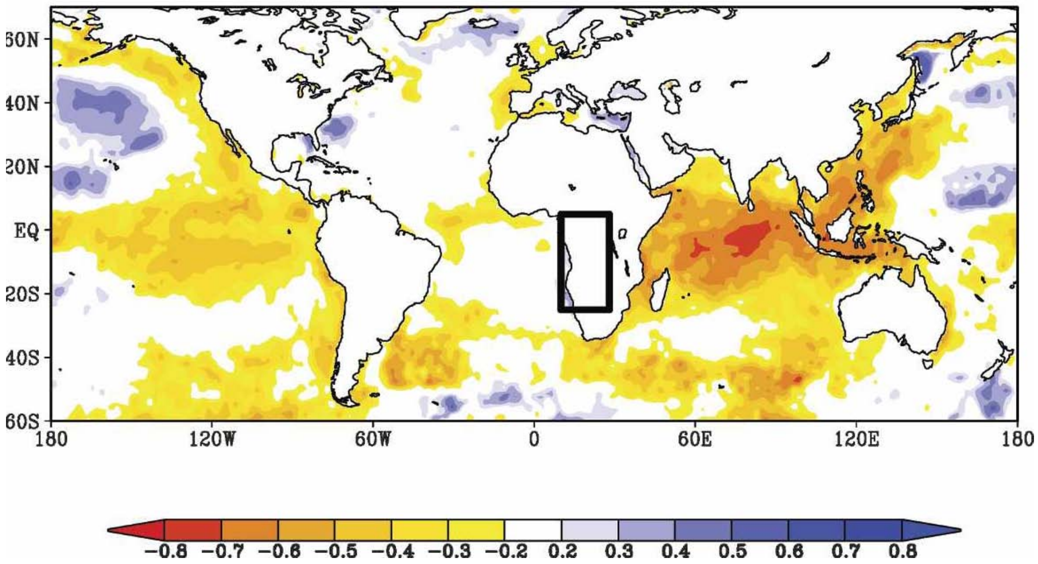
Hoerling et al. 2006, J. Climate -
Looked at impact of SST warming trends 1950-99.

Forcing for Feb-Mar-Apr:
a) Global SSTs 1950-99
b) Atlantic SSTs only - climatology elsewhere
c) Indian Ocean - idealized 1o warming, climatology elsewhere
FLAW: The study was not about East Africa

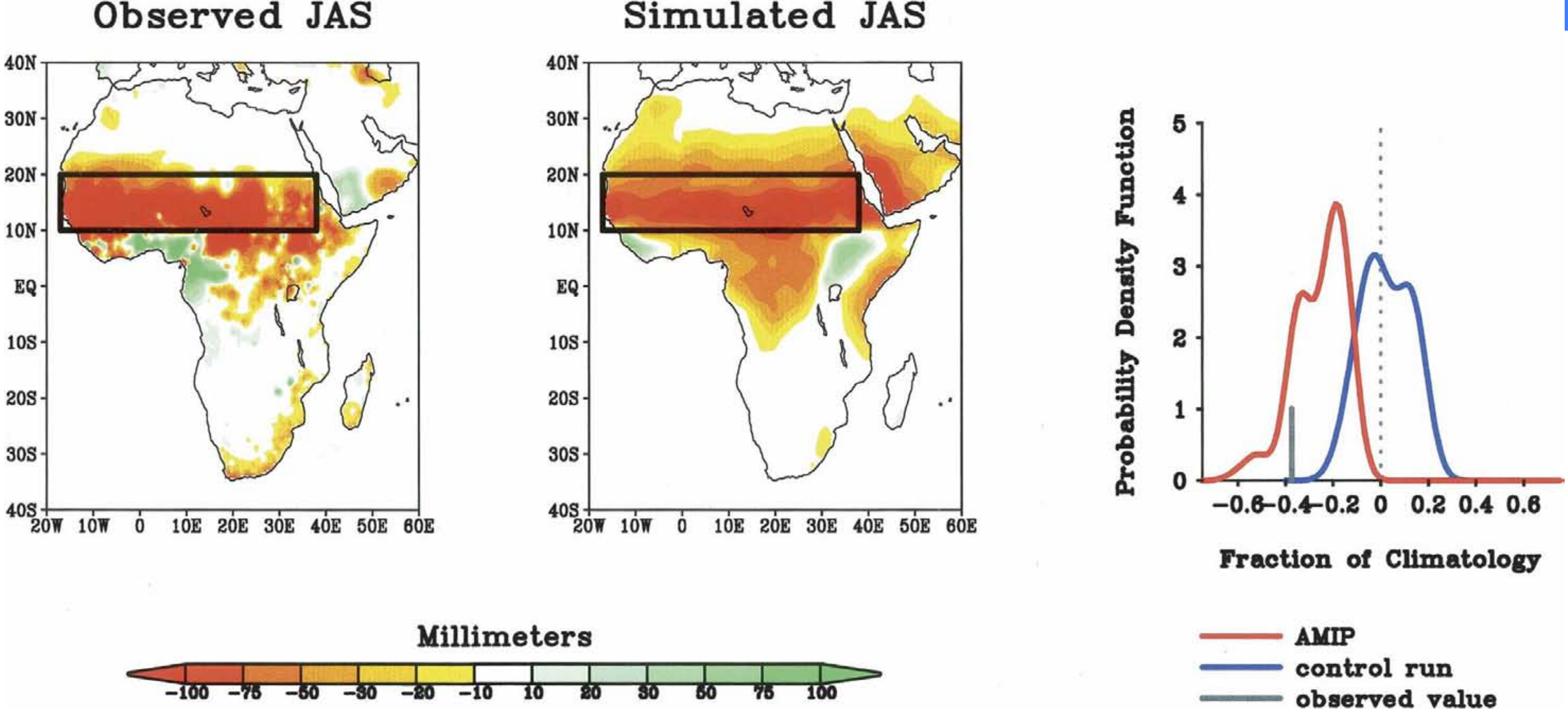
JJA SSTs



FMA SSTs

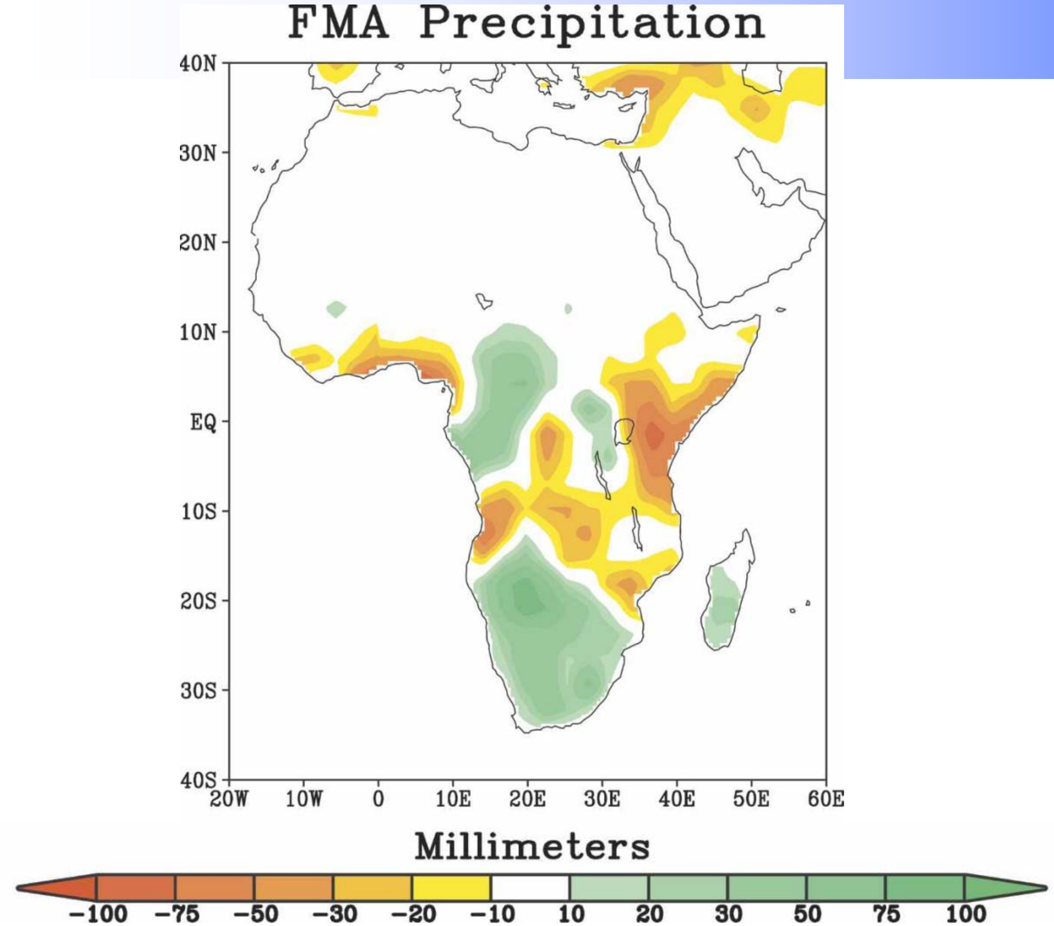


The 1950–99 temporal correlation between the ensemble mean simulated rainfall time series and global SSTs for (top right) the JAS northern African rainy season and (bottom right) the FMA southern African rainy season.



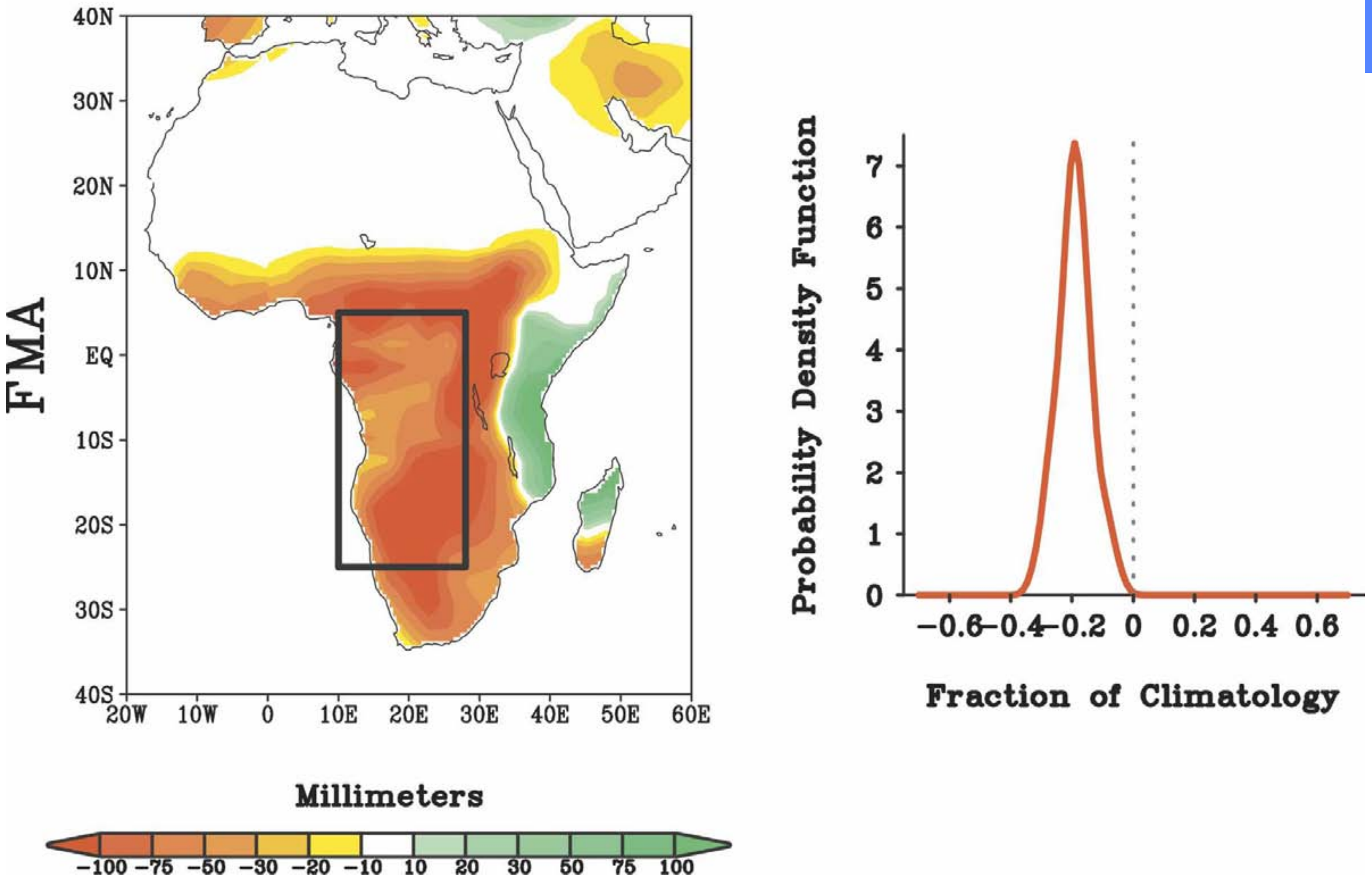
The 1950–99 trends of (left) observed and (middle) atmospheric GCM simulated seasonal African rainfall for JAS. Plotted is the total seasonal rainfall change (mm) over the 50-yr period. (right) The empirical PDFs of JAS 50-yr rainfall trends averaged over the Sahel region.

Forcing by Atlantic SST's

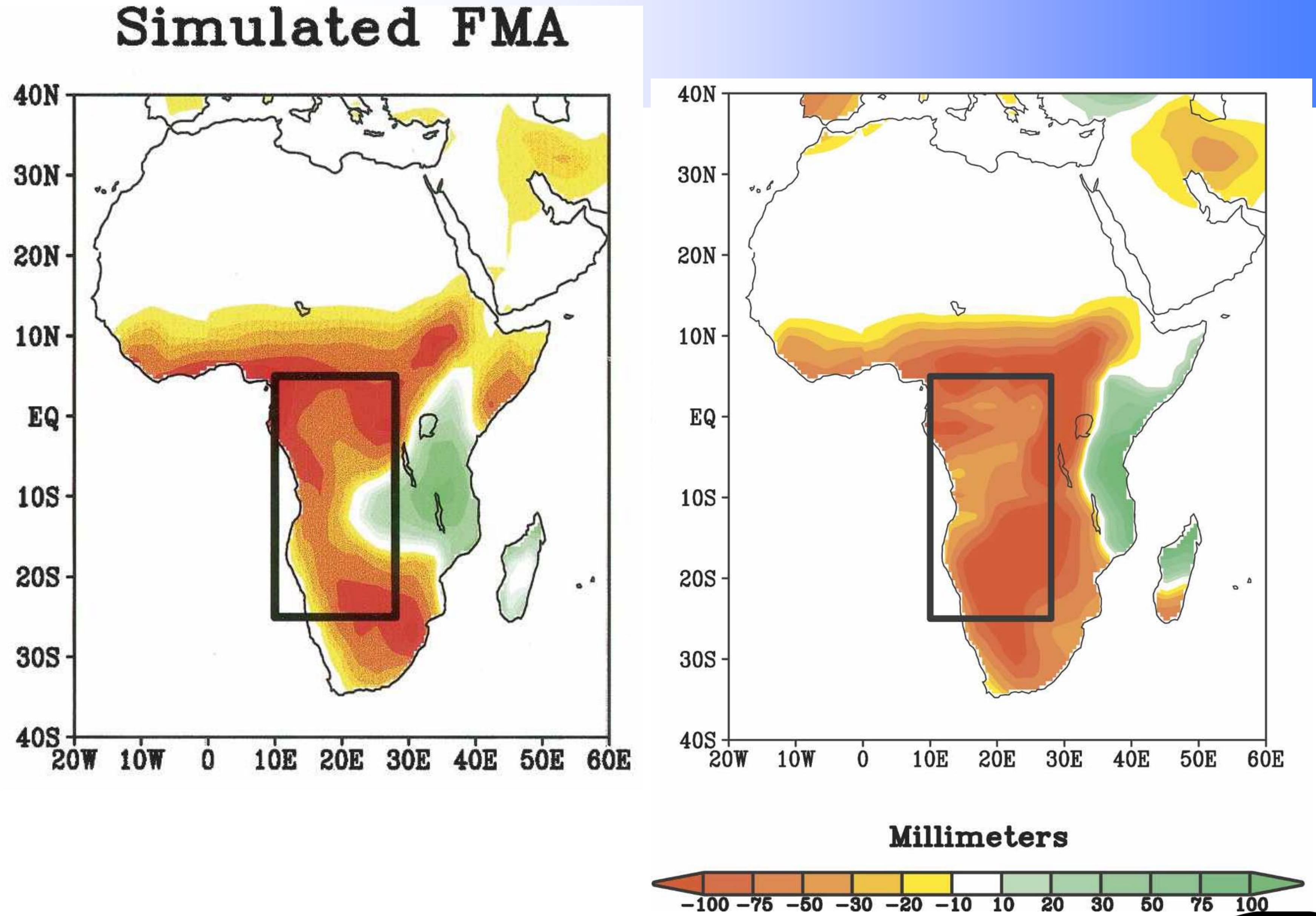


The atmospheric GCM simulated 50-yr African rainfall trends for (left) JAS and (right) FMA. Rainfall is based on the monthly, gridded output of a 4-member ensemble average of a single atmospheric GCM that was forced by the time-varying, monthly observed SST variations over the Atlantic Ocean basin only. Plotte total seasonal rainfall change (mm) over the 50-yr period.

Indian Ocean warming impact (FMA rainfall)



Atmospheric GCM simulated African rainfall responses (mm) to a specified 1°C Indian Ocean sea surface warming during (top left) JAS and (bottom left) FMA. (right) Plots of the empirical PDFs of the seasonal rainfall response from individual members of the AGCM simulations.



Simulated FMA

Goddard and Graham 1999, J. Geophys. Res.

Simulate impact of SST variability 1970-1992.

Looked at impact of

Global oceans (GOGA)

Indian Ocean (IOGA)

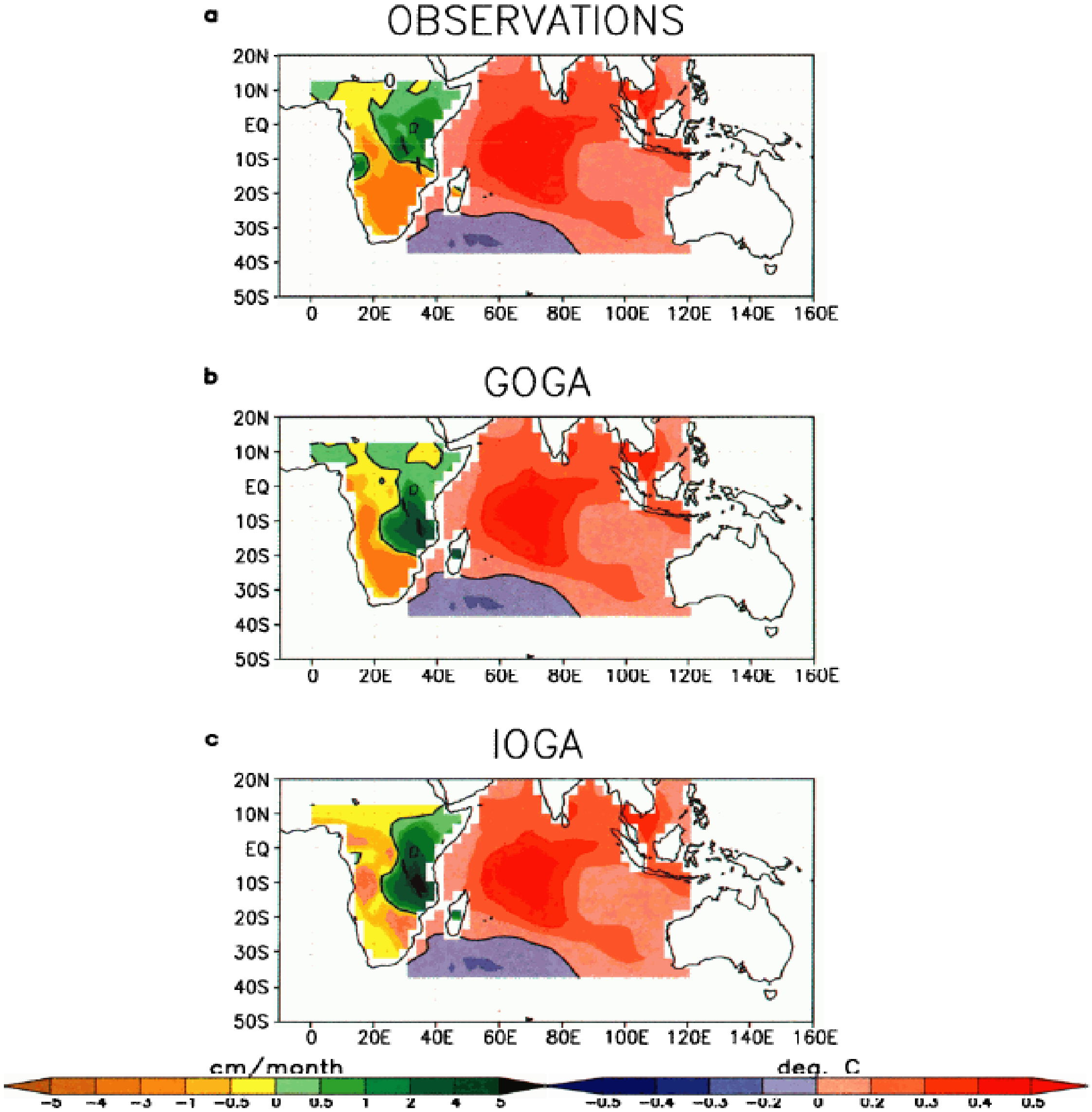
Pacific (IOGA)

Flaw: looked at Nov-Dec-Jan (not really either East African rainy season)

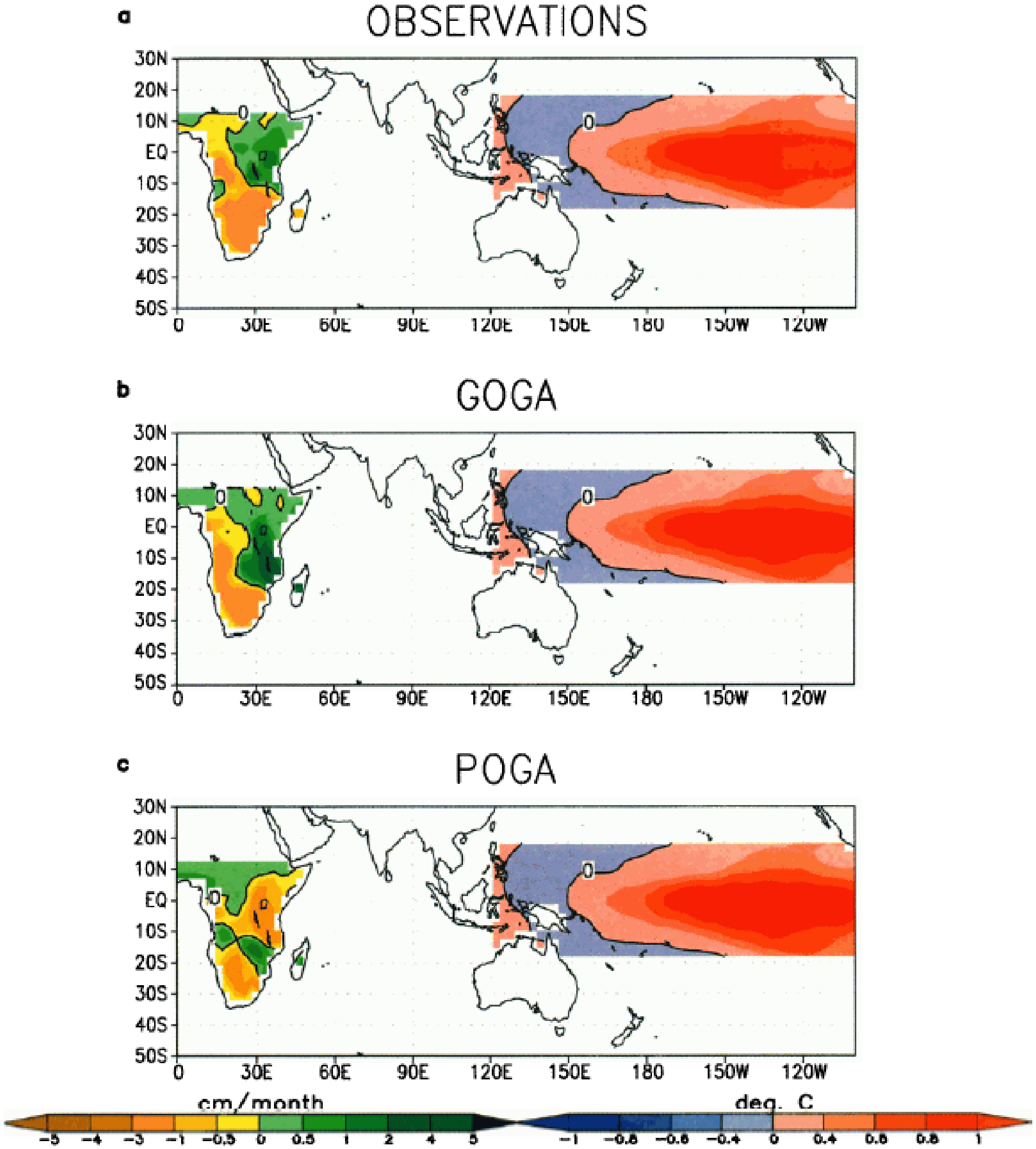
Strong point: actually looked at processes and atmospheric circulation

There are competing influences from the Indian and Pacific Oceans.

Indian Ocean SSTs needed to adequately simulate East African rainfall variability

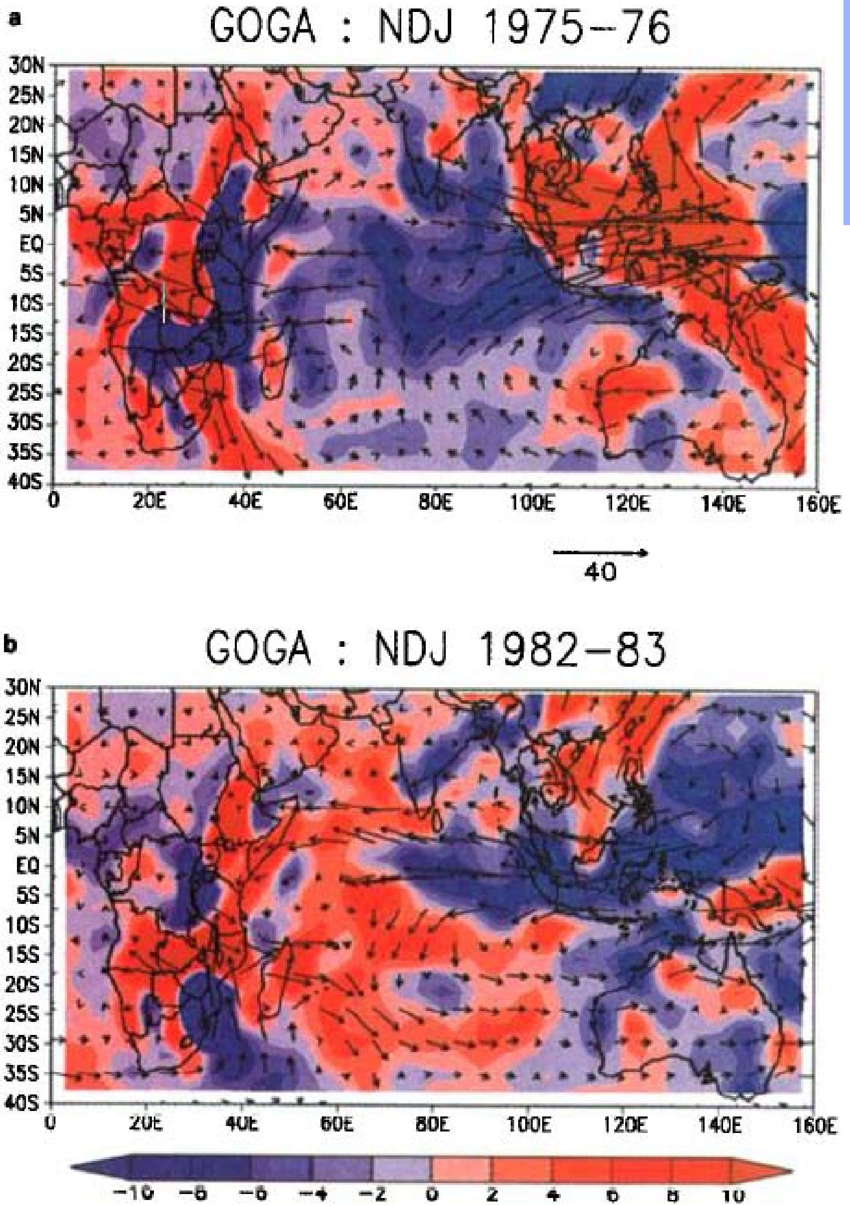


Dominant patterns of precipitation variability over Africa and SST variability over the Indian Ocean for November-December-January of 1970-1992. In all cases the SST is represented by the homogeneous response map on the basis of observed data. The precipitation pattern is based on (a) observations showing the heterogeneous response map; (b) GOGA experiment showing the pseudo-he response map; and (c) IOGA experiment showing the pseudo-hetrogeneoues response map.



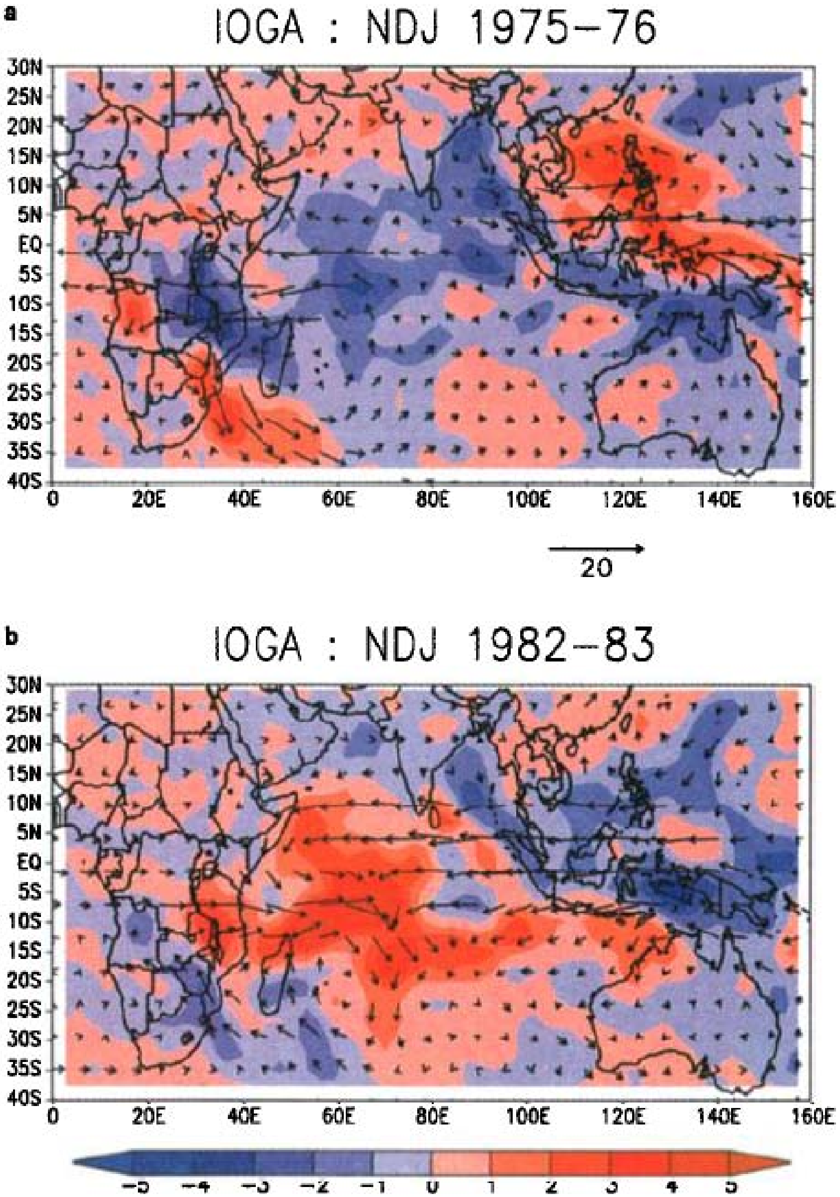
Similar to previous plat, here relating precipitation to Pacific SST varia

(a) observations(,b) GOGA experiment, and (c) POGA experiment

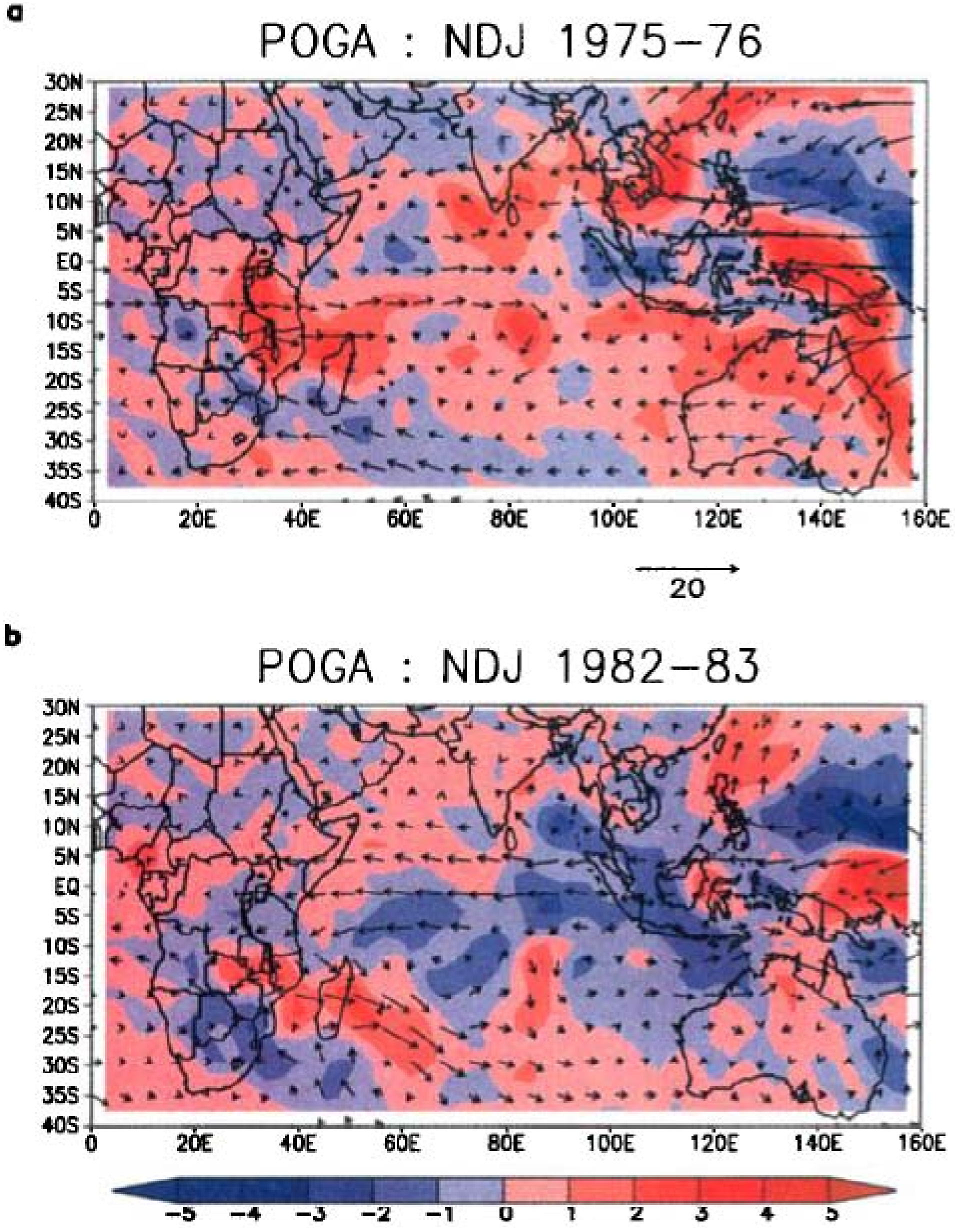


Anomalous NDJ moisture fluxes at 850 mbar (arrows) in m s /(g kg) and associated moisture convergence (shadingg) g / (kg s) from the GOGA experiment for (a) 1975-1976, a "cold year," negative manifestation of central eastern/southern Africa rainfall dipole; and (b) 1

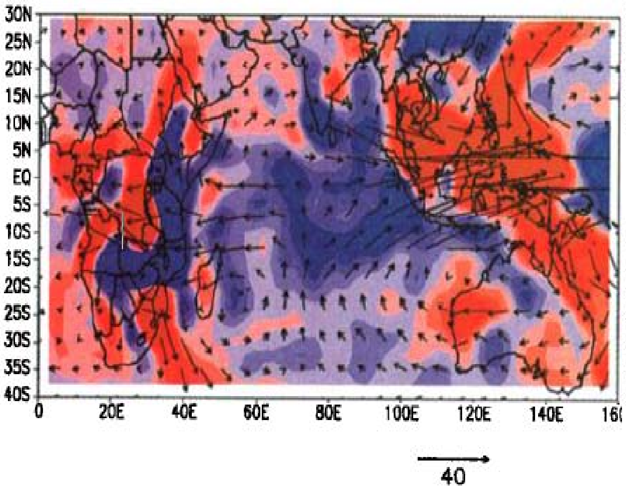
"warm" year, positive manifestation of dipole



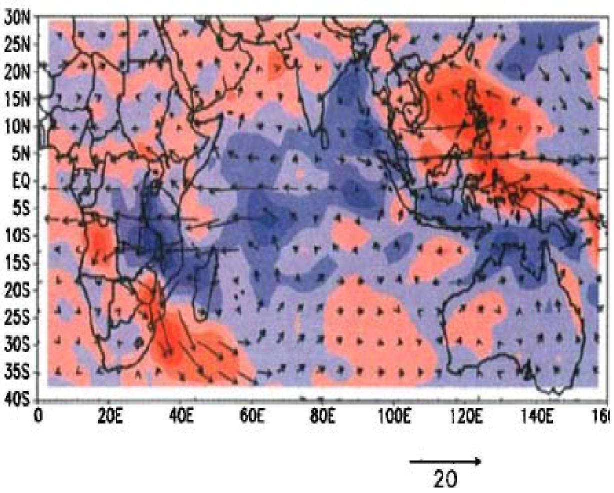
Similar to the previous Plate but for the IOGA experiment. Now showing vertically integrated moisture fluxes and flux convergences.



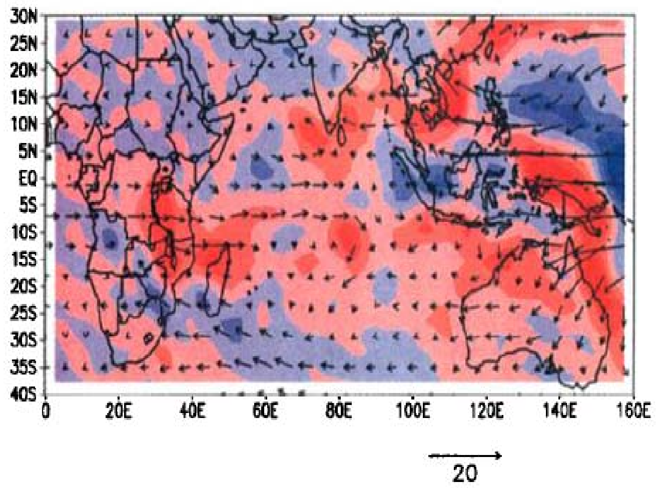
Similar to the previous Plate but for the POGA experiment



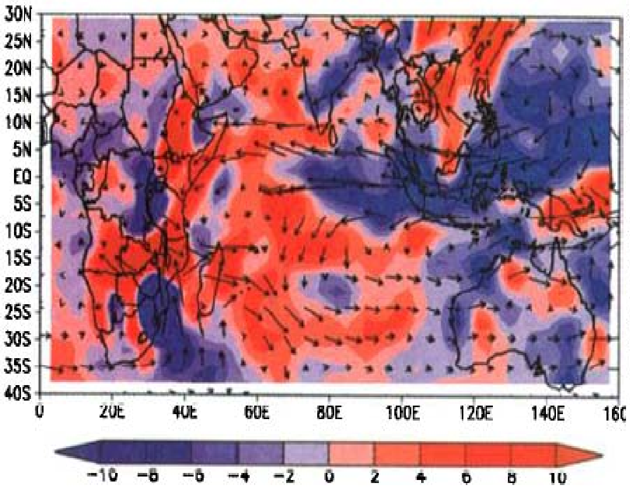
a GOGA : NDJ 1975–76



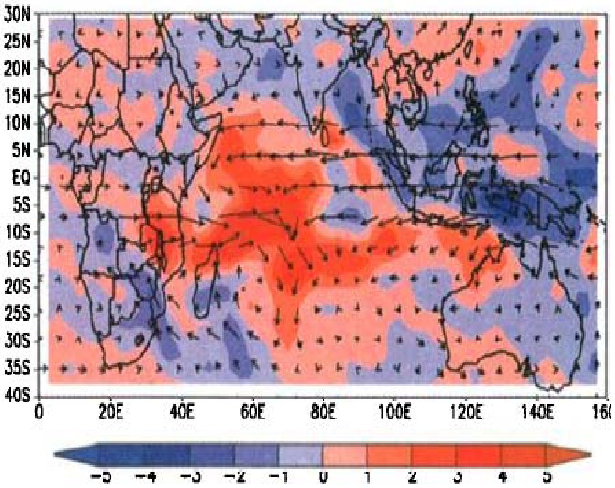
a IOGA : NDJ 1975–76



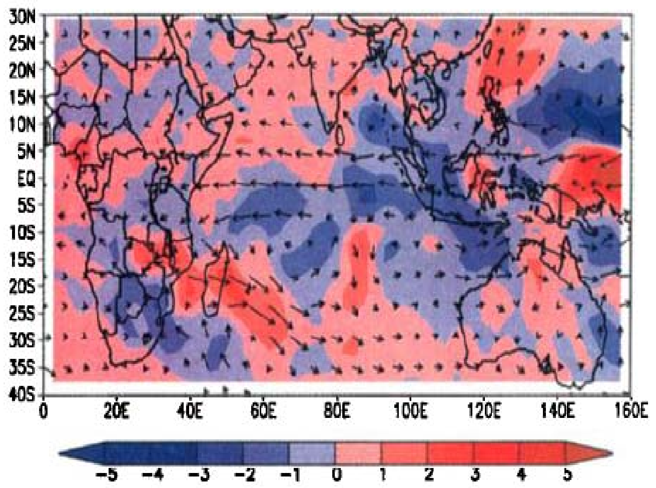
a POGA : NDJ 1975–76



b GOGA : NDJ 1982–83



b IOGA : NDJ 1982–83



b POGA : NDJ 1982–83

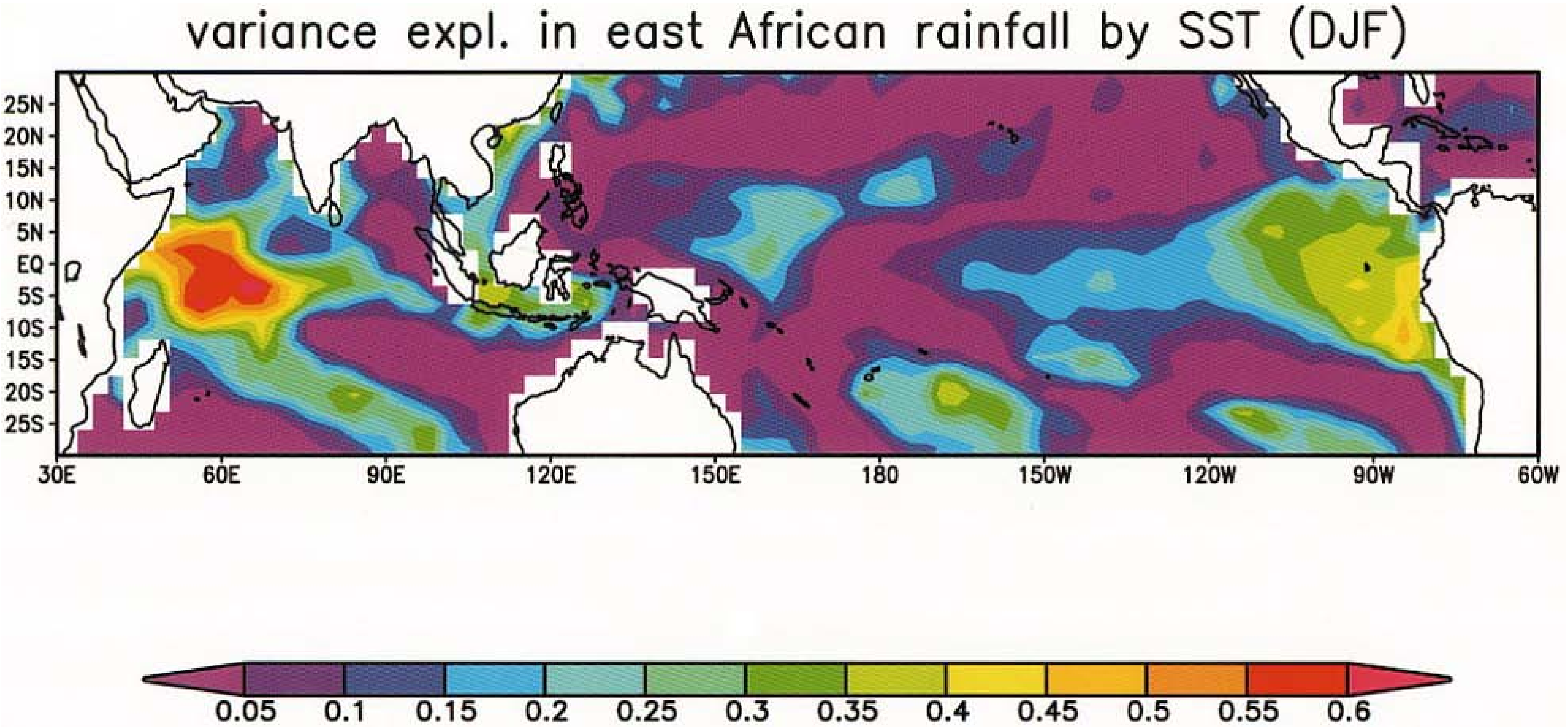
The Indian Ocean may play a role independently of the Pacific.

The impact of the Pacific may be opposite that of the Indian Ocean

Latif et al. 1999, J. Climate - Analysis of flood situation of Dec-Jan, 1997/98

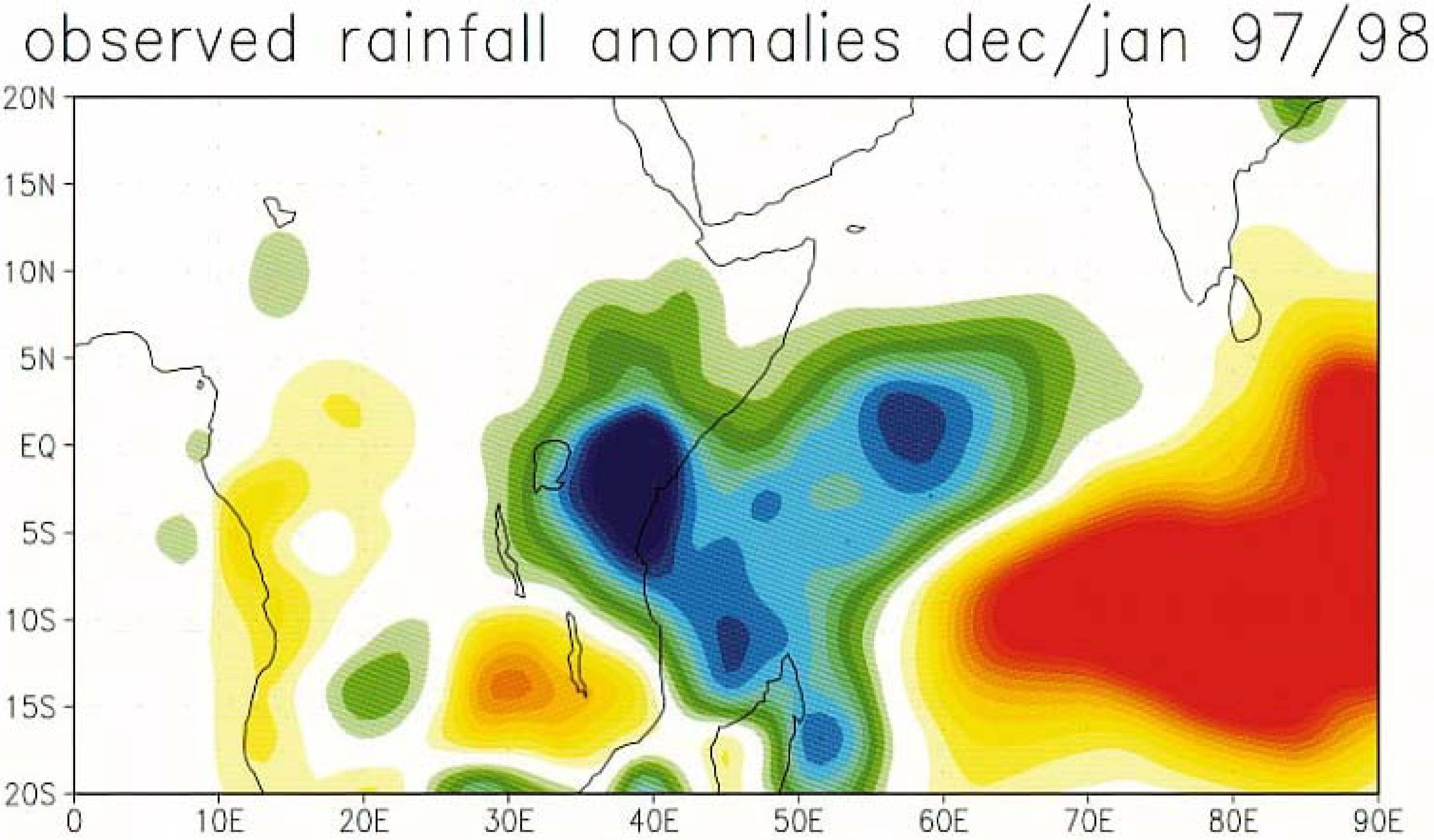
FLAW: Anomalous event, occurred during dry season.

Floods of Dec-Jan 1997/98 – Latif et al. 1999, J. Climate

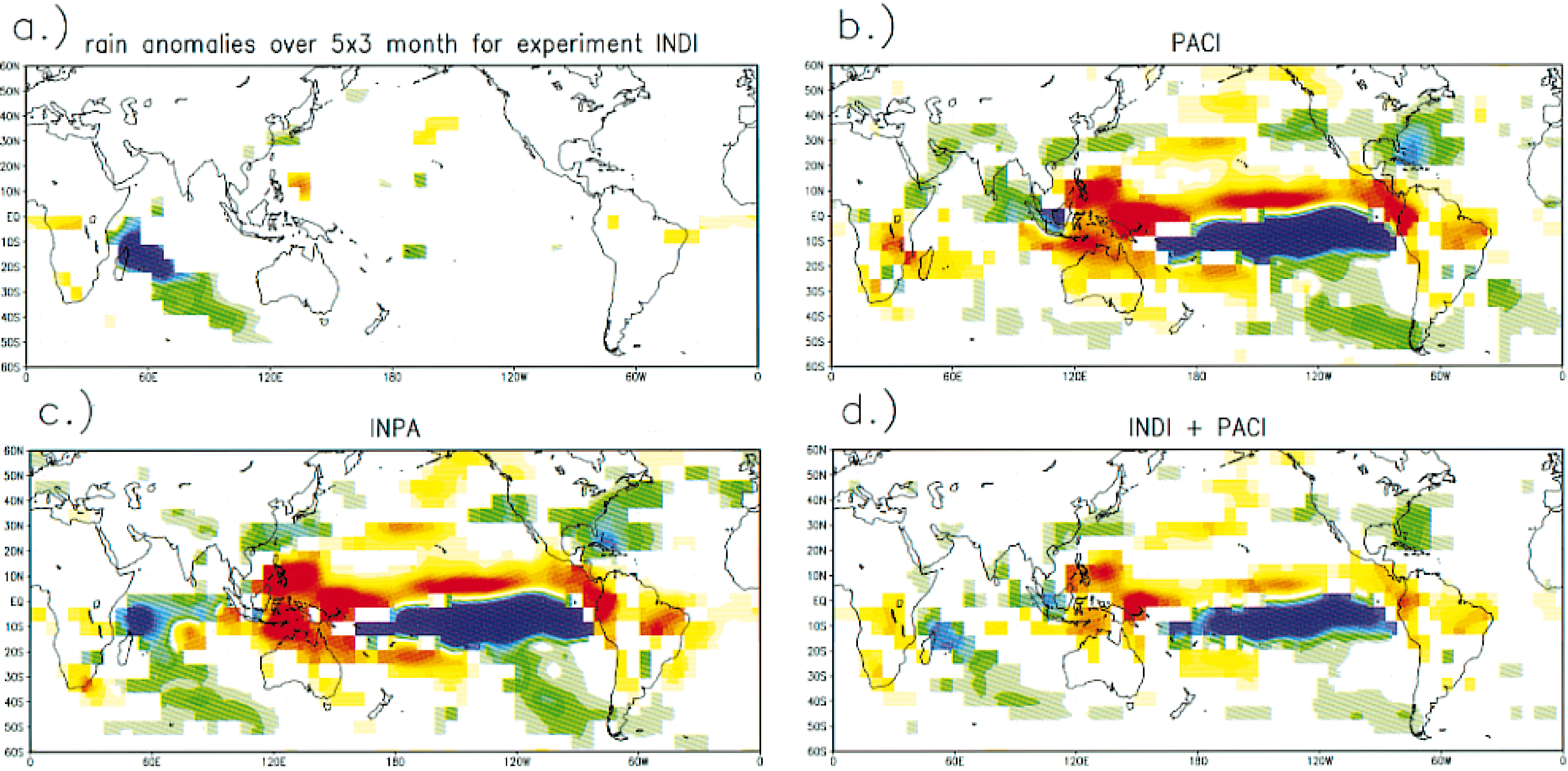


Variances explained in an index of eastern equatorial African rainfall anomalies by the SST anomalies in the Indian and Pacific Oceans for the winter season (DJF) and the period 1979–98. The eastern equatorial African rainfall index is an area average over the region 5 ° N–5 ° S and 35 °–50 ° E. The rainfall and SST data were obtained fr datasets of Reynolds and Smith (1994) and Xie and Arkin (1997), respectively.

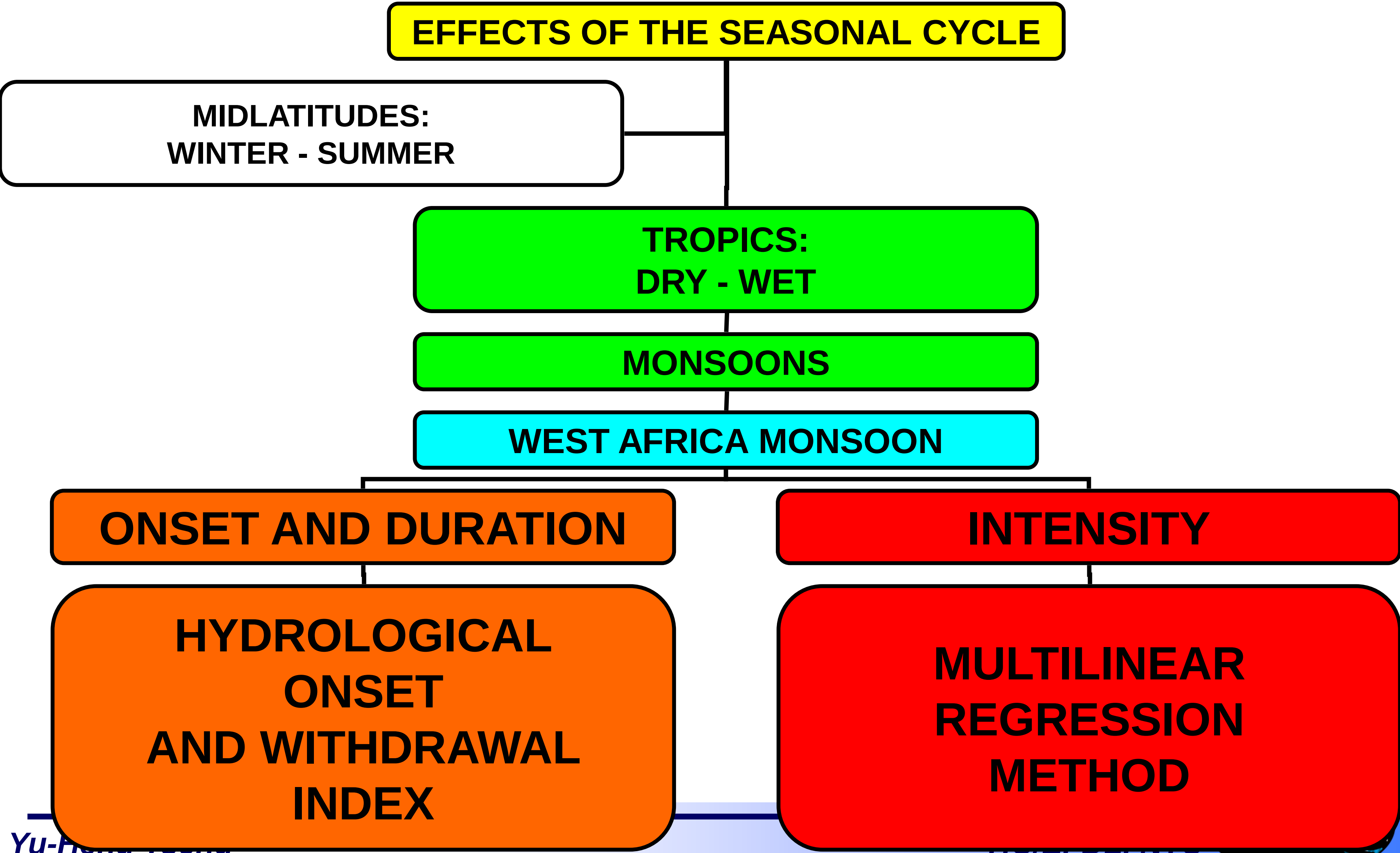
blue = above normal, red = below normal



Simulation based on SSTs in Indian Ocean (a), Pacific Ocean (b), and both oceans (c and d). Low resolution run



Ensemble mean precipitation responses (mm day21) of the atmosphere model ECHAM3 (T21) to the SST anomaly patterns (a) Response to the Indian Ocean SST anomaly, (b) response to the Pacific Ocean SST anomaly, (c) response to the complete Indo–Pacific SST anomaly, and (d) linear superposition of the responses shown in (a) and (b). Shown are the anomalies (relative to a 50-yr control run with climatological SSTs) that exceed the 95% significance level to a *t* test.



EFFECTS OF THE SEASONAL CYCLE

MIDLATITUDES:
WINTER - SUMMER

TROPICS:
DRY - WET

MONSOONS

WEST AFRICA MONSOON

ONSET AND DURATION

HYDROLOGICAL
ONSET
AND WITHDRAWAL
INDEX

INTENSITY

MULTILINEAR
REGRESSION
METHOD

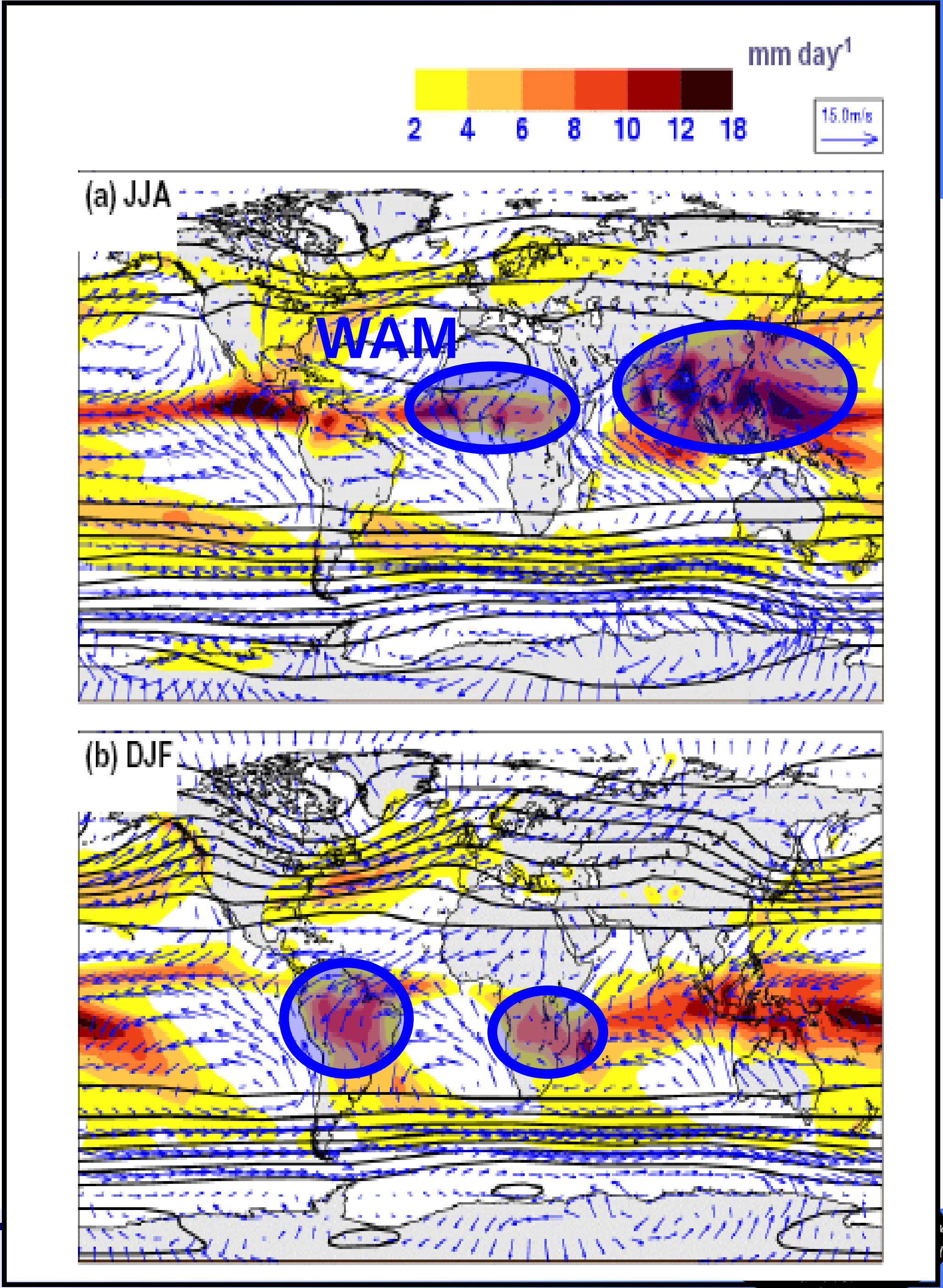
MONSOONS

OCEAN – CONTINENT TEMPERATURE CONTRAST

SUBSTANTIAL CHANGE OF DIRECTION OF THE LARGE SCALE FLOW

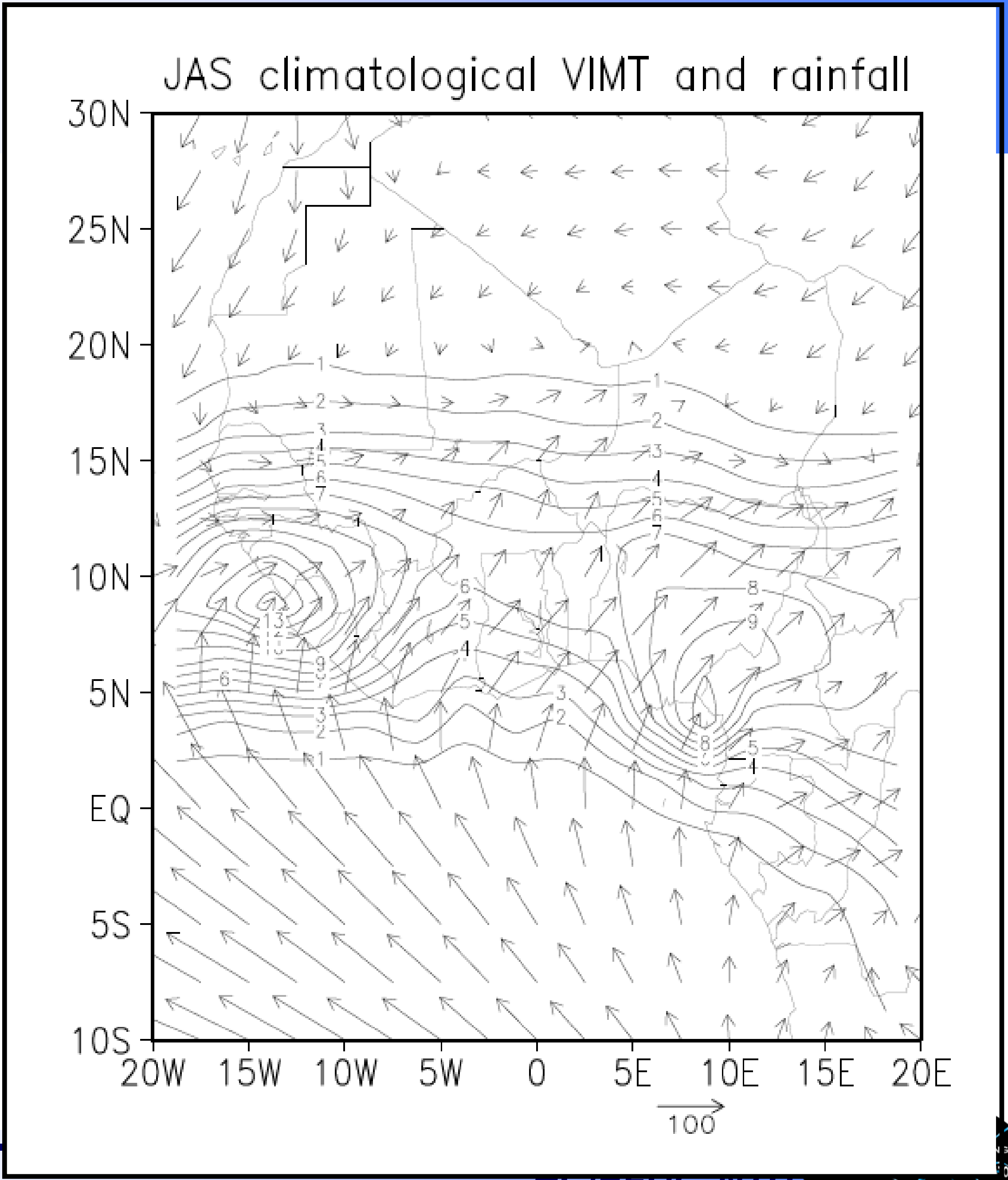
DRIVING THE OCEAN MOISTURE FAR INLAND

ABUNDANT SEASONAL RAINFALL



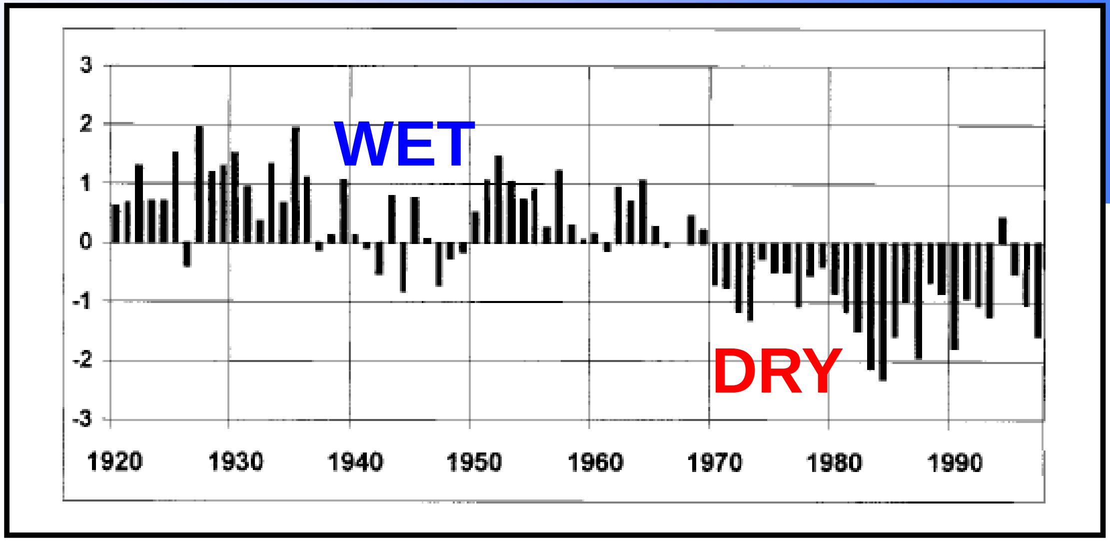
Biblio: Asnani, 1993;
Webster et al., 1987 – 1998.

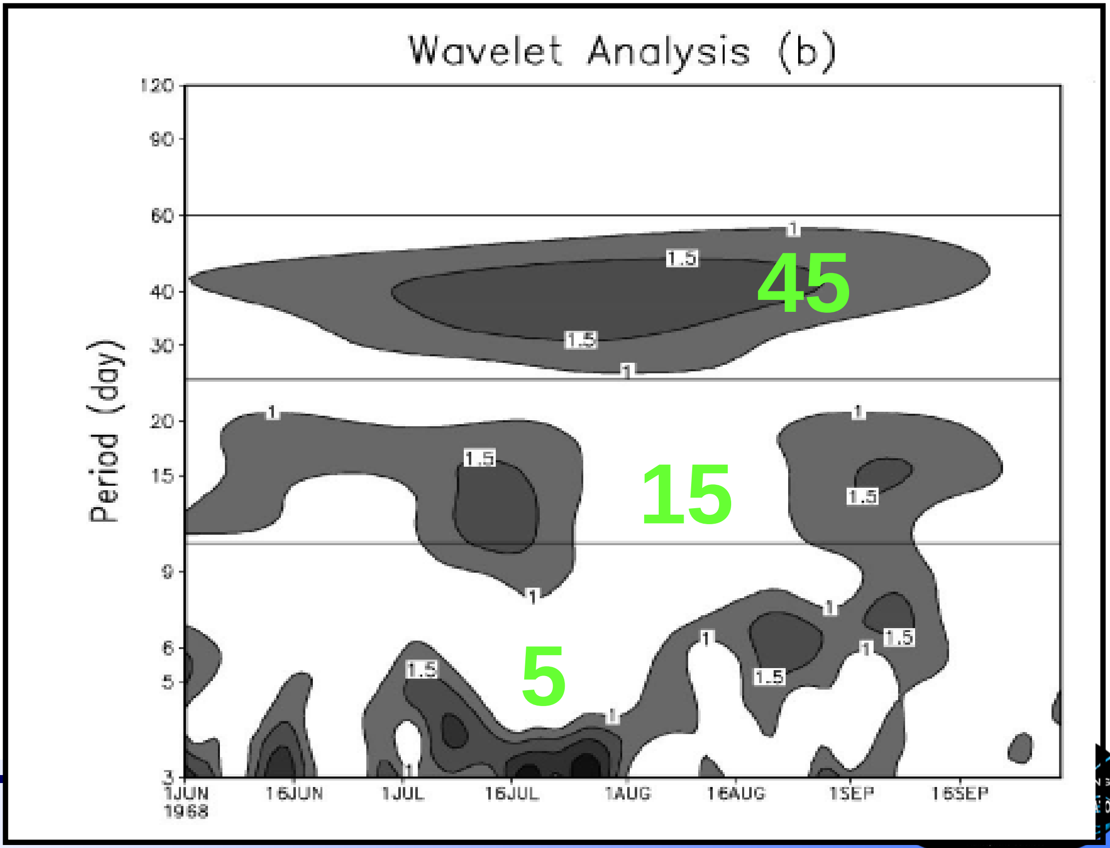
The West Africa monsoon (WAM) originates in the Gulf of Guinea when the thermal sea-land contrast turns the PBL flow to southwesterly, advecting ocean moisture inland and triggering the monsoonal rainfall.



The WAM rainfall shows <u>variability</u> on a wide range of time scales: from decadal trends to few days periodicities.

These many different time scales heavily affect the onset, the duration and the intensity of the monsoon.





Biblio: Le Barbe' et al., 2002; Sultan et al., 2003.